Desalination and Water Treatment
www.deswater.com
1944-3994 / 1944-3986 © 2009 Desalination Publications. All rights reserved.
doi: 10.5004/dwt.2009.917

12 (2009) 155–161

Thermal desalination using a non-boiling bubble column

M.J. Francis, R.M. Pashley*

Division of Research and Development, Murdoch University, Perth, WA 6150, Australia
Tel. +61 (8) 9360 7429; Fax +61 (8) 9360 6452; email: r.pashley@murdoch.edu.au, M.Francis@murdoch.edu.au

Received 1 July 2009; Accepted 17 September 2009

ABSTRACT

An unusual property of seawater, that is its ability to inhibit air bubble coalescence, has been used as the basis for a new method of desalination. In this process water vapour can be captured, transferred and collected using a simple, continuous, fine bubble column operated at temperatures well below the boiling point. The inhibition of bubble coalescence in salt solutions facilitates the design of a bubble column with a high volume fraction of small air bubbles, continuously colliding but not coalescing. This produces a uniform, efficient exchange of water vapour into the bubbles, which can then be condensed and collected as pure water. This new method has many potential advantages over reverse osmosis and typical thermal/evaporative methods in current commercial use.

Keywords: Thermal desalination; Non-boiling desalination; Bubble coalescence; Seawater

1. Introduction

The production of drinking water from seawater by desalination is becoming increasingly important, as water becomes more precious. Most of the water on the planet is in the salty sea (about 97%). The remaining fresh water is mostly trapped in the polar ice and many glaciers. Only a very small proportion exists as potable water, readily accessible in fresh water rivers and lakes — that is only about 0.007% of the total water on Earth. There is already insufficient clean water for the global population. Producing drinking water from seawater has a long history but only recently have reasonably economic methods become available. The use of any process, commercially, depends almost entirely on its cost. There are two main processes in current use. These are based on reverse osmosis (RO) membrane filtration and thermal evaporation/distillation. At the end of 2002, reverse osmosis and thermal/evaporative processes each produced about half of all desalinated water worldwide, with thermal/evaporative processes accounting for most of the seawater desalination [1]. The market for large scale desalination is growing rapidly; fuelled by government and business alike. The United Nations [2] has labelled this century "the century of ocean water desalination". It is easy to see why the production of drinking water from seawater is one of the most important problems facing us in the near future.

In recent years, RO membrane filtration has become the most popular method for seawater desalination but it has many disadvantages which add to its cost. Large volumes of concentrated salt have to be returned to the sea, as only a small fraction actually passes as clean water through the membranes. RO membranes are easily fouled and so the seawater feed has to be extensively pre cleaned and, even then, the membranes only last about 5 years. Also, the high osmotic pressure of seawater (typically around 30 atm) means that sophisticated and expensive liquid pumping is required at pressures of around 65 atm (Water Corporation, Perth, Western Australia). However,

---

* Corresponding author.

high pressure liquid pumping can be made relatively efficient and this has been achieved recently by the use of mechanical pressure recovery devices. The best practice commercial energy cost for the membrane desalination of seawater is currently at about 2.5 kWh/m^3 or 9 MJ/m^3 [3].

The minimum work required to desalinate seawater can be calculated from the work done by applying a pressure infinitesimally higher than the natural osmotic pressure of the sea and so obtain the reversible work done, at constant temperature, to move a semi permeable membrane an infinitesimal distance, so desalinating a very small volume of solution. This gives a minimum work required of about 3 MJ/m^3 of pure water. Commercial RO systems are less efficient, typically in the range of 10–20 MJ/m^3.

These various factors demonstrate clearly why the simple process of thermal evaporation appears attractive. Of course, this is the mechanism by which clouds are formed and produce drinking water in the form of rain, because salt is absent from the vapour phase. The interface between water and air (or vapour) offers a natural barrier to the transport of salt. This transfer does not require a membrane and does not require the use of the very high pressures needed with membranes. Hence, this interface offers the most simple exchange barrier for pure water and, perhaps, ought to offer the best commercial process, when suitably harnessed. This is the aim of the study reported here.

