A Holistic Sustainable Approach to Small-Scale Water Desalination in Remote Regions:
Development of a thermal desalination method based on vapour transfer processes in water-filled bubble columns

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This thesis is submitted in fulfilment of the requirements of the Degree of

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Statement of Originality

This thesis is the result of my own research and contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Mario Schmack

A note on formatting and style

This PhD thesis is based on a number of published peer reviewed research papers. These documents, individually formatted according to journal requirements, are incorporated into the thesis along with additional text that introduces and links the published work. This structure allows for the development of a cohesive body of research that can be easily followed. The PhD thesis has continuous pagination, which can be seen at the bottom centre of each page. For the published documents, the original journal page numbers are also provided.
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Abstract

This thesis describes the development of a novel thermal desalination process based on the vapour transfer processes occurring in a water-filled bubble column. A strong focus on facilitating the involvement of local people and on promoting local capacity building by utilising simple technologies steers the research towards thermal desalination. The problem is addressed by first identifying alternative and previously unused water sources that can be utilised for sustainable water provision in remote places. The experimental analysis of a new desalination concept that combines a bubble column evaporator with a simple passive flat-plate copper condenser is then provided. A comprehensive condenser assessment under a range of different physical conditions that examine the effects of external water cooling, partial insulation and aspects of air circulation on condenser performance is presented. Subsequently, for the purpose of mitigating high bubble column vapour temperatures without risking greenhouse plant survival in a prospective Bubble-Greenhouse, an alternative set of cooling and pre-condensing devices is assessed. Based on the findings, a conceptual Bubble-Greenhouse design that promotes a holistic sustainable approach to combined water provision and community development is then described.

A prototype bubble evaporator is quantitatively and qualitatively assessed for the consistency of its performance and demonstrates a steady evaporation rate. The resulting data provides the basis for extrapolation of bubble evaporator capacity, both for relatively small standalone systems and for significantly up-scaled components that would operate in a Bubble-Greenhouse. In passive mode, condensate recovery rates of around 73% are achieved without the need for external cooling. Estimated by extrapolation, a standalone bubble desalination system with a 1m² condenser may produce around 19 litres of distilled water per day. The
common feature of the alternative set of cooling and pre-condensing devices is that they are easy to manufacture, of low energy demand and low investment cost and technically and operationally appropriate for local people in remote places. Under laboratory conditions, the passive copper tube concepts achieve water recovery rates of between 65-75% and the air cooled bubble condenser columns achieve condensate recovery rates of at least 50%. However, it emerges that a well designed latent heat recovery system is required to keep the energy demand of a thermal desalination system within acceptable limits, both technically and financially. Although the stacked evaporator-condenser bubble column array cannot demonstrate a significant cooling and condensing advantage over the flat-plate condenser, the concept facilitates the implementation of a heat recovery cycle. This attribute ultimately leads to the multistage evaporator-condenser module concept with an effective latent heat recovery system that is integrated into the horizontally stacked chambers, a key element of the Bubble-Greenhouse technology. The greenhouse desalination system is designed with a water production capacity of 8m$^3$ per day. Due to the strongly reduced water demand of plants inside a humidified greenhouse, only a fraction is required for irrigation and the bulk of water is intended for human consumption.

This study aims to contribute to the field of water service provision in remote communities, particularly by improving some of the shortcomings of conventional high-tech water treatment technologies that often fail in these situations. A comprehensive discussion posits the Bubble-Greenhouse concept in the context of these remote community water provision shortcomings and highlights how the proposed new treatment method aims to alleviate these. Consequently, the findings presented here may help to inform the essential transition from externally-led water service provision towards a self-determined community operated service, with significantly improved outcomes on the ground. A conclusion section with
recommendations for future research and recommendations for implementation of a Bubble-Greenhouse field trial conclude the thesis.
Publications arising from this thesis


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General Introduction

Water is a fascinating substance. Long before I recognised that it underpins all life forms on earth, its physical appearance whether in liquid, solid or gaseous form, never failed to astound me.\(^1\) As children growing up in Germany, we were always drawn to the large expanses of water that magically occurred after each year’s snow melt and I managed twice to completely submerge myself in the dark and icy waters of the fast flowing creek. Back then, there never seemed to be any shortage of water in our rural part of the world. However, there was the occasional sign of pollution, most often caused by excessive farming practices or by illegal activities such as cleaning out paint buckets into the creek in the dark of night. Over the years, a steady decline of amphibians was testament to a diminishing water quality.

In the 1980s and 1990s I worked for the local health department, in the field of drinking water screening. The majority of the water supply in the Hesse region comes from sweet groundwater, filtered through countless layers of sandstone. While this natural filtration system generally makes for excellent water quality, many of the deep wells utilised by the largest water corporation of the state are located right underneath an area previously occupied by the world’s biggest armmunitions factory during the Second World War. As a consequence, ever since the establishment of frequent and comprehensive quality screening, the water utility’s biggest concern has been if and when the Trinitrotoluene (TNT) residue would eventually be flushed out through the sandstone layers and pollute the drinking water.

\(^1\) I acknowledge that it is not traditional to use the first person in a science based thesis, however I wanted to situate myself in relation to the broad field of water science. I only used the first person in this Introduction chapter, the remainder of the thesis is written in the third person.
The occasional small village or unconnected dwelling on the outskirts of a town is not serviced by the large water utility and relies on their own water sources, often from shallow wells sunk into unconfined aquifers. During the winter months, these wells are regularly affected by elevated nitrate, a consequence of the generous application of cow manure onto frozen fields. It always astounded me that residents would risk polluting their own drinking water out of the economic pressures that result from the business of decentralised animal husbandry. This attitude neatly represents modern society’s emotional distance from nature generally and a disregard for water as an essential life-giving and -sustaining element. In contrast, Indigenous people in remote places who are still maintaining a close bond with nature through a hunter-gatherer mindset, view water as their cultural and spiritual lifeblood (Schelwald-van der Kley and Reijerkerk, 2009). This respect for water differs so much from our ‘modern’ use of water as a medium for disposing off and transporting away biological and industrial wastes.

In the modern world, the notion of progress is inseparably linked to economic growth, with the result that the prospect of short-term financial gain becomes irresistible (Jessop, 2002). European people with their inventive minds brought this worldview with them wherever they arrived and modern societies developed accordingly. While many of us may feel a strong connection and love for the natural world, it is impossible for us to comprehend the horror that must be felt by Indigenous peoples when they witness the tearing up of sacred places and the ‘accidental’ pollution of sacred waters, as a result of careless mining activities introduced to Australia and elsewhere. One only has to look at the scars left by the Wittenoom asbestos mines or the countless uranium exploration sites and consider that the ripped up contaminants will forever be distributed by flood events and ultimately infiltrate the ground and the groundwater many kilometres away. As ‘progress’ is reliant on the transformation of energy,
we are now entering a new and perhaps even more threatening development that could result in large-scale geological destruction and an unforeseen scale of groundwater pollution, caused by coal seam gas extraction (Sundaram and Coram, 2009).

While travelling through inland Australia, it is easy to recognise the hydro-geological peculiarity of the landscape that is expressed in large watersheds with no drainage to the surrounding oceans. Notwithstanding the modest precipitation in the arid landscape, a constant water recharge into underground basins occurs. As a result, extensive water reservoirs underlie vast areas of the continent but on its surface, remote Australia is characterised by a rarity of open water. The arid climate that has developed in response to the low precipitation and an annual pan evaporation rate that often exceeds annual rainfall figures by tenfold (Luke et al., 2003), conveys a strong sense of the preciousness of clean drinking water. Relying on a jerry can filled with no more than 20 litres of water teaches the remote traveller not to waste a drop. In light of this, it is perplexing that remote settlements, many of which were established during the outstation movement of the 1980s, nowadays experience water wastage on an enormous scale. While maintaining a reliable freshwater supply requires more and more effort, a running tap is often ignored and no one takes responsibility for turning it off.

Providing clean water for remote communities is technically and environmentally challenging and in addition, comes at a high financial burden (FDRC, 1994). Conventional water service provision to Western Australia’s remote locations, based on well-established water treatment technologies such as reverse osmosis (RO), often struggles to be sustainable in the long-term for two principal reasons. First, a large number of remote communities rely on the infrequent maintenance delivered by external service providers and as a result, infrastructure failures,
leakages and delayed repair operations cause substantial water wastage in these locations (Ho et al., 2009; 88). Second, residential disinterest to turn off running taps is an expression of the general lack of local ownership for the water supply and the resulting lack of residential responsibility for water conservation (DFID, 1999). In order to achieve sustainable water provision, it is crucial to address these two components by building local capacity and facilitate skills development so that residents are equipped and motivated to look after the water supply themselves. This in turn will build and enhance a feeling of ownership of the water supply system and provide a strong incentive for water supply protection.

In the spring of 2007, I prepared an integrated water management plan for Parnngurr Aboriginal community and visited Jigalong in the Western Desert with my subsequent PhD co-supervisor Dr. Martin Anda. Here I was able to gain deeper insight into the practical realities of remote community water provision. Parnngurr and Jigalong, both relatively large communities with over 100 permanent residents, receive the full range of essential water and wastewater services by the Remote Area Essential Services Program (Arup, 2005) and operate a school and a health clinic. Noteworthy, a distinct characteristic of remote communities that makes service provision particularly difficult is the large increase or decrease in population that can occur overnight due to ceremonies, sporting events or during periods of mourning (Anda et al. 2006). For the many communities with less than 50 residents that are now included in the RAESP program, the frequent population variation is even harder to provide with appropriately sized infrastructure.

While discussing perceptions of water quality and technical aspects of water provision and water quality management with Jigalong’s community members and resident health professionals, several points were highlighted that gave rise to the work presented here:
1. Conventional high-tech water treatment technologies such as reverse osmosis (RO), often fail in remote locations as their maintenance and repair relies on highly skilled external operators that are usually not immediately available;

2. As their operation is complicated they provide little opportunity for capacity-building processes from the ground up for local people;

3. Additional benefits, for example improved health outcomes from combining water desalination with local food production as realised in the seawater greenhouse concept (Davies and Paton, 2005), would enhance economic feasibility of a novel water treatment system;

4. A greenhouse type water and food enterprise would hold great potential for community involvement, local ownership and capacity-building.

5. The large population variability highlights the need for flexible water provision that can operate on a module basis, thus allowing for variable production rates in response to fluctuating population numbers.

By developing and assessing a novel water treatment technology with particular emphasis on technical, social and cultural appropriateness for Indigenous people, this thesis at its core aims to contribute to a new direction in remote community water provision. With the limited success rate of conventional high-tech solutions in mind, the first stage was to identify alternative and previously unused water sources with a relatively low technical demand, thus supportive of remote peoples’ sustainable development. The developing novel technology would have to satisfy the crucial proviso of facilitating the involvement of local people at all stages of the water provision process and to promote capacity building.
Specifically, this thesis describes the process from recognizing the shortcomings of conventional water provision, identifying potential novel ways of water treatment and the ability of these methods in regards to sustainable water provision in remote places. It then reports on the experimental work that was carried out to assess a novel humidification-dehumidification (HD) process on the basis of a bubble column evaporator coupled with simple condensation devices, as components for an innovative HD water system. From here it proceeds towards the conceptualisation of a multipurpose water and food producing greenhouse that facilitates capacity building and empowerment of local people in remote communities.

The overarching research objective that guides this thesis concerns the development of a new water treatment technology on the basis of bubble-column driven thermal desalination, as a means of sustainable water provision in remote communities. As the evaporation capacity of the bubble process has previously been highlighted (Francis and Pashley, 2009), the initial focus was on developing a condensing technology that could be matched with the bubble column evaporator and to assess whether the resulting HD concept would be technically, environmentally and economically feasible for remote locations. As a result of its flexible approach to the task of developing and informing this novel bubble-column based water treatment method, a subset of research questions emerged throughout the study that are separately addressed in the individual papers.

In Chapter I, the literature review is presented. Here, concepts and technologies relevant to the task of capturing water vapour from novel sources for the purpose of subsequent condensation in a greenhouse type or similar construction are examined. The research objective underlying this literature review is to identify novel water sources and suitable
technologies under particular consideration of the social, technical and environmental distinctiveness of remote communities. To this end, a wide range of desalination processes that utilise solar thermal energy as the principal driver for brackish and saline water desalination are assessed, beginning with simple passive and active solar stills to more elaborate concepts that are constantly evolving in order to increase their condensate output. Still-greenhouse concepts and the seawater greenhouse are also discussed. The paper then proceeds to evaluate the potential of evaporative brine technologies such as wind-aided intensified evaporation (WAIV), solar dryer technology or the bubble column as novel freshwater sources.

Chapter II contains a peer reviewed paper presented at the Ozwater 2013 Conference in Perth, Western Australia (Appendix 1). Here, a new desalination concept that combines a bubble column evaporator with a simple passive flat-plate copper condenser is introduced. The principal objective guiding this stage of the research is to determine how the vapour from a bubble column can successfully be trapped and condensed as a source for distilled water via a low-tech method. The flat-plate copper construction described here is originally manufactured in order to provide a defined section for quantifying the heat and mass transfer processes that occur on a condensation surface. In combination with the bubble column, the condenser prototype that subsequently evolves demonstrates strong potential as a novel stand-alone desalination concept akin to a solar still.

In Chapter III, a comprehensive assessment of the flat-plate copper condenser is presented. The overarching research objective of this publication is to assess and optimise the performance of the condensing surface under a range of different physical conditions. With this underlying principle in mind, but also with consideration for increasing the productivity
of a novel small-scale bubble column based desalination system at low cost impact, the condenser prototype is assessed in the context of several research sub-questions that examine the effects of external water cooling, partial insulation and aspects of air circulation on condenser performance. In addition, the bubble evaporator is quantitatively and qualitatively assessed for the consistency of its performance, with the findings allowing for extrapolation calculations towards larger-scale representations of the bubble evaporation technology. Consequently, while the paper to a certain extent discusses the bubble column and condenser concept as a stand-alone method for small-scale water production, the findings strongly inform the conceptualisation of an up-scaled water desalination system that combines a bubble-column-based HD desalination concept with a condensing greenhouse.

Chapter IV explores a range of simple vapour cooling and pre-condensing concepts that are assessed for the purpose of mitigating bubble column vapour temperatures, a critical aspect for the development of a bubble column driven greenhouse desalination system. The research objective steering this work aims at achieving sufficient vapour cooling under a number of important provisos such as low energy demand, low environmental impact, cost efficiency, ease of manufacture and maintenance, durability and technical and operational appropriateness for local people in remote places. Besides their vapour cooling potential, the condensing capability and condensate production rates of the tested devices form an important part of the assessment.

Chapter V draws on the findings from the literature review and the experimental Chapters II, III and IV and posits them into the conceptual Bubble-Greenhouse desalination concept. The Bubble-Greenhouse combines the well established Seawater Greenhouse technology with a novel HD process that is based on the large air/water interface generated by bubble
evaporators and condensers. The multistage bubble column modules allow for effective recovery and reuse of latent heat via a heating/cooling circuit throughout all column stages. In accordance with the previously stated requirements for sustainable community development, the technology is conceptually simple to implement and holds great potential for community participation, empowerment, skills development and capacity building of local people in remote communities.

In Chapter VI, a comprehensive discussion posits the Bubble-Greenhouse concept in the context of the shortcomings of current water provision in remote communities. By highlighting how the proposed new water treatment method aims to alleviate these shortcomings, the overarching research objective is addressed. The thesis reaches its conclusion in Chapter VII. Here, recommendations for future research that will inform optimisation of the technology and recommendations for implementation of a Bubble-Greenhouse field trial are presented.
References

Chapter I: Saline water desalination with vapour capture device:
a literature review of foundational technologies and underlying principles

Attribution

MS reviewed the relevant literature and drafted the manuscript. GH and MA provided feedback on draft. All authors critically reviewed and approved the final version.

MS: 90%
Saline water desalination with vapour capture device: a literature review of foundational technologies and underlying principles

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This review was motivated by the growing need for sustainable water supply technologies in arid lands worldwide. A key driver of this review is to evaluate the potential of presently unused freshwater sources such as from evaporative brine management technologies. In doing so, this paper provides a conceptual building block for innovative water systems in the future with a focus on ecologically, socially and economically sustainable freshwater production. The utilization of solar thermal and wind energy as the principal drivers for brackish and saline water desalination projects provides the link between the technologies and devices that are discussed and evaluated in this review. Of the solar still concepts reviewed, higher productivity rates are achieved with increased optimization of heat and mass transfer processes within the system and productivity is closely linked to the technological complexity of the stills. Water production ranges from 2 to 3 L/m²/day for passive stills up to 100 L/m²/day and more for novel systems with multiple latent heat use. Still–greenhouse systems and seawater greenhouse systems are capable of producing distilled water while providing a vital humid environment for the growth of crops in a greenhouse system. Water production rates of 0.5–2.5 L/m²/day for ‘still in a greenhouse’ systems and up to 55 L/m²/day for seawater greenhouses with improved passive condenser technology can be achieved. Water vapour producing technologies such as wind-aided intensified evaporation, solar dryer technology or the bubble column concept, are assessed for their potential to form part of a novel water desalination scheme.

Keywords: vapour capture; solar still; seawater greenhouse; brine management; bubble column

Introduction

Large tracts of inland Australia count amongst the most arid regions in the world with annual pan evaporation rates often exceeding annual rainfall figures by 10-fold.[1] As a result, surface freshwater expressions are rare and brackish groundwater is frequently the only source of potable water in remote Australia. In the past, implementation of well established but advanced desalination technologies such as reverse osmosis (RO) often failed to produce the desired outcomes.[2] By focussing on the utilization of novel and previously untapped water sources there exists large potential not only for sustainable provision of drinking water but furthermore, for capacity building and ultimately, for self-reliance for the development of remote communities worldwide.[3] The purpose of this paper is therefore to assess the potential of ‘green’ water production concepts that are principally based on the utilization of solar thermal and wind energy. Findings may inform the physical conceptualization of a project to capture moisture from brine evaporative technologies or from other water vapour sources, such as from a bubble column. Amongst the technologies reviewed in this paper are solar stills, ‘still in a greenhouse’ designs, seawater greenhouses, brine evaporation and dew collection concepts.

Capacity building

One of the key elements to long-term sustainability in developing communities is empowerment, participation and capacity building of local people.[4] The ability to improve performance and outcomes of development projects themselves, provides not only empowerment, but also allows for success to be celebrated, leading to further encouragement to participate. In the context of social and economic progress, the absence of a demand-responsive market system in many remote Australian communities confines the applicability of participatory methods to sectors such as natural resource management and essential services provision.[5] As such, these sectors provide some excellent potential for participatory programmes.

Variations of the concepts and technologies presented here may lead to the emergence of novel and environmentally inspired water schemes in remote regions. Principal requirements for such schemes, be it vapour capture devices, solar distillers or their large-scale counterparts such as brackish water greenhouses, are that they should be very simple, hardy, easy to maintain and repair by local people with limited technical means in order to facilitate skills development and self-reliance.[6] Besides the technical benefits of such installations (non-reliance on fossil

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fuels; source for potable water and agricultural products) the social benefits, if appropriately valued, can make these schemes viable, even if they may not be solely on the basis of their water production rate. Furthermore, it is crucially important for these schemes to strike the right balance between efficiency and green development.

**Literature review**

**Distillation for survival**

A simple method that can be used to gather small volumes of fresh water in arid regions is by collecting evapotranspiration from the leaves of bushes or small trees.[7] This is done by wrapping a suitably leafed plant in a large sheet of clear plastic and channelling the water droplets that condense on the underside of the plastic into a container. Making use of the same physical principles that drive the process described above, solar still distillation has long been used to gather small amounts of potable water.

**Simple solar stills**

A solar still can be built very easily. It consist of a sealed box with a basin that contains dirty or salty water and a transparent cover that allows for sun rays to enter the enclosure.[8] Solar energy is absorbed by the contaminated water and provides water molecules with the energy needed to evaporate away from the water body and enter the still cavity above as water vapour. As the warm vapour laden air comes in contact with the cooler surface of the glass cover, the loss of thermal energy through conduction reduces the ability of water molecules at the glass–air interface to remain in a vapour state. As a consequence, the reduced energy state forces water molecules to liquefy, expressed as condensation. As more and more water molecules condense, droplets of desalinated water form and are pulled by gravity to run down the sloped underside of the cover into a gutter, where they are collected.[8] In its most basic form and under optimum climatic conditions a basin type solar still of 1 m² may produce up to 4L of distilled water per day.[9]

In the 1960s, the solar still principle was considered capable of producing drinking water on a large centralized scale for inland Australia. Based on the development of a prototype bay type still by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Melbourne,[10] a large-scale solar distillation plant was installed in Coober Pedy in order to purify saline well water for people and livestock.[11] Regrettably, the technology failed to gather momentum due to a number of reasons, such as large physical footprint requirements, low water output, dependence on sunshine and a relatively high initial cost.

The principal drawback in solar still distillation technology stems from the double function of the transparent cover. There are effectively two physical processes occurring inside a still. First, there is evaporation or humidification which primarily relies on the maximum amount of solar radiation as energy that can enter the still cavity. Second, there is condensation or dehumidification which relies on the temperature difference between the vapour laden air inside the still and the condensation surface. As both processes are directly dependent on the transparent cover, each process is somewhat hindered by its counterpart. Solar input into the still is hindered by reflection effects (Mie scattering) resulting from the condensed droplets inside the glass cover[12] and the high temperature inside the still adds to the warming of the condensing cover, thus reducing condensation. In addition, the release of latent heat from condensation further contributes to the warming of the glass cover, resulting in even lower productivity. In order to overcome these problems affecting still efficiency and to increase their water production rate, many innovative solar still concepts have been developed. A number of comprehensive reviews on the current status of solar distillation and the most recent developments in solar still technology are available in the literature.[13–15] Following is a review of some popular still concepts, illustrating many of the underlying aspects and physical principles that are relevant to the present study.

**Innovations to increase distillate output**

Generally, solar stills can be classified as passive and active stills. Passive stills can be further divided into basin type and wick type stills. In both cases, solar energy, that is directly received by either the basin water (basin type still) or the evaporation surface (wick type still), is the only energy source driving the process. The main factors affecting productivity in passive stills, and are thus subject to ongoing research work, are basin water depth, basin material, wind velocity, solar radiation, ambient temperature and inclination angle.[15] In contrast, active stills aim at increasing distillate output via improving the evaporation rate, either by pre-heating the contaminated water before it enters the basin (via the use of solar heaters or solar concentrators), or by employing different concepts of waste heat recovery. Taking the concept of waste heat recovery further, numerous multi-effect systems have been developed. A qualitative and quantitative comparison of the different still systems, including the much larger but essentially similar greenhouse concepts, is summarized in Table 1 and these stills are elaborated further below.

**Passive stills**

As the rate of condensation or dehumidification relies primarily on the temperature difference between the moist air inside the still and the condensation surface,[16] there are a number of ways to improve water output of a basin type still, either by increasing the basin water temperature or by decreasing the cover temperature, or both. One approach is
to cool the outside of the glass cover with flowing water.[17] By adjusting water flow at a uniform velocity, Tiwari and Bapeshwara Rao [17] achieved maximum cooling effect of the cover. As a result, distillate output of the cooled system almost doubled compared with a non-cooled cover still. A different approach to increasing the temperature deviation between the basin water and the glass cover is by passively increasing basin water temperature. This can be achieved in a number of ways. One method is to incorporate black basin liners in order to increase absorptivity.[18] Srivastava et al.[18] described the effects of absorptivity on basin temperature and distillate output. They found that as basin liner absorptivity values increased from 0.10 to 0.90, peak distillate output increased up to fourfold.

In wick type stills, evaporation commonly occurs off the surface of one or more pieces of blackened jute cloth.[13] The cloth is dipped in a saline water tank and kept wet by capillary suction. Two of the foremost problems affecting conventional solar stills are alleviated by modifying the evaporation surface via the use of wick material. First, the water surface in a conventional basin is horizontal, while a wick can be attached at an incline, thus being able to intercept maximum solar radiation. Second, the large thermal capacity of the basin water requires more energy, while in a wick type still significantly less water mass needs to be heated in order to achieve maximum evaporation. Consequently, experimental analysis confirmed that multiple wick stills are able to outperform their conventional counterparts, either through increased distillate production,[19] or based on their significantly lower cost compared with a conventional basin type still.[20]

An unusual approach to increase the distillate output of a passive solar still is to bubble ambient air through the water contained in the basin.[21] Initial tests with humid ambient air resulted in a modest distillate increase of 6–7%. After drying the ambient air previous to bubbling, by channelling it through a series of CaCl2 moisture traps, an overall distillate increase of 33.5% was achieved. The author suggested that this method could be effective in the absence of solar radiation and could thus allow for nocturnal distillation, further increasing the overall productivity of the still. In regards to the forced airflow required for the bubbling process, the author proposed the development of a technology (e.g. tunnelling) that could utilize available wind energy.

### Active stills

Active solar stills are characterized by external water heating components, with the aim to supplement the solar radiation input that heats the still basin directly. By preheating the feed water and thus, achieving higher basin water temperature and air temperature inside the still cavity, distillate output can be increased. There are a number of ways to raise feed water temperatures, for example, by coupling a solar still with a flat-plate solar collector or by maximizing heat recovery in multi-effect solar stills.

The heat storage effect of active stills can extend distillate production well beyond sunshine hours.[22] Moreover,
by achieving the necessary still basin temperatures through external heat generating methods, the condensing cover is liberated from one of its previous functions, namely as an entry point for solar energy. Consequently, it can be altered in a number of ways, for example, by coating the glass cover.[23] Investigating the effects of condensing cover alteration, Varol and Yazar [23] modified a single-basin solar still coupled with a flat-plate solar collector by applying a thin coating layer of SnO2 to the upper side of the transparent cover plate. The layer of SnO2 was found to lower thermal radiation loss, one of the major sources of heat energy loss inside a solar still, while retaining a lower condensing cover temperature at the same time. As a result, Varol and Yazar achieved a distillate yield of 6.7 L/m2/day or an overall yield increase in more than three times that of a conventional still.

Due to individual thermal conductivity properties, the type of condensing cover material and condensing cover thickness are directly related to the amount of condensation produced.[24] Investigating a range of materials, Dimri et al.[24] found that copper gave a greater yield compared with glass and plastic as a result of its superior thermal conductivity. By relying exclusively on heat exchangers or solar collectors for heating the basin water to its required temperature, they confirmed that the glass cover was not obligatory as an entry point for solar radiation. Consequently, the condensing surface could be substituted altogether by a different material with superior thermal conductivity, thus increasing the rate of condensation and distillate production rate.

While employing the same physical principle as a conventional still, a humidification–dehumidification (HD) system described by Nafey et al.[25] that incorporated a solar water heater, solar air heater, humidifier tower and dehumidifier exchanger had little resemblance to the original solar still concept. In addition to pre-heating the brackish water, the concept involved pre-heating the air before it entered the evaporator (humidifier tower). The dehumidifier was a water-cooled copper-coiled condenser unit with aluminium fins. By optimizing the relevant parameters such as feed water flow rate, inlet air temperature, cooling water temperature, solar radiation and wind speed, the system was capable of producing more than 10 L/m2/day of distillate.[25]

El-Bahi and Inan [26] describe a different solar still concept where evaporation and condensation processes are spatially separated. Their system utilized the naturally occurring pressure difference that developed as a consequence of temperature differences between the heated evaporator unit and the colder outside condenser. A basin type solar still with minimum inclination (4°) was connected to an external condenser. In addition to the direct solar radiation heating the basin, the feed water was preheated by using a solar reflector. While a small amount of distillate was condensed on the underside of the glass cover, the bulk of water vapour was purged to the outside condenser due to pressure difference between the evaporator and condenser. In this way, the system produced a distillate yield of up to 7 L/m2/day without the need for mechanical pressure reduction and the associated energy demand.

**Latent heat recovery**

Spatially separating the regions where evaporation and condensation occur results in a reduced loss of latent heat of condensation onto the glass cover and thus, passively increases productivity of solar desalination units.[14] By recovering the latent heat of condensation and integrating it into a HD process, efficiency of a solar distillation system can be improved even further. This becomes clear when considering the large amounts of condensation energy lost from a conventional still. Fath et al.[27] estimated that the combined evaporation, convection and radiation energy received by the condensation surface of a conventional still represented about 40–50% of the energy lost to the atmosphere. In order to overcome this problem, they developed a stepped still made from aluminium sheeting and glass cover that contained a series of insulated black coated water basins (Figure 1). A central stepped absorber sheet divided the still into an upper section (evaporation chamber) and lower section (condensation chamber). The dividing structure functioned as a latent energy storage system for after sunset energy recovery. For this purpose, it contained two phase change materials, Paraffin wax for basin energy storage (absorber and storage) and Glauber’s salt for condensation energy storage and recovery (passive condenser and storage). As circular movement of air between the upper and lower chamber was an essential element of the concept, Fath et al.[27] investigated the effects of forced versus natural circulation. They found that still productivity in the naturally circulated mode was about 5.1 L/m2/day, similar to that of a forced circulation model.

An interesting concept that is based on wick type stills while focusing on the recovery of latent heat is the diffusion type still, described by Ouahes et al.[6] Instead of a jute cloth, this still utilized a very thin fabric comprising a single, finely woven layer. This fabric was kept in contact with an overhanging steel plate via the formation of a capillary film at the plate fabric interface. The metal plate acted as a heat exchanger and the heat dissipated by the condensation of steam on the front face of a metal plate was used on the back face of the plate for the evaporation of an equivalent quantity of water.[28] Based on the highly efficient use of latent heat within the system, the still was capable of producing 15 L/m2/day of distilled water.[6]

A novel system that combined many of the aforementioned aspects used a series of evaporators (triple-effect evaporators) for distillation (Figure 2).[29] Solar thermal energy was transferred from evaporator to evaporator by the movement of steam. The low temperature of the raw brackish water provided enough cooling throughout daily operation. A large storage tank, filled with heated brine during the day, effectively provided a large heat sink.
night time and in accordance with the ambient temperature drop, this water-cooled down and nocturnal distillation inside the system added to water productivity. In order to maximize vaporization of water molecules from the liquid phase, the system operated under vacuum evaporation conditions. Due to its complexity, its efficient utilization of heat and mass transfer processes through repeated use of latent heat, and innovative wastewater use, water productivity was many times larger than in conventional solar stills. In addition to the high distillate output, the system was exclusively powered by solar energy (flat-plate solar collectors and solar cells for electric power generation), making it completely independent from non-renewable energy sources.

