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 CaCl$_2$ 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 libered 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
water). While it forms an effective barrier for matter in this way, it allows for thermal energy (heat) that is contained in that matter to pass through. Materials with a high thermal conductivity - such as copper sheet - quickly allow for the heat energy that is stored in the vapour-saturated air inside the condenser to be released into the cooler ambient air outside the condenser, through the process of conduction (Lienhard and Lienhard 2012). The larger the temperature gradient between inside and outside, the more heat is removed by conduction. Resulting from this heat reduction at the condenser surface, the ability of water molecules to remain in a vapour state is reduced. As a consequence, the reduced energy state forces water molecules to change phase, expressed as condensation. As more and more water molecules condense, droplets of desalinated water form and can be collected (Bouchekima 2002).

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 vapourisation 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 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. 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-url)

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 0.6 m$^3$ 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 (2258 kJ kg$^{-1}$) for 61.4 grams of water is 138.6 kJ, for 82 grams of water it is 185.2 kJ.

The total amount of heat made available to the evaporation process by the heating coil is determined by the temperature drop of 11.4 L of water (the total volume of heating water circulated through the heating coil from 2:30 to 3:30, using the heat energy equation $q = 4.18 \times 11400 \text{ml} \times (70-61.5^\circ C)$), 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 0.6 m$^3$ of vapourised air. In contrast, the actual measured distillate amount was 60.4 grams. The specific latent heat of vaporisation (2258 kJ kg$^{-1}$) for 46.3 (60.4) grams of water is 104.5 kJ (136.4 kJ). The difference between the latent heat input into the condenser (185.2 kJ) and the heat output through condensation (136.4 kJ) 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 35,000 ppm) is fed into the column. In the present experiments, this was not crucial as the duration of the individual experiments was around 5½ 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 (34,500 ppm ±895 Stdev), this resulted in an average sodium chloride end concentration of around 41,267 ppm ±2,050 Stdev 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 65 ppm (101 Stdev) in the first experiment to as low as 44 ppm (69 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.

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, Kamiya, 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, Beysens, and Milmou-Melnytchoy 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