The most common current commercial form of this basic process of evaporation is called multi stage flash (MSF) distillation. In this process salt water is heated close to its boiling point, and then the local atmospheric pressure is reduced to initiate boiling. The salt water boils at a temperature significantly below its normal boiling point and the vapour is condensed and collected. Only a small proportion of the water boils off at each stage of the process and so a series of 'multi stages' are required. No membrane is needed but substantial energy is required to vaporise significant volumes. The latent heat of vaporization of water is about 2.3 MJ/l at 100°C and about 2.4 MJ/l at room temperature. These values are not altered much by the addition of salt. Although these values are high, most of this thermal energy is, in practice, recycled on condensation of the water vapour, and is used to heat the salt water feed. This substantially reduces the overall energy cost. The energy demand of evaporative methods can also be reduced using ambient or solar heat to preheat the seawater and by using waste industrial heat. Commercial thermal/evaporative units [4] typically have energy costs in the range 20–300 MJ/m^3, which reflects the high efficiency of their heat recycling processes. These plants are still widely used because of their significantly lower capital costs and equipment replacement costs and, often, because of the availability of waste industrial heat.

The current work was aimed at developing a novel process to improve the fundamental thermal/evaporation process, in terms of both efficiency and energy cost. The new process is based partly on the realisation that, at equilibrium, the vapour content in a bubble is determined by the temperature, alone, and does not depend on whether the water is at its boiling point. For example, the amount of water vapour contained in an air bubble immersed in water at 70°C (Fig. 1) is the same as that in a boiling bubble, created in water boiling under a reduced pressure at the same temperature. To take advantage of this situation, it is necessary to develop a process that can produce an efficient vapour exchange process with a high water/air interfacial area, without boiling. This can be achieved using a remarkable but still unexplained property of seawater. Russian mineral flotation engineers discovered many years ago that adding salt to a flotation chamber significantly improved its efficiency because finer bubbles were produced. This occurs because the bubbles formed at a porous sinter or frit do not coalesce above a certain salt concentration. Although there is still no clear explanation for this phenomenon, it has been well studied [5,6]. It turns out that some salts inhibit bubble coalescence and some have no effect. Common salt does cause inhibition and this reaches a maximum effect above about 0.17 M, which surprisingly, happens to be the salt level in the human body. It has been suggested that this is not by coincidence, but that this salt level is important because it protects our body from decompression sickness, even at atmospheric pressure [5,6]. Further increases in the salt level have no greater effect. Salt levels in seawater vary but are typically around 0.55 M. The effect of added salt is dramatic and is illustrated in Fig. 2a and 2b. In these photographs the same gas flow rate was used through the same porous sinter, but one was obtained using pure water and the other with a salt solution. The foaming of waves on the sea shore is also due to this effect of salt. This strange phenomenon means that a very

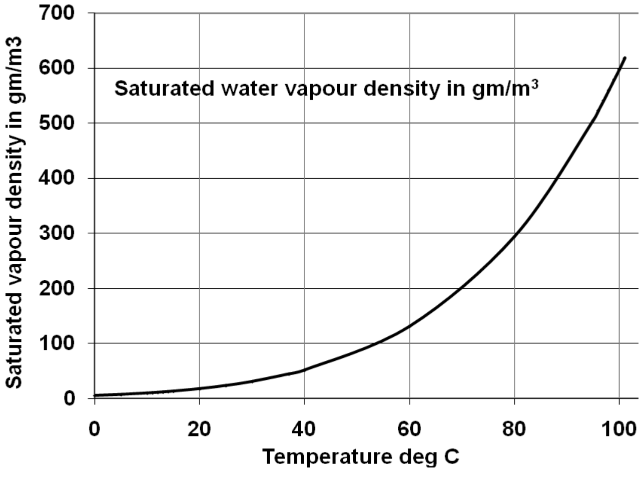

Fig 1. Temperature dependency of saturated water vapour density.