Dewvaporation is a multi-stage HD concept, characterized by its highly efficient utilization of latent heat.[30] Dewvaporation towers contain two chambers separated by an internal heat transfer wall, one for evaporation and the other for dew-formation.[31] The latent heat required on the evaporation side is provided by the heat released from dewfall condensation on the opposing side. Only a small amount of external energy input is required to boost the steam temperature resulting from the evaporation side for the return into the condensation input side. This allows the system...
Figure 3. Greenhouse distillation concepts. (a) Still in a greenhouse [37]; (b) seawater greenhouse [40]; (c) air flow in the Watergy greenhouse during daytime and night time.[49]

to be operated with a number of low grade heat sources such as solar or waste heat. Due to its optimized latent heat reuse, operating cost for a 3.8 m$^3$/day unit is less than $4 per day.[32]

**Up-scaling the still concept**
The idea to build a large solar still and integrate it into a greenhouse for crop production has been around for some time.[33] Various theoretical models and experimental studies on different greenhouse-still concepts can be found in the literature.[18,34–36] In general terms, the aim is to tailor and optimize the HD process inside a greenhouse, while making use of the structural components of the greenhouse itself, primarily as a condensing surface.

**Still in a greenhouse**
In a recent study, García Marí et al.[37] described a system consisting of a medium-sized greenhouse (approximately 60 m$^2$ footprint) that was stacked with 28 water basins, resulting in a total evaporation surface of 28 m$^2$ (Figure 3).
Unlike in conventional stills, water vapour evaporating from the basins was not trapped by individual basin covers, but instead filled the sealed top part of the greenhouse, described as the ‘solar still cavity’. The greenhouse roof acted as the condensation surface. Integrating a still assembly into a greenhouse in this way, several points needed to be considered. First, the still structure in the roof area strongly influences the intensity of solar radiation (impacting on greenhouse heating) and photosynthetically active radiation (PAR – responsible for plant growth). Second, a crucial aspect in a greenhouse combined with a still is the risk of overheating and the resulting risk to plant survival. In this context, the thermal inertia of the greenhouse cavity (growing area) needs to be sufficiently greater than the still area, in order to stay within the temperature limits for horticultural crops.[37]

In order to allow for maximum solar radiation to be transmitted to the crop area, Garcia Mari et al.[37] used transparent basins in their greenhouse-still design. As a result, radiation absorption into the basins was low, leading to reduced evaporation and thus, a significantly lower distillate output (0.5 L/m²/day) compared with conventional solar stills. They suggested that one method to overcome this problem could be to add a specific additive to the basin water that was capable of absorbing far infrared radiation and transmit the PAR spectrum to the crop area inside the greenhouse. As this would result in more heat being captured inside the basins, air temperatures inside the greenhouse would be maintained lower. Consequently, there would be less need for ventilation (greenhouse cooling) and irrigation requirements would also decrease given the reduced crop transpiration.[37]

A problem affecting large greenhouses is the development of a thermal gradient along the direction of the airflow.[38] Kittas et al.[38] found that the use of evaporative pads and extracting fans in a commercial greenhouse of 60 m length resulted in large temperature gradients of up to 8°C from pads to fans. They noted that while high ventilation rates and shading reduced the temperature gradients inside the greenhouse, increasing ventilation rates could also lead to enhanced plant transpiration and thus, contribute to plant water stress.

Investigating a comparably sized greenhouse-still concept in an arid environment, Radhwan and Fath[39] reported a distillate production of up to 2.5 L/m²/day. They noted that plants inside the humidified greenhouse required as little as 10% of the fresh water demand of plants grown outside a greenhouse. Due to this strongly reduced demand they suggested that solar distillation inside a greenhouse could, in most cases, provide the water needed for plant irrigation. An added benefit of the greenhouse-still system was that the distillate produced inside the greenhouse did not need to be stored or transported but was immediately available for irrigation. However, the downside was — not unlike a conventional greenhouse — its tendency to strong heating and the need to cool the greenhouse in a hot climate in order to protect plants from heat stress.

The seawater greenhouse
So as to overcome two major problems associated with still—greenhouse systems — limited heat absorbing capacity of water basins inside a greenhouse and the general necessity for greenhouse cooling — feed water vaporization and temperature control may be carried out by using customized evaporators. This idea led to the development of the seawater greenhouse concept, where a large greenhouse structure was humidified by trickling surface seawater down porous evaporators, made from cardboard honeycomb lattice (Figure 3). [40] As air was fanned through the evaporators, the greenhouse was humidified. A condenser, which was cooled using cold deep seawater or cool seawater from the evaporators, was then used to dehumidify the saturated air and produce fresh water. In this way, the greenhouse acted as a solar still while providing a controlled environment suited to the cultivation of crops inside the greenhouse. The most cost-effective greenhouse construction was based on a standard wide span poly-tunnel greenhouse and the roof material for the greenhouse was a film with very high transmission (60%) of PAR but with a low transmission of infrared, resulting in a total energy transmission of 38%. [40] One of a number of follow-up studies found that the greatest overall effect on distillate productivity and energy efficiency was determined by the dimensions of the greenhouse.[41]

The performance of the seawater greenhouse could be improved by placing an array of plastic pipes through which seawater was circulated, above the growing area. [42] While this array was primarily intended to preheat the feed water, it provided a number of additional benefits. First, based on the superior ability of water to extract heat from the greenhouse as compared with air, the temperature was kept lower in the centre of the planting area. Second, the installation provided shading, which in turn further reduced the need for greenhouse cooling. The warmed seawater from the pipes was fed into a second evaporator (back evaporator) inside the greenhouse, thus boosting fresh water production (≈ 5L/m²/day, based on greenhouse footprint). The downside to the addition of a pre-heating system inside the greenhouse was the considerable energy demand due to water pumping requirements. This added to the already large electric energy demand required by the greenhouse to produce fresh water.

The principal power consumers in the system were the feed pump (seawater), cold tank pump (evaporator), hot tank pump (second evaporator), wall fans and roof fans. [43] In an attempt to overcome its demand on fossil fuels, Mahmoudi et al. [43] assessed the feasibility of using hybrid (wind and solar) energy conversion systems to meet the energy needs required by a seawater greenhouse. It was found that corresponding with peak solar radiation, between
9 a.m. and 5 p.m. the greenhouse produced 98% of the total freshwater by relying solely on wind and solar energy. This suggested that it could be technically feasible to power the seawater greenhouse with renewable energy, without the back-up support of fossil fuel energy sources.

The condenser design in seawater greenhouses is recognized as one of the main bottlenecks in the commercialization of the technology.[44] Economically, the large energy demands of pump-driven condensers add significantly to the relatively high cost of freshwater produced from seawater greenhouse distillation. In addition, tubular condensers commonly used in seawater greenhouse desalination are at risk of developing leaks in pipes which in turn could contaminate the distillate. Aimed at reducing energy demand and increasing condenser productivity, Mahmoudi et al.[44] investigated new passive condenser concepts that were based on the natural circulation of water in response to density and temperature gradients. By assessing condenser productivity via the development of a mathematical model, their findings indicated that the passive condenser had a much greater water production capacity (up to 55 L/m²/day) than the existing pump-driven system and thus, that the passive containment cooling system was a promising improvement in the further development of greenhouse desalination.

The watergy greenhouse

A greenhouse concept that significantly reduces the need for fan and pad cooling systems and water-cooled condensation was described by Janssen et al. (Figure 3).[45] The Watergy greenhouse is a closed system, designed for free air circulation based on the buoyancy of moist air.[46] The system essentially represents a solar-driven cooling system where air is being channelled into a buoyancy tower by convection and cooled during the day with an integrated central heat exchanger.[47] In this way, the effective utilization of heat transfer processes that occur during the combined evaporation and condensation processes inside the system are sufficient to cool and heat the Watergy greenhouse.[46] In addition to the convective airflow concept inside the greenhouse, a number of design parameters are crucial to its effectiveness. The greenhouse skin is manufactured from near infrared radiation—reflective cover material that blocks up to 50% of the outside solar energy from entering the greenhouse, thus reducing cooling requirements.[47] Due to its high reflectivity, it was suggested that this material could also be integrated in the design of a parabolic or circular shaped reflector, which would in turn deliver sufficient electric energy to drive a photovoltaic (PV) cell at its focus. This energy could then be used for a back-up fan and pad cooling system or for desalination and/or energy supply.[47] Due to its closed nature, the system was found to reduce water consumption by 75%, while continuous plant production even during hot summer conditions was demonstrated.[48]

Table 2. Water production cost of HD systems.

<table>
<thead>
<tr>
<th>Still type</th>
<th>Capital cost (m²)</th>
<th>Operating cost</th>
<th>Energy cost per m³ water (PV and other)</th>
<th>Approximated water production cost per m³ (for 20-year life cycle)</th>
<th>Total energy requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple basin still</td>
<td>A$ 100–300</td>
<td>Minimal</td>
<td>none</td>
<td>A$ 20 (for 1 m² still size)</td>
<td>• Solar</td>
</tr>
<tr>
<td>Passive improved stills (basin liner, wick type, etc.)</td>
<td>A$ 300–500</td>
<td>Minimal</td>
<td>A$ 12</td>
<td>A$ 25 (for 1 m² still size)</td>
<td>• Solar (incl. pumps)</td>
</tr>
<tr>
<td>Active improved stills</td>
<td>A$ 400–1000</td>
<td>Minimal</td>
<td>A$ 12</td>
<td>A$ 30 (for 1 m² still size)</td>
<td>• Manual</td>
</tr>
<tr>
<td>Latent heat recovery stills</td>
<td>A$ 400–1000</td>
<td>Low</td>
<td>A$ 8</td>
<td>A$ 25 (for 1 m² still size)</td>
<td>• Solar (incl. pumps)</td>
</tr>
<tr>
<td>Novel systems with multiple latent heat recovery</td>
<td>&gt;A$ 1000</td>
<td>Low</td>
<td>A$ 2</td>
<td>A$ 7 (for 1 m² still size)</td>
<td>• Solar (incl. pumps)</td>
</tr>
<tr>
<td>Still in a greenhouse</td>
<td>&gt;A$ 50</td>
<td>Moderate</td>
<td>A$ 4.5</td>
<td>A$ 14 (for 60 m² greenhouse area)</td>
<td>• Solar (incl. pumps)</td>
</tr>
<tr>
<td>Seawater greenhouse</td>
<td>&gt;A$ 40</td>
<td>High</td>
<td>A$ 3</td>
<td>A$ 5 (for 750 m² greenhouse area)</td>
<td>• Fossil fuels (cooling; ventilation)</td>
</tr>
<tr>
<td>Seawater greenhouse with passive condenser</td>
<td>&gt;A$ 40</td>
<td>High</td>
<td>A$ 1.2</td>
<td>A$ 1.5 (for 750 m² greenhouse area)</td>
<td>• Solar (incl. pumps)</td>
</tr>
</tbody>
</table>

Economic considerations

In terms of economics, actual water production costs naturally decrease with an increase in technological complexity and plant scale (Table 2). For a cost comparison, the price of scheme water in Australia that is commonly blended from water conservation measures, desalination, recycling and
groundwater supplies, lies between $1 and 2 per m$^3$.\[50\] In contrast, a supply from 1500km away, as considered by proponents of a Kimberley to Perth Canal would cost in the order of $5–6 per m$^3$.\[50\] For the large majority of passive and active solar stills the energy demand is less problematic as it is satisfied exclusively with solar radiation. For greenhouse-still designs and the increasingly larger seawater greenhouses, energy demand becomes a critical factor. This is strongly influenced by the width to depth ratio of the greenhouse. In simulation studies it was found that a wide shallow greenhouse with an overall planting area of 200 m wide by 50 m depth consumed 1.16 kWh/m$^3$, while a narrow deep structure (50 m wide by 200 m depth) consumed 5.02 kWh/m$^3$.\[51\] As a comparison, the current energy requirement benchmark of Sea Water RO desalination processes is 3.5 kWh/m$^3$.\[52\] Locally, at the Kwinana RO facility in Perth, Western Australia the total energy used per unit of water is approximately 4.6 kWh/m$^3$.\[52\]

**Brine management technologies**

Open surface evaporation ponds are often used in the separation of minerals from brackish water or seawater or in the reduction of water content from large-scale desalination operations.\[53\] The water vapour evaporating off the open water surface is released into the atmosphere and carried away by air transfer. The major drawback of these evaporation ponds from an economical point of view is their large physical footprint. Environmentally, the water vapour evaporating into the atmosphere can potentially be a valuable fresh water resource. However, due to the large size of the evaporative surface, an attempt to capture the water vapour rising from an evaporation pond would require a very large and economically as well as technically impractical capture device.

A broad range of alternative brine concentration processes have been developed, for example, with the aim to develop zero discharge desalination systems \[54\] or for the purpose of sequential extraction of valuable chemical products from inorganic saline waters.\[55\] These processes often have a significant energy demand and alternative sources such as thermal energy from salinity-gradient solar ponds are being investigated as a means to provide the energy required by brine concentration processes.\[56\] A common feature of the processes described below is their aim to reduce physical footprint demand and as a consequence, a more concentrated vapour release. Capturing the water vapour and utilizing it as a valuable resource for distilled water could potentially add economical and ecological value to brine concentration processes and allow offsetting some of the process running costs.

The evaporation rate in open ponds under environmental conditions is around 4 L/m$^2$/day.\[57\] In order to reduce the footprint area required for evaporation ponds, Arnal et al.\[57\] aimed to increase the natural evaporation rate by placing adsorbent materials floating on top of the brine. A number of different adsorbent surfaces were exposed to wind action and were kept wet by means of capillarity. The tests were performed using varying air speeds in the range between 1.8 and 7.2 km/h. Results showed that after 170 h of test evaporation and maximum air velocity, the best performing adsorbent exceeded the open water surface comparison by 100%. This suggested that the use of surface absorbent materials could reduce evaporation pond sizes. However, the surface area reduction resulting from this application would still be impractically large for vapour capture.

A technology that allows for multiple reduction of the physical footprint area required for brine management is the wind-aided intensified evaporation (WAIV) system (Figure 4).\[58\] By stacking a large number of vertically
mounted and continuously wetted evaporation surfaces with packing densities of 20 m$^2$/m$^2$ footprint, Gilron et al.[58] found that WAIV evaporation was 13-fold based on a footprint-to-footprint comparison with open pan evaporation. This was despite the fact that the close packed array of evaporation surfaces resulted in a certain drop-off in efficiency relative to open pan evaporation (evaporation rates of up to 90% of those of open water surfaces could be achieved). Based on these figures, a WAIV unit would significantly minimize spatial moisture output and thus, strongly improve the prospect of capturing its water vapour product.

Collares-Pereira et al.[59] developed a solar dryer concept with the aim to improve the economical and environmental performance of a multi-effect distillation desalination plant. The solar passive dryer prototype was built on the basis of a thermal convection multi-sectoral greenhouse, supplied with a single central solar chimney. Solar irradiation absorption heated the inside of the greenhouse and the solar chimney. The driving force for the airflow necessary for effective brine evaporation was the pressure difference between the cold atmospheric air and the heated air inside the solar chimney (thermosiphon effect). A layer of brine was placed inside the greenhouse and heated by solar irradiation absorption. The resulting water vapour was constantly removed through the chimney, subject to the convective force. The system was capable of evaporating the same amount of brine as an open evaporation pond for a 10 times reduced footprint. Moreover, due to its construction the vapour was effectively ‘captured’ inside the greenhouse and released over a very small area (chimney radius was approximately 1/10th of the greenhouse radius). This effectively reduced the vapour release area by a factor 100 as compared with an open evaporation pond, thus making it very practical for vapour capture.

**Alternative water vapour sources**

The bubble column concept has recently emerged as a potential basis for a new method of salt water desalination (Figure 5). The unusual property of salt water to inhibit air bubble coalescence facilitates the design of a bubble column with a high volume fraction of small air bubbles, continuously colliding but not coalescing. Compressed air or nitrogen gas is pumped into a column that contains salt water, at process temperatures well below boiling point. The inhibition of bubble coalescence and the oscillating rise of bubbles results in a large and constantly renewed gas/water interface and thus, uniform and efficient exchange of water vapour into the bubbles. Maximum saturation (saturated vapour pressure) is achieved within a travel distance of less than 20cm. The resulting water vapour can be captured, transferred and then be condensed and collected as potable water.

Based on the highly efficient vaporization of water and the relatively low energy demand that can potentially be

![Figure 5. Bubble column desalination concept.][60]
provided from solar collectors or waste heat from industrial processes nearby, bubble column desalination may hold a number of potential advantages over current commercial desalination technologies. The point source release of vapour over a very small area as realized by the bubble column would allow for maximum and efficient vapour capture and therefore provide an excellent source of vapour for the development of a vapour capture device. In addition, the cooling effect observed in a continuous bubble column [61] could be utilized for cooling requirements inside a greenhouse that may also function as a condensation chamber.

Condensation

A key to the feasibility of novel HD concepts is their potential for ‘low energy demand condensation’, so as to eliminate the need for conventional condensers that have a number of technological and economical disadvantages, the underside of a greenhouse roof structure may be considered as the principal condensing surface in vapour capture – condensation systems. Here, maximizing the utilization of radiative cooling processes and recovery and effective reuse of latent heat transfer are two ways to increase condensation rates. Some of the underlying principles relevant to this concept can be found in the science of dew collection.

In dew collection systems, the condensing surface is often provided by roofs of houses and sheds, most commonly made from corrugated sheet metal. The temperature difference between the moist air adjacent to the roof and the roof material itself is a determining factor for the condensation rate. Therefore, roof materials need to satisfy primarily one condition, that is to lose heat by radiative exchange more rapidly than the surrounding air.[62] If the cooling rate of the material is fast enough to cool down to the dew point temperature of the surrounding air, condensation will occur. Besides the financial benefits of using already existing roof structures, there is an additional advantage in that water is produced high up on roof tops and thus, water distribution into houses (or greenhouses) can be gravity fed.[63]

Dew condensation strongly depends on the optically selective and adhesive properties of the condensing surface.[64] One method to increase the yield of dew harvesting is by modifying the emitting properties of the condensing surface.[65,66] In their experiments, Muselli et al.[66] investigated the radiative cooling properties of condenser foil made of TiO2 and BaSO4 microspheres embedded in polyethylene. This material demonstrated improved emitting properties in the near infrared spectrum and as a result, a significant gain in dew collection. By comparing their condenser design with a horizontal Plexiglas reference plate, Muselli et al.[66] found that for a period of 478 days there were 145 dew-formation days for the reference plate (30%) but 214 dew-formation days for the condenser (45%). Overall the dew yield of their collector was quite low, at around 0.12 L/m²/day. Using an improved condenser design with optimized angle for funnel cooling (30° with respect to horizontal), the dew collection rate could be increased to 0.15 L/m²/day.[67]

Discussion

A number of brine concentrating technologies have demonstrated considerable evaporation rates on a strongly reduced physical footprint. This has made them potentially very interesting as a source for desalinated fresh water via the process of moisture capture and subsequent condensation. As centralized desalination processes (e.g. RO seawater desalination plants) become more important in a world of diminishing freshwater supplies, their environmental as well as economical sustainability is strongly linked with the management of brine. The separation of valuable minerals from brine wastewater is already the focus of economic improvements to brine management processes.[68] By considering the previously unused but potentially valuable fresh water component in brine, the cost of brine reduction technology and thus, desalination itself, could be further offset.

The major obstacle to vapour capture from open evaporation ponds is their large footprint, thus rendering such a scheme neither practical nor economically feasible. Applying the vapour capture concept to a WAIV evaporation unit is also problematic, as it would restrict free airflow — the prime feature making the WAIV technology feasible. A better option would therefore be to focus on technologies with a very small (point source) vapour release area, such as the solar-drier chimney. Better yet, bubble column technology offers a very controllable and efficient evaporation process and allows for easy channelling of the water vapour into a condenser device, thus making it an excellent component for a vapour capture and condensation scheme. However, unlike the before mentioned solar-driven evaporative concepts, operating a bubble column in this context requires future investigation into the feasibility of solar, wind or wave power as an energy source required to produce compressed air for the bubbling process.

Solar stills and seawater greenhouses make use of the HD process in one way or another while generally aiming to utilize ‘green’ energy sources. Many of the concepts discussed above are relevant to the humidification process that occurs in brine concentrating technologies (e.g. pre-heating brine via solar collectors prior to treatment). In developing and assessing a device to capture and condense the moisture from evaporative brine technologies or a bubble column, primary focus is on the condensation or dehumidification side. Here, many of the concepts discussed in the review play a significant role in the optimization of a vapour capture scheme.

The condensation chamber could potentially resemble a large greenhouse, possibly in combination with crop production. Depending on its requirements regarding the solar radiation spectrum, the condensation chamber could...
make use of selective films that reduce transmission of infrared radiation [40] or perhaps be coated in order to restrict solar heating of the chamber.[23] The choice of condenser will strongly influence the feasibility, both practically and economically, of a moisture capture system. If the underside of a greenhouse skin is utilized as the sole condensing surface, cooling the outside of the film via a sprinkler system – comparable to the water-cooled basin still design described by Tiwari and Bapeshwara Rao [17] – can improve the condensation rate during daytime hours and thus, increase distillate production. Alternatively, passive condenser systems developed for the seawater greenhouse could be used.[44]

Aiming to be a ‘green’ technology, vapour capture and condensation would perhaps only be feasible without the need for large fans and excessive pumping requirements. With this in mind, a strong focus would be to capitalize on the temperature difference that occurs in response to the difference between the warmer capture device and the cooler condenser chamber, as a means of circulating the moist air.[26,45–48] Where pumping is required (e.g. sprinkler systems), energy needs could be satisfied by solar cells [29] or waste heat from brine evaporation ponds.[56]

Future research should aim to gain a thorough understanding of the heat transfer processes that drive the condensation rate inside a condenser chamber (i.e. greenhouse). This will provide the basis for an optimization of the efficiency of a vapour capture and condensation system. Amongst the aspects important for the development of such a system are the choice of building materials and additional condenser options (e.g. evaporative cooling) in order to achieve maximum condensation rates; investigation of the thermodynamics of the process, both practical and theoretical (i.e. temperature and humidity requirements, air flow measurements and solar radiation); and economic aspects (i.e. construction materials and operating costs).

Conclusion

The principal research question for future work will be to assess whether the water vapour generated from brine evaporative technologies or from other water vapour sources, such as from a bubble column, can be successfully trapped and condensed as a source for distilled water. As they influence the efficiency of the key processes in HD systems, many of the concepts developed with the intention to improve the performance of solar stills and seawater greenhouses are strongly relevant for the present work. Nevertheless, based on the literature reviewed, it appears that the single most important aspect to the successful development of a water vapour capture and condensation device is the optimization of heat and mass transfer process within such a system.

References


Summary and link to next chapter

In Chapter I a range of water vapour producing evaporation technologies were reviewed. Amongst them, the wind-aided intensified evaporation (WAIV) concept, a method that is driven by the free convection of warm dry air, stood out. Here, brine from RO desalination is effectively concentrated in a process that produces considerable evaporation rates on a strongly reduced physical footprint. This makes the WAIV technology potentially interesting as a source for vapour that can subsequently be condensed in a vapour capture device. In order to practically assess the WAIV concept for its potential to form part of a novel water desalination scheme, several small-scale models were assembled and their performance measured in wind tunnel experiments. Additionally, a laboratory scale greenhouse was built with the aim to capture the moisture that was released from the evaporative surfaces of the WAIV model. The underlying theory resembled a Seawater Greenhouse with the principal difference being that the honeycomb cardboard evaporator commonly used in a Seawater Greenhouse was to be replaced by the WAIV unit, with the hypothesis of achieving higher evaporation rates in the process. However, combining the vapour capture concept with a WAIV evaporation unit proved to be problematic, as it significantly restricts free airflow, the very feature that makes the WAIV technology feasible. Therefore, based on the preliminary experiments it was conceded that the two technologies were not compatible.

This setback led to the consideration of the bubble column as an alternative vapour source. Here, pressurised air is continuously introduced into a column filled with salty or brackish water. A fine sinter disk produces a constant stream of countless air bubbles that oscillate upwards and collect water vapour along the way. The bubble column technology offers a very controllable and efficient evaporation process and allows for easy channelling of the
water vapour into a condenser device. Preliminary experiments with a small commercially available chromatography column demonstrated its good potential as the evaporative component of a novel HD technology. In order to develop a new bubble-column-based desalination concept, the principal research question was to assess whether the water vapour generated from a bubble column could be successfully trapped and condensed as a source for distilled water, with minimal technical complexity and energy expenditure. Therefore, the primary focus of the next chapter was on developing a device to capture and condense the moisture from a bubble column and to assess its performance on a discrete section of surface area. What originated from the need to measure heat and mass transfer processes on a distinct condensing section evolved into a novel condenser prototype that is presented here. ²

² In the Abstract, the unit used for distillate salt concentration is incorrect. The actual values provided describe electrical conductivity and the correct unit is µS/cm.
Chapter II: A novel passive condenser for small-scale water desalination – preliminary findings

Attribution

MS developed the concept, reviewed the literature, conducted the experiments, performed the statistical analysis, designed the figures and drafted the manuscript. GH assisted in interpreting the findings. GH and MA provided feedback on the draft. All authors critically reviewed and approved the final version.

MS: 90%
Abstract

This paper reports on the development and experimental evaluation of a bubble column – passive condenser system as a method for small-scale brackish water or seawater desalination. Particular focus is on the novel condenser prototype. A long narrow condenser of 10cm width and 150cm length demonstrates the best results. In the winter season under favourable ambient conditions, distillate recovery rates of 73% are commonly achieved. Sodium chloride salt removal is found to be highly effective with distillate salt concentrations between 69µS and 101µS. The condenser prototype presented here provides a building block towards the development of a novel bubble column – greenhouse desalination system.

Keywords: novel passive condenser, bubble column evaporation, greenhouse condensation, sustainable water desalination

Introduction

Large tracts of inland Australia count amongst the most arid regions in the world with annual pan evaporation rates often exceeding annual rainfall figures by tenfold (Luke, Burke, and O’Brien 2003). As a result, surface freshwater expressions are rare and brackish groundwater is frequently the only source of potable water in remote Australia. In the past, the implementation of well established but advanced desalination technologies such as reverse osmosis (RO) often failed to produce the desired outcomes (Werner and Schäfer 2007). By focussing on the utilisation of novel and previously untapped water sources there exists large potential not only for sustainable provision of drinking water but furthermore, for capacity-building and ultimately, for self-reliance for the development of remote communities worldwide (Estrella and Gaventa 1998).

A simple method that can be used to gather small volumes of fresh water in arid regions is by collecting evapo-transpiration from the leaves of bushes or small trees (Stein 2008). This is done by wrapping a suitably leafed plant in a large sheet of clear plastic and channelling the water droplets that condense on the underside of the plastic into a container. Making use of the same physical principles that drive the process described above, solar still distillation is a well established technology to gather small amounts of potable water (Arjunan, Aybar, and Nedunchezhian 2009; Aybar and Assefi 2009; Sampathkumar et al. 2010). The principal drawback in solar still distillation is that the two key processes, evaporation and condensation, are directly dependent on the transparent cover.

For effective evaporation, maximum solar radiation input into the still is required. This in turn adds sensible heat to the transparent cover, which needs to be as cool as possible for maximum condensation to occur.

One approach to separate the two processes is to bubble ambient air through the water contained in the still basin (Pandey 1984). Pandey reported a modest distillate increase of 6-7% in initial tests with humid ambient air. After drying the ambient air previous to the bubbling process, by channelling it through a series of CaCl₂ moisture traps, an overall distillate increase of 33.5% was achieved. The author suggested that this method could be effective in the absence of solar radiation and could thus allow for nocturnal distillation, further increasing the overall productivity of the still. Taking this idea further, the condensing cover could be completely liberated from one of its previous functions, namely as an entry point for solar energy. It could therefore be substituted altogether by a different material with superior thermal conductivity, such as copper sheet, thus increasing the rate of condensation and consequently, distillate production rate (Dimri et al. 2008).

For a water condenser, the rate of condensation, and thus, the net gain of desalinated water (distillate), is principally governed by the temperature gradient between the warm vapour saturated carrier medium (e.g. air) and the cooler condensing surface. The condensing surface essentially acts as a physical barrier between the warm moist air on one side and the cooler opposite medium (e.g. ambient air or cooling...
A technology that builds on the water bubbling principle developed by Pandey is the bubble column (Francis and Pashley 2009a). This concept has recently been described as a potential vapour source for a novel desalination system, based on the humidification-dehumidification (HD) principle. Here, a continuous stream of air is bubbled through a column containing salty water. The unusual property of salt water to inhibit air bubble coalescence facilitates the performance of the bubble column with a high volume fraction of small air bubbles, continuously colliding but not coalescing. In contrast to basin type solar stills or flash distillation systems, where essentially only the surface of the liquid comes in contact with the air above, the bubble column produces a manifold liquid/air interface and as a result, a high exchange rate of water molecules from liquid into gas phase. Based on the highly efficient vaporisation of water and the relatively moderate energy demand that can potentially be provided from solar collectors or waste heat from industrial processes nearby, bubble column desalination may hold a number of advantages over current commercial desalination technologies.

To make small-scale bubble column desalination feasible, the energy demand on the evaporation side (compressed air bubbling process) needs to be further offset by a low energy demand on the condensation side. Based on this key proviso, the underlying research motivation for the work presented here was to assess and report the potential of a novel passive condenser prototype, developed especially for condensing the water vapour produced by a bubble column, as a source of desalinated drinking water. Long-term, the findings aim to inform the physical conceptualisation of a novel medium-scale water desalination system that combines a bubble column with a condensing greenhouse.

**Methods**

**Bubble column design**

The bubble column was manufactured from a clear Perspex cylinder of 500mm height and 120mm internal diameter. A 40-60 microns pore size glass sinter was sealed into the column with Selleys Araldite two-component glue. Top and bottom covers were attached and sealed with Selleys Roof & Gutter Silicone. During operation, the lower part of the column was heated by an internal plastic pipe heating spiral, fed from a water bath with a feed temperature of 70°C. The column was filled with sodium chloride salt solution with a concentration similar to seawater. Compressed air was continuously pumped through an inlet hose from below at a rate of 10 L/min, creating a high density of fine air bubbles (1–3mm diameter). From an outlet hose on the column top, the heated vapour laden air was channelled into the condenser. During the experiments, sheets of flexible foam were used to insulate the column and the heating pipes, in order to prevent heat loss to the ambient.