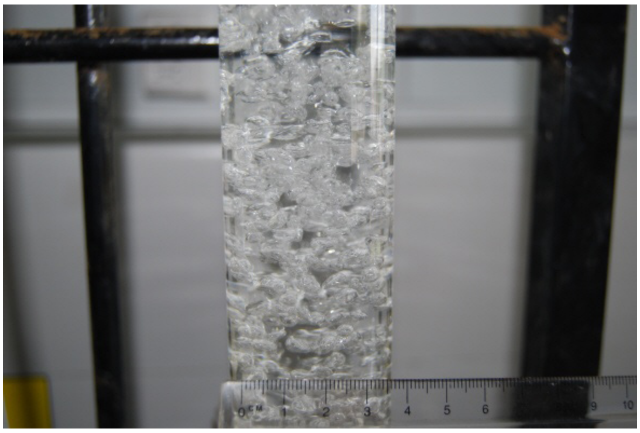

Fig. 2a. Nitrogen bubbles in pure water.

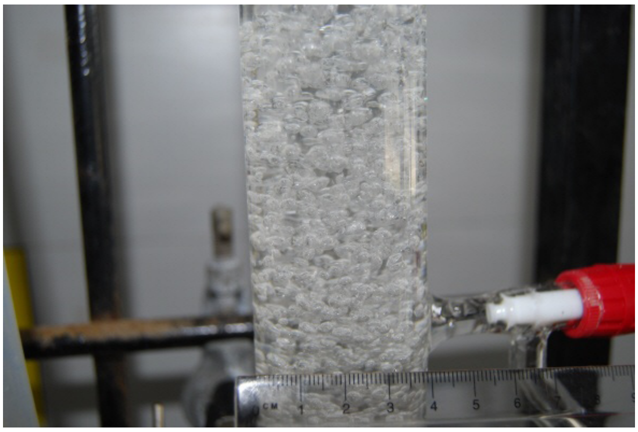

Fig. 2b. Nitrogen bubbles in 0.2M salt solution.

efficient vapour transfer process can be created using a simple bubble column.

Warming the salt solution to about 50°C has only a slight effect and actually reduces bubble coalescence still further [5,6]. Basic physical chemistry tells us that close to the boiling point, about 30 l of bubbles will carry about 20 ml of liquid water, as vapour, at atmospheric pressure. Hence, if air were bubbled into even a modest sized laboratory column of heated seawater, at a rate of 1 l/s, this could produce about 60 l of drinking water per day. Note that from Raoult's law the effect of sea salt only reduces the water vapour pressure by about 2%.

2. Methods

A high surface area air/water interface was continuously produced by pumping air through a 40–100 microns pore size glass sinter into a 14 cm diameter Perspex column and, in a separate study, into a 4cm diameter glass column. Bubbling at a modest rate into a column filled with salt water at the level of seawater produces fine bubbles (1–3 mm diameter) and an opaque column, compared with the relatively clear column produced in drinking water, which produces larger bubbles (Fig. 2a and 2b). Use of salt water in the column therefore significantly improves the efficiency of evaporation and transportation of saturated water vapour from which drinking water can be produced. By comparison, flash distillation essentially uses only the surface of the liquid as the main water vapour transfer barrier. Furthermore, the boiling process itself is an irregular process that is hard to control and leads to an accelerated rate of corrosion. In comparison, a high density of small air bubbles flowing continuously through the salt solution, held below the boiling point, will collect water vapour throughout the entire body of the salt solution in a regular, uniform process, until the saturation point at that temperature and pressure. An example of a dense bubble column created in heated seawater is shown in Fig. 3. If the seawater is heated to just below its boiling point (at normal or reduced pressure), then the air bubbles entering the base of a column will become completely filled with water vapour, which can then be transported, in a regular controlled process, into a condenser and collected, as illustrated in the schematic diagram in Fig. 4. There is no need to boil the water in this process. 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.