**Condenser design**

The condenser framework was constructed from rectangular plastic pipe with cross section dimensions of 100mm x 50mm. The total condenser length was 1527mm. One wide side of the plastic pipe was removed and replaced by a sheet of copper with a thickness of 0.55mm. Selleys Roof & Gutter Silicone was used to seal the condenser. The copper sheet surface dimensions were 100mm x 1500mm. This resulted in a condenser volume capacity of 7.2L. At the experimental bubbling airflow rate of 10 L/min, the humid air resided inside the condenser for 43 seconds. The condenser was positioned at an inclination of 30°. Vapour laden air from the bubble column was channelled into the lower end of the condenser via a thermally insulated hose, to prevent heat loss and subsequent water condensation in this section. An exhaust pipe at the far (upper) end allowed for the partly dehumidified air to exit the condenser cavity. A length of rubber hose was attached to the lowest point of the condenser to allow for condensed water to flow out by gravity. A number of sensors were placed inside and outside the condenser (Figure 1). Humidity loggers (HOBO U23-002) were used to obtain temperature and humidity profiles inside the condenser. In addition, reference measurements of the compressed air used for bubbling and of the ambient temperature and humidity conditions were recorded. Thermocouples (PTFE type K / T. M. Electronics) were used to measure copper surface temperatures inside and outside the condenser in order to assess the heat exchange through the copper sheet.
Previous to the experiments all thermocouples where calibrated using a ZEAL alcohol thermometer (20-30°C±0.02°C). The Hobo loggers were group-tested in a steam chamber for their humidity accuracy, particularly in the extreme upper region of maximum saturation. The air flow meter used was calibrated against a 5 litre flowmeter (Influx UK 5±0.2L) and a second 25 litre flowmeter (Fisher Controls 25±1L). At the start of each experiment, two litres of sodium chloride salt solution were prepared and adjusted to a TDS concentration of approximately 35000ppm by measuring conductivity (Hanna Instruments HI8733 Conductivity Meter) and transferred into the bubble column. Once the experiment had reached steady state conditions (after a running time of approximately 2½ hours), hourly measurements of bubble column water loss from evaporation and distillate production from condensation were obtained by weighing (A&D Limited GF 2000 / 2100±0.1g; A&D Limited HW-15K / 15000±1g). Manual measurements of water bath temperature were recorded. For each experiment, heating coil flow rate was recorded. At the end of each experiment, bubble column volume, conductivity of the concentrated salt solution inside the bubble column and condensate conductivity were recorded.

Results and Discussion

Once each individual experiment had reached steady state conditions, as determined by thermocouple readings, the process continued for one hour before water measurements were taken. Over three one-hour blocks, actual evaporation rates were measured as weight loss inside the bubble column and condensation rates were recorded by weighing the actual amount of distillate being captured. In addition, thermocouple and humidity logger readings were used to calculate the theoretical amounts of evaporation and condensation per time unit, as governed by psychrometric law.

Preliminary experiments with an oversized condenser prototype with a copper surface area of 900 x 550mm (length to width ratio = 1.6:1) had produced only a small distillate return of around 35% per evaporated unit of saltwater (detailed results not presented here). In this condenser, the region of condensation as determined by conductive heat loss was restricted to the immediate area of vapour entry. For the greater part of the condenser surface the temperature gradient between condenser inside and outside was too small to drive any further condensation. This was despite the use of a perforated pipe system inside the condenser, to distribute the warm vapourised air over a wider region along the bottom side of the condenser. These findings suggested that the condenser surface area, condenser volume and the resulting retention time of vapourised air were a mismatch for the bubble column used in this study. It was therefore considered that a more slender condenser design with a length of 1500mm and a width of 100mm (length to width ratio =
15:1) would be more effective in combination with the bubble column.

This improved condenser demonstrated good condensing capability. The actual distillate recovery rate after 5½ hours running time for the three experiments was 73.3%, 73.7% and 73.0% respectively, resulting in an average distillate recovery rate of 73.3% (±0.4Stdev) per evaporated unit of saltwater. These results were obtained during the winter season, with average ambient temperatures inside the laboratory of around 17.8°C (±0.8Stdev). The relatively cool compressed air used for the bubbling process and the water heating spiral feed at 70°C combined to an average column temperature of 55°C above the froth line inside the bubble column. The temperature gradient between ambient air and the vapour laden column air as it entered the condenser was therefore quite large, at 37.3°C (±0.5Stdev).

Theoretical evaporation rates and theoretical condensation rates for the period from 2:30 to 3:30 were obtained via psychrometric chart calculations. On the evaporation side, the temperature and humidity values inside the bubble column minus the values for compressed air as the bubbling source were used to determine the theoretical amount of water evaporated during that period, as 61.0mL (±1.2Stdev). On the condensation side, temperature and humidity values were taken from condenser inlet pipe and condenser exhaust, with the associated reduction determining the theoretical condensation amount, as 46.4mL (±0.5Stdev). The ratios for actual evaporation divided by theoretical evaporation (1.38±0.04Stdev) and actual condensation divided by theoretical condensation (1.32±0.03Stdev) were calculated. They represent supersaturation of the humidified air, caused by the absence of condensation nuclei inside the evaporation chamber and the increased air pressure during the bubbling process (Rogers 1975). A ratio of 1.38 represents 138% (super-) saturation. In addition, a small but not quantified proportion of this increased amount can be attributed to entrainment of water droplets into the humidified air.

Throughout the experiments, saltwater evaporation rates in the bubble column remained fairly constant, within a range of 80-88mL per hour. The variation within experiments between time blocks was small, suggesting that the system was operating in steady state. Figure 2 depicts the very close relationship between evaporation and condensation rates. The graph demonstrates that the condenser worked very linear under the prevailing temperature conditions, with the variation in distillate productivity being strongly influenced by the variation in saltwater evaporation.

![Evaporation and Condensation Rates](image)

Figure 2: Bubble column evaporation and condensation rates per time periods
Heat balance calculations

Temperature and humidity measurements from one of the experiments were used to calculate a heat balance for the combined inputs and outputs of latent and sensible heat. The theoretical amount of water vaporized from 2:30 to 3:30 was 102.3 grams per cubic metre of air or 61.4 grams of water for the actual 0.6m$^3$ of air bubbled through the column during that period (calculated by psychrometric chart). This is in contrast to the actual measured weight loss of 82 grams, i.e. the real evaporation during that time. The specific latent heat of vaporisation (2258kJ.kg$^{-1}$) for 61.4 grams of water is 138.6kJ, for 82 grams of water it is 185.2kJ.

The total amount of heat made available to the evaporation process by the heating coil is determined by the temperature drop of 11.4L of water (the total volume of heating water circulated through the heating coil from 2:30 to 3:30, using the heat energy equation \( q = 4.18 \times 1.4400 \text{ml} \times (70-61.5^\circ \text{C}) \), is 405 kJ. A very small portion of this heat is unaccounted for as heat loss throughout the heating supply system, despite practicable insulation of the pipes and the bubble column. The largest part of the excess heat not used for evaporation is required as sensible heat, in order to counteract the evaporative cooling effect of the bubble process and to heat up the continuous stream of cool compressed air into the column, which would ultimately cool the column to the temperature of the compressed air. This is supported by the frequent observation, that the evaporation process as measured by weight loss inside the bubble column started around 45 minutes into the experiment, when the column top temperature had almost reached its steady state. The implication here is that all the heat input up to that point was used as sensible heat and only then some of the excess heat became available as latent heat input for the water evaporation process itself.

Regarding condensation, the theoretical amount of distillate from 2:30 to 3:30, as calculated by psychrometric chart (values taken from condenser inlet pipe and condenser exhaust) was 46.3 grams of distilled water per 0.6m$^3$ of vapourised air. In contrast, the actual measured distillate amount was 60.4 grams. The specific latent heat of vaporisation (2258kJ.kg$^{-1}$) for 46.3 (60.4) grams of water is 104.5kJ (136.4kJ). The difference between the latent heat input into the condenser (185.2kJ) and the heat output through condensation (136.4kJ) represents the amount of latent heat and thus, water vapour, that was lost through the condenser exhaust (approximately 27% per unit of evaporated saltwater).

Water quality

In regards to the physical aspects associated with operating a bubble column (e.g. hydrostatic pressure) and its practical operation, detailed findings have been published elsewhere (Francis and Pashley 2009a, 2009b) and are therefore not discussed here. Importantly, one of the challenges of operating a bubble column in continuous mode is to maintain a steady salt concentration inside the chamber, by removing the concentrated salt solution at a rate equal to the rate at which saltwater (i.e. at 35,000ppm) is fed into the column. In the present experiments, this was not crucial as the duration of the individual experiments was around 5½ hours and the total evaporation loss during that period equated to approximately 16%. Beginning the experiments with a sodium chloride salt concentration similar to seawater (34,500ppm ±889 Stdev), this resulted in an average sodium chloride end concentration of around 41,267ppm (±2,050Stdev) inside the column and was considered acceptable for the assessment of the condenser performance. Monitoring distillate throughout the series of experiment, it appeared that distillate salt concentrations declined steadily overall, from around 65ppm (101µS) in the first experiment to as low as 44ppm (69µS). The likely reason for this was a condenser priming effect, responsible for flushing out salt, minerals and small particles that had resulted from the condenser manufacturing process. Post experiment, the higher salt concentrations measured inside the bubble column were found to be in good agreement with the amount of water evaporated from the column.

Bubble column – novel condenser system versus conventional thermal methods

Unlike in conventional thermal desalination processes, a bubble column evaporator does not require boiling water (Francis and Pashley 2009a). This is because the amount of water vapour in an air bubble immersed and equilibrated with water close to its boiling point is almost identical to that in a bubble created by boiling. As the need for boiling water is eliminated, a reduced energy demand is required for the process overall. However, due to the need to overcome the static water pressure, the energy required to produce
pressurised air for the bubble column operation is relatively high. Based on the necessity to offset this demand, it has been stressed that a bubble column desalination system might only be commercially viable when combined with an energy efficient vapour condensation component (Francis and Pashley 2009a). Novel concepts that utilise available wind energy as a means of providing pressurised air e.g. wind tunnelling (Pandey 1984), or hot exhaust air from industrial processes nearby could potentially reduce the energy requirements of a bubble column desalination system. Regarding water transport (e.g. pumping), energy needs could be satisfied by solar cells (Abu-Jabal, Karniya, and Narasaki 2001) or waste heat from brine evaporation ponds (Lu, Walton, and Swift 2001).

Besides its energy efficiency, the obvious determining factor for a bubble column condenser system is its water production capacity. When compared to a conventional solar still with a distillate productivity of 2-3L/m²/d or a more sophisticated wick type Fcubed Carocell™ still with a productivity of around 5L/m²/d (Johnstone 2010), an up-scaled bubble column-condenser system with a 1m² condenser size and a similar efficiency rate as the condenser presented in this study could produce around 19L of distilled water per day, thus achieve three to four times the productivity of a wick type solar still. Noteworthy, the evaporation chamber temperature in a Carocell is significantly higher than in the bubble column under the conditions reported here. One aspect of future research should therefore focus on operating a bubble column at a much higher temperature than the 55°C achieved in this study. This could be realised by utilising hot industrial exhaust air for the bubbling process. Resulting from this a significant increase in evaporation and consequently, a considerable distillate output of this novel HD system is anticipated.

**Future research**

As the aim of this paper is to provide a building block towards the development of a bubble column - greenhouse desalination system, the principal question for future research will be to assess if the concept presented here can be successfully up-scaled and whether the water vapour generated from a larger bubble column or a number of individual columns can be trapped economically and condensed inside a crop growing greenhouse, as a source for desalinated water. A key aspect of the investigation would be to assess the impact of the bubble column itself on the heat balance of the greenhouse, with its known tendency for overheating and the resulting risk to plant survival (Garcia Mari, Gutierrez Colomer, and Blaise-Ombrecht 2007). Drawing on the experience gained from seawater greenhouse desalination systems, placing an array of cool water-circulated plastic pipes above the growing area could help extract heat from the greenhouse and additionally provide shading, which would in turn reduce the need for greenhouse cooling (Davies and Paton 2005).

The bubble column – greenhouse system could hold a number of benefits, foremost by making use of the structural components of the greenhouse itself as the primary condensing surface. In addition, the distillate produced inside the greenhouse would not need to be stored or transported but would immediately be available for irrigation. As a large amount of condensation would form high up below the greenhouse roof, it could be gravity fed into the planting area (Sharan, Baysens, and Milimouk-Melnytchouk 2007). Furthermore, plants inside a humidified greenhouse have been found to require as little as 10% of the fresh water demand of plants grown outside a greenhouse (Radhwan and Fath 2005). Due to this strongly reduced demand, a large part of the water needed for plant irrigation could be provided from greenhouse condensation.

While a bubble column – greenhouse system offers a very controllable and efficient evaporation process and allows for easy provision of water vapour towards the condensing surface, operating a bubble column in this context requires future investigation into the feasibility of solar, wind and wave power as potential energy sources for process operation. Crucially, aiming to be a green technology, operating the greenhouse would only be feasible without the need for large fans and excessive pumping requirements. Recent work on the seawater greenhouse system suggests that corresponding with peak solar radiation, between 9am and 5pm the greenhouse produced 98% of the total freshwater by relying solely on wind and solar energy (Mahmoudi et al. 2008). This indicates that it could be technically feasible to power a greenhouse similar to the seawater greenhouse with renewable energy, without the back-up support of fossil fuel energy sources.
Conclusion

The novel bubble column based HD system described here holds strong potential as a small-scale energy efficient new method of producing high quality drinking water. As the process operates effectively at temperatures well below boiling point, the energy requirements are significantly lower than for conventional thermal evaporation technologies. The novel condenser component aids energy efficiency overall, requiring no energy input under appropriate climatic conditions. The condenser copper surface with its high thermal conductivity quickly allows for the heat energy contained in the vapour laden air feed to be released into the cooler ambient medium outside the condenser, resulting in effective condensation and distillate recovery.

The principal objective of this paper was to report on the condensing performance of the condenser prototype presented here. It was found that condenser design plays an important role in the process. A condenser design with a width of 10cm and a length of 150cm appeared to produce the best results. Sodium chloride salt removal was found to be highly effective with distillate salt concentrations between 70µS and 135µS, suggesting that the process could produce drinking water of a high quality. Regarding the chemical composition of the distillate produced in the process, e.g. copper content, further research is needed.

Besides their high energy demand, conventional desalination technologies like multi-stage flash distillation, reverse osmosis or electro dialysis are costly for the production of small amounts of fresh water. A further aspect is their reliance on highly skilled personal for regular maintenance and crisis management. In contrast, the bubble column with passive condenser technology described here holds strong potential for the production of small amounts of high quality drinking water in remote and arid regions. The compressor required to produce bubbling air in the absence of other sources such as waste heat outlets, can be powered with renewable solar, wind or wave energy. Equally important, the system is economically feasible and technically and operationally appropriate for remote places.

Future research should aim to gain a thorough understanding of the heat transfer processes that drive the condensation rate inside a condensing greenhouse. This will provide the basis for an optimisation of the efficiency of a vapour capture and condensation system on the basis of the bubble column – condensing greenhouse. Amongst the aspects important for the development of such a system are the choice of optimum process materials, investigation of the thermodynamics of the process, both practical and theoretical (i.e. temperature and humidity requirements, air flow measurements, solar radiation) and economic aspects (i.e. construction materials and operating costs).

References


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Summary and link to next chapter

Initially, the condenser had developed from the need to measure a discrete section of condensation surface, in order to assess the heat and mass transfer processes that occur on a condensation surface. With the promising findings from the preliminary condenser trials, the condenser assessment was extended to determine its performance under a range of physical conditions. While the following publication emphasizes the novel condenser as a standalone small-scale desalination unit for applications in remote regions, the findings hold significant relevance for the conceptualisation of a larger vapour capture and condensing device such as a greenhouse skin. In particular, effects of water cooling and air circulation alongside a condensation surface as reported on below are significant for the design of a Bubble-Greenhouse HD desalination concept. With an unchanging experimental design on the evaporator side, the large number of tests that were conducted provided a comprehensive data set demonstrative of the bubble evaporator’s performance consistency. The resulting data provided the basis for extrapolation of bubble evaporator capacity, both for relatively small standalone systems and for significantly up-scaled components that would supply a Bubble-Greenhouse.\(^3\)\(^4\)

\(^3\) In the Abstract, the unit used for distillate salt concentration is incorrect. The actual values provided describe electrical conductivity and the correct unit is µS/cm.

\(^4\) On page 51, the electrical conductivity of 125µS/cm is converted to 80ppm. However, from literature values 123.7µS/cm at standard 25°C corresponds to 60ppm. The variance is explained by using the Lenntech online conductivity converter to convert measured conductivity into total dissolved solids in ppm. Although not explicitly stated, the converter relates to tap water with a mixture of ions as opposed to the standard NaCl values. This explains the small ppm salt level variance.
Chapter III: A bubble column evaporator with basic flat-plate condenser for brackish and seawater desalination

Attribution

MS developed the concept, reviewed the literature, conducted the experiments, performed the statistical analysis, designed the figures and drafted the manuscript. GH assisted in interpreting the findings. GH and MA provided feedback on the draft. All authors critically reviewed and approved the final version.

MS: 90%
A bubble column evaporator with basic flat-plate condenser for brackish and seawater desalination

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This paper describes the development and experimental evaluation of a novel bubble column-based humidification–dehumidification system, for small-scale desalination of saline groundwater or seawater in remote regions. A bubble evaporator prototype was built and matched with a simple flat-plate type condenser for concept assessment. Consistent bubble evaporation rates of between 80 and 88 ml per hour were demonstrated. Particular focus was on the performance of the simple condenser prototype, manufactured from rectangular polyvinylchlorid plastic pipe and copper sheet, a material with a high thermal conductivity that quickly allows for conduction of the heat energy. Under laboratory conditions, a long narrow condenser model of 1500 mm length and 100 mm width achieved condensate recovery rates of around 73%, without the need for external cooling. The condenser prototype was assessed under a range of different physical conditions, that is, external water cooling, partial insulation and aspects of air circulation, via implementing an internal honeycomb screen structure. Estimated by extrapolation, an up-scaled bubble desalination system with a 1 m² condenser may produce around 19 l of distilled water per day. Sodium chloride salt removal was found to be highly effective with condensate salt concentrations between 70 and 135 μS. Based on findings and with the intent to reduce material cost of the system, a shorter condenser length of 750 mm for the non-cooled (passive) condenser and of 500 mm for the water-cooled condenser was considered to be equally efficient as the experimentally evaluated prototype of 1500 mm length.

Keywords: bubble column evaporation; flat-plate condenser; seawater desalination; brackish water desalination; bubble-greenhouse

1. Introduction
This paper describes the physical conceptualization and evaluation of a bubble column-based water desalination system that aims at producing small amounts of potable water for remote regions, in a technologically undemanding manner. Based on its proposed desalination potential of up to 191 per day for a 1 m² condenser, it is potentially five times more productive than common basin-type solar stills and could be utilized in their place. A key objective of the proposed concept was to achieve maximum water production while keeping the technology conceptually simple, thus allowing for operation under challenging environmental and economical conditions, that is, by local people in remote places with limited technical means.[1]
While the underlying physical principles of bubble column evaporation have been comprehensively described elsewhere,[2] this paper reports on the specific evaporation rate that was achieved with a laboratory-scale prototype. The quantitative data obtained from this model allows for estimation of larger-scale bubble desalination systems under varying temperature conditions, by extrapolation. The bubble evaporator is matched with a simple ‘home-made’ copper-plate condenser. The condenser is novel in the sense that it bears resemblance to a simple solar still, both in its simplicity of operation and in its relatively inexpensive fabrication. Unlike its more elaborate water-cooled counterparts such as evaporative spray condensers [3] or tube and grill type condensers that are, for example, used in seawater greenhouses,[4] it is also very easy to manufacture.

Small-scale water desalination on the basis of the humidification–dehumidification (HD) principle has come a long way since its inception.[5–8] In simple solar stills, the principal drawback stems from the double function of the transparent cover as the entry point for solar radiation and as the condensation surface, each process somewhat hindered by its counterpart.[5] In order to overcome the problems associated with the double function of the solar still cover, El-Bahi and Inan [9] developed a novel solar still concept where evaporation and condensation processes are spatially separated. While the evaporation process continued to be driven by heating basin water with solar radiation, the condensation process occurred in a separate chamber. The system utilized the naturally occurring pressure difference that developed as a consequence of temperature differences between the heated evaporator unit and the cooler condenser, as shown in a diagram. The system is principally governed by the temperature difference between the warm vapour saturated carrier medium (e.g. air) and the cooler condensing surface. The condensing surface essentially acts as a physical barrier between the warm moist air on one side and the cooler opposite medium (e.g. ambient air or cooling water). While it forms an effective barrier for matter in this way, it allows for thermal energy (heat) contained in the matter to pass through.[11] The larger the temperature difference between inside and outside, the more rapid heat is removed by a process known as conduction. Resulting from this heat reduction at the condenser surface, the reduced energy state forces nearby water molecules to change phase, expressed as condensation. As more water molecules condense, droplets and ultimately large drops of desalinated water form and can be collected.[12]

The condenser prototype presented here forms part of a larger study that aims to inform the development of a novel bubble column greenhouse desalination system. This overarching concept proposes the combined production of water and food, a new trend in water desalination that has recently gained strong traction.[13] The flat-plate condenser concept originated from the need to measure heat transfer processes within a defined section of a condensing surface, as a means of assessing the potential for purely passive condensation along a hypothetical greenhouse surface, in response to radiative cooling effects. With this underlying principle in mind but also with a focus on increasing the productivity of a novel stand-alone desalination system at low cost impact, the condenser prototype that had evolved was assessed in the context of five research questions:

1. What is the optimum condenser size to match the bubble column used in the study?
2. How does partial insulation of the condenser influence distillate production?
3. How does water cooling of the condenser top influence distillate production?
(4) How does air flow regulation (honeycomb screen) and air flow direction influence distillate production?

(5) What is the optimum length for the improved condenser design?

2. Methods

2.1. Component design

2.1.1. Bubble column

The bubble column was manufactured from a clear Perspex cylinder of 500 mm height and 120 mm internal diameter. A 40–60 μm pore size glass sinter was sealed into the column with commercially available two-component glue. Top and bottom covers were attached and sealed with commercially available roofing type silicone. During operation, the lower part of the column was heated by an internal plastic pipe heating spiral, fed from a water bath with a feed temperature of 70°C. The column was filled with sodium chloride (NaCl) salt solution with a concentration similar to seawater. Compressed air was continuously pumped through an inlet hose and through the glass sinter from below at a rate of 13.5 l/min, creating high density of fine air bubbles (1–3 mm diameter). Due to the inhibition of bubble coalescence, a large and constantly renewed gas/water interface was formed by the oscillating rise of bubbles, thus achieving a uniform and efficient exchange of water vapour into the bubbles.[2] From an outlet hose on the column top, the heated vapour laden air was then channelled into the condenser. Compressed air was continuously pumped through an inlet hose and through the glass sinter from below at a rate of 13.5 l/min, creating high density of fine air bubbles (1–3 mm diameter). Due to the inhibition of bubble coalescence, a large and constantly renewed gas/water interface was formed by the oscillating rise of bubbles, thus achieving a uniform and efficient exchange of water vapour into the bubbles.[2] From an outlet hose on the column top, the heated vapour laden air was then channelled into the condenser. During the experiments, sheets of flexible polyurethane foam were used to insulate the bubble column and the heating pipes, in order to prevent heat loss to the ambient.

2.1.2. Condenser

The condenser framework was constructed from rectangular polyvinylchlorid (PVC) plastic pipe of 1500 mm length with cross section dimensions of 100 mm × 50 mm. One 100 mm face of the plastic pipe was removed and replaced by a sheet of copper (0.55 mm thickness; 1500 mm × 100 mm surface area) and sealed with commercially available roofing type silicone. This resulted in a total condenser volume of 7.2 l. Taking into account the pressure drop over the bubble column sinter and the hydrostatic pressure as imparted by the head of water, the experimental airflow rate into the condenser was set to 13.5 l/min. Consequently, the average air residence time inside the condenser was around 32 s. The condenser was positioned at an incline of 30°. Vapour laden air from the bubble column was channelled into the lower end of the condenser via a thermally insulated hose, to prevent heat loss and subsequent water condensation in this section. An exhaust pipe at the far (upper) end allowed for the partly dehumidified air to exit the condenser cavity. A length of rubber hose was attached to the lowest point of the condenser to allow for condensed water to flow out by gravity. Data loggers (HOBO U23-002) were used to obtain temperature and humidity profiles inside the condenser (Figure 1). In addition, temperature and humidity conditions of the compressed air used for bubbling and of the ambient air were recorded for reference. Thermocouples (PTFE type K/T.M. Electronics) were used to measure copper surface temperatures inside and outside the condenser in order to assess the rate of heat exchange through the copper sheet.

2.2. Experimental setup

At the start of each experiment, 2 l of NaCl solution were prepared and adjusted by conductivity measurement, to a

![Figure 1. Flat-plate condenser cross section, indicating logger and thermocouple locations for temperature and humidity measurements.](image)
TDS of approximately 35,000 ppm and transferred into the bubble column. Once the experiment had reached steady state conditions, hourly measurements of bubble column weight loss (from feedwater evaporation) and distillate production (from condensation) were obtained via use of electronic scales. Manual measurements of water bath temperature and cooling water temperature (where applicable) were recorded. For each experiment, heating-coil water flow rate and cooling flow rate (where applicable) were recorded. According to the research questions, the various condenser modifications were assessed by obtaining temperature and humidity profiles for the bubble column evaporator and the condenser itself. At the end of each experiment, feedwater volume and conductivity (concentrate from bubble column) and distillate conductivity were recorded. For each experiment, heating-coil water temperature and cooling water temperature (where applicable) were recorded. According to the research questions, the various condenser modifications were assessed by obtaining temperature and humidity profiles for the bubble column evaporator and the condenser itself. At the end of each experiment, feedwater volume and conductivity (concentrate from bubble column) and distillate conductivity were recorded.

In total, the four treatments — control, insulation, cooling and screen — were each repeated three times in a randomized order. For the control experiments, the condenser was evaluated in its plain form. For the insulation experiments, Styrofoam sheets of 15 mm thickness were attached to the condenser underside and sides to assess the effect of insulating the PVC component of the condenser and thus, to determine the percentage of condensation occurring solely over the copper sheet. In order to assess the impact of water cooling on the condenser, ice water was trickled down the copper sheet at a flow rate of 7 l per hour. For the air flow regulation experiments, a honeycomb structure (screen) was made from commercially available drink straws of 4 mm diameter and 100 mm length, densely packed and placed at the halfway point inside the condenser, elongated in the direction of air flow. The structure covered the entire cross section of the condenser and was intended to reduce turbulent eddies that might otherwise occur. One additional experiment with the condenser in its plain form (control) was carried out with the aim to assess whether the system would perform differently if the direction of air flowing through the condenser was reversed. In this experiment, vapour was channelled into the condenser from the upper end with the condenser exhaust being located at the lower end.

2.2.1. Heat balance calculations

Temperature and humidity data obtained from the experiments was used to calculate a heat balance for the inputs and outputs of latent and sensible heat. The specific heat capacity or the total amount of heat supplied from the heating coil into the bubble column, \( q \), was given by

\[
q = m \ast C \ast (T_i - T_f),
\]

where \( m \) is the water flow rate per hour, \( C \) is the heat capacity of water (4.18 J/C g), \( T_i \) is the water temperature at heating coil outlet and \( T_f \) is the water temperature at heating coil inlet. The specific enthalpy of dry air, \( h \), reflects the amount of sensible heat leaving the condenser. It can be expressed as

\[
h = c_{pa} \ast t,
\]

where \( c_{pa} \) is the specific heat capacity of air (1.006 kJ/kg °C) and \( t \) is the air temperature (°C) relative to zero. The specific enthalpy of water vapour, \( h_w \), represents the amount of latent heat that is taken up or released by water molecules. It can be expressed as

\[
h_w = c_{pw} \ast t + h_{we},
\]

where \( c_{pw} \) is the specific heat of water vapour at constant pressure (1.84 kJ/kg°C), \( t \) is the water vapour temperature (°C) and \( h_{we} \) is the evaporation heat of water at 0°C (2501 kJ/kg). Combining formulas 2 and 3, the enthalpy of moist air, \( h_m \), which represents the sum of latent and sensible heat per unit of moist air, can be expressed as

\[
h = c_{pa} \ast t + x_s[c_{pw} \ast t + h_{we}],
\]

where \( x_s \) is the humidity ratio at saturation in kg of water per kg of air. This is a more accurate depiction of the total enthalpy in a vapour/non-condensable gas mixture as opposed to the enthalpy of vaporization of water, which does not take into account the actual temperature change of the carrier gas.

3. Results and discussion

Throughout the series of experiments the bubble column evaporator demonstrated strong continuity, with evaporation rates of between 80 and 88 ml per hour (Figure 2(a)). Statistically, there was no significant difference between the individual treatment groups. Furthermore, there was no statistical significance between hourly blocks within experiments (i.e. treatment groups), confirming that at the times of data recording the system was operating under steady state conditions. It must be noted that in the bubble concept described here, the evaporation rate as determined by the heat energy input into the column is achieved by cycling heated water through a coil, not unlike an electric water heater element. There are several other ways to supply heat energy to the evaporator column, for example, by bubbling hot air from a waste heat outlet. For this reason, the heat input by the water bath and the energy input from the compressed air in this particular setting are not discussed here and the bubble evaporator productivity is assessed purely in relation to its process operating temperature.

3.1. Condenser variables

3.1.1. Improved condenser size

Preliminary experiments with an oversized condenser prototype with a copper surface area of 900 mm × 550 mm (length to width ratio = 1.6:1) had produced only a small
distillate return of around 35% per evaporated unit of saltwater (detailed results not presented here). In this condenser, the region of condensation as determined by conductive heat loss was restricted to the immediate area of vapour entry. For the greater part of the condenser surface the temperature difference between condenser inside and outside was too small to drive any further condensation. This was despite the use of a perforated pipe system inside the condenser, to distribute the warm vapourized air over a wider region along the bottom side of the condenser. These findings suggested that the condenser surface area, condenser volume and the resulting retention time of vapourized air were a mismatch for the bubble column used in this study. It was therefore considered that a more slender condenser design with a length to width ratio of 15:1 (1500 × 100 mm) would be more effective in combination with the bubble column.

This improved condenser prototype demonstrated good condensing capability. The actual distillate recovery rate from 14:30 to 15:30 for the three control experiments was 73.3%, 73.7% and 73.0%, respectively, resulting in an average ('mean') distillate recovery rate of 73.3% (± 0.4 std. dev.) per evaporated unit of saltwater with the remainder exiting the condenser as vapour. While this was...
M. Schmack

achieved without external cooling of the condenser, these results were obtained during the winter season, with average ambient temperatures of around 17.8°C (± 0.8 std. dev.). The temperature difference between ambient air and bubble column steam entering the condenser was therefore quite large, at 37.3°C (± 0.5 std. dev.).