In the second method, condensation was produced in the upper, cooled, section of the bubble column. The base of the column was heated to capture water vapour in the rising bubbles. Hence, in this system water vapour was carried from the hot salt solution at the bottom of the column, which becomes more concentrated, and was then condensed in the cooler, top section of the column, where the salt solution becomes increasingly diluted. A steady state can be created by removing both the (bottom) concentrate and the (top) diluant at a combined rate equal to the rate at which seawater is fed into the column.

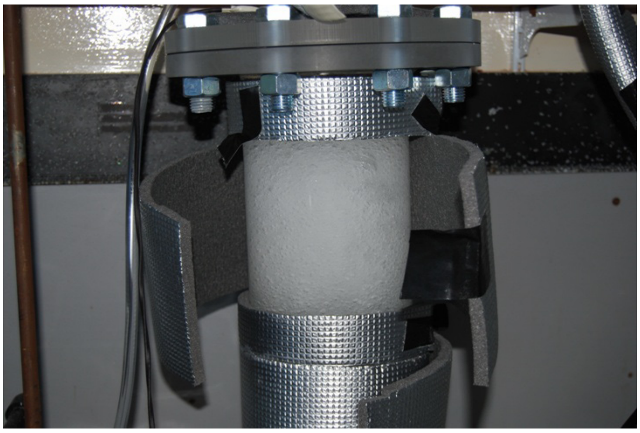

Fig. 3. Dense air bubble column created in heated seawater.

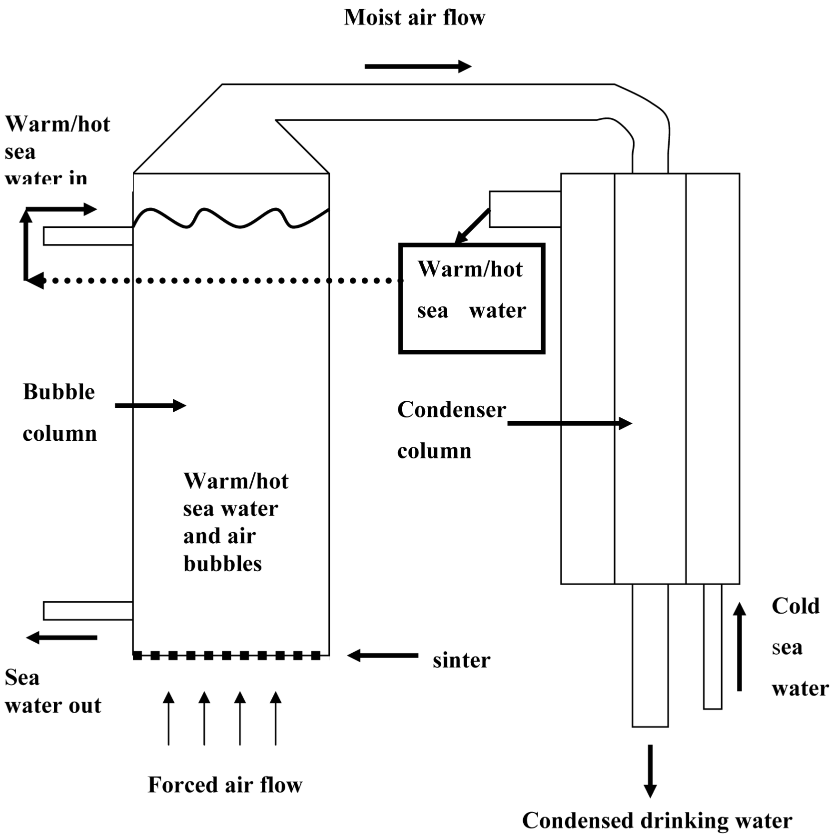

Fig. 4. Schematic diagram of a bubble column desalination process.