3.1.2. Summarising the four treatment groups

The distillate recovery rate gives a good indication of the significant condensation rate variations under the respective condenser treatments (Figure 2(b)). The values are expressed in percentage points, based on the condensation to evaporation ratios. Overall, the insulated condenser produced significantly less condensate compared to the control condenser. The difference between mean control condensate production and mean insulation condensate production was 10.4 ml or 16.3%. The water cooling experiments in which ice water was used to cool the condenser copper surface to a temperature of around 5°C produced a significantly higher condensate output compared to control experiments under ambient temperature conditions of 17.8°C (± 0.8 std. dev.). The difference between mean cooling values and mean control values was 9.3 ml or 12.7%. The air flow experiments (screen) produced a slightly lower distillate output of 3.8 ml or 5.9%, compared to the control values. Multiple comparison statistics, using a one-way analysis of variance test, produced significance at the 0.05 level for all groups (control versus insulation: \( p = .000/\) control versus cooling: \( p = .000/\) control versus screen: \( p = .047\)).

3.1.3. Partial condenser insulation

Investigating the effects of partial insulation (underneath and alongside the condenser) on distillate recovery, it was found that the majority of conductive heat transfer and thus, forced condensation, occurred over the copper condensing surface itself. Due to its large thermal conductivity \( (K) \) of 401 W/m K,[11] the copper sheet effectively carried heat from the warmer inside to the colder outside of the condenser at a much faster rate than the PVC material that formed the remaining majority of the condenser surface area. The difference between mean control values and mean insulated values was used to calculate the percentage of condensation that occurred solely over the copper top as 83.8%. Consequently, the percentage of condensation that occurred over the three remaining sides of the condenser was 16.2%.

Noteworthy, as the thermal conductivity of PVC at 0.19 W/(m K) [11] is about 2000 times lower than that of copper and the PVC component was also four times thicker (2 mm thickness) than the copper sheet used, this fraction appears rather large. An explanation might be that there exist three heat transfer barriers between condenser inside and ambient air. These are (1) the copper sheet itself, (2) a condensate film inside the condenser and (3) a thin air film above the copper top. Together, these three layers form the ‘equivalent heat transfer coefficient’ \( K_H \). Depending on the heat transfer rates of condensate and/or air film a more or less strong insulation effect and thus, a significant reduction of \( K_H \) results. In this way, these layers have a ‘moderation effect’ on the otherwise much larger \( K \)-divergence of the two condenser materials copper and PVC.

3.1.4. Water cooling the condenser top

In the context of an advanced solar HD desalination system, water cooling of the condenser surface as a means of increasing the temperature difference between the inside and outside of the condenser has previously been reported as an effective method to improve condensate production.[14] The ability of a material to hold heat is known as specific heat capacity. For copper, it is quite low at 0.39 J/kg K.[11] As this heat is released by the copper, it is absorbed by an adjacent medium, for example, ambient air. However, it is crucial to carry maximum heat away from the condenser top for continuous condensation to occur. For this purpose water was chosen as a suitable cooling medium due to its large heat capacity of 4.18 J/kg K [11] and for its practical application that allowed for a thin water film to flow over the condenser copper surface. For practicable reasons, this was achieved by circulating the cooling water from an ice water filled bowl. While this was initially not considered to be disadvantageous, it did not allow for calculation of the specific energy consumption required for the cooling process.

The control experiments had demonstrated that under an initial temperature difference of 37.3°C (± 0.5 std. dev.) between the inside and outside of the condenser, condensate recovery was on average around 73%. Cooling the condenser to around 5°C and thus, increasing the temperature difference between ambient cooling water and vapour laden air inside the condenser to around 50°C, a modest condensate recovery increase of 9.3 ml or 12.7% resulted. This is due to the temperature dependency of saturated water vapour, which stipulates that at low temperature conditions, namely a reduction from 17°C to 5°C, there is only a small amount of condensable water vapour available. Therefore, under prevailing ambient conditions of below 20°C, the additional cooling expenditure for a small percentage distillate increase would perhaps not be justified. However, under warmer ambient conditions, where the temperature difference were too small to drive effective condensation, the need for external cooling of the condenser top would be required in order to achieve a significant condensate recovery rate.

Evidently, in individual situations a decision as to the need for additional condenser cooling would be subject to cost-benefit considerations. If the condenser was operated in an open environment and exposed to warm daytime temperatures, cooling the outside of the copper
top via a sprinkler system, comparable to the water-cooled basin still design described by Tiwari and Bapeshwara Rao,[15] could improve the condensation rate during daytime hours. During night time, the temperature difference would increase naturally due to radiative cooling, and sufficient condensation would occur without additional water cooling.

3.1.5. Airflow regulation and airflow direction

The notion idea turbulent air circulation (formation of eddies) inside the condenser may influence distillate productivity was investigated through the implantation of an elongated honeycomb structure (screen), placed at the midpoint inside the condenser. The underlying rationale was to eliminate potential zoning and to streamline air movement through the condenser and thus, to facilitate maximum contact time for the vapour laden air alongside the copper surface. However, experimental findings demonstrated that there was no benefit from regulating air flow in this way. Rather, the screen experiments resulted in a slightly lower condensate productivity of 3.8 ml or 5.9% compared to the control experiments. A possible explanation might be that in the region where the screen structure was in contact with the condenser copper (around 1/15th of the total copper surface area), heat transfer was restricted by the plastic straw material. As a consequence of the reduced area available for heat transfer, less condensation was achieved for the condenser overall.

In simplified terms, evaporation and condensation in natural weather making processes occur in response to heat input from solar radiation and heat loss from adiabatic cooling as a result of air circulation processes in the atmosphere.[16] This physical stipulation of natural air circulation forms the basis of the chosen airflow direction inside the condenser. In order to guarantee optimum contact of moist air with the copper surface as it travels inside the condenser, the majority of the experiments were carried out with an upward air flow direction. However, for the purpose of assessing the effect of a reversed air flow direction, a downward air flow experiment was performed. As shown in Figure 2(c), condensate productivity for the three upward flow experiments varied slightly, due to ambient temperature variations during the respective trials. Taking into account this ambient temperature variable, statistical analysis of the results demonstrated that reversal of the air flow direction did not significantly alter distillate productivity ($p = .782$).

3.1.6. Optimum length of the improved condenser design

Measuring humidity and temperature for discrete sections of the condenser allowed for an estimation of the optimum condenser lengths under non-cooled and cooled conditions (Figure 3). It emerged that in the control experiment the regions of maximum condensation, as determined by the measured temperature reduction between sections and governed by psychrometric law, extended from the condenser 0–50 mm section through to the condenser 50–375 mm and condenser 375–750 mm sections. After this point, negligible further condensation occurred. Noteworthy, the temperature of the air leaving the condenser exhaust was on average 26.0°C ($\pm 1.1$ std. dev.), thus still eight degrees warmer than the ambient temperature of 17.8°C ($\pm 0.8$ std. dev.). While this high exhaust temperature initially suggested that the 1500 mm condenser was too short, the findings here demonstrated the ‘insulating’ influence of the two adjacent films and the resultant need for a relatively higher temperature difference, to drive the condensation process in this condenser prototype. Importantly, it emerged that a non-cooled condenser under the prevailing conditions would not need to exceed 750 mm in length to achieve maximum efficiency.

![Theoretical Condensation per Condenser Section](image)

Figure 3. Regions of condensation calculated from temperature reduction per discrete section, for cooled and non-cooled condensers.
In contrast, for the water-cooled condenser the majority of condensation occurred almost immediately in the condenser 0–50 mm section. Some more condensation occurred in the condenser 50–375 mm section. After that point, only little additional condensation of around 5 ml distillate occurred. While the full-length (1500 mm) water-cooled condenser version had achieved a total gain of 9.3 ml or 12.7% over the non-cooled condenser, these findings suggest that a water-cooled condenser of 500 mm length would be sufficient to produce a similar amount of distillate as the non-cooled version, while saving considerably on material cost.

3.2. Heat balance calculations

Temperature and humidity measurements from a control experiment were used to calculate a heat balance for the inputs and outputs of latent and sensible heat (Figure 4).

The diagram designates discrete sections of the condenser and their respective condensing performance. Generally, the inputs and outputs for both water budget and heat budget are in good agreement. Applicable to all treatment groups, water and heat balances are well accounted for, suggesting that the condenser works closely within the physical stipulations of heat transfer. Table 1 provides an overview of the heat budgets under the prevailing conditions of the individual condenser treatments. The differences in condenser inlet temperatures between individual experiments and consequently, to the amount of heat supplied to the condenser, are due to two factors. First, to small variations in the heating coil flow rate that supplies heat to the system and second, to varying degrees of unintended heat loss due to the effectiveness of bubble column foam insulation.

3.2.1. Calculating thermal conductivity for discrete sections

Fourier’s Law [11] describes conductive heat transfer ($q$) as the product of thermal conductivity ($k$) of the material involved, multiplied by heat transfer area ($A$) and multiplied by temperature difference across the material ($\Delta T$), divided by material thickness ($s$). $\Delta T$ is calculated by averaging the temperature inside the condenser for a discrete section, minus the ambient temperature. Solving the equation for $k$, the thermal conductivity for individual sections of the condenser copper surface can be calculated. Using temperature measurements from an insulation experiment where condensation over the three remaining (non-copper) sides of the condenser was suppressed allows for quantifying condensation that occurred over the copper sheet alone. For the condenser 0–50 mm section, the amount of heat transferred through the copper sheet was calculated as:

$$k = \frac{q \times s}{A \times \Delta T} = 63.8 \text{ kJ/h} \times \frac{0.00055}{0.005} \times 32.6^\circ \text{C} = 0.0059 \text{ kJ m/min m}^2 \circ \text{C}. \quad (5)$$

While the thickness of the copper plate itself is known, there exist two more barriers to the transfer of heat, whose thicknesses are not known. The combined heat transfer rate through the copper plate and the two adjacent films

![Figure 4. Temperature boundaries and total and sectional inputs and outputs of water and heat for the control condenser (totals from 14 to 15).](image)
Table 1. Heat budget for different treatments (totals from 14.3°C to 15.3°C), calculated by using equations 1–4 (Section 2.4); percentage values are given to detail the heat input variation, for better comparison.

<table>
<thead>
<tr>
<th>Experiment type</th>
<th>Control</th>
<th>Water cooling</th>
<th>Insulation</th>
<th>Reverse airflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser inlet temperature (°C)</td>
<td>53.3</td>
<td>55.1</td>
<td>55.5</td>
<td>55</td>
</tr>
<tr>
<td>Condenser inlet humidity (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Condenser inlet humidity ratio (kg/kg)</td>
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<td>0.114</td>
<td>0.116</td>
<td>0.114</td>
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<tr>
<td>Condenser outlet temperature (°C)</td>
<td>24.3</td>
<td>12.5</td>
<td>33.4</td>
<td>25.9</td>
</tr>
<tr>
<td>Condenser outlet humidity (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Condenser outlet humidity ratio (kg/kg)</td>
<td>0.022</td>
<td>0.011</td>
<td>0.036</td>
<td>0.024</td>
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<tr>
<td>Distillate volume measured (g)</td>
<td>60.6</td>
<td>75.3</td>
<td>54.7</td>
<td>63.3</td>
</tr>
<tr>
<td>Heat supplied to condenser (kJ)</td>
<td>238.6</td>
<td>255.3</td>
<td>258.2</td>
<td>253.9</td>
</tr>
<tr>
<td>Latent heat conducted (kJ)</td>
<td>136.8</td>
<td>170.0</td>
<td>123.5</td>
<td>142.9</td>
</tr>
<tr>
<td>Sensible heat conducted (kJ)</td>
<td>30.1</td>
<td>44.2</td>
<td>30.2</td>
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<td>Sum of latent and sensible heat (kJ)</td>
<td>166.9</td>
<td>214.3</td>
<td>146.5</td>
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<tr>
<td>Heat lost with exhaust vapour (kJ)</td>
<td>59.7</td>
<td>29.9</td>
<td>93.4</td>
<td>64.8</td>
</tr>
<tr>
<td>Heat contained in condensate (kJ)</td>
<td>8.2</td>
<td>3.3</td>
<td>8.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Percentage of heat conducted (%)</td>
<td>70</td>
<td>84</td>
<td>57</td>
<td>68</td>
</tr>
<tr>
<td>Percentage of exhaust heat loss (%)</td>
<td>25</td>
<td>12</td>
<td>36</td>
<td>26</td>
</tr>
<tr>
<td>Percentage of distillate heat (%)</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total heat accounted for (%)</td>
<td>98</td>
<td>97</td>
<td>96</td>
<td>97</td>
</tr>
</tbody>
</table>

is known as the 'equivalent heat transfer coefficient' $K_H$ and can be calculated by omitting copper thickness ($= k/s$) from the previous equation. From this follows that the combined (copper plate and adjacent films) thermal conductivity or heat transfer coefficient for the condenser 0-50 mm section is

$$K_H = \frac{q}{A \Delta T} = 6.5 \text{ kJ/min m}^2 \text{ °C} \text{ or } 108.3 \text{ W/m}^2 \text{ K}.$$ 

As shown in Figure 5, a significantly larger $K_H$ for the relatively small condenser 0–50 mm section was achieved than for any other condenser sections. There are a number of reasons for this observation. First, the ability of air to hold water vapour is stipulated by the temperature dependency of saturated water vapour pressure. This is not a linear function but rather, with increasing air temperature, the amount of water vapour that can be held in the air increases at a disproportionately higher rate. As a consequence, at the relatively high condenser inlet temperature of 55.5°C, a much larger amount of water vapour is contained in the saturated airstream compared to later condenser sections, which in turn contains significantly more water vapour than at lower temperatures. This results in a higher moisture content of the air and, consequently, a higher condensation rate, leading to a larger $K_H$ for the condenser 0–50 mm section.

![Figure 5. Comparison of $K_H$ values for individual condenser sections (temperature and humidity measurements taken from insulation experiment).](image-url)
latent heat. Second, the air film above the condenser surface acts as an insulation layer, effectively limiting the $\Delta T$ between the condenser plate and the ambient. While this insulation effect occurs along the whole condenser, there remains a much larger $\Delta T$ at the first condenser section to drive effective condensation, whereas in subsequent condenser sections the insulating air film causes a much reduced ‘real’ $\Delta T$, than the measured condenser/ambient differential suggests. Third, the condensation film on the underside of the copper sheet is strongly affected by air movement from the steam inlet tube. This leads to a rapid exchange (or ‘thinning’) of the condensation film in that region and thus, a weakening of the insulation effect, consequently resulting in a significantly larger $K_H$ for that section.

In general terms, $K_H$ depends on the temperature drop per discrete length of condenser and the area determined by this length. It is shown that the large temperature drop over the relatively short condenser 0–50 mm section results in a very high $K_H$ for this section compared to all other – and much larger – condenser sections. By taking into account the actual areas of condensation through ‘weighting’ of the individual $K_H$ values, the average condenser $K_H$ can be calculated:

1. Condenser 0–50 mm:

$$K_H = 108.3 \text{ W/m}^2 \text{K} \times \text{weight factor}$$

$$0.005 \text{ m}^2 / 0.15 \text{ m}^2 = 3.7 \text{ W/m}^2 \text{K}.$$  

2. Condenser 50–750 mm:

$$K_H = 12.5 \text{ W/m}^2 \text{K} \times \text{weight factor}$$

$$0.07 \text{ m}^2 / 0.15 \text{ m}^2 = 5.8 \text{ W/m}^2 \text{K}.$$  

3. Condenser 750–1500 mm:

$$K_H = 2.0 \text{ W/m}^2 \text{K} \times \text{weight factor}$$

$$0.075 \text{ m}^2 / 0.15 \text{ m}^2 = 1.0 \text{ W/m}^2 \text{K}.$$ 

Adding the weighted values of all four condenser sections, the average $K_H$ for the condenser is 10.5 W/m² K. This number is in close agreement with the $K_H$ calculated from figures obtained for the whole condenser (condenser 0–1500 mm), as 10.3 W/m² K. Since these numbers are strongly determined by the two films adjacent to the copper plate, improvements to the $K_H$ value and thus, to heat transfer, could be achieved by manipulating one or both of the films, perhaps through increased air circulation, both inside and outside the condenser.

### 3.3. Water quality

Regarding the physical aspects associated with operating a bubble column evaporator (e.g. hydrostatic pressure) and its practical operation, detailed findings have been published elsewhere [2,17] and are therefore not discussed here. Importantly, one of the challenges of operating a bubble column in continuous mode is to maintain a steady salt concentration inside the chamber, by removing excess salt at a rate equal to the rate at which saltwater (i.e. at 35,000 ppm) is fed into the column. In the present experiments, this was not crucial as the duration of the individual experiments was around 5½ h and the total evaporation loss during that period equated to approximately 16%. Beginning the experiments with a NaCl concentration similar to seawater (34,700 ppm ± 595 std. dev.), this resulted in an average NaCl end concentration of around 40,660 ppm (± 1298 std. dev.) inside the column and was considered acceptable for the assessment of condenser performance. Monitoring distillate throughout the series of experiment, it appeared that distillate salt concentrations declined steadily overall, from around 80 ppm (125 μS) in the first experiments to as low as 32 ppm (50 μS). The likely reason for this was a condenser priming effect, responsible for flushing out salt, minerals and small particles that had resulted from the condenser manufacturing process. Post experiment, the higher salt concentrations measured inside the bubble column were found to be in good agreement with the amount of water evaporated from the column.

### 3.4. Bubble column versus conventional desalination systems

 Unlike in conventional thermal desalination processes such as MSF, a bubble column evaporator does not require boiling water.[2] This is because the amount of water vapour in an air bubble immersed and equilibrated with water close to its boiling point is almost identical to that in a bubble created by boiling. As the need for boiling water is eliminated, a reduced energy demand is required for the process overall. The principal energy requirement results from the need for sufficient air flow in order to overcome the static water pressure and the resistance from the bubble generating sinter disc(s). As such, assuming a series of eleven bubble columns would be operated at 88°C, the air pumping energy required by a typical regenerative blower (e.g. Republic HRB 402/1) running at 1.65 kW is estimated at around 2 kWh per m³ of evaporated water.[2] For a comparison, this figure lies well within the relatively large range of water desalination costs for comparable technologies.[18] In the Australian context, it is less than half the energy requirement of the Kwinana reverse osmosis (RO) facility in Perth, Western Australia, where the total energy used per unit of water is approximately 4.6 kWh/m³.[19]

The principal difference making a bubble desalination system advantageous over a traditional solar still is the spatial separation of evaporation and condensation processes.
This means that unlike in the one-chamber still, here the condenser can be cooled without affecting the heat input into the evaporation chamber. A conventional solar still can produce 2–3 litres of distillate per square metre and day and a more sophisticated wick type still such as *Fcubed Carocell™* may produce around 5 L m$^{-2}$/d, according to manufacturer’s information. Based on extrapolation of the experimental findings, where approximately 60 ml of condensate per hour could be recovered from a 0.075 m$^2$ condenser plate, an up-scaled condenser with an area of 1 m$^2$ and a similar efficiency rate and operating temperature might produce around 19 l of distilled water per day and thus, achieve three to four times the productivity of a wick type solar still. While solar still productivity may further be improved by overall still design, for example, by integrating a copper heating plate into a conventional sloped solar still and by optimizing the effects of heat transfer fluid rate,[20] there is a definite limitation on the productivity of solar stills on a m$^2$/m$^2$ footprint comparison.

[The 19] [I calculated above are based on a temperature difference of around] 37.5°C, (vapour temperature at inlet = [55°C; ambient] temperature ≈ 17.5°C). The average vapour temperature drop inside the condenser under these conditions was around 28.5°C, resulting in the condensation of around 60 ml water per hour. As the saturated water vapour density has an exponential dependence on temperature, under a bubble evaporator process temperature of 70°C roughly the same amount of condensation would be achieved by cooling the vapour stream merely to around 58°C. This should easily be accomplishable in the field, even with an ambient air temperature as high as 35–40°C. In yet more extreme conditions, cooling the condenser could perhaps be facilitated by covering the copper plate with a wetted cloth and utilizing the evaporative cooling effect.

Owing to their high energy demand, conventional desalination technologies like multi-stage MSF, RO or electro dialysis are costly for the production of freshwater.[21] An additional drawback is their reliance on highly skilled personal for regular maintenance and often, for crisis management in remote locations. In contrast, the bubble column desalination system holds strong potential for the production of small amounts of high quality drinking water in remote and arid regions, not only in itself but as a potential building block towards a future bubble column-based desalination greenhouse. The system can be operated with renewable energy (RE) sources such as solar, geothermal, wind or wave technology. Despite the situation at present where technological and economic constraints hinder large-scale RE-driven desalination applications, with an increasing price of fossil fuels, the concept will eventually become feasible, particularly when replacing the already high-cost fossil fuel-based water supply methods in remote off-grid areas.[21] This puts the bubble column desalination concept at the forefront of the transition to RE-driven desalination. Importantly, based on its simplicity the system is also technically and operationally appropriate for remote places.

4. Conclusion

The novel bubble column-based HD system described here operates effectively at temperatures well below boiling point and the thermal energy demand for evaporation can be supplied by low grade energy sources, for example, from solar or waste heat. Reliable evaporation rates where demonstrated throughout the investigation. By proving concept viability and by quantifying the evaporation rate of the small-scale laboratory evaporator, extrapolation can be used to predict the performance of up-scaled bubble evaporators. The condenser prototype is inexpensive and easy to manufacture. Due to its simple construction, the component aids energy efficiency to the bubble desalination process overall, requiring only a small energy input when operated in water-cooled mode. Condenser design plays an important role in the process. Certain aspects that might increase the performance of the prototype, such as air speed over the copper surface or cooling fins, have not been investigated in this work but should be subject of future research.

NaCl salt removal was found to be highly effective with distillate salt concentrations between 70 and 135 μS, suggesting that the process could produce drinking water of high quality. Regarding the chemical analysis of the distillate produced, for example, copper content and assessment of corrosion effects with respect to using copper with seawater, further research is needed. While a detailed cost analysis is not the subject of this paper, the investment and operating cost of the system is perhaps several times higher than for a simple solar still. This should however be recoverable through the increased productivity of the system. Future research should also aim towards exploring the potential of the bubble desalination system when operated at a significantly higher temperature than the 55°C achieved in this study.

Disclosure statement

No potential conflict of interest was reported by the authors.

References


Summary and link to next chapter

In the previous chapter, the heat and mass transfer processes that occurred within a discrete section of condensation area were reported on. Copper with its very high thermal conductivity was used as the condensing surface, in order to recover a measurable amount of condensable water vapour as produced by the relatively small experimental bubble column. While the low-tech copper condenser prototype evolved from this premise, the findings were also valuable to inform the conceptualisation of a larger Bubble-Greenhouse desalination concept particularly in regards to external water cooling, air circulation and performance differences between the condensation surface materials copper and PVC. Due to its strong heat transfer capability, the copper surface demonstrated very effective condensation capability. However, when utilising a greenhouse structure as a vapour capture device, the greenhouse skin itself acts as the condensing surface. Copper as a cover material - whether fully or partially - would not be feasible, as it restricts sunlight required for plant growth. Furthermore, it would be too costly and structurally impractical. On the other hand, the conventionally used polycarbonate greenhouse film material would due to a significantly lower heat transfer rate (HTR) result in significantly less condensation and as a result, in much lower lower water production.

A crucial factor in the desalination productivity of a Bubble-Greenhouse system is the operating temperature of the bubble evaporator. As expressed by the non-linear function describing the temperature dependency of saturated vapour pressure, the ability to hold water vapour strongly rises with air temperature. From this follows that if a bubble evaporator is operated at a higher temperature than in the laboratory experiments described, the evaporation rate will rise exponentially. Unfortunately, such a high vapour temperature is
prohibitive for greenhouse humidification. Therefore, aiming for a higher bubble process
temperature without risking greenhouse plant survival ultimately requires placing a third
component between the bubble evaporator and the condensing greenhouse. This element
simultaneously acts as a cooling device and as a first condenser stage previous to channelling
the vapour into the greenhouse. In addition to mitigating the mismatch between high
evaporator temperature and actual greenhouse temperature requirements, the condensate
recovery rate is strongly enhanced by incorporating the pre-condenser, compared to the
alternative that relies solely on greenhouse skin condensation.

For proof of concept, several simple and easy to make cooling devices are tested and reported
on in the next chapter. The essential rationale for the different methods is that they should be
easy to manufacture, be of low energy demand and low investment cost and importantly, be
technically and operationally appropriate for local people in remote places. The passive
condenser systems developed for the seawater greenhouse by Davies and Paton (2005)
provide inspiration for the simple copper tube concepts. Once again, copper is chosen for its
superior HTR, in order to assess the concept in the laboratory setting for both, air and water
cooled operation. The idea to trial a bubble column as a condenser results from the
encouraging findings in the previous chapter, where the bubble evaporator demonstrated a
strongly enhanced exchange rate of water molecules from liquid to gas phase as a result of
the manifold liquid/air interface provided by the process. It is anticipated that similar to the
bubble evaporation process that is facilitated by the large surface area, in a bubble condenser
the larger condensing surface provided by the continuously renewed air/water interface may
also lead to an enhanced condensation rate.
Chapter IV: Technical evaluation of simple condenser devices for a bubble column desalinator

Attribution

MS developed the concept, reviewed the literature, conducted the experiments, performed the statistical analysis, designed the figures and drafted the manuscript. GH assisted in interpreting the findings. GH and MA provided feedback on the draft. All authors critically reviewed and approved the final version.

MS: 90%
Technical evaluation of simple condenser devices for a bubble column desalinator

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ABSTRACT

Several simple vapour cooling and pre-condensing concepts were assessed for the purpose of mitigating bubble column vapour temperatures, a critical aspect for the development of a bubble column driven greenhouse desalination system. Particular emphasis was on low-energy demand of the devices, ease of manufacture, low investment cost and technical and operational appropriateness for local people in remote places. Under laboratory conditions, the copper tube type I and II concepts achieved water recovery rates of between 65 and 75%. The water-tank cooled tube achieved 83% condensate recovery, albeit at the cost of large cooling water requirements, whereas the air cooled and passive sleeve-cooled bubble condenser columns achieved condensate recovery rates of at least 50% under favourable ambient conditions. A “self-cooling” effect was observed for the passive sleeve columns that could perhaps be tailored to produce small quantities of potable water in hot and arid regions. The effectiveness–NTU method was used to allow for a meaningful comparison between the devices. While the majority of the tested concepts represented a “single-stage” approach to the humidification–dehumidification cycle, it is stressed that a well-designed latent heat recovery system would be crucial for the economic viability of a bubble greenhouse.

Keywords: Bubble column evaporation; Bubble-greenhouse; Passive condenser; Seawater desalination; Brackish water desalination

1. Introduction

This work was motivated by the need to mitigate the vapour temperature from a bubble column evaporator, as a means of humidifying a conceptual bubble greenhouse. The novel greenhouse-based desalination system aims at utilising low-key devices with minimal technical complexity and energy demand. Bubble column technology has recently gathered attention as a prospective method for water desalination, both for humidifying [1] and dehumidifying [2] purposes. While technically advanced multi-stage bubble column condensers have reached a level of maturity that suggests commercialisation in the near future [3–5], the humidification–dehumidification (HD) concepts investigated here employ a single-stage bubble column evaporator in combination with several easy-to-make condensation devices, under the important proviso of being a low-tech method that is operational by local
people in remote regions [6]. As such, this paper provides important insights into steam cooling dynamics for the conceptual bubble-greenhouse desalination system and identifies future research areas.

Solar stills are the most basic exponents of small-scale desalination systems, utilising the quintessential principles of solar thermal desalination. Some of their key advantages are that they are very simple, hardy and easy to maintain and repair by local people with limited technical means [7]. The idea to upscale the solar still concept by integrating large evaporation basins into a crop producing greenhouse has been around for some time [8]. A considerable number of studies on different still-greenhouse designs are available in the literature [9–12]. In general terms, the aim is to tailor and optimise the HD process inside a greenhouse, while making use of the structural components of the greenhouse itself, primarily as a condensing surface. However, based on the necessity to capture large amounts of heat from solar radiation as the driver for basin water evaporation, a crucial aspect in this concept is the risk of overheating the greenhouse and the resulting risk to plant survival.

An alternative method of humidification is realised in the Seawater Greenhouse. Here, surface seawater is trickled down porous evaporators that are made from a cardboard honeycomb lattice, for the dual purposes of feed water vapourisation and greenhouse temperature control [13]. While the greatest overall effect on condensate productivity and energy efficiency is determined by the dimensions of the greenhouse [14], the condenser design in seawater greenhouses is recognised as one of the main bottlenecks in the commercialisation of the technology [15]. Importantly, the evaporation rate of the cardboard honeycomb evaporator is linked to and thus, limited by ambient temperature conditions.

Owing to the relationship between saturated water vapour density and air temperatures [16], the higher process temperatures achievable with a bubble column evaporator can accomplish significantly larger evaporation rates. The process works by pumping a continuous stream of air from below through a column containing salty water. The unusual property of salt water to inhibit air bubble coalescence facilitates the performance of the bubble column with a high volume fraction of small air bubbles, continuously colliding but not coalescing [17]. In contrast to solar basin stills or flash distillation, where essentially only the surface of the liquid comes in contact with the air above, the bubble column produces a manifold liquid/air interface and as a result, a high exchange rate of water molecules from liquid to gas phase can be achieved.

While the higher evaporation rates of a bubble column over a conventional Seawater Greenhouse evaporator promote it as an alternative source for greenhouse desalination, the high vapour temperature—if left unmitigated—is problematic for plant survival. Crucially therefore, previous to greenhouse humidification it is essential to cool the vapour temperature to an acceptable level. This can be achieved by linking bubble column and greenhouse with a pre-cooling device, which has the added benefit of recovering a significant amount of condensate prior to greenhouse humidification. As the vapour stream is cooled down, the saturated vapour pressure remains at a maximum (i.e. 100% humidity), providing the greenhouse with a humidified environment that is conducive to crop production under a strongly reduced plant water demand [18].

For a conventional water condenser, the rate of condensation and thus, the net gain of desalinated water, are principally governed by the temperature difference between the warm vapour-saturated carrier medium (e.g. air) and the cooler condensing surface. The condensing surface in turn is kept cooler by the medium opposite (e.g. ambient air or cooling water). In this way, the condensing surface essentially acts as a physical barrier for matter, however, it allows for thermal energy (heat) contained in that matter to pass through. Condenser materials with a high thermal conductivity such as copper sheet excel at releasing heat through a process known as conduction [19]. The larger the temperature difference between inside and outside, the more and quicker heat is removed at the condenser surface. As a consequence, nearby water molecules are forced into a reduced energy state, expressed as a change from vapour to liquid water. As more and more water molecules condense, droplets and ultimately large drops of desalinated water form and can be collected [20].

The work presented here investigates several “simple-to-make” vapour cooling devices. The principal research question is how to achieve sufficient vapour cooling under a number of important provisos such as low-energy demand, low environmental impact, cost efficiency, durability and ease of maintenance. Besides their vapour cooling potential, the devices function as pre-condensing elements and their condensation production rates form an important part of the assessment. In its most basic expression, the vapour cooling concept explores several surface-type condensation devices in the form of copper tubes that operate under ambient air-cooled conditions or are installed inside a water-filled passive cooling tank. The pairing of two separate bubble columns into an evaporation–condensation module represents a unique and novel
approach to the HD challenge. A quantitative assessment of the water production capability is presented to demonstrate the potential of this concept.

2. Materials and methods

2.1. Evaporator design

The bubble column evaporator was manufactured from a clear Perspex cylinder of 500 mm height and 120 mm internal diameter. A 40–100 μm pore size glass sinter was sealed into the column with commercially available two-component glue. Top and bottom covers were attached and sealed with commercial Roof & Gutter Silicone. During operation, the lower part of the column was heated by an internal plastic tube heating spiral, fed from a water bath with a feed temperature of 70˚C. This resulted in a steam outlet temperature of around 55˚C, the maximum temperature practically achievable with this particular experimental set-up. Based on the exponential rise of water vapour density with temperature [16], the evaporation rate in a bubble column increases significantly with rising process temperatures, thus achieving higher output rates with smaller vessels. While the higher steam temperatures require mitigation previous to greenhouse humidification, a strongly improved “water production rate per infrastructure cost ratio” justifies the steam cooling expenditure, provided the cooling method is simple, effective and of low cost in terms of energy use and infrastructure.

The bubble column was filled with 2 L of sodium chloride (NaCl) salt solution with a concentration similar to seawater (35,000 ppm). During individual experiments, the evaporation chambers were not replenished, leading to a gradual salinity increase of about 15% above starting levels (40,500 ppm). Compressed air was continuously pumped through an inlet hose and through the glass sinter from below at a rate of 13.5 L min⁻¹, creating a high density of fine air bubbles. Due to a property of seawater, bubble coalescence was inhibited and the oscillating rise of bubbles resulted in a large and constantly renewed gas/water interface and thus, a uniform and efficient exchange of water vapour into the bubbles [17]. From an outlet hose on the column top, the heated vapour stream was channelled into the respective cooling devices. During the experiments, sheets of flexible foam were used to insulate the bubble column evaporator and the heating pipes, in order to prevent heat loss to the ambient air.

2.2. Vapour cooling concepts

Four types of cooling concepts were studied. These were air-cooled copper tubes (A), tank water-cooled copper tube (B), water-cooled glass column bubble condensers (C) and air-cooled and water-cooled copper column bubble condenser (D).

2.2.1. Copper cooling tube type I and II

The cooling tubes type I and II consisted of a section of commercially available annealed copper tube. Tube dimensions, experimental airflow rate and the resulting vapour residence times are given in Table 1. Thermocouples (PTFE type K/T.M. Electronics) were placed in pairs at defined locations (Table 1) to measure the rate of heat exchange through the copper wall as well as the lengthways temperature drop. Additional thermocouples were used to measure evaporator column temperature and heating coil inlet and outlet temperatures. Data loggers (HOBO-ware/Onset Computer Corporation) were used to measure temperature and humidity at the cooling tube exhaust, the compressed air inlet and of the ambient air. The tubes were directly attached to the bubble column vapour outlet and positioned with a gentle downwards slope (approximately 5%), to allow for condensation to flow out by gravity and to be collected and weighed for data collection. Passive tube cooling was induced by the temperature difference between the vapour stream and the ambient air.

2.2.2. Copper cooling tube type II in temperature gradient water tank

For this method, a plastic barrel filled with 160 L of water was used as a passive cooling device (Fig. 1). A section of annealed copper tube was coiled inside the cooling tank at a downward angle, to promote condensate outflow by gravitational force. Inside/outside pairs of thermocouples were placed near the copper tube inlet and outlet to determine the amount of heat released into the tank. Two additional thermocouples were placed inside the cooling tank, at 50 mm above tank bottom and 50 mm below the cooling water surface, to assess the developing tank temperature gradient and the thermal inertia relationship of the components.

2.2.3. Glass bubble column condenser

The bubble column condenser was manufactured from a sintered glass chromatography column with a
pore size of 40–100 μm (herewith termed core), sleeved by a section of commercially available 90 mm PVC stormwater pipe (sleeve), that allowed for cooling water to be contained (Fig. 2). The core column was filled to the top with desalinated water. Excess condensate that was constantly produced by the process was collected through an overflow outlet and determined by weight. The connection pipe between the evaporator column and the condenser column was shielded with insulation tubing in order to eliminate heat loss and unwanted condensation in this section as much as possible.

Pairs of thermocouples were placed at defined locations to measure the temperatures of core water and cooling water contained in the sleeve (Fig. 2). Overall, for assessment of the glass column condenser concept a series of experiments with varying cooling regimes were performed. Active cooling (or active sleeve) of the system was achieved by circulating cold water through a plastic tube coiled inside the sleeve.

| Dimensions and experimental parameters of individual vapour cooling concepts |
|-------------------------------|---------------------|-----------------|-----------------|-----------------|-------------------|-------------------|
|                              | Length (m) | Internal diameter (mm) | Volume (L) | Airflow rate (L min⁻¹) | Residence time (s) | Thermocouple placement | Cooling method |
| Copper cooling tube type I    | 3          | 5                  | 0.06      | 13.5                 | 0.3                | Inside/outside pairs near tube inlet and outlet | Ambient air |
| Copper cooling tube type II   | 3          | 10.9               | 0.28      | 13.5                 | 1.2                | Inside/outside pairs near tube inlet and outlet | Ambient air |
| Copper tube type II in water tank | 3          | 10.9               | 0.28      | 13.5                 | 1.2                | Inside/outside pairs near tube inlet and outlet | Water tank |
| Glass bubble column condenser | 0.4        | 42                 | 0.55      | 13.5                 | 2.5                | Inside/outside pairs (bottom, mid and top) | Water sleeve |
| Copper bubble column condenser | 0.4        | 40                 | 0.48      | 13.5                 | 2.1                | Inside/outside pairs (bottom, mid and top) | Water sleeve |

Fig. 1. Experimental design and sensor placement for the temperature gradient water tank experiments.
cooling level was controlled by the rate of cold water circulation. Moderate cooling was achieved by a slower circulation rate and with increased cold water circulation, strong cooling was realised. Additionally, several passive sleeve (no cooling) experiments were carried out, where the sleeve contained “cooling” water that was however not actively cooled by cold water circulation.

2.2.4. Copper bubble column condenser

This version of the stacked bubble cooling column consisted of the lower part of a sintered chromatography column with a section of copper tube attached. For this concept, several experiments were carried out with and without a sleeve. The un-sleeved cooling column was cooled by ambient air. For the sleeved version, a section of PVC pipe was fitted similar to the glass column described above (Fig. 2). The water contained in the passive sleeve was not cooled by cold water circulation. Thermocouple and humidity logger placement corresponded with the glass column experiments.

2.3. Experimental setup

Previous to all experiments the thermocouples were calibrated, using a precision alcohol thermometer (20–30 ± 0.02°C). The humidity loggers were group tested in a steam chamber for their accuracy, particularly in the extreme upper region of maximum saturation. The rotameter used to measure airflow rate (Fisher Controls 25 ± 1 L) was calibrated through a volume displacement device. At the start of each experiment, two litres of NaCl salt solution were prepared and adjusted to a TDS concentration of 35,000 ppm with a conductivity meter (Hanna Instruments HI8733) and transferred into the bubble column evaporator.

Once the system had established steady state conditions as represented by thermocouple measurements, three one-hour measurement blocks for bubble column weight reduction (from saltwater evaporation) and condensate production were obtained using electronic scales (A&D Limited HW-15 K, 15,000 ± 1 g and A&D Limited GF 2000, 2,100 ± 0.1 g). Temperature and humidity readings from thermocouples and loggers were used to calculate the expected theoretical amount of evaporation and condensation per time unit, as governed by psychrometric law. Manual measurements of water bath temperature and cooling water temperature (where applicable) and heating flow rate and cooling flow rate (where applicable) were recorded. At the end of each experiment, water volume and conductivity of the column brine content and condensate conductivity were recorded.
2.4. Equations and parameters

Specific heat capacity:

\[ Q = m \times C \times \Delta T \]  

where \( Q \) is the rate of heat transfer (amount of heat energy gained or lost by substance) in kJ s\(^{-1}\), \( m \) is the mass flow rate per time in kg s\(^{-1}\), \( C \) is the specific enthalpy of condensation (heat capacity) in kJ kg\(^{-1}\) C\(^{-1}\) and \( \Delta T \) is the temperature change in °C.

Logarithmic mean temperature difference by LMTD method:

\[ \Delta T_{\text{mean}} = \frac{\Delta T_{\text{out}} - \Delta T_{\text{in}}}{\ln(\Delta T_{\text{out}}/\Delta T_{\text{in}})} \]  

where \( \Delta T_{\text{in,parallel flow}} = t_{h,\text{in}} - t_{c,\text{in}} \) (inlet hot and inlet cold stream in °C), \( \Delta T_{\text{out,parallel flow}} = t_{h,\text{out}} - t_{c,\text{out}} \) (outlet hot and outlet cold stream in °C), \( \Delta T_{\text{in,counter flow}} = t_{h,\text{in}} - t_{c,\text{out}} \) (inlet hot and outlet cold stream in °C) and \( \Delta T_{\text{out,counter flow}} = t_{h,\text{out}} - t_{c,\text{in}} \) (outlet hot and inlet cold stream in °C).

Overall heat transfer coefficient:

\[ U = \frac{Q}{A \times \Delta T_{\text{mean}}} \]  

where \( A \) is the surface area in m\(^2\).

Energy balance in a single phase heat exchanger:

\[ m_h \times C_h \times (T_{h,\text{in}} - T_{h,\text{out}}) = m_c \times C_c \times (T_{c,\text{out}} - T_{c,\text{in}}) \]  

where \( m_h \) and \( m_c \) are the mass flow rates of the hot and cold fluid, respectively, in kg h\(^{-1}\), \( C_h \) and \( C_c \) are the mass heat capacities of the hot and cold fluid, respectively, in kJ kg\(^{-1}\) °C\(^{-1}\), \( T_{h,\text{in}} \) and \( T_{h,\text{out}} \) are the inlet and outlet temperatures on exchanger hot side, respectively, in °C and \( T_{c,\text{in}} \) and \( T_{c,\text{out}} \) are the inlet and outlet temperatures on exchanger cold side, respectively, in °C.

Enthalpy of moist air (sum of latent and sensible heat):

\[ h = c_{p,a} \times T + x_a [c_{v,w} \times T + h_{w,e}] \]  

where \( c_{p,a} \) is the specific heat capacity of air (1.006 kJ kg\(^{-1}\) °C\(^{-1}\)), \( T \) is the air temperature (in °C, relative to zero), \( x_a \) is the humidity ratio at saturation in kg of water per kg of air, \( c_{v,w} \) is the specific heat of water vapour at constant pressure (1.875 kJ kg\(^{-1}\) °C\(^{-1}\)) and \( h_{w,e} \) is the evaporation heat of water at 0°C (2,501 kJ kg\(^{-1}\)).

Effectiveness:

\[ \varepsilon = \frac{C_h \times (T_{h,\text{in}} - T_{h,\text{out}})}{C_{\min} \times (T_{h,\text{in}} - T_{c,\text{in}})} \]  

where \( C_{\min} \) is the smaller value of \( C_h \) (hot stream) and \( C_c \) (cold stream).

Number of transfer units (NTU):

\[ \text{NTU}_{\text{counter–flow}} = \frac{1}{(C_{\text{ratio}} - 1)} \times \ln\left(\frac{\varepsilon - 1}{\varepsilon \times C_{\text{ratio}} - 1}\right) \]  

\[ \text{NTU}_{\text{parallel–flow}} = -\ln(1 - \varepsilon)\left(1 + C_{\text{ratio}}\right) \]  

where

\[ C_{\text{ratio}} = \frac{C_{\text{min}}}{C_{\text{max}}} \]

Overall heat transfer coefficient:

\[ U = \text{NTU} \times C_{\text{min}} / A \]  

where \( A \) is the surface area in m\(^2\).

3. Results and discussion

3.1. Bubble column evaporation

The fine sinter with a pore size of less than 100 μm produced a small bubble diameter (1–3 mm) and a large ratio of air bubbles to water volume, some of the key parameters that influence the diffusion of water into the air bubbles [21]. Consequently, the fine bubble size produced by the evaporator prototype directly translates into a shorter travel distance for equilibrium vapour pressure to occur. Throughout the experiments, height of the air bubble and water mixture was kept to 200 mm which was sufficient for achieving maximum saturation. In all experiments, the bubble column evaporator produced steady evaporation rates of 80–86 ml per hour, well correlated with expected theoretical values as determined by psychrometric chart.

While many factors such as water temperature, headwater difference and air velocity strongly influence humidification efficiency [22], the effect of rising salinity on the evaporation rate has, to our knowledge, not been previously assessed. For NaCl salt, bubble coalescence inhibition begins at a concentration above 5,000 ppm upwards. At the upper
range, the evaporation figures remained constant within 80–86 ml per hour throughout the three-hour measurement blocks, despite the steady salinity increase that occurred due to the particularities of the experimental design. As the evaporation rate appeared unaffected by the increasing salt concentration, it was concluded that higher salinities, at least up to 40,500 ppm, would not reduce humidification efficiency.

3.2. Cooling concepts

3.2.1. Copper cooling tube type I and II

A simple approach to vapour temperature reduction was investigated by channelling the vapour stream directly through a length of copper tube that would be cooled passively by ambient air. Generally, the principal factors that influenced the cooling rate were (a) the temperature difference between bubble column vapour and the cooling medium ambient air and (b) the length of the cooling tube and the resulting vapour residence time. The main differences between type I and type II tubes were their wall thickness (0.55 mm vs. 0.9 mm) and their internal diameter (5 mm vs. 10.9 mm) which directly factored into vapour residence time (0.5 s vs. 2.2 s).

While the larger diameter of tube type II resulted in a four times longer residence time under the unchanged airflow regime, after correcting for ambient temperature, there was only a slightly stronger cooling effect of 0.7°C compared to tube I. This translated into 56.5 ml of condensate production for type I vs. 53.8 ml for type II tube. A second factor influencing condensate productivity was the difference in total surface area of the tubes (0.12 m² for type II vs. 0.06 m² for type I). In order to allow for a meaningful comparison, the heat transfer rate (Q) for both tube types was calculated (Eq. (1)) as 0.0115 kJ s⁻¹ (type I) and 0.0114 kJ s⁻¹ (type II). The overall heat transfer coefficient (U) of compact single-phase heat exchangers (counter and parallel flow) is determined by a non-linear function, known as the logarithmic mean temperature difference, or LMTD method. Using Eq. (2), a LMTD of 12.0°C for tube type I and for type II as 7.8 W m⁻²°C⁻¹, likely reflecting the different tube wall thicknesses of 0.55 mm for type II vs. 0.9 mm for type I tube.

These findings suggested the likely interplay of several factors being responsible for the relatively similar water production rate of the tubes. The twice as large heat transfer coefficient (type I) was counteracted by the four times larger residence time (type II), both being masked by the diffusion resistance effect that occurs in surface-type condensers [23]. It was therefore concluded that the thin-walled type I tube would be more effective as a passive vapour pre-cooling method under favourable ambient temperature conditions such as those experienced during the experiments. In regards to incorporating a tube-type cooling component into a conceptual bubble-greenhouse system, the use of type I tube would translate into considerable material savings.

3.2.2. Copper cooling tube type II in temperature gradient water tank

The latent heat of vaporisation per kilogram of pure water at 100°C is around 2,258 kJ. While this figure slightly decreases with an increase in salinity (at 35,000 ppm it is about 2,180 kJ), thermal evaporation of saline water is very energy intensive. Unless a bubble column desalination system utilises a waste heat source from industrial processes [17], effective recovery of latent heat becomes a crucial aspect of its economic viability. By incorporating a large cooling water tank (160 L) as a heat collector, the tube cooling concept aimed to assess the potential for latent heat recovery in a technologically undemanding manner. Due to the tube placement and a property of water to exhibit a natural stratification effect in response to density and temperature gradients [15], this cooling method was regarded as a counter flow heat exchanger, where the two streams—vapour and cooling water—move in opposite directions.

As the vapour tube entered the tank from above, the largest part of latent and sensible heat was released into the upper tank region. Within the 3 m length of copper tube, the vapour temperature was reduced from 53.8°C at the inlet to 16°C at the tube outlet, only slightly higher than the ambient temperature (15.4°C). The total enthalpy transferred into the cooling tank during the one-hour measurement period was 217 kJ (Eq. (5); ΔT_inlet/outlet). By rearranging the specific heat capacity equation (Eq. (1)) for ΔT, it was found that if the heat had been distributed evenly, the average temperature increase in the cooling tank would only be 0.32°C. In reality, however, the main deposition of heat occurred in the upper tank region (Fig. 3) and only a very small temperature increase was observed at the bottom of the tank during the measuring period, confirming the temperature stratification effect that developed.
While a more detailed description of the temperature distribution in the tank would require further investigation and is outside the scope of this paper, these results suggest some potential for latent heat recovery with minimum technical difficulty. The stratification effect could be utilised by continuously cycling the warmest water away from the upper tank region and extracting the sensible heat along the way. In an industrialised setting, this could be achieved by cycling the water through a passive radiator type air heater, where it would be cooled and re-fed into the lower tank region. The regenerative blowers used to supply air to the bubble columns would be placed in such a way that they drag ambient air through the radiator array. By preheating the air stream previous to entering the evaporator bubble column, some sensible heat from the tank water cycle would be reused.

The following section on modelling the cooling tank size is based on a conceptual bubble greenhouse with an assumed water production rate of 8 m³ per day [24]. Extrapolated from the evaporation rate that was achieved with the laboratory-scale bubble column (with a sinter area of 78.5 cm² and an airflow rate of 0.81 m³ h⁻¹), the total column sinter surface area required for evaporation of 8 m³ of saltwater at a process temperature of 80°C would be 12.9 m². This would require a large number of columns (e.g. 70 columns with a sinter area of 1,850 cm² or 49 cm diameter each), to be organised in a modular configuration. The 70 columns could be arranged in 7 modules, with a series of 10 bubble columns per module. Each of the seven modules would be cooled by an individual cooling tank.

Total airflow demand per module would be 190 m³ h⁻¹. A typical regenerative blower such as Republic HRB 402/1, running at 1.65 kW, produces an airflow rate of 192 m³ h⁻¹ and a working pressure of 343 mbar [17]. One of these blowers could supply air to 10 bubble columns in series, each up to 30 cm high. At a column process temperature of 80°C, the total energy requirement for air pumping would be about 3.4 kW h m⁻³ of water produced, less than best practice thermal desalination processes (using vapour compression) that operate at about 4 kW h m⁻³ [25]. Total bubble column evaporation per module would be 55 L h⁻¹ (1.3 m³ d⁻¹). Assuming there was little heat loss between bubble column output and cooling tank inlet, the temperature at the cooling tube inlet would be close to 80°C. Total enthalpy contained in the 55 L h⁻¹ of condensable water vapour per cooling tank would be 115 MJ h⁻¹. At an ambient temperature of 35°C and an optimal vapour temperature reduction to
this point, the enthalpy contained in the “vapour-to-greenhouse” stream would be 19 MJ h\(^{-1}\) (in 7.5 L h\(^{-1}\)) and the amount of heat released into the tank from condensation and cooling of 48 L h\(^{-1}\) would be 96 MJ h\(^{-1}\).

As an approximation, using the Δ\(T_{\text{in}}\) Δ\(T_{\text{out}}\) and LMTD relationship from the experimental data and extrapolating for a steam inlet temperature (\(T_{\text{h,in}}\)) of 80°C and cooling water (\(T_{\text{c,in}}\)) of 35°C from below, the cooling water temperature in the highest region of the tank (\(T_{\text{c,out}}\)) would be 55°C and the steam temperature leaving the tank (\(T_{\text{h,out}}\)) would be 37°C. Assuming that the cooling water was constantly removed from the top, the water flow rate needed to carry away this heat would be 1.13 m\(^3\) h\(^{-1}\) (Eq. (1)). However, there exists a strong limitation to the recovery of sensible heat in this system as a result of the significantly inferior heat capacity of air compared to water. As the 190 m\(^3\) of air required per hour for the bubbling process would be heated by dragging it through the radiator array, due to its weight of around 228 kg and its low specific heat capacity of 1.006 kJ kg\(^{-1}\) °C\(^{-1}\), there would not be enough airflow to recover sufficient amounts of energy. Of the 96 MJ h\(^{-1}\) cycled away from the tank, only 12 MJ or 13% of energy would be reused in this way (Eq. (1)). Based on this, the use of air as a heat recovery medium would be too inefficient and a more sophisticated cooling tank design would be required for improved heat recovery and thus, for a more economical bubble-greenhouse concept. Note that the conventional recovery method of using heated cooling water to feed the evaporator is only viable in true counter-flow heat exchangers, where the active transport of heat away from the hot fluid results in much less cold fluid demand. Due to the strong mismatch of water volumes in the laboratory experiment (160 L of cooling water vs. 80–88 ml h\(^{-1}\) of evaporator refill) it is not a viable option here.

3.2.3. Glass bubble column condenser

In the presence of a non-condensable carrier gas such as air, diffusion resistance to transport vapour through the non-condensable gas/vapour mixture strongly diminishes condensers’ efficiency [23]. Heat transfer rates (HTR) for surface condensers can be two orders of magnitude lower than pure vapour systems, with an equivalent heat transfer coefficient as low as 1 W m\(^{-1}\) °C\(^{-1}\). Consequently, surface condensers require a large heat transfer area to be effective. Condensing vapour in a water column rather than on a condenser surface can substantially improve the HTR. In a bubble column, the large condensing surface is provided by a continuously renewed air/water interface, in permanent motion due to the oscillating nature of upwards rising bubbles. For that reason, diffusion resistance is significantly reduced and strongly improved heat and mass transfer rates can be realised albeit the presence of non-condensable gas [23].

In order to assess the effectiveness of the concept, a chromatography column was modified into a simple glass column condenser (cooling column). It contained a sintered disk with a pore size of 40–100 μm that produced a fine bubble stream to oscillate upwards. As the cooling column was filled with deionised water, bubble coalescence was not inhibited in this environment and the bubbles created by the process were larger than in saltwater. While this resulted in a considerably smaller air/water interface in the cooling column compared to the evaporator column, it nonetheless provided a large condensation surface for water vapour to return to liquid phase. Closely correlated with theoretical condensation rates, with increasing cooling effort, condensate recovery rates of 51% for no cooling, 68% for moderate cooling and 73% for strong cooling experiments were recorded.

Under strong cooling conditions, rapid cooling of the vapour stream to 25.9°C occurred almost immediately within a very short distance. Throughout the remainder of the cooling column, only a modest further temperature reduction to 25.0°C was observed. This suggests that a much shorter cooling column with perhaps no more than 50 mm height could be equally effective under similar cooling conditions. For both the moderate and strong cooling experiments, a cooling sleeve temperature increase from bottom to top was observed, demonstrating the development of a temperature gradient similar to the previous tank concept. This was different for the no cooling (passive sleeve) experiment, where the temperature at cool-sleeve top was 0.2°C lower than cool-sleeve mid, indicating some process that had somehow counteracted the establishment of the temperature gradient in this upper region.

The latent heat released from condensation of 58.6 g of water during the final one-hour block in the strong cooling experiment was 132 kJ. It can be assumed that the majority of this heat was conducted through the glass wall into the cooling sleeve and then carried away with the circulating ice water. In contrast, the 93 kJ of heat released in the no cooling experiment (from condensation of 41.2 g of water) was first conducted into the non-circulated or passive sleeve water, from where secondary heat release occurred as (a) conduction through the PVC sleeve wall and (b) over the water surface at the uncovered sleeve top. Noteworthy, the previously mentioned effect that
seemed to have counteracted the establishment of the temperature gradient in the upper sleeve region, caused the temperature at cool-sleeve top to plateau at around 43.2°C, more than 10°C below the cooling column inlet temperature of 53.5°C (Fig. 4). As a result of this anomaly, an impressive 51% of the evaporated water could passively be recovered from condensation.

In the upper region of the cooling sleeve, starting from the water surface down to approximately 30–40 mm below surface, the formation of air bubbles around the glass column wall was observed. This process, known as nucleate bubble formation [26], was caused by the existence of metastable gas cavities on the glass surface. Under the supersaturation conditions caused by constant heat input into the cooling sleeve water, bubbles continuously formed and grew. Simultaneously, a quantity of cooling sleeve water vaporised into the bubbles and produced an evaporative cooling effect around the outside of the glass column. With bubbles detaching and rising to the surface with some regularity, a considerable amount of heat was released from the cooling sleeve water surface in this way. While the overall performance of the passive sleeve glass cooling column was controlled by the temperature difference between the incoming vapour from the evaporator column and the ambient air, the heat released through nucleate bubble formation—a process that could perhaps best be described as a “self-cooling effect”—was presumably due to the particular design of the apparatus.

3.2.4. Copper bubble column condenser

The underlying motivation for the stacked column array had been to utilise the relatively large air/liquid interface as created by the bubble process for condensation and to investigate whether effective cooling could be achieved within a relatively small vessel, thus making a short bubble column condenser advantageous over a simple flat-plate condenser previously assessed [27]. As shown above, the condensing capability of an actively cooled glass column came at the cost of considerable cooling and pumping demand, in addition to an already increased air pumping requirement to overcome the hydrostatic water pressure of the stacked evaporator/cooling column array. In terms of condensation output, no significant improvement of the cooling column over the flat-plate condenser could be demonstrated.

Since the passive sleeve or no cooling column demonstrated only a relatively modest vapour temperature reduction of around 10°C, it would not be an effective vapour cooling device for the purpose of greenhouse
humidity. However, based on the observed “self-cooling” effect, a stacked evaporator/condenser module could perhaps hold some potential as a standalone small-scale desalination method, where the focus was simply on energy efficient condensation. It was therefore decided to investigate the concept further by substituting the glass cooling column with a modified copper column, based on the vastly larger thermal conductivity of copper (401 W m\(^{-1}\) °C\(^{-1}\)) over glass (1.05 W m\(^{-1}\) °C\(^{-1}\)) and its superior HTR.

Initially, the performance of an unsleeved copper column was assessed under air-cooled conditions. While the temperature difference between cooling column inlet and ambient air was relatively large (32.7°C), the total vapour temperature reduction over the length of the column was only 10.7°C. This resulted in a low condensate recovery rate of 36% (29.7 ml), likely caused by the considerably lesser heat capacity of the cooling medium air compared to water (1.01 kJ kg\(^{-1}\) °C\(^{-1}\) vs. 4.18 kJ kg\(^{-1}\) °C\(^{-1}\)) and the vertical orientation of the cooling column that limited the movement of warm ambient air away from the copper surface. Nevertheless, encouraged by the promising condensate recovery rate of 51% that was achieved with the passive sleeve glass column, a PVC sleeve was fitted in a similar manner to the copper column. In passive sleeve mode, the condensation rates recorded for glass (41.2 ml) and copper (42.0 ml) columns were fairly similar and nucleate bubble formation was also observed around the copper column. However, the copper column demonstrated a faster initial temperature reduction at the inlet location which correspondingly suggested an increased heat input into the cooling sleeve. Contradictory, all of the cool-sleeve sensor locations showed a significantly lower temperature than in the glass column experiment which would require a faster heat release to the ambient air and away from the cooling sleeve itself. The temperature at cool sleeve top levelled at around 41.0°C, more than 11°C below the cooling column inlet temperature of 52.1°C. This suggests a slightly stronger heat release effect through the nucleate bubble formation process. Notwithstanding this, the relatively small condensate gain over the glass column did not reflect the vastly superior heat transfer capacity of copper.

### 3.3. Condenser effectiveness

All of the concepts assessed in this paper essentially represented simple embodiments of compact heat exchangers. For a better comparison of the different approaches to the vapour cooling task, the effectiveness–NTU method was used [19]. Effectiveness (\(\varepsilon\)) is the actual heat transferred, divided by the maximum heat that could possibly be transferred from one stream to the other (\(q / q_{\text{max}}\)). The tube-based devices resembled shell and tube-type heat exchangers, whereas the bubble columns fell under the category of direct contact heat exchangers. In their air-cooled embodiments where heat transport relied on natural convection, the copper tubes and the copper column were neither truly parallel nor counter flow, however they were considered closer to parallel flow in that the air surrounding the tube at the inlet was much warmer than the air around the tube outlet position (with a gradual temperature reduction along the way). All water-cooled devices were considered as counter flow, based on the temperature stratification that developed in the cooling sleeve and cooling tank.

In order to define the effectiveness of a heat exchanger, an energy balance allows calculating the maximum possible heat transfer that can be hypothetically achieved. As the cold stream mass flow could not be practically measured in the air-cooled and passive sleeve experiments, it was calculated by considering the heat lost by the hot fluid and the heat gained by the cold fluid to be in a balanced relationship. The energy balance (Eq. (4)) can be solved for one unknown variable, in this case for the cold stream mass flow rate \(M_c\) (Table 2; Column 8). Mass heat capacity \(C_h\) used in the equation was calculated by subtracting the enthalpy of moist air (Eq. (5)) at the respective cooling device’s vapour inlet point (\(T_{h,in}\)) from the enthalpy of moist air at its vapour outlet point (\(T_{h,out}\)). As there was no active transport of heat away from the air-cooled devices, large amount of air needed to be replaced by passive forces, i.e. rising of warm air away from the condenser and upwards into the room. This process was strongly limited by the much smaller “footprint” of the vertically placed copper column and the correspondingly low amount of air movement, compared to the horizontally placed 3 m long copper tubes with a much larger “footprint” area (Table 2; Column 9).