The pressure drop over the sinter and the hydrostatic pressure imparted by the head of water in the column were measured by inserting a side arm into the system prior to the sinter. This allowed the working pressure of the bubble column to be measured directly.

3. Results and discussion

In the following sections, experimental results are reported on two types of bubble column desalination systems, based on these physical principles. In the first system, water vapour was carried from a heated bubble column and separately condensed. The second system incorporated the evaporation and condensation process within the same bubble column.

The air bubbles formed in this simple process were typically about 1–3 mm in diameter. These bubbles rise at a limited rate of between about 15 and 35 cm/s in quiescent, clean water because they undergo shape oscillations which dampen their rise rate [7,8]. These oscillations accelerate the transfer of water vapour into the bubbles and so enhance the rate of vapour collection. Equilibrium vapour pressure is therefore attained quite quickly, within a few tenths of a second [7]. Hence, these bubbles will reach saturated vapour pressure within a travel distance of 10 cm, or less.

The nature of the bubble vapour desalination process means that a wide variety of experimental conditions can be selected, such as, gas flow rate and column operating temperature. As an example of the first method, which uses a separate condenser, a vertical Perspex column of internal diameter 0.07 m and height of 0.5 m was filled with seawater and heated to a starting temperature of 70°C. Air bubbles were then passed through the glass sinter at the base of the column at a rate of about 13 L/min. Typically, the fine bubbles produced occupied about 20–30% of the total volume in the column. A schematic diagram of this apparatus is given in Fig. 4. After bubbling for 60 min, the temperature of the solution in the column had fallen to about 52°C. The starting and finishing temperatures were used to estimate the theoretical yield expected for complete collection and condensation of the water vapour, at the average temperature of the column. Relative humidity monitoring indicated that very little vapour was lost to the atmosphere after passing through the condenser. The results obtained in this study also showed that vapour collection and transport observed using this apparatus, was close to that expected from the equilibrium vapour data given in Fig. 1. In addition, the conductivity of the water produced, typically at about 6 μS/cm, was much better than that required for drinking water. This 'distilled water' quality product was easily obtained with the bubble column method using feed water with a salt level similar to that found in seawater, with an electrical conductivity of about 49 mS/cm.

In the second method, both evaporation and condensation were contained within the same column, by maintaining a significant temperature differential across the column. A glass column of 4 cm internal diameter and 1.2 m height was preheated to give a starting temperature of 65°C. The air flow used was about 3 L/min, which allowed the air bubbles to flow upwards in the column in a fairly laminar, ordered manner with minimal mixing turbulence. Under these conditions, the average bubble volume fraction was once again about 0.3. The bubble sizes were between 1–3 mm in diameter, with a bubble rise rate of about 15 cm/s. The salt solution feed had a concentration of about 0.4 M NaCl and an electrical conductivity of 40 mS/cm, at 25°C. The top section of the glass column was cooled using a glass condenser which had a cooling water flow rate of 0.48 L/min, at an inlet temperature of 0.173°C and an outlet temperature of 6.112°C. With this cooling, the temperature at the top of the column was maintained at 20.0°C. After 5 h, the conductivity at the top of the column was reduced to 15.9 mS/cm, which corresponds to a salt concentration of 0.15 M. The conductivity in the middle of the column was 47.3 mS/cm at a temperature of 25°C (measured using an IR detector, so as not to affect the measurements) and the conductivity at the base of the column was 52.4 mS/cm, at a temperature of 42°C (again measured by IR). Thus, after several hours, this column of modest height and with a relatively small temperature differential of only just over 20°C, produced a significant concentration gradient of 0.6 M at the base to 0.15 M at the top. This dilution rate, of about 4×, was very close to that expected from the estimated amount of water vapour carried over for this flow rate and temperature. Extending the column length, increasing the temperature differential and increasing the gas flow rate should further increase the dilution rate within the column. One of the advantages of this second method is that the quality of the water produced can be easily varied.

The efficiency of the bubble column desalination process depends on many factors. The brief residence time required for the bubbles to reach vapour saturation, typically within a few tenths of a second for the bubble sizes used, and the limited rise rate means that bubble columns, with a separate condenser system, need only be about 20–30 cm high. This substantially reduces the costs and size of the bubble column unit required. Another important factor is that the measured pressure drop across the column and sinter is low, which reduces air pumping costs. For example, a typical regenerative blower (e.g. Republic HRB 402/1) running at 1.65 kW, has an air flow rate of 192 m^3/h and a working pressure of 343 mbar. One of these pumps could run up to 11 bubble columns in series, each 30 cm high. Assuming each unit was operated at 88°C, the total air pumping energy requirement would be about 2 kWh/m^3, which for comparison is half the energy requirement of a best-practise commercial RO plant. The thermal energy costs will depend on the source, such as solar, waste heat or direct heat pump supplies. Commercially available figures suggest that efficient vapour condensation systems produce a thermal energy conservation of 99% or better, since best practice thermal desalination processes (using vapour compression) operate at about 4 kWh/m^3 [4], whereas the latent heat of vaporisation of water (at 70°C) is about 670 kWh/m^3. These figures indicate that the bubble column process could be commercially viable when combined with an energy efficient vapour condensation system.

The size of a desalination plant designed using bubble columns would also be much smaller than current RO plants. Due to the modest 30 cm height of the units, they could be readily stacked in racks such as current RO membrane units are. For a 4 m high warehouse, 144 ML/d (output of Kwinana RO plant at peak) could be produced from a building less than 60 m by 60 m. The main advantage with this plant size is that the pre-treatment facilities, which are usually a main part of the land needed for a desalination plant, are not needed for this process. Using this system for desalination could yield smaller and hence more efficient desalination plants.

The two new methods for sub boiling, thermal desalination presented here are based on the unusual properties of seawater, that above a certain salt concentration air bubbles are inhibited from coalescence. This behaviour allows the construction of an efficient air bubble vapour transfer system with a high volume fraction of air. Since, bubble coalescence inhibition is the basis for these novel desalination processes, it is useful to examine the mechanisms involved. Unfortunately, there is still no proper explanation for the effects of salt on bubble coalescence inhibition. Indeed, at first sight, adding salt would be expected to enhance coalescence because this increases the surface tension of water and hence the bubble energy. Also, adding salt should effectively screen out any repulsive electrostatic force between charged bubbles [9]. Short range van der Waals forces between bubbles will be attractive [9], as will any long range hydrophobic forces [10].

Although the explanation for this effect is still illusive [11], it seems likely that the cause is related to dynamic effects, since, when two individual bubbles are forced together, they will eventually always coalesce, even in water at high salt levels. Currently, the most likely explanation is based on hydrodynamic effects related to the drainage film formed between two colliding bubbles [11]. Surface effects can arise because even though ions are repelled from the surface of water, due to an image charge repulsion, once the bulk salt concentration is sufficiently high, ions will be forced to reside at the surface. To reduce energy, they will most likely adsorb as ion pairs and this could set up a local electrostatic field at the surface, which could immobilise adjacent water layers. If this happens it will induce a 'zero slip' boundary condition at the surface, which will reduce the rate of film drainage between two approaching bubbles, and so increase the likelihood of the bubbles separating before they can coalesce, especially within a turbulent bubble chamber. In addition, the observation that some salts inhibit coalescence and others do not [5,6], could then be explained in terms of their ability to create this local electrostatic field, as ions are forced into the surface region at high concentrations. Some salts will produce this immobilisation, whereas others will not. This important problem remains the subject of investigation [11]. Whatever the cause, there is no doubt that added NaCl inhibits bubble coalescence in water, at the salt level in the sea.