For the passive sleeve glass and copper columns, the theoretical amount of cooling water required to transport away the heat would be 18 and 11 L, respectively. However, as there was no actual cooling water exchange, heat removal occurred by means of the previously mentioned “self-cooling” effect. For the moderate and strong cooled glass column experiments where there was cooling water circulation, only a slightly higher amount of 19 and 22 L, respectively (compared to the 18 L in passive sleeve), was calculated. This suggested that the added expenditure for water circulation was not justified and a well-designed passive sleeve concept could be a cost-effective low key method.
In order to calculate the overall heat transfer coefficient \( (U) \), the heat capacity rates \( C_h \) (hot stream) and \( C_c \) (cold stream) were calculated by multiplying the mass flow rate \( (m) \) of the fluid (in kg h\(^{-1}\)) with the mass heat capacity \( (C) \) of the fluid (in kJ kg\(^{-1}\) C\(^{-1}\)). \( C_{\text{min}} \) is denoted as the smaller value of \( C_h \) and \( C_c \). In all cooling concepts presented, \( C_h \) equalled \( C_{\text{min}} \), which allowed for the terms to be omitted from the effectiveness equation (Eq. (6)). By calculating effectiveness (Eq. (6)), followed by NTU calculation (Eq. (7)) and (Eq. (8)), the overall heat transfer coefficient for all tested devices was determined (Table 3).

Compared to commercial steam radiators \( (U = 5-20) \), air heaters \( (U = 10-50) \) or industrial condensers \( (U > 1,000) \) [28], all the tested devices had very low heat transfer coefficients. In praxis however, the overall heat transfer \( U \) is strongly influenced by the volume of the hot stream and moreover, by a well-matched relationship between hot and cold flows. In the laboratory set-up, very low amounts of steam \( (0.97 \text{ kg h}^{-1}) \) were processed, compared to the significantly larger inputs in commercial applications. If for example, the vapour flow \( (M_h) \) rate was increased by an order of magnitude, the cold flow rate and \( U \) would increase by the same factor (calculated by using Eqs. (4), (6)–(8)).

With this in mind, the tested devices aimed at achieving a reasonable cooling effect and condensation “return” in passive mode, without particular consideration for the matching of streams, for example, by utilising natural convection of an unspecified amount of air that can freely move away from the copper tubes. Of all air-cooled devices, the best results were achieved by the narrow type I tube, while type II was less effective (Table 3), based on the factors outlined above (Section 3.2.1). The air-cooled copper bubble condenser was inferior to the tubes, due to its vertical placement and a resulting smaller heat release footprint that limited heat removal by free air convection.

### Table 2

<table>
<thead>
<tr>
<th>Mass (weight and volume) flow rates, heat capacities and hot and cold temperatures of individual condenser streams ( (C_h ) and ( C_c ) are in kJ kg(^{-1}) C(^{-1}))</th>
<th>( M_h ) (kg h(^{-1}))</th>
<th>( C_h )</th>
<th>( T_{h,\text{in}} ) (°C)</th>
<th>( T_{h,\text{out}} ) (°C)</th>
<th>( C_c )</th>
<th>( T_{c,\text{in}} ) (°C)</th>
<th>( T_{c,\text{out}} ) (°C)</th>
<th>( M_c ) (kg h(^{-1}))</th>
<th>( Vol_c ) (m(^3) h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper tube type I</td>
<td>0.97</td>
<td>159.4</td>
<td>52.9</td>
<td>28.8</td>
<td>1.006</td>
<td>19.2</td>
<td>26.3</td>
<td>523</td>
<td>436</td>
</tr>
<tr>
<td>Copper tube type II</td>
<td>0.97</td>
<td>177.9</td>
<td>53.5</td>
<td>26</td>
<td>1.006</td>
<td>16.2</td>
<td>23.9</td>
<td>614</td>
<td>512</td>
</tr>
<tr>
<td>Type II in cooling tank</td>
<td>0.97</td>
<td>213.2</td>
<td>53.8</td>
<td>16</td>
<td>4.181</td>
<td>13.8</td>
<td>29.1</td>
<td>122</td>
<td>0.122</td>
</tr>
<tr>
<td>Glass col. passive sleeve</td>
<td>0.97</td>
<td>80.7</td>
<td>53.5</td>
<td>43.9</td>
<td>4.181</td>
<td>41.8</td>
<td>43.2</td>
<td>129</td>
<td>0.129</td>
</tr>
<tr>
<td>Glass col. moderate cool</td>
<td>0.97</td>
<td>149.3</td>
<td>53.5</td>
<td>32.2</td>
<td>4.181</td>
<td>25.2</td>
<td>31.5</td>
<td>117</td>
<td>0.117</td>
</tr>
<tr>
<td>Glass col. strong cool</td>
<td>0.97</td>
<td>184.2</td>
<td>53.7</td>
<td>25</td>
<td>4.181</td>
<td>13.6</td>
<td>23.6</td>
<td>123</td>
<td>0.123</td>
</tr>
<tr>
<td>Copper col. passive sleeve</td>
<td>0.97</td>
<td>81.2</td>
<td>52.1</td>
<td>42</td>
<td>4.181</td>
<td>38.6</td>
<td>41</td>
<td>305</td>
<td>254</td>
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<tr>
<td>Copper col. air cooling</td>
<td>0.97</td>
<td>49.3</td>
<td>51.9</td>
<td>46</td>
<td>1.006</td>
<td>19</td>
<td>24.2</td>
<td>54</td>
<td>45</td>
</tr>
<tr>
<td>Flat-plate condenser ( a )</td>
<td>0.97</td>
<td>182.0</td>
<td>53.3</td>
<td>24.3</td>
<td>1.006</td>
<td>17</td>
<td>33.7</td>
<td>122</td>
<td>0.122</td>
</tr>
</tbody>
</table>

\( a \)Flat-plate condenser in air-cooled mode [27].

In order to calculate the overall heat transfer coefficient \( (U) \), the heat capacity rates \( C_h \) (hot stream) and \( C_c \) (cold stream) were calculated by multiplying the mass flow rate \( (m) \) of the fluid (in kg h\(^{-1}\)) with the mass heat capacity \( (C) \) of the fluid (in kJ kg\(^{-1}\) C\(^{-1}\)). \( C_{\text{min}} \) is denoted as the smaller value of \( C_h \) and \( C_c \). In all cooling concepts presented, \( C_h \) equalled \( C_{\text{min}} \), which allowed for the terms to be omitted from the effectiveness equation (Eq. (6)). By calculating effectiveness (Eq. (6)), followed by NTU calculation (Eq. (7)) and (Eq. (8)), the overall heat transfer coefficient for all tested devices was determined (Table 3).

Compared to commercial steam radiators \( (U = 5-20) \), air heaters \( (U = 10-50) \) or industrial condensers \( (U > 1,000) \) [28], all the tested devices had very low heat transfer coefficients. In praxis however, the overall heat transfer \( U \) is strongly influenced by the volume of the hot stream and moreover, by a well-matched relationship between hot and cold flows. In the laboratory set-up, very low amounts of steam \( (0.97 \text{ kg h}^{-1}) \) were processed, compared to the significantly larger inputs in commercial applications. If for example, the vapour flow \( (M_h) \) rate was increased by an order of magnitude, the cold flow rate and \( U \) would increase by the same factor (calculated by using Eqs. (4), (6)–(8)).

With this in mind, the tested devices aimed at achieving a reasonable cooling effect and condensation “return” in passive mode, without particular consideration for the matching of streams, for example, by utilising natural convection of an unspecified amount of air that can freely move away from the copper tubes. Of all air-cooled devices, the best results were achieved by the narrow type I tube, while type II was less effective (Table 3), based on the factors outlined above (Section 3.2.1). The air-cooled copper bubble condenser was inferior to the tubes, due to its vertical placement and a resulting smaller heat release footprint that limited heat removal by free air convection.

### Table 3

Comparison of effectiveness and overall heat transfer coefficient \( (U) \) for individual cooling concepts; \( \varepsilon = \) counter flow /\( (p) \) = parallel flow

<table>
<thead>
<tr>
<th>( C_h ) (W K(^{-1}))</th>
<th>( C_c ) (W K(^{-1}))</th>
<th>( C_{\text{min}} ) (W K(^{-1}))</th>
<th>( C_{\text{ratio}} )</th>
<th>( \varepsilon )</th>
<th>( A ) (m(^2))</th>
<th>NTU ( c/(p) )</th>
<th>( U c/(p) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper tube type I</td>
<td>0.043</td>
<td>0.146</td>
<td>0.043</td>
<td>0.29</td>
<td>0.72</td>
<td>0.06</td>
<td>1.4 (2.0)</td>
</tr>
<tr>
<td>Copper tube type II</td>
<td>0.048</td>
<td>0.172</td>
<td>0.048</td>
<td>0.28</td>
<td>0.74</td>
<td>0.12</td>
<td>1.5 (2.2)</td>
</tr>
<tr>
<td>Type II in cooling tank</td>
<td>0.058</td>
<td>0.142</td>
<td>0.058</td>
<td>0.40</td>
<td>0.95</td>
<td>0.12</td>
<td>4.1 (na)</td>
</tr>
<tr>
<td>Glass col. passive sleeve</td>
<td>0.023</td>
<td>0.149</td>
<td>0.023</td>
<td>0.15</td>
<td>0.82</td>
<td>0.06</td>
<td>1.9 (2.5)</td>
</tr>
<tr>
<td>Glass col. moderate cool</td>
<td>0.040</td>
<td>0.136</td>
<td>0.040</td>
<td>0.30</td>
<td>0.75</td>
<td>0.06</td>
<td>1.6 (2.9)</td>
</tr>
<tr>
<td>Glass col. strong cool</td>
<td>0.050</td>
<td>0.143</td>
<td>0.050</td>
<td>0.35</td>
<td>0.72</td>
<td>0.06</td>
<td>1.5 (2.5)</td>
</tr>
<tr>
<td>Copper col. passive sleeve</td>
<td>0.022</td>
<td>0.092</td>
<td>0.022</td>
<td>0.24</td>
<td>0.75</td>
<td>0.04</td>
<td>1.6 (2.1)</td>
</tr>
<tr>
<td>Copper col. air cooling</td>
<td>0.013</td>
<td>0.015</td>
<td>0.013</td>
<td>0.88</td>
<td>0.18</td>
<td>0.04</td>
<td>0.2 (0.2)</td>
</tr>
<tr>
<td>Flat-plate condenser ( a )</td>
<td>0.049</td>
<td>0.085</td>
<td>0.049</td>
<td>0.58</td>
<td>0.80</td>
<td>0.15</td>
<td>2.3 (na)</td>
</tr>
</tbody>
</table>

\( a \)Flat-plate condenser in air-cooled mode [27].
The best heat transfer rate overall was achieved with the tube in tank design but the outcome was heavily biased by the mismatch between the hot vapour stream and the considerably oversized cooling stream (i.e. tank content). For a vapour stream several orders of magnitude larger, as is required for a conceptual bubble greenhouse, this ratio would be impossible to maintain. On the other hand, the compact water-cooled bubble columns were relatively effective and in order to increase their HTR while simultaneously maintaining their simplicity, adjustment of hot and cold mass flow rates would further improve their performance, for example by increasing the cooling water cycling rate, albeit the cost of additional energy use for cooling and pumping. The observed “self-cooling” of the passive sleeve concept that could not be further examined within the timeframe of this study, suggest for now a unexplained mechanism that may hold great potential for passive condensation in small-scale desalination systems, particularly under higher vapour temperature conditions, where a presumed 10˚C drop would produce distinctly higher yields than those achieved under the conditions of around 53˚C reported here.

3.4. Suitability of individual passive cooling concepts for greenhouse vapour pre-treatment

Besides determining their ability to produce condensate, the primary motivation for this research was to assess the vapour cooling concepts in terms of their vapour temperature reduction potential. Of the passive devices, the air-cooled copper tubes achieved considerable temperature reductions of 25–28˚C under the ambient conditions of around 16–19˚C (Table 4). However, their cooling ability would be diminished when considering two important aspects. First, in an open environment the ambient temperatures could be much higher depending on the location of a full-scale bubble greenhouse and second, in order to increase the system productivity, the bubble column would ideally be operated at a significantly higher temperature than the 55˚C tested here.

Under the prevailing ambient laboratory conditions of 15.4˚C, the cooling tank system could achieve a total temperature reduction of 38.5˚C, with a vapour exhaust temperature just above ambient level. This would not only be safe for the primary purpose of greenhouse humidification, but could also be tailored as a standalone approach to air conditioning the greenhouse when required. However, up-scaling this system into a larger bubble greenhouse would only be feasible with an efficient heat extraction design as highlighted above. The passive glass and copper column condensers were generally not found capable of reducing vapour temperature sufficiently, neither in sleeved nor un-sleeved mode. Under ambient temperatures of around 20–25˚C, only modest vapour temperature reduction in the range of 8–12˚C could be achieved. Importantly, the two factors (1) elevated ambient temperatures depending on location and (2) higher bubble column operating temperatures would be equally detrimental to their performance.

Notwithstanding their limited effectiveness for vapour cooling purposes, most of the tested devices demonstrated some potential as the condensing component for a standalone bubble column-based small-scale desalination system, perhaps substituting a conventional solar still. Based on their passive operation and technical simplicity, their limited water production rate would be acceptable where brackish water and sunshine are abundant. While the air-cooled devices would be strongly influenced by the ambient temperature at particular locations, the “self-cooling” sleeve concept could potentially offer an

<table>
<thead>
<tr>
<th>Cooling type</th>
<th>Copper tube type I air cooling</th>
<th>Copper tube type II air cooling</th>
<th>Copper tube type II passive tank cooling</th>
<th>Glass column passive sleeve</th>
<th>Copper column air cooling</th>
<th>Copper column passive sleeve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble column top temperature in °C</td>
<td>54.1</td>
<td>54.3</td>
<td>54.5</td>
<td>55.0</td>
<td>53.9</td>
<td>54.3</td>
</tr>
<tr>
<td>Exhaust vapour temperature in °C</td>
<td>28.8</td>
<td>26.0</td>
<td>16.0</td>
<td>43.9</td>
<td>46.0</td>
<td>42.0</td>
</tr>
<tr>
<td>Ambient temperature in °C</td>
<td>18.8</td>
<td>16.1</td>
<td>15.4</td>
<td>25.4</td>
<td>19.2</td>
<td>19.8</td>
</tr>
<tr>
<td>ΔT from column top to exhaust; in °C</td>
<td>25.3</td>
<td>28.3</td>
<td>38.5</td>
<td>12.1</td>
<td>7.9</td>
<td>12.3</td>
</tr>
<tr>
<td>ΔT from exhaust to ambient; in °C</td>
<td>10.0</td>
<td>9.9</td>
<td>0.6</td>
<td>17.5</td>
<td>26.8</td>
<td>22.2</td>
</tr>
</tbody>
</table>
ambient independent solution that warrants further investigation. The passive cooling tank concept with its impressive condensate recovery rate of over 80% could perhaps be expanded into a larger system, where a substantial water tank (e.g. water storage for dust suppression purpose in mining operations) could act as an oversized heat sink.

4. Conclusion

The findings presented here provide valuable insights into low-key passive cooling methods and their heat exchange ability and thus, inform the conceptualisation of a bubble-greenhouse desalination system. While the investigated devices were based on a number of different physical concepts, their common feature was the necessity for effective cooling under the proviso of relatively low-energy demand for the component itself. Furthermore, they should be easy to manufacture, of low investment cost, economically feasible and technically and operationally appropriate for local people in remote places.

For the purpose of cooling bubble column vapour to acceptable greenhouse temperatures, most of the passive devices could not deliver the desired results. While the copper tube prototypes achieved promising water recovery rates and temperature reductions under laboratory conditions, elevated ambient air temperatures would be detrimental to their productivity. Therefore, the concept might only be conditionally suitable, for example during cooler seasons or when utilised in generally colder desert climates. Further research into the tube concept could lead to innovative designs, where cooling tubes were placed below the ground surface to utilise the cooler soil temperatures or buried into the natural slope of a hill to utilise gravity for unforced condensate outflow. All tested devices represent a single-stage approach to thermal desalination and may therefore only be valid in a larger setting where free heat, e.g. from industrial combustion processes, is available. Otherwise, a well designed latent heat recovery system would be crucial for the economic feasibility of a bubble greenhouse. To some degree, heat recycling would be possible with a relatively simple cooling tank design, where a circulation system extracts heat from the tank and makes it available for the evaporation process via the air bubbling process. By varying dimensions, circulation rates, etc., a cooling tank design could perhaps be tailored to mitigate the vapour for safe greenhouse humidification. To that end, future work should focus on improving the heat recovery concept, ideally by direct heat transfer via the recovery cycle into the bubble column evaporator.

The stacked evaporator/condenser bubble column array, thought to be advantageous due to its large air/water interface, did not demonstrate a significant cooling/condensing advantage over a simple flat-plate homemade condenser. However, the observed “self-cooling” effect could perhaps be utilised to produce small quantities of potable water in hot and arid regions, as a simple alternative to conventional solar stills. Despite the limited condensation and cooling ability of the stacked evaporator/condenser bubble module, further research of the concept is warranted based on its potential for passive condensation.

Finally, while thermal desalination systems such as the conceptual bubble greenhouse have a high energy demand, their main focus is on participation and the involvement of local people in process operation, maintenance and repair. Herein lies its advantage over conventional water treatment methods like reverse osmosis, as its simplicity translates into numerous social benefits such as capacity building, self determination and empowerment of people in remote locations. Putting a monetary value on these communal benefits will allow offsetting the cost of water production from alternative but ultimately, sustainable schemes.

List of symbols

- \( A \) — surface area in m²
- \( C \) — specific enthalpy of condensation (heat capacity) in kJ kg⁻¹°C⁻¹
- \( C_h \) and \( C_c \) — mass heat capacity of the hot and cold fluid in kJ kg⁻¹°C⁻¹
- \( C_{min} \) — smaller value of \( C_h \) (hot stream) and \( C_c \) (cold stream)
- \( c_{pa} \) — specific heat capacity of air (1.006 kJ kg⁻¹°C⁻¹)
- \( c_{pv} \) — specific heat of water vapour at constant pressure (1.875 kJ kg⁻¹°C⁻¹)
- \( c_{ratio} \) — \( C_{min}/C_{max} \)
- \( \varepsilon \) — effectiveness
- \( h_m \) — enthalpy of moist air
- \( h_{we} \) — evaporation heat of water at 0°C (2,501 kJ kg⁻¹)
- \( m \) — mass flow rate per time in kg s⁻¹
- \( m_h \) and \( m_c \) — mass flow rate of the hot and cold fluid in kg h⁻¹
- \( NTU \) — number of transfer units
- \( Q \) — rate of heat transfer in kJ s⁻¹
- \( T \) — air temperature (in °C, relative to zero)
- \( T_{c,in} \) and \( T_{c,out} \) — inlet and outlet temperatures on exchanger cold side in °C
- \( T_{h,in} \) and \( T_{h,out} \) — inlet and outlet temperatures on exchanger hot side in °C
- \( \Delta T \) — temperature change in °C
- \( \Delta T_{in,counter \ flow} \) — \( t_{in} - t_{out} \) (inlet hot and outlet cold stream in °C)
\[ \Delta T_{\text{in,parallel flow}} = h_{\text{in}} - t_{\text{in}} \text{ (inlet hot and inlet cold stream in } ^\circ\text{C)} \]
\[ \Delta T_{\text{mean}} = \text{logarithmic mean temperature difference (LMTD)} \]
\[ \Delta T_{\text{out,counter flow}} = h_{\text{out}} - t_{\text{in}} \text{ (outlet hot and inlet cold stream in } ^\circ\text{C)} \]
\[ \Delta T_{\text{out,parallel flow}} = h_{\text{out}} - t_{\text{out}} \text{ (outlet hot and outlet cold stream in } ^\circ\text{C)} \]
\[ U = \text{overall heat transfer coefficient} \]
\[ x_a = \text{humidity ratio at saturation in kg of water per kg of air} \]

**References**


Summary and link to next chapter

The cooling devices investigated in Chapter IV provide valuable insights into low-key passive cooling methods, considered to be crucial for the conceptualisation of a Bubble-Greenhouse desalination system. While they are based on a number of different physical concepts, their common features are a strong focus on simplicity and the necessity for effective cooling under the proviso of relatively low energy demand of the cooling component itself. Furthermore, they should be easy to manufacture, of low investment cost, economically feasible and technically and operationally appropriate for local people in remote places.

Although the stacked evaporator-condenser bubble column array does not demonstrate a significant condensing advantage over a simple flat plat homemade condenser, the increased HTR of bubble condensers over surface condensers is considered to provide better efficiency per unit size. Therefore, based on its potential for passive condensation, a stacked (or alternatively, paired) evaporator-condenser bubble module strongly warrants further research. The choice of a pre-condenser and cooling system will strongly influence the feasibility, both practically and economically, of a Bubble-Greenhouse system. Crucially, while the majority of the tested concepts in Chapter IV represented a single-stage approach to the HD process, it is stressed that a well designed latent heat recovery system is required to keep the energy demand of a thermal HD system within acceptable limits, both technically and financially.

Recent technological developments have seen the bubble condensation concept evolve strongly (Narayan and Lienhard V, 2012). These authors developed a multistage bubble condenser that has demonstrated strong potential and is now trialled at a prototype stage.
concept is particularly noteworthy for the effective latent heat recovery system that is integrated into the horizontally stacked chambers. Based on the findings described in Chapter III and Chapter IV and the groundbreaking work of Narayan et al. (Narayan et al., 2010; Narayan and Lienhard V, 2012; Narayan, Thiel, et al., 2013; Narayan, Chehayeb, et al., 2013; Chehayeb et al., 2014), the multistage condenser principle is adopted and developed into a combined multistage evaporator-condenser module with an integrated latent heat recovery cycle. This conceptual technology is described in Chapter V. Through effective latent heat reuse, the concept aims at keeping the energy requirement low in order to reduce solar collector demand. After exiting the evaporator and condenser stages, the temperature-mitigated vapour can now be channelled into a greenhouse where it provides a humid environment for food production and where additional condensation along the greenhouse skin occurs.
Chapter V: The Bubble-Greenhouse: a holistic sustainable approach to small-scale water desalination in remote regions

Attribution

MS developed the concept, reviewed the literature, designed the figures and drafted the manuscript. GH and MA provided feedback on the draft. All authors critically reviewed and approved the final version.

MS: 90%
The Bubble-Greenhouse: A holistic sustainable approach to small-scale water desalination in remote regions

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HIGHLIGHTS
• Multistage bubble column based thermal desalination with latent heat recovery
• Greenhouse food production in remote regions as a by-product of water desalination
• Strongly reduced plant water demand of greenhouse plants in humid environment
• Social, economic and environmentally sustainable development for remote settlements

GRAPHICAL ABSTRACT

The Bubble-Greenhouse system combines the well established Seawater Greenhouse concept with a novel humidification–dehumidification (HD) process, based on the large air/water interface generated by bubbling air through a water filled column. Multistage bubble evaporators and multistage bubble condensers allow for effective recovery and reuse of latent heat via a heating/cooling circuit throughout all column stages. The system can operate with salinities of 5000–35,000 ppm. Following the HD process, cooled vapour provides the tropical type greenhouse with a humid environment for selected crops. Additional condensation occurs along the greenhouse skin and is gravity-fed to drip line irrigation. Low grade energy options such as solar-thermal, photovoltaic, wind, geo-thermal and salinity-gradient solar ponds provide the energy for the Bubble-Greenhouse. Alternatively, waste heat from diesel power stations nearby can provide cogeneration of electricity and bubble evaporator heat and pressure requirements. Crops grown inside a greenhouse demonstrate a strongly reduced water demand and the closed environment protects crops from insects and diseases. As the technology is conceptually simple to implement, it holds great potential for community participation, empowerment, skills development and capacity building of local people in remote locations.

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1. Introduction

This paper informs the conceptualisation of a novel Bubble-Greenhouse concept for brackish or seawater desalination and greenhouse food production. The theoretical performance parameters provided are based on previous experimental evaluations of a bubble...
column evaporator prototype and a range of simple condenser concepts [49,50]. Findings from these experiments have been used to calculate theoretical desalination rates by extrapolation and allow for system sizing considerations. The work presented here was motivated by the need for sustainable water supply schemes in remote communities, with a strong focus on the social development of local people under the critical proviso of empowerment, self-determination and capacity building.

Due to their remoteness, conventional desalination technologies like reverse osmosis (RO) are often burdened by the consequences of poor source water quality and a dependency on external maintenance and repair specialists. Innovative schemes such as the solar powered Memsys Vapour Membrane distillation pilot plant currently trialled by the Tjuntjuntjara community (Western Australia) and Murdoch University’s National Centre of Excellence in Desalination [40], aim to provide a long-term improvement to water provision and self-reliance of remote communities. On a global scale, initiatives like the Desal Water Prize [58] are calling for sustainable water supply technologies with a focus on self-sufficient system operation and maintenance by local people.

Worldwide, society’s demand for freshwater relies strongly on water supply from surface water sources that are intimately linked to atmospheric precipitation and are therefore highly susceptible to climatic variability. In response to evolving land and water use patterns, almost half the countries on earth have long suffered from serious water shortages, to the extent that by the year 1993 alone, twenty-six nations including Egypt, Jordan, Israel, Syria, Iraq, Iran, and Saudi Arabia were defined as water scarce [11]. This situation is steadily exacerbated in many regions by continuous population growth, a strongly increased demand for irrigation, for agricultural produce and the well documented effects of climate change.

While the average precipitation for most continents is approximately 700 mm/year (7 million L/ha), Australia experiences significantly less precipitation, with 450 mm/year on average [52]. Consequently, large tracts of inland Australia count amongst the most arid regions in the world with annual pan evaporation rates often exceeding annual rainfall figures by tenfold [29]. As surface freshwater expressions are rare in remote Australia, ground water is frequently the only source of potable water. However, due to the geological particularity of this strongly weathered landmass, high concentrations of dissolved salts render most of the groundwater here brackish and salinities akin to seawater concentrations are not uncommon [22].

A very effective method of separating dissolved salts from brackish or seawater is by thermal desalination. Exponents of this technology range in size from simple solar stills in remote locations for the distillation of a few litres of drinking water to large-scale commercial technologies such as multistage flash (MSF) or multi-effect distillation (MED). Many different solar desalination concepts have been developed to facilitate small-scale freshwater production in remote regions by local people with limited technical means [4,34,46,48]. Amongst the different approaches to improve their condensate output were the spatial separation of evaporation and condensation processes, for example by connecting an outside condenser to a solar still [10] or by bubbling warm air into a still basin in order to provide an enlarged air/water interface for vapour transfer [41].

The idea to up-scale the solar still principle into a crop producing still-greenhouse system has been around for some time [39]. In general terms, the aim is to tailor and optimise the humidification–dehumidification (HD) process inside a greenhouse, while making use of the structural components of the greenhouse itself, primarily as a condensing surface. Besides the freshwater output, a number of additional benefits arise from this approach. First, plants inside a humidified greenhouse demonstrate a strongly reduced irrigation demand, requiring as little as 10% of the freshwater of plants grown outside a greenhouse [44]. Second, a large part of the condensation is produced high above in the greenhouse and can be distributed to the growing area by gravity, thus reducing water pumping needs.

Crucially, a serious disadvantage of the still-greenhouse concept is its reliance on solar radiation to drive still basin evaporation and as a consequence, the resulting risk of overheating the greenhouse [15]. The Seawater Greenhouse addresses this problem by substituting the evaporation basins with customised cardboard honeycomb lattice evaporators [42]. Here, surface seawater trickles down a porous evaporator and hot ambient air is dragged through the structure by use of large fans. Besides humidifying the greenhouse, the evaporative cooling effect causes a significant air temperature reduction and thus, greenhouse cooling is achieved. A condenser, cycling cold deep seawater or cooled seawater from the evaporators is then used to dehumidify the saturated air and produce the freshwater for crop irrigation.

Drawing on the principles introduced above, an alternative approach to the greenhouse desalination concept is proposed. The innovative system termed Bubble-Greenhouse combines aspects of the well-established Seawater Greenhouse [9] with a novel humidification technology that employs modified bubble column evaporators [13] and multistage bubble condensers [33]. The key benefits of the novel bubble column HD system are (1) improved evaporation and condensation rates, (2) reduced energy demand through efficient latent heat recovery design, (3) technological simplicity promoting self-sufficiency of remote communities and (4) a modular arrangement to allow for flexibility in response to fluctuating population rates in highly mobile settlements. Therefore, the paper aims to outline and discuss the potential of this new desalination method, and to provide a stepping stone towards the physical conceptualisation of a Bubble-Greenhouse in the near future.

Unlike in Seawater Greenhouse evaporators, where ambient air is humidified and cooled by the evaporative cooling effect and then channelled through the greenhouse, the bubble evaporation process is most efficient at higher process temperatures, ideally around 80 °C. However, as the high temperature of the vapour product would strongly exceed temperature limits for greenhouse plants, an external vapour cooling element is integral to the functionality of the Bubble-Greenhouse. While temperature mitigation initially is the most important objective of this component, a consequence of the external vapour cooling process is that the majority of condensate production takes place prior to greenhouse humidification, typically in the range of 85% of total Bubble-Greenhouse condensation amount.

The bubble column HD concept evolved from a number of experimental studies. Initially, a laboratory-scale bubble column was developed with the aim to quantify evaporation rates and to obtain reference figures for up-scaling calculations. The column was matched with a simple ‘home-made’ copper plate condenser, to investigate the potential for passive condensation with strong emphasis on sustainability and operational simplicity of the device [49]. Here, consistent bubble evaporation rates of between 80–88 mL per hour were demonstrated. Under laboratory conditions, the condenser prototype of 100 mm width and 1500 mm length achieved condensate recovery rates of around 73%, without the need for external cooling. Estimated by extrapolation, it was proposed that an up-scaled bubble desalination system with a 1 m² condenser may produce around 19 L of distilled water per day.

In a follow-up study, several ‘simple to make’ vapour cooling and precondensing concepts were assessed for the purpose of mitigating bubble column vapour temperatures, as a crucial aspect for the development of a bubble-greenhouse [50]. Particular emphasis was on low energy demand of the devices, ease of manufacture, low investment cost and technical and operational appropriateness for local people in remote places. Although most of the tested concepts could not successfully reduce bubble column vapour to acceptable greenhouse temperatures in passive mode, important insights into the temperature mitigation problematic were gained. While the majority of the tested concepts represented a ‘single-stage’ approach, the utilisation of latent heat transfer within the HD process was stressed as an important aspect of the economic feasibility of a future Bubble-Greenhouse. In their sum, findings from the practical evaluation of the bubble column desalination concept suggested the strong
potential for a Bubble-Greenhouse as an effective alternative to conventional greenhouse desalination concepts, e.g. the Seawater Greenhouse.

2. Concept description

Inspired by recommendations and performance criteria set by the USAID Desal Water Prize competition — an international initiative to promote environmentally sustainable brackish water desalination technologies — the proposed Bubble-Greenhouse system is designed for a desalination rate of approximately 8 m³ per 24 h cycle. It essentially exists of three elements, the HD modules, the greenhouse structures and the solar energy collector array. The HD process column design is inspired by a recently described multistage bubble column condenser with integrated heat recovery cycle [35]. Albeit coming at a cost of technical complexity and increased air pressure demand for bubble generation, this concept offers a significant improvement to the bubble column HD energy budget overall, through effective recycling and reuse of latent heat.

2.1. Humidification–dehumidification (HD) modules

In total, the Bubble-Greenhouse desalination system consists of seven individual HD modules which can conveniently be operated independently from each other, e.g. during module maintenance procedures. Each module consists of a six-stage bubble column evaporator and a six-stage bubble column condenser (Fig. 1), not unlike the multi-stage condenser device invented by Narayan and Lienhard V [33]. The columns are manufactured from high density poly-ethylene (HDPE). The evaporator columns approach a salt concentration of 45,000 TDS, they are completely drained. The resulting brine is treated for mineral recovery in evaporation ponds [1]. In order to shield the evaporator columns from heat loss to the ambient, they are enclosed with high grade thermal insulator material (Aspen Aerogels Pyrogel 6350) and an outer layer of aluminium foil.

The condenser columns physically resemble the evaporator columns. The main difference is that in contrast to the brackish water content in the evaporator columns, all condenser chambers are filled with desalinated water. While bubble coalescence is not inhibited here due to the absence of salt from the chambers, the resulting bubble stream generated by the sinter discs nevertheless provides a large surface area for effective condensation. The pairs of evaporator and condenser columns (i.e. modules) are physically connected by two well insulated streams, in order to prevent heat loss to the ambient. These are (1) a saturated air stream that transports vapour from evaporator to condenser columns and (2) a latent heat recovery stream that runs in a counter flow direction through each of the evaporator and condenser column chambers (Fig. 1).

![Fig. 1. Heat transfer processes of the Bubble-Greenhouse HD module. Bubble condenser concept adopted from Narayan et al. [35].](image-url)
The saturated air stream is initially produced by pumping ambient air through the brackish water in the evaporator columns. By use of regenerative blowers, compressed air is continuously pumped through the bottom sinter disc from below, creating a high density of fine air bubbles. As the air travels up through the chambers, vapour content gradually increases in response to the increasing chamber temperatures. From an outlet hose above stage six of the evaporator column, the heated saturated air exits at a temperature of 80 °C and is then channelled to the condenser column. Effective insolation maintains the process temperature throughout the connection pipe and into the condenser column. As the vapour laden air is bubbled through the distilled water content of the condenser columns, cooling and subsequent condensation occurs. The condensation produced in each of the condenser columns drains away and is collected in water storage tanks.

A latent heat recovery circuit connects the evaporator and condenser columns that form individual HD modules. In both columns, the circuit enters from the top and runs downwards through all chambers. The closed system conduit is filled with deionised water to prevent corrosion. Throughout the condenser stages, stepwise latent heat release from condensation in each chamber is directly transferred to the circuit water, thus allowing for direct heat recovery and a continuous circuit temperature increase. Based on industrial application experience [27], a DTmin value (the minimum allowable temperature difference, representing the minimum driving force allowed in a heat exchanger, without violating the second law of thermodynamics) of 3–5 °C is anticipated to be effective for the low temperature heat recovery processes. This temperature value is supported by the temperature-enthalpy profile of a balanced multistage dehumidifier concept with multiple extraction and injection points [7]. A more precise and potentially lower DTmin, thus reducing the entropy generation and increasing the energy efficiency, would be subject to fine-tuning the heat recovery concept in regards to general design and component sizing that determines the cold and hot streams.

Based on the current estimation, the heat recovery circuit exits the bottom condenser chamber at around 75 °C. The well insulated circuit then runs through the solar driven temperature booster module, where the circuit temperature is raised to 85 °C. Next, the circuit enters the evaporator column top chamber from where it cools downwards through the individual chambers, similar to the arrangement in the condenser column. In accordance with the established steady state temperatures in the respective evaporator chambers, the previously stored heat is fractionally released throughout the stages to drive the evaporation process. In this way, a gradual reduction of the heat recovery circuit temperature is achieved while a maximum amount of latent heat is utilized for evaporation. After the circuit fluid exits the evaporator column through the bottom chamber at a temperature of approximately 30 °C, it is returned to the condenser column top chamber, where the heat collecting process is repeated. As booster energy is made available during night-time from the heat storage system, the modules can be operated continuously.

2.2. HD system sizing

The following calculations for sizing the evaporator and condenser columns are based on a theoretical Bubble-Greenhouse system with an estimated water production rate of 8 m³ per day. At a process temperature of 80 °C, the laboratory-scale column evaporator prototype with a sinter area of 78.5 cm² would be capable of evaporating 7 L of saltwater in 24 h [49]. Using extrapolation, the total column sinter surface area required for evaporation of 8 m³ of brackish or salty water (assuming near 100% condensate recovery for the greenhouse system overall) would be 9 m². For a single bubble column, this area translates into an impractically large diameter of 3.4 m. Instead, seven individual evaporator-condenser modules with a sinter area of 1.28 m² or 1.3 m diameter per column are proposed.

In order to keep hydrostatic head to a minimum while achieving efficient vapour transfer into and out of the bubbles, the overall multistage column height for evaporator and condenser columns is 1200 mm, with an individual chamber height of 200 mm. Total air flow demand for the whole greenhouse system (seven modules) is 27,487 m³/day (or 1145 m³/h or 19.05 m³/min). Divided into seven modules, the airflow demand is 164 m³/h (2.7 m³/min) per module, provided by high pressure regenerative blowers. The total water evaporation rate for the seven module greenhouse system is 333 L/h (8 m³/day) or 47.8 L/h (1.14 m³/day) per module.

The enthalpy of moist air, hₘ, which represents the sum of latent and sensible heat per unit of moist air, can be expressed as

\[ hₘ = cₚₐ * t + xₛ * cₚₑ * (t + hₑₑ) \]  (1)

where \( cₚₐ \) is the specific heat capacity of air (1.006 kJ·kg⁻¹·°C⁻¹), \( t \) is the air temperature (°C) relative to zero, \( xₛ \) is the humidity ratio at saturation in kg of water per kg of air, \( cₚₑ \) is the specific heat of water vapour at constant pressure (1.84 kJ·kg⁻¹·°C⁻¹) and \( hₑₑ \) is the evaporation heat of water at 0 °C (2501 kJ·kg⁻¹·°C⁻¹). From this follows that the total enthalpy contained in 164 m³ of vapour produced per hour per module is 139.7 MJ with a latent heat component of 107.9 MJ in the 47.8 L/h of condensable water vapour (Table 1). Besides the majority of heat provided by the heat recovery cycle, several additional sources supply heat to the evaporator chambers. As a result of raising the recovery circuit temperature from 75–85 °C, 20.6 MJ/h is introduced to the heat cycle by the solar booster. At an ambient air temperature of 30 °C, 6 MJ/h is contained in the air that drives the bubble process. A further 6 MJ/h is introduced through top-up of 47.8 L/h of brackish water at a temperature of 30 °C.

On the condenser side, in accordance with the steam temperature reduction from 80 °C to 35 °C, the total amount of heat released into the condenser chambers is 108.9 MJ/h from condensation of 41.3 L/h. As the vapour stream designated for greenhouse humidification extends from the condenser top at a temperature of 35 °C, it contains 6.5 L/h (156 L/day) of condensable water and a total enthalpy of 20.5 MJ/h (per module). In addition, 10.3 MJ/h is contained as sensible heat in the distillate (Table 2). For maximum heat recovery, the latent heat cycle is set at a flow rate of 493 L/h (or 8.2 L/min). Assuming near complete recovery based on optimum enthalpy pinch and system design, and no or little connect-pipe loss, heat input into the evaporator column from this source alone is around 107.5 MJ/h. This figure is calculated by subtracting heat input from the booster, ambient air and brackish water top-up from the total enthalpy value (139.7 MJ/h). The slight difference between this figure and the actual enthalpy available from condensation (107.5 MJ divided by 108.9 MJ) suggests close to 99% efficiency of the heat recovery cycle and very little energy loss throughout the system. This level of efficiency is also represented by the ratio of 20.5 MJ/h that is

| Table 1: Energy and water inputs and outputs (figures are per HD module). |
|-----------------------------------|-----------------|-----------------|
| Component                          | Source           | Energy (MJ/h)   |
| Evaporator input                   | From heat recovery cycle | 107.5          |
|                                   | From oil heated booster | 20.6           |
|                                   | From ambient air   | 6              |
|                                   | From brackish water top-up | 6            |
|                                   | Total input       | 139.7          |
| Evaporator output                  | Vapour to condenser | 139.7          |
| Condenser input                    | Vapour from evaporator | 139.7        |
| Condenser output                   | Total enthalpy from condensation | 108.9  |
|                                   | Sensible heat in distillate | 10.3     |
|                                   | Enthalpy of moist air to greenhouse | 20.5   |
contained in the moist air to greenhouse component, divided by the 20.6 MJ/h of heat provided by the solar booster.

### 2.3. Greenhouse

The cooled vapour streams departing the HD modules are channelled into the greenhouse, thus creating a saturated environment within an acceptable temperature range. Along the greenhouse skin and in response to the radiative cooling effect during nighttime, more condensation occurs independently from the HD module operation and is collected and distributed to drip line irrigation. Depending on greenhouse location and climatic conditions, the greenhouse might require cooling during sunshine hours to avoid plant stress. For this purpose, one (or more) evaporator columns can be operated in unheated mode and independently from the condenser columns. The strong evaporative cooling effect produced by the bubbling process [14, 33] is then utilised for greenhouse temperature mitigation. While greenhouse humidification is maintained in this way, there will be reduced condensate production from the HD process modules during greenhouse temperature mitigation periods, depending on the number of modules utilised.

Resulting from the absence of harsh temperature and humidity variations inside the Bubble-Greenhouse, an increased risk of agricultural pest development exists. In response, the Bubble-Greenhouse concept proposes the operation of two greenhouse structures in semi-annual rotation. By opening up and exposing the dormant greenhouse to the typically arid climatic conditions, humidophilous plant diseases and agricultural nuisance insect species are controlled and eradicated without the need for excessive pest management. Importantly, many regions in Australia and elsewhere are frequently subject to extreme weather events such as tropical cyclones [56]. As it is economically and technically not feasible to build a greenhouse that can withstand such weather events, the greenhouses are instead manufactured from simple sturdy materials that can easily be dismantled and safely stored if necessary.

Based on a commercially available non partitioned standard wide span shallow poly-tunnel design, the greenhouse framework is made from aluminium or steel components. The greenhouse skin is manufactured from a special polycarbonate NIR-reflective (near infrared radiation) film, that allows for the photosynthetically active radiation (PAR) spectrum to be transmitted to the crop area inside the greenhouse [15, 53]. Overall, this film with very high transmission (60%) of PAR but with a low transmission of infra-red, results in a total energy transmission of 38% [42], thus helping greenhouse temperature to remain lower.

Total greenhouse footprint area is set at 150 m² (Fig. 2). The centre height of the individual tunnel sections is 5 m and the vertical wall height is 3 m, resulting in a total volume of approximately 700 m³ per greenhouse. Sizing of the Bubble-Greenhouse takes into consideration the Sundrop Farm experience, where a monoculture crop of approximately 150 tonnes of tomatoes is produced per year within a footprint area of 2000 m² [47]. With a similar production rate, the Bubble-Greenhouse would approximately produce 30 kg of crops per day. However, as there would be a large combination of crop species, with implications on stocking density and growth intensity, crop production rate would likely be significantly less.

### 2.4. Solar collector

For Bubble-Greenhouse operation, the largest part of energy would be required by the oil-heated booster, in order to raise the heat recovery circuit temperature previous to evaporator column entry. With current modelling, the solar energy required for heating 493 L/h of circuit water from 75–85 °C is 20.6 MJ/h per module or 144 MJ/h for the whole greenhouse system. The parabolic mirror solar collector array proposed for providing the energy to the Bubble-Greenhouse focuses solar energy onto a centre tube, thus heating the thermal oil contained in the tube up to 165 °C [47]. In this way, the systems allows for excellent heat collection and storage, to maintain HD operation during night-time.

Given that the average daily solar energy in central Australia is 6 kWh·m⁻² (i.e. 0.9 MJ/h), a collector area of 160 m² would be required when employing an oil-heated parabolic mirror array similar to the one operated at Sundrop Farm [47]. As this makes solar capture technology the most expensive component of the Bubble-Greenhouse, it would perhaps render the desalination concept economically prohibitive for now. However, it is anticipated that with future optimisation of the heat recovery cycle, for example by extracting and reusing sensible heat contained in distillate (Table 2), and with continuous evolution of the solar technology itself, collector demand could be substantially reduced. Importantly, the Bubble-Greenhouse desalination system allows for other ‘easy to do’ concepts to be integrated, in order to further increase overall energy efficiency. Drawing on the knowledge and expertise of local peoples, external heating components such as black coiled plastic pipes could be integrated to preheat the incoming evaporator air and water top-up streams and further boost the evaporator temperature.

### 2.5. Regenerative blowers

Bubble column operation requires large volumes of air to be pumped against the water head pressure and the resistance of the column sinter discs, a process that comes at a relatively high cost of electrical energy. A typical regenerative blower (e.g. Republic HRB 402/1) running at 1.65 kW, can provide an air flow rate of 192 m³/h at a working pressure of 343 mbar [13]. The authors suggest that one of these pumps could run up to eleven bubble columns of 300 mm height. Assuming each unit was operated at 88 °C, the total air pumping energy requirement would then be about 2 kWh·m⁻³, a figure less than half the energy requirement of the Kwinana RO facility in Perth, Western Australia, where the total energy used per unit of water is approximately 4.6 kWh·m⁻³ [57]. Importantly, this would only be achievable by running the eleven columns in series, a process that requires separation of the vapour from the carrier gas (through condensation) at each stage, followed by introduction of the carrier gas (now under slightly reduced pressure) to the next column and so on. However, as the ‘in series’ approach results in technical complexity and the resulting difficulty for efficient latent heat recovery, it is not considered to be the optimum solution.

For the proposed Bubble-Greenhouse, running the modules in parallel with one blower per module and with an estimated multi-stage
column height of 1.2 m, a blower like the one mentioned above would be adequate to satisfy air flow (164 m³/h) and pressure demand (approximately 250 mbar) to a single HD module while allowing for ample ‘headroom’. Assuming an operating temperature of 80 °C, the total amount of energy required per blower would then be very high at 34.6 kWh·m⁻³ of freshwater produced. While this figure exceeds the energy demand of RO installations by a large factor, it is important to consider that much of this demand would be offset by the strongly reduced solar booster requirement, based on the efficient reuse of latent heat in the multi-stage concept.

Based on current multi-stage column sizing, blower energy demand for an 8 m²/day greenhouse desalination system would amount to an additional solar collector area requirement of 40 m². However, based on the brief residence time required in a single-stage bubble column, where saturated vapour pressure is typically achieved within a few tenths of a second and the water column therefore only needs be about 200–300 mm high [13], future development should lead to a reduction of the overall height of a six-stage column, perhaps to half its currently proposed height of 1.2 m. It is anticipated that such a height-reduced column would still provide enough bubble residence time to achieve maximum vapour saturation through the sum of its stages, while allowing for effective latent heat recovery at the same time. With reduced height, one blower could perhaps be operating two HD modules in series and as a consequence, the investment cost for regenerative blowers and the associated renewable-energy capture technology would be substantially reduced.

3. Discussion

3.1. Thermal desalination

By closely mimicking the natural weather processes of cloud formation and rain precipitation, thermal desalination techniques have long been used to desalinate brackish- or seawater. While their extensive energy demand traditionally confines their suitability to regions with either high solar radiation or an abundance of fossil fuel, cogeneration plants for simultaneous production of water and electricity have nowadays somewhat lessened their ecological and economical drawbacks [19]. One of the biggest advantages of thermal desalination over membrane desalination technology e.g. reverse osmosis (RO) is that the process capably separates high concentrations of organics or dissolved problem salt species such as boron from the feedwater, which translates into simpler and less expensive source water pre-treatment [60].

3.2. Bubble column

A salt- or brackish-water filled column through which air is bubbled promotes a highly effective evaporation process [13]. Key to this concept is the unusual property of saltwater to inhibit air bubble coalescence. Hereby, the process provides a high volume fraction of small air bubbles, continuously colliding but not coalescing. In contrast to solar still evaporation or flash distillation, where essentially only the surface of the liquid comes in contact with the air above, the bubble process translates into a manifold liquid/air interface through which rapid water vapourisation can be achieved at operating temperatures well below boiling point. As the countless air bubbles oscillate upwards through the salt solution, water vapour is collected throughout the entire column in a regular and uniform process, until the saturation point determined by the prevailing temperature and pressure is reached.

Besides its highly efficient vapour transfer, bubble column desalination holds a number of advantages over conventional desalination technologies. It can be operated with relatively low quality energy provided from renewable energy sources. Common with other thermal desalination processes, extensive pre-treatment facilities that are usually associated with RO desalination plants are not needed for the bubble desalination process, allowing for smaller and hence more efficient desalination plants. Furthermore, the technical simplicity of the bubble column process and its ability for self-cleaning [13] translate into a simple operating process and reduced maintenance requirements. The current significant drawback of the technology resulting from its high energy demand for blower operation must be the subject of future process optimisation. However, the potential benefits of a multi-stage bubble column over their single-stage expression, mainly in terms of the potential for latent heat recovery with strong implications for solar collector demand, outweigh the additional blower energy demand.

3.3. Condensation

Under the operating conditions proposed for the Bubble-Greenhouse concept, the temperature of the vapour extending from the bubble column evaporator would be around 80 °C. As this would immediately overheat the greenhouse, it is essential to pre-cool the vapour to an acceptable level for plant survival. Generally, this can be achieved by incorporating a pre-cooling device between the bubble evaporator and the greenhouse [50]. The device may resemble a simple ‘homemade’ type condenser that has the added benefit of extracting a significant amount of condensate from the air stream. Importantly, as liquid water condenses out of the airstream in response to the vapour temperature reduction, the saturated vapour pressure of the airstream intended for greenhouse injection remains at maximum saturation (100% humidity).

For a conventional plate or tube type condenser, the rate of condensation is principally governed by the temperature gradient between the warm vapour saturated carrier medium (e.g. air) and the cooler condensing surface. While the condensing surface represents a physical barrier between the warm moist air on one side and the cooler opposite medium (e.g. ambient air or cooling water), it allows for thermal energy (heat) that is contained in that matter to pass through. In order to reduce energy demand of the HD process overall, a condenser should ideally operate in a way that allows for efficient latent heat recovery.

For a flat-plate type condenser this can easily be achieved, for example in the multistage Dewvaporation HD concept. Here, the process tower contains two chambers — one for evaporation and the other for dew formation — that are separated by an internal heat transfer wall [20]. The latent heat required on the evaporation side is provided by the heat released from dew fall condensation on the opposing side. Only a small amount of external energy input is required to raise the steam temperature resulting from the evaporation side for the return into the condensation side. This efficient heat recovery system allows for the Dewvaporation tower to be operated with a moderate amount of low grade heat.

In contrast to tube or plate type condensers, the condensing surface in a bubble column evaporator is essentially the air/water interface provided by each bubble. Therefore, it is not possible to harness the latent heat in the same way. In order to overcome this problem Narayan et al. [35] developed and patented a multistage bubble column condenser that allows for effective latent heat recovery by cycling a heat collector circuit through the column stages. When condensing vapour in a water column rather than on a condenser surface, the heat transfer rate (HTR) can substantially improve. The reason for this is that in the presence of a non-condensable carrier gas (e.g. air) diffusion resistance to transport vapour through the non-condensable gas/vapour mixture increases [33]. As a consequence, the thermal resistance to vapour condensation on a cold surface is much higher than in a pure vapour environment. HTR’s for surface condenser systems can be two orders of magnitude lower than pure vapour systems and even in the presence of a few moles of non-condensable gas in the condensing fluid, HTR’s could be reduced by as much as an order of magnitude. As 60 to 90% of air is not uncommon in the condensing stream of HD systems, the dehumidifiers used in these systems have low heat transfer rates and an equivalent heat transfer coefficient as low as 1 Wm⁻¹·C⁻¹. Consequently, a large heat transfer area is required for surface dehumidifiers.
A HD system based on the pairing of multistage bubble columns — one for evaporation and the other for condensation — can be arranged into modules and organised into a small physical footprint. From here it becomes relatively easy to shield the system components — mainly the evaporator columns and connection pipes — from unwanted heat loss, by thorough insulation with appropriate heat insulation materials such as Aspen Aerogels Pyrogel 6350. The principal drawback of the multistage bubble column concept is the increased air pressure demand in response to column height and quantity of chambers, where a water head of 1.2 m and a series of airflow-restricting sinter discs must be overcome for each column.

3.4. Greenhouse

Drawing on the experience from the Seawater Greenhouse, non-welded aluminium or steel members are the preferred construction material, providing an easy to build and extremely sturdy greenhouse framework. This is particularly important in light of potentially challenging weather events e.g. tropical cyclones [56], where the greenhouse skin may be removed as a precaution, but the structural framework could safely withstand such events undamaged. Conversely, the framework can easily be dismantled and relocated, thus extending its lifecycle and making it a recyclable and sustainable choice.

While the majority of freshwater is produced by the multistage condensers in the Bubble-Greenhouse system, a percentage of condensation occurs over the greenhouse skin itself. Here, condensation primarily occurs during night-time in response to radiative cooling of the ambient air. The concept is similar to many dew collection systems, where the condensing surface is provided by roofs of houses and sheds [51]. Besides the financial benefits of using already existing roof structures for condensate production, there is an additional advantage in that water is produced high up on roof tops and can thus be distributed into houses or greenhouses by gravity. This reduces pumping demand and consequently, lessens the operational expenditure of water supply.

Dew condensation strongly depends on the optically selective and adhesive properties of the condensing surface [36]. One method to increase the yield of dew harvesting is by modifying the emitting properties of the condensing surface [32,37]. In their experiments, Muselli et al. [32] investigated the radiative cooling properties of condenser foil made of TiO₂ and BaSO₄ microspheres embedded in polyethylene. This material demonstrated improved emitting properties in the near infrared spectrum and as a result, a significant gain in dew collection. Therefore, in regions with abundant solar radiation, a two-part greenhouse skin could be an effective improvement to the Bubble-Greenhouse concept. The lower part or side walls would be covered with PAR film to promote plant growth while the roof area could utilise a film with high emitting properties, thus increasing condensate production during night-time.

3.5. Greenhouse climate control

The Bubble-Greenhouse is designed to provide a vapour saturated environment for plant growth, essentially simulating the climatic growing conditions of the constant wet tropics. As a consequence, temperature and humidity remain fairly consistent throughout greenhouse operation periods. As no seasonal variations comparable to temperate zone winters or annual droughts of the seasonally dry tropics exist inside the Bubble-Greenhouse, plant diseases and agricultural pests are less restricted and able to flourish year-round [12]. In order to overcome this drawback, the Bubble-Greenhouse system operates two greenhouses alternately and semi-annually, thus eradicating humidophilic pest populations through a seasonal greenhouse shutdown and exposure to ambient arid conditions.

In a continuous flow air bubble column, a strong evaporative cooling effect is produced [14]. Each bubble oscillating upwards through the column releases precisely the amount of thermal energy required to evaporate water to saturate that bubble, causing a significant air (bubble) temperature reduction. Francis and Pashley [14] note that for a steady state equilibrium bubble column with an inlet air temperature of 22 °C, an outlet vapour temperature reduction to about 8 °C can be achieved. By calculating the final steady state temperature of the bubble column directly from the temperature of the inlet gas, its heat capacity, the heat of vaporisation of water and the saturated water vapour density, individual bubble columns can be easily adjusted and used to temporarily maintain greenhouse temperatures within a desired range.

Seawater Greenhouse analysis showed that the greatest overall effect on greenhouse performance was determined by the dimensions of the greenhouse. A wide shallow structure demonstrated superior performance over a long narrow one, both in terms of climate management and condensate productivity [42,45]. The main reason for this is that with increasing length, conventional fan cooled greenhouses develop a strong thermal gradient of up to 8 °C along the direction of the airflow [26]. For the Bubble-Greenhouse, temperature management is greatly simplified by positioning numerous vapour injection points throughout the greenhouse, thus avoiding temperature gradient development and eliminating the ventilation requirements that burden conventional greenhouses.

3.6. Carbon dioxide (CO₂)

In low-venturing greenhouses, CO₂ levels can be drawn down significantly as the plants metabolise the available gas. A non-limiting supply of CO₂ is an important requirement for greenhouse crop production and supplementary CO₂ fertilisation has been found to result in 30% productivity increase when greenhouse levels were raised by around 350 ppm over baseline concentrations [5]. For tomatoes, a CO₂ increase by as much as 700 ppm has demonstrated similar growth rate improvements. However, supplementation of CO₂ tends to increase the technical and economical expenditure for greenhouse agriculture and the use of ‘waste products’ from incineration processes can provide an attractive alternative. In the context of a Bubble-Greenhouse that would be operated by waste heat from industrial processes (e.g. diesel power station exhaust stack), tri-generation of electricity, desalinated water and CO₂ supplementation for crop production could be an economically attractive prospect.

Where the Bubble-Greenhouse system was operated solely by renewable energy, CO₂ supplementation would be provided by incineration of organic agricultural dry waste resulting from the greenhouse growing process. The incinerator exhaust steam would be channelled directly into the bubble evaporator column(s), thus boosting the system with CO₂. While temperature and humidity transfer occurs throughout the different stages of the HD process, the CO₂ concentration in the air stream (in ppm relative to carrier gas) remains constant and is subsequently made available for crop growth. In line with holistic sustainability principles, excess agricultural dry waste that is not required to boost greenhouse CO₂ levels is composted and used as high nutrient fertiliser in the crop growing process.

Avoidance of a thermal gradient via the use of regular vapour injection points eliminates the need for greenhouses ventilation. This leads to a significantly reduced plant transpiration rate and thus, a strongly reduced plant water demand. For the Watergy greenhouse — a closed system designed for free air circulation based on the buoyancy of moist air — plant water consumption was shown to be reduced by 75%, while continuous plant production even during hot summer conditions was demonstrated [6,54]. A saturated greenhouse climate translates into a low vapour deficit (the capacity of air to absorb water) and therefore, into strongly reduced plant water loss from evapotranspiration. As a result, plant water demand inside a humidified greenhouse could be as little as 10% of the fresh water demand of plants grown outside a greenhouse [44]. Although this figure might in practical application be closer to 20% [62], this leads to significant water savings for irrigation. Furthermore, the film condensation occurring inside the
Bubble-Greenhouse during night-time provides some portion of this strongly reduced plant water demand in situ, which makes it available for gravity-fed drip line irrigation and thus reduces pumping expenditure.

As the bubble column HD process results in high purity distilled water [49], consideration must be given to the absence of minerals and especially bivalent ions such as calcium, magnesium and sulphate, with strong implications for irrigation as well as human health. In order to make the distillate product (both, from HD modules and greenhouse film condensate) fit for consumption, it must be re-mineralised either by standard methods such as dosing with chemical solutions based on calcium chloride and calcium bicarbonate or by milk of lime or limestone dissolution by CO₂ [21]. Alternatively, depending on mineral composition of the feedwater (i.e., where no health risks exist from problem minerals such as uranium), a more simple approach such as blending the distillate with a portion of feedwater can be used.

A further important aspect is the acidification of feedwater as a method of controlling scaling in water treatment applications, particularly RO plants. By adding CO₂ to the feedwater, a reduction of pH to 5–7 is achieved. This increases the solubility of alkaline scale, especially calcium carbonate and calcium phosphate scale [2]. However, while this pre-treatment step is critical for the management of membrane based desalination methods, due to the mechanical processes occurring in a bubble column, there exists a strong self cleaning effect that allows for operation without anti scaling pre-treatment [13].

3.7. Bubble-Greenhouse outcomes

A range of environmental, social and economic benefits derive from a community scale Bubble-Greenhouse operated in a remote settlement. In addition to highly purified water for human consumption and irrigation purposes, the greenhouse produces healthy food locally, thus reducing food transportation costs and greenhouse gas pollution. Worldwide, the total embedded water demand in food production and industrial processes averages approximately 1800 L per person per day and 87% of the fresh water withdrawn in the world is used by agriculture [43]. By growing plants locally and inside a closed greenhouse, this figure can be significantly reduced from the current approximate 1500 L to perhaps as low as 300 L per person per day.

With a focus on prevention hygiene, greenhouse crops are more protected from insect pests and diseases, leading to a reduced need for insecticides and pesticides [5]. Moreover, beneficial biological control organisms which parasitise the pest species can easily be introduced and carefully managed in a closed system, for both preventive and curative treatment. Based on the use of two greenhouses in rotation, potential pests and diseases that may have gained access over time can be controlled by semi-annual greenhouse shutdown and by recycling all organic matter as a source of incinerator fuel for CO₂ supplementation, thus eradicating pathogens that are harmful to crop production.

As the operating climate inside the Bubble-Greenhouse resembles the climate conditions of the constant hot and wet tropics, careful selection of appropriate crops is an important aspect of the concept. For the tropical-type Seawater Greenhouse, aubergines, cucumbers, melons, peppers and pineapple have demonstrated suitability to these conditions [42]. However, there are many more popular food plant groups including roots and tubers (e.g. sweet potatoes, yams, cassava and Queensland arrowroot), grains (e.g. corn, okra and wax gourd), legumes (e.g. Catjang cowpeas, winged beans, Dolichos lablab beans and asparagus beans), leafy vegetables (e.g. chaya, sunset hibiscus, Tahitian taro and tropical lettuce), fruit vegetables (e.g. tropical pumpkin, okra, small-fruited tomatoes, hot peppers and wax gourd) and trees (e.g. bananas, breadfruit, West Indian limes, tamarind, papaya and mangoes), that can be grown in a saturated greenhouse environment [31].

In the past, the implementation of well established but advanced desalination technologies such as reverse osmosis (RO) often failed to produce the desired outcomes [59]. Conventional desalination systems in remote locations often experience technical challenges, mainly from maintenance and repair issues that often cause water supply disruptions or complete system breakdown. Moreover, these technologies do not promote the key elements to long-term sustainability in developing communities, namely empowerment, skills development and capacity-building of local people [23]. In contrast, the Bubble-Greenhouse system relies on basic technology such as regenerative blowers and technically undemanding water pumps. As such, it is conceptually simple to implement, hardy, easy to maintain and repair by local people with limited technical means [38]. By facilitating the considerable ‘bush mechanic’ skills of remote people, it represents great potential for community participation and sustainable development and thus provides a stepping stone to self-reliance for remote communities.

In the context of social and economic progress, the absence of a demand-responsive market system in many remote Australian locations confines community participation to sectors such as natural resource management and essential services provision [55]. Alternatively, a crop growing venture may not only provide food for local people but hold some excellent potential for commercialisation, providing a market base for trade between communities. Admittedly, compared with conventional water desalination technologies the Bubble-Greenhouse scheme is currently not competitive when assessed solely on the basis of its water production rate. However, a number of additional social benefits — if appropriately valued — make it economically viable. While these ‘soft’ factors are hard to quantify, they represent a strong reward for community wellbeing. Importantly, local people’s ability to improve performance and outcomes of the Bubble-Greenhouse themselves, provides not only empowerment but also allows for success to be celebrated, leading to further encouragement to participate [23].

3.8. Brine management

In order to avoid long-term environmental degradation, brine management in remote desalination schemes should aim for a ‘zero discharge’ outcome [18]. Subject to geographic and geologic conditions, a method requiring the least effort and expenditure is to manage desalination brine by open surface evaporation ponds. As water vapour evaporates off from the open water surface and is carried away by air transfer, potentially valuable minerals remain behind and can be sequential extracted, thus aiding economic improvement of the Bubble-Greenhouse concept [125]. Conversely, sequential extraction processes often have a significant energy demand and alternative sources such as thermal energy from salinity-gradient solar ponds themselves are being investigated as a means to provide the energy required by brine concentration processes [28].

A significant drawback of evaporation ponds is their large physical footprint. As a rule of thumb, the evaporation rate in open ponds under environmental conditions is around 4 L/m²/day [3]. For the 8 m² per day operation proposed here and source water salinities likely to be well below seawater concentrations, brine production and therefore, evaporation pond size requirements would under normal circumstances be negligible. However, where environmental aspects forbid the use of open ponds, evaporative technologies such as the WAIV (Wind Aided Intensiﬁed eVaporation) system can be utilised [17]. Here, a large number of vertically mounted and continuously wetted evaporation surfaces are stacked with packing densities of 20 m²/m² footprint, thus allowing for multiple reduction of the area required for brine management. Based on a footprint to footprint comparison with open pan evaporation, the system produces a 13-fold evaporation rate. In addition, the WAIV unit provides an excellent opportunity for mineral recovery [25], thus enhancing economic and environmental potential of the Bubble-Greenhouse concept. Importantly, for the purpose of the Bubble-Greenhouse development, a decision on brine management will differ from case to case, depending on a large number of factors such as land availability, source water quality, mineral composition, aquifer vulnerability, depth of water table, cost considerations, etc.
3.9. Energy options

Subject to geographic location and prevailing climatic conditions, a range of sustainable energy options such as solar, wind and geothermal [61] can be utilised to operate the Bubble-Greenhouse. For climate dependent options such as solar and wind energy, diesel generators are required as a back-up supply in the short-term. If available, waste heat from diesel power generation nearby can be used to drive the bubble process. By adopting a co-generation approach, the economic feasibility of the Bubble-Greenhouse can be further improved. Crucially, this would be subject to careful monitoring of CO₂ concentrations, to ensure optimum plant growing conditions. Where a waste heat outlet is not at hand and bio incineration is used for CO₂ supplementation, the bio incineration may also be used as a short-term back-up energy supply option.

In the long-term, increased efficiency of battery storage systems and heat storage fluids in well insulated collection tanks will form the basis for continuous water production and greenhouse operation, independent from climatic fluctuations and the limitations of sunshine availability. Already, combined wind and solar ‘hybrid’ energy conversion systems suggest strong potential for desalination projects such as the Seawater Greenhouse [30]. Corresponding with peak solar radiation, between 9 am and 5 pm the Seawater Greenhouse prototype in Oman produced 98% of the total freshwater by relying solely on wind and solar energy. By improving solar energy storage systems, greenhouse power demand may soon be exclusively satisfied with renewable energy, throughout a 24 h cycle and without the back-up support of fossil fuel energy sources.

Until recently, the Seawater Greenhouse prototypes that operate in the Middle East relied mainly on fossil fuel energy conversion. A notable improvement to the concept was the inclusion of a parabolic mirror solar collector array. The Sundrop Farm Seawater Greenhouse prototype at Port Augusta, South Australia, utilises a 75 m-line of motorised parabolic mirrors with a total collector area of approximately 300 m², to track the sun during the day [47]. Solar energy is collected in a thermal oil filled centre tube, with the oil temperature reaching up to 165 °C. By effectively storing daytime energy in this way, the technology provides a crucial step towards night-time renewable energy operation.

Besides the latent heat required for evaporation, the principal power consumers in the Bubble-Greenhouse system are the feed pumps for brackish water supply, the water pumps for the heat recovery cycle and the regenerative blowers used for the bubbling process. While these components can be operated with low grade energy sources such as photovoltaic or wind power, their common characteristic is a strong reliance on efficient energy storage, in order to extend Bubble-Greenhouse operation beyond sunshine hours and wind still periods. Once again, economically and technically improved energy storage systems should become feasible in the near future, to operate the Bubble-Greenhouse system solely with renewable energy.

For the design of the multistage bubble columns, trade-off considerations had to be made regarding the large amount of heat required for evaporation, versus the energy needed to generate blower pressure in order to overcome the water head. Pumping air through a series of stacked bubble columns requires a large pressure input and places a significant energy and technical demand on evaporative blowers and compressors. However, as the thermal energy demand for water vapourisation is very large at around 670 kWh/m³ [13], the latent heat recovery system based on the multistage columns results in a comparatively smaller investment for solar energy capture. Therefore, while the stacked array comes at the cost of additional bubbling pressure demand, the ability to recover a large amount of latent heat and to insulate the multistage columns more efficiently against unwanted heat loss, result in a strongly reduced solar collector area requirement and thus, a much reduced Bubble-Greenhouse investment cost overall.

3.10. Economics

In common with most water supply schemes, Bubble-Greenhouse water and food production costs would naturally decrease with an increase in Bubble-Greenhouse plant scale. In general, based on their large energy demand, thermal evaporation processes are characterized by high capital costs. However, while their combined energy requirements are much greater than for membrane processes, they can be operated with low-grade energy, for example waste heat from power stations. Thus, cogeneration applications that provide electricity and heat required for thermal desalination can significantly improve the economics of the process [60].

Where renewable energy sources are relied upon, multiple reuse of the latent heat strongly determines project-specific economics, chiefly by reducing the demand on energy capture infrastructure. With the currently estimated booster demand and the cost of the technology, a parabolic mirror array required to boost the heating recovery cycle would be immoderately expensive. Industry figures for the oil-heated solar thermal capture technology are in the range of 200A$/m². For the 8 m³/day water production rate of the Bubble-Greenhouse system, this would amount to approximately 30,000A$ (Table 3). Future efficiency improvements of the latent heat cycle would lead to substantially reduced solar collector demand and thus, to a strongly reduced cost of the energy capture system and the Bubble-Greenhouse overall.

Total cost of materials and manufacture for a six-stage bubble column could be in the range of 4000–5000A$ per column. For an 8 m³ Bubble-Greenhouse system operating seven HD modules (i.e. 14 columns), this would amount to perhaps 60,000A$. With mass production, this figure would be substantially reduced. As sintered discs would likely represent the most expensive material component, alternative options such as open mesh fabrics, sandwiched between circular plastic grid frames, could lead to strong cost reductions. In the context of facilitating skills development, sense of ownership and empowerment of local people, manufacture costs could also be reduced by transporting materials to remote locations and building the components with the help of local participants. This would lead to further investment cost reduction overall.

Many variables influence the cost of the greenhouse itself. A ballpark figure provided from commercial greenhouse suppliers suggests a cost of approximately 65A$ per square metre. For a 150 m² greenhouse, this would amount to around 10,000A$. Once again, significant cost reduction would likely be achieved by assembling the greenhouses on site with the help of local collaborators. As the currently high capital cost of the Bubble-Greenhouse system would mostly derive from the cost of the HD modules and the energy capture technology, the insignificant additional cost of using two greenhouses in semi-annual rotation would be justified by the long-term benefits regarding disease management.

In regards to future operating costs of the Bubble-Greenhouse, the power demand of blowers and pumps is anticipated to be provided by sustainable and, as such ‘free’ means, mainly from solar energy capture. This is subject to energy storage options (e.g. batteries) which will in turn have an influence on overall investment cost. Labour costs will strongly depend on community participation, and geographical and social opportunities to transition towards a market based production of greenhouse goods. It is therefore at this development stage of the Bubble-Greenhouse relatively difficult to estimate the real cost of fresh water, based on the uncertainty of a number of factors such as economies of scale or the potential for market based economic improvement.

When comparing the sole cost of water production with RO the Bubble-Greenhouse is currently not competitive. While photovoltaic-powered RO is technically mature and capable of procuring water at costs as low as 2–3 US$ per m⁻³ [16], the maintenance problems and their lack of accessibility for local input remains. Furthermore, based on the large economies of scale that exist for RO plants [34], the cost of RO water desalination can vary significantly, particularly for small-scale system. For brackish water desalination, the real water cost of
RO plants with less than 20 m$^3$/day is between 5.60–12.90US$ per m$^{-3}$ and for seawater RO plants with less than 100 m$^3$/day is between 15.00–18.75US$ per m$^{-3}$ [24]. Assuming an average water cost of 10US$ per m$^{-3}$, this would amount to 29,200 US$ per annum, a figure only half the Bubble-Greenhouse investment cost of approximately 60,000A$ (including future energy storage systems). When appropriately valued, the additional social benefits such as skills development, capacity building and self determination of local people that are facilitated by this simpler and more accessible technology, shift the balance even further in favour of the Bubble-Greenhouse.

4. Conclusion

By combining the three elements — bubble evaporator, bubble condenser and condensing greenhouse — into a desalination system for remote communities, the individual components can be tailored for varying population rates and for economical water and food production. As the system is technically simple to manufacture and operate, it allows for local people to tap into their ‘bush mechanic’ skills and work towards self determination, capacity building and social development in remote places. Generally, based on their availability in respective locations, a range of renewable low grade energy sources such as solar-thermal, photovoltaic, wind turbine, bio-energy, geo-thermal and solar gradient pond can provide the energy for this new technology. Optimal utilisation of latent heat recovery and radiative cooling processes further improves energy efficiency and thus, reduced investment and operating cost of the Bubble-Greenhouse system.

Depending on their presence in individual locations, waste heat outlets for example from diesel power generators can be utilised as the energy driver for bubble evaporation, thus transforming power plants into more efficient cogeneration systems. Evolving energy storage concepts such as the thermal oil containing parabolic mirror array at Sundrop Farm will allow for sustainable operation independently from sunshine hours. More research is needed to further develop and trial multistage HD modules, to optimise the latent heat recovery cycle for energy efficiency, to select and assess high pressure blower and compressor technology and to improve energy storage systems. With these objectives in mind, the conceptualisation of a Bubble-Greenhouse with a strong focus on ecologically, socially and economically sustainable fresh water production may soon become a reality.

References


Summary and link to General Discussion

The Bubble-Greenhouse concept presented in Chapter V has been developed with a focus on promoting sustainable water provision in remote communities. It is marked by its technical simplicity which allows for participation and the involvement of local people at all process stages, from manufacture of components, system assembly and installation, process operation and quality monitoring, to maintenance and repair requirements. The system operates on a module basis that allows for flexible water production rates in response to fluctuating population numbers. As the procurement of the energy required for the thermal desalination process comes at a high cost, the price per cubic meter of water produced is currently not competitive with conventional desalination methods such as RO.

However, it must be emphasized that the Bubble-Greenhouse concept provides a large range of additional benefits that facilitate the social, environmental and economic sustainability of remote communities and it should therefore not be judged solely on its water productivity. The numerous long-term benefits, when appropriately valued, will offset the currently higher water production cost and make the concept feasible in the long-term. In addition, with a rapidly evolving sustainability sector, solar PV technology becomes more and more affordable and will bring about significant cost reduction in the field of thermal desalination. This trend is well documented in the context of groundwater pumping, where small PV systems are already advantageous over diesel fuelled installations in regards to their lower annual operating costs (Ould-Amrouche et al., 2010).
Chapter VI: General discussion

The literature review uncovered a range of undeveloped evaporative technologies with some potential for sustainable water production in remote locations. However, the biggest obstacle to the utilisation of moisture resulting from evaporative technologies such as WAIV (Wind Aided Intensified eVaporation) is the need to capture and store enormous volumes of air that contain relatively little moisture at ambient temperatures. This moisture would then need to be extracted via condensation, a process that would by completely relying on the surface area of the vapour capture device be highly inefficient. In addition, a vapour capture device would restrict free air movement through the WAIV installation, the exact feature that the evaporative WAIF technology relies on to be so highly effective. From the knowledge gained in Chapter I, it became clear that the two main factors crucial to maximising the evaporative side of a new desalination method were 1) to strongly reduce the outlet area of an evaporative device, for example by utilising the point source of a bubble evaporator and 2) to increase the amount of vapour that could be held in air, by increasing the process temperature of the evaporative component well above ambient temperatures.

Based on these findings, a laboratory-scale bubble evaporator prototype was manufactured. This device demonstrated reliable and steady evaporation rates in accordance with the physical stipulations of heat transfer. In order to determine how the vapour from the bubble evaporator could successfully be trapped and condensed via a low-tech method, the evaporator was combined with a simple condenser, made from rectangular polyvinylchloride (PVC) tubing and an attached section of copper sheet. A comprehensive assessment of the condenser was performed under a range of different physical conditions such as external water cooling, partial insulation and aspects of air circulation inside the condenser. Overall,
the laboratory-scale HD system confirmed its viability and operated effectively at temperatures well below boiling point, thus allowing for the use of low-grade energy to drive the process. The findings from these experiments, comprehensively discussed in Chapter III, were instrumental in the conceptualisation of the Bubble-Greenhouse. Quantifying the evaporation rate of the small-scale laboratory bubble column allowed for extrapolation to predict the performance of up-scaled bubble evaporators.

While the bubble evaporation concept was proven viable in Chapters II and III, the heat exiting a bubble column, both latent and sensible, would need to be strongly reduced before humidifying a greenhouse, particularly in light of potentially higher bubble evaporator process temperatures than described here. For this purpose, a range of simple vapour cooling and pre-condensing concepts were developed and assessed in Chapter IV. Unfortunately, most of the tested single-stage devices could not deliver the desired results, indicating that a well designed latent heat recovery system would be crucial for the economic feasibility of a Bubble-Greenhouse. While the novel stacked evaporator-condenser bubble column array could not demonstrate a significant cooling and condensing advantage over the flat plat condenser described in Chapters II and III, the concept facilitates the implementation of an effective heat recovery cycle. This attribute of the stacked array ultimately led to the multistage evaporator-condenser modules, conceptualised in the Bubble-Greenhouse (Chapter V).

6.1. Addressing the problems of conventional water service

Combining findings from the literature review and the experimental Chapters II, III and IV, this thesis reaches its central objective with the conceptual Bubble-Greenhouse desalination
system presented in Chapter V. With the recognition that building of local ownership and enhancement of local capacity and skills are the key elements to promote long-term sustainability in developing communities (Federal Race Discrimination Commissioner, 1994), the principal research question was to develop a novel water treatment technology as a means of sustainable community development. Consequently, the Bubble-Greenhouse aims to address a large number of problems that are commonly associated with failing water supply technologies in remote communities. These are:

1. Excessive water wastage through lack of local expertise;
2. Excessive water wastage through lack of ownership;
3. Lack of livelihoods;
4. Development obstruction through high-tech applications; and
5. Excessive water supply design figures

6.1.1. Excessive water wastage through lack of local expertise in servicing and repair - the establishment and capacity building of local operators

Remote communities rarely have their own maintenance teams and mostly rely on infrequent maintenance delivered by external service providers. As a consequence, infrastructure failures and leakage, caused by corrosion or excessive mineral scaling, and subsequently delayed repair operations are the leading cause of the substantial water wastage seen in many communities (Yuen, 2005). Moreover, most of the RAESP-coordinated operations and maintenance service delivered to Aboriginal communities in Western Australia remain the responsibility of resource centres (Barton and Brooks 2005). Almost all the decisions about services are made far away from the community, in regional centres and capital cities, thus completely preventing local input or participation in the process. Consequently, this approach
has also resulted in minimal local capacity (Grey-Gardner 2006). Due to its technical simplicity and ease of operation and maintenance, the proposed Bubble-Greenhouse promotes the building of local capacity and skills development. One of the anticipated outcomes of the technology is that will help to establish local maintenance and repair teams. The resulting skill set could significantly reduce system repair durations, not limited to the Bubble-Greenhouse but also extending to the existing community water infrastructure, which in turn could greatly reduce water loss from infrastructure damage.

6.1.2. Lack of residential responsibility for water conservation measures and a general lack of ownership for the water supply

Numerous studies have demonstrated that conventional water service provision to underdeveloped locations where technologies are constructed without obligation to end users and with little responsibility for ongoing operations and maintenance, either fails or struggles to be sustainable in the long-term (Carter et al., 1999). A process called conventional monitoring and evaluation (M&E), led by outside experts without the participation of the programmes’ intended beneficiaries is often used to routinely control the technologies involved (GSDRC, 2006). Regrettably, when information gathered from M&E programs is removed from its original source and taken elsewhere (e.g. to government agencies), local stakeholders are not only prevented from building their own knowledge base but also from making their own judgments and decisions and from retaining ownership (Estrella et al., 2000).

The Bubble-Greenhouse proposes the use of participatory methods throughout all stages of the technologies lifecycle. This includes the planning and design of the technology, manufacture and assembly of technical components, ongoing operation and maintenance and
water quality monitoring. It is hoped that the ability to improve performance and project outcomes provides empowerment and further encouragement to participate, thus leading to a strong incentive for communities to accept responsibility for their water supplies (Guijt, 1999).

6.1.3. Livelihoods creation

The absence of a demand-responsive market system in many remote Australian communities (Stanley, 2008) confines the applicability of participatory methods to sectors such as natural resource management and essential services provision. As one of the essential elements of community life, water supply management provides great opportunities for development, towards economic activity and established labour markets in remote areas (Davis et al., 1993). By drawing on the Livelihoods framework, a guideline towards development of a market-based economy that is required to allow for demand responsive services and better sustainability outcomes (Anda et al., 2006), the Bubble-Greenhouse facilitates job creation at all stages of the project, during implementation and subsequent management. Additionally, it aims at initiating a market-based economy on the basis of locally produced vegetable goods. This may help to shift communities into a stronger socio-economic position, in turn providing an additional incentive to look after their own water supply.

6.1.4. Technical challenges - development obstruction through high-tech installations

Conventional water treatment technologies such as reverse osmosis, ion exchange and electro-dialysis reversal often fail in remote locations, as a result of cost-, maintenance-, energy- or socially-related factors (Kinsela et al., 2012). While these high-tech installations are technically sound in urban applications and can produce water at a competitive cost, their
biggest disadvantage is that their maintenance and repair relies almost exclusively on highly skilled external operators that are usually not immediately available during emergencies. The recruitment and training of local operators would lead to less reliance on external personal and in turn to shorter downtimes of the water treatment technology. However, due to their technological complexity these high-tech solutions do not facilitate skills development from the ground up and they also perpetuate a lack of ownership mentality and a feeling that water supply management is owned by external stakeholders. The Bubble-Greenhouse concept counteracts this by involving local people at all phases of the process, beginning with system design (i.e. number of modules and greenhouse size) and assembly of components on-site in order to allow for a thorough understanding of the technologies and physical concepts involved. As these concepts are generally relatively simple and easily understood and operatable by people with ‘bush-mechanic’ skills, they provide excellent entry points for community involvement and skills development.

6.1.5. Excessive water supply design figures – ‘fit for purpose’ approach

In response to the excessive water usage figures that are observed from time to time in remote communities, water supply design figures of 800-1000L per person per day have been adopted by the Western Australian Department of Housing (Yuen, 2001). This is three times the average water use of Perth residents (≈300 L/p/d), already one of the highest water using cities in Australia (NWC, 2011). Both technically and cost-wise, the specified water supply guideline places extreme pressure on water treatment installations. A case study confirmed the occasionally excessive water usage figures, showing the daily per capita household consumption at a remote community to vary between 170 to 1,600 L/p/d (Yuen, 2005). In a separate study where only kitchen taps were monitored, a substantially lower consumption of around 4-6 L/p/d was observed (Yuen, 2005). This suggests that only a very small amount of
water is actually used for drinking and cooking purposes, thus providing scope for a dual water supply. In this ‘fit for purpose’ approach, the bulk of the water stream would merely be filtered and softened in order to protect the infrastructure from scaling or corrosion and only a tiny fraction used for drinking and cooking would be treated by a high-end desalination technology. Adopting this approach would allow for a relatively small thermal desalination system with a water production rate of not more than 5-10kL/d for a whole community. The conceptual Bubble-Greenhouse with a design figure of 8kL/d aims at facilitating this ‘fit for purpose’ approach, providing an adequate amount of water for human consumption while bringing about considerable cost savings and significantly less stress on the community water supply overall.

6.2. Incentives for healthy living - combining water treatment with improved nutrition

The idea to combine water treatment with vegetable production for improved nutrition of community residents was first raised in discussion with the medical staff at Jigalong clinic during the field trip in 2007. Commonly, greenhouse based desalination concepts, e.g. the Seawater Greenhouse, have thus far focussed on producing sufficient water for crop irrigation. The Bubble-Greenhouse differs in this respect as it is designed for surplus water production intended for human consumption, while providing locally produced nutrition at the same time. Besides the already emphasised social and economic benefits, it is anticipated that the concept can positively influence dietary behaviours, enhance environmental awareness and appreciation and will positively impact food choice, nutrition knowledge and cooking skills, in a similar way to community gardens elsewhere (Lautenschlager and Smith, 2007).
6.3. Achieving sustainability

For long-term sustainable development of Aboriginal communities it is crucial to identify and build on existing Indigenous capacity in an environment of mutual respect and to incorporate capacity building as an integral aspect of design (Anda et al. 2006). Implementing sustainable local water management in remote communities requires contemplation of the financial, technical and social constraints for capacity building that exist in these places. It is then crucial to allow for the community to exercise control to the extent of adjusting the system to suit their changing circumstances. Community decision-making about the scope, timing and affordability of maintenance options and the building of informed capacity around water quality and quantity issues must be allowed and encouraged.

While external technicians should initially be involved in certain processes such as safeguarding against technical failures, an information sharing approach needs to be promoted in order to support informed decision-making by local residents (Grey-Gardner 2006). Development of the means for communities to receive and respond to independent scientific and technical advice is equally important. At all stages of the process, community participation, capacity-building and the recognition of community responsibilities are crucial elements for sustainable water quality management and water conservation, improved health conditions and sustainable development of remote communities.

The underlying motivation of the work presented here is to develop a water treatment method that can facilitate the transition to participatory water service management, with all the intended benefits resulting from such a process. The resulting Bubble-Greenhouse concept has been designed with particular focus on facilitating a participatory approach, a crucial
requirement to achieve sustainable development in remote Australia. By including local operators, their capacity building and skills development and ultimately, self determination, a strong culture of ‘looking after’ the water supply will develop and strengthen. It is envisaged to create a new form of water service provision and management that involves local participation at all stages of the Bubble-Greenhouse lifecycle, including planning and site-specific system design, site selection and preparation, system construction, operation and maintenance, quality monitoring, decommissioning and recycling of components. This new approach to water service delivery would require strong governmental support for the reinstatement and governance of capacity-building. Importantly, capacity building initiatives need to be a consistent component of the water management plan development, as a training program simply tacked on at the end of a project will not sustain management (Grey-Gardner and Walker 2001).

6.4. Cost aspects

While upsized solar still desalination technologies require a large capital investment, an effective measure of reducing the high cost of these projects in remote regions is to have installations which use local materials and local manpower as much as possible (Malik et al., 1996). Currently, the mayor cost in thermal desalination arises from the need to convert solar energy as the principal driver for evaporation. With the cost of solar capture technology continually decreasing, solar driven methods are constantly improving economically. In Saudi Arabia, the investment cost of supplying solar thermal desalinated water at a community scale was estimated at US$ 53,000 for a proposed solar still with a capacity 5.8kL/d (Hasnain and Alajlan, 1998). This figure is relatively on par with the cost of the proposed 8kL/d Bubble-Greenhouse system. Crucially, conventional solar still concepts
strongly rely on regular cleaning and maintenance of the stills, whereas maintenance requirements in the Bubble-Greenhouse are significantly reduced, owing to the self-cleaning ability of the evaporator and condenser columns (Francis and Pashley, 2009). This strongly reduces the cost of ongoing maintenance of the system. In addition, while thermal desalination based on a conventionally applied price per m³ of water is currently not competitive, cost-benefit considerations should take into account the considerable annual savings that can be made from reduced servicing and repair operations by external providers and from the strong capacity-building potential that ultimately contributes to economic development.
Chapter VII: Conclusions and recommendations

This thesis has achieved its stated objective of developing a novel water treatment method that could facilitate improved water provision in remote communities. The resulting technology is simple to implement and holds great potential for sustainable community development, participation, empowerment, skills and capacity building of local people in remote locations. The thesis consists of a series of published papers. It begins with a literature review, where conventional service delivery to remote communities is discussed and an evaluation of alternative water sources for remote regions is provided (Chapter I). This review leads to a focus on solar desalination technologies. Laboratory analysis of a bubble column evaporator prototype as a source for water vapour is then conducted and reported on (Chapters II and III).

The bubble evaporator is matched with a condenser device that initially developed from the need to assess heat and mass transfer along a condensation surface. This condenser in combination with the bubble evaporator evolves into a novel standalone HD system. The subsequent cooling methods experiments describe simple low-tech and low energy demand options for mitigating bubble column vapour temperatures even more effective so that the vapour can be channelled into a greenhouse afterwards, for the purpose of providing a humidified crop growing environment (Chapter IV). The conceptual Bubble-Greenhouse is developed by combining all the elements and findings from the laboratory trials (Chapter V). It promises to be a sustainable method for water provision in remote communities, particularly in that it facilitates the participation and empowerment of local beneficiaries at all stages.
In demonstrating the consistency of the bubble evaporator as a reliable source of water vapour, this research informs the development of a novel bubble column based desalination project. Besides their considerable potential as small-scale standalone desalination technologies, the low-tech and easy to make condensation and cooling devices have provided valuable insight into the task of mitigating the vapour temperature for the purpose of humidifying the Bubble-Greenhouse without harm to the crops. Since remote outstations have high costs stemming from poor economies of scale, poor support and service networks and limited information about varying strategies (including low technology options) for securing their existing water supplies, a broader water management program based on the Bubble-Greenhouse concept is sought. The project represents a low-tech method that provides an excellent entry point and great opportunities for community participation, capacity building and development. This holistic participatory approach focuses on the principles and practices of water risk management coupled with the community-based priorities of affordability, aspirations and sustainability of Livelihood outcomes.

7.1. Recommendations for future research

More research is needed to continuously develop multistage HD modules, in order to optimise their latent heat recovery cycle for energy efficiency. This will lead to substantially reduced solar collector demand. Trialling the modules under a range of process temperatures will help to determine the optimum ‘energy demand versus water output’ ratio and further aid cost efficiency. Due to the brief residence time required in a single-stage bubble column, where saturated vapour pressure is typically achieved within a few tenths of a second and the water column therefore only needs to be about 200-300mm high, future research should also focus on reducing the overall height of a six-stage column, perhaps to half its currently
proposed height of 1.2 meters, thus leading to substantially reduced energy demand for bubble generation. Fine-tuning and matching the system with optimum air blower technology requires an investigation into the available regenerative blower devices. Similarly, as economically and technically improved energy storage systems will soon be feasible to operate the Bubble-Greenhouse system solely with renewable energy, investigation and close monitoring of the already available options and of the development in battery storage will help to further optimise the Bubble-Greenhouse concept.

7.2. Recommendations for implementation

At this stage of the research, the Bubble-Greenhouse with its bubble column driven HD concept with innovative latent heat recovery cycle and its implementation is of a conceptual nature. Therefore, a practical trial of a community-scale Bubble-Greenhouse prototype is required to fine-tune its performance and to continuously improve its outcomes, both in regards to water and food output and also in regards to its water production cost. This study will also inform the advancement of participatory methods in remote Australia and elsewhere and will provide a blueprint for community based projects with the aim of long-term sustainable development in remote places.

It is hoped that the Bubble-Greenhouse concept can be developed into a real-world prototype and be trialled in a remote location in the near future. This trial would be tailored in such a way as to contribute to our understanding of participatory methods, especially conceptual, methodological, and capacity-building issues (Estrella et al. 2000), but also to real empowerment and skills development on the ground. Based on its size, human capital and existing infrastructure, Jigalong as a relatively large community with several hundred
residents would be an ideal location to trial a Bubble-Greenhouse prototype and to assess the physical and psychological effects of community involvement and the health and economic effects of locally produced food. Owing to its strong potential as a hub of communal activity, it is anticipated that the Bubble-Greenhouse project has the capacity to provide improved water service and improved community well-being, both from meaningful activities and healthy nutrition. Last but not least, the study would also contribute to knowledge building on the rapid emergence of solar energy utilisation for water treatment projects.

7.3. Final thoughts

Since publication of the Bubble-Greenhouse, the strong media interest that has been expressed in a number of interview requests and journalistic articles, suggests that the concept is received with great interest worldwide (SciDefNet, 2015; Kessler, 2015). The technology provides an excellent prospect for a more sustainable approach to remote service provision and great opportunities for community participation, capacity-building and development. It should not be concealed that some international researchers have voiced their concerns regarding the cost of water production. As the authors, we are well aware of the currently high cost but we believe that the simplicity of the system translates into numerous social benefits such as capacity building, self determination and empowerment, improved nutritional health and social wellbeing of people in remote locations that are often not considered appropriately. Putting a monetary value on these communal benefits will allow offsetting the currently high cost of water production from unconventional but ultimately, sustainable schemes such as the Bubble-Greenhouse.
Reference list for all references introduced in general discussion


Appendix 1: Acceptance of Platform Presentation Details *Ozwater ’13*

6 November 2012 *(Ref: 669)*

Dear Mario,

Thank you for submitting an abstract for Ozwater ’13, 8-10 May 2012, Sydney. I am pleased to advise that your abstract has been accepted for oral presentation at the conference.

Please find following details of your presentation:

<table>
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**Full Papers**

Conference papers will be published in the conference proceedings on a USB drive and issued to conference delegates. All presenters are required to submit a full paper by COB Friday 18 January 2013. Papers that are not received by 18 January will be withdrawn from the conference program.

Papers will be peer-reviewed by the Ozwater ’13 Program Committee and AWA Members. You may receive a request from the reviewers to revise your paper. Revised papers are due Thursday 28 March 2013. If you do not receive any correspondence from reviewers, your paper will be included in the conference proceedings unchanged.

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