The non-boiling, bubble column system described in this work has many potential advantages over other desalination processes. This is partly because it has the potential to harness sustainable energy sources directly, for example, from solar heating and wind turbines. An even more direct application might be in the use of industrial waste flue gases. For example, a typical calciner plant produces 500 tons of waste gas, per hour, at a temperature of 165°C. It is interesting to calculate the operating temperature of a bubble column heated entirely by hot feed gases. In this situation, steady state is reached when the thermal heat capacity of the inlet (hot) gas precisely equals the latent heat of vaporization required to produce the equilibrated water vapour. The results of this calculation are given in Fig. 5. As an example, the calciner flue gases pumped into the column at 3 atm pressure is sufficient to maintain the column temperature at an operating temperature of 60°C. This system would be capable of producing high quality water from seawater at a rate of about 0.15 l per m^3 of gas (see Fig. 1). It is likely that any initial commercial application of this bubble process will be most efficiently used when linked directly to industrial plants that produce waste heat and flue gases.

Another significant advantage of the bubble column method is its potential to substantially reduce the energy demand for desalinating seawater, compared with RO membrane methods. This is because most commercial seawater RO treatment plants produce a 2× concentrate reject stream, typically returned kilometres out to sea [3] or discarded. This increase in concentration corresponds to a higher operating osmotic pressure (i.e. over 2× the osmotic pressure of seawater) and significantly higher energy (pumping) costs. This concentration level is used because the feed salt water must be thoroughly filtered prior to exposure to the RO membranes, to reduce the extensive fouling caused by dirty water. However, the bubble column method can be used to concentrate the reject stream to, say, only 20% above sea salt levels because this method does not require costly pre-filtration and so it can be operated with much larger reject volumes. This is partly because the bubble column acts as a self-cleaning, flotation column where contaminants float to the surface and are swept away. Suitable biocides could also be added to prevent algal growth. A process producing only 20% enhanced salt solution has the potential to almost halve the minimum energy required per litre of drinking water produced and will also allow disposal of the concentrate closer to shore, at a reduced cost and with little environmental impact. Accurate estimates of the energy costs of bubble desalination processes could only be obtained by analysis of a larger scale system, where the issues associated with efficient vapour condensation and energy collection and recycling can be addressed.

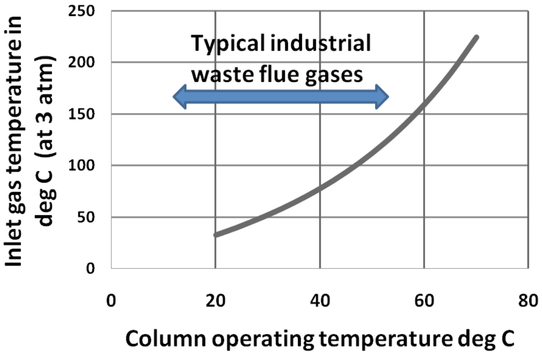

Fig. 5. Estimated gas inlet temperature required to maintain bubble column temperature.

4. Conclusions

These initial studies demonstrate that water vapour capture and condensation within a non-boiling, salt water bubble column can be used to obtain high quality water in a single stage process. The energy demand of the required air flow is well within the range of commercial RO energy costs. A bubble column process offers substantial advantages, such as reduced capital cost and low capital operating costs, compared with RO and other thermal methods because of the simplicity of the process and its ability for self cleaning. Commercially, this is one of the most important considerations [12], since waste low quality heat and waste vent gases are widely available, at low cost. In a situation where producing waste energy is increasingly hard to justify, this new process might offer a useful solution.

References

[1] A.D. Khawaji, I.K. Kutubkhanah and J-M. Wie, Desalination, 221 (2008) 47–69.
[2] B. Pilat, Desalination, 139 (2001) 385–392.
[3] Personal communication from Dr. Keith Cadee, General Manager, Water Corporation (Perth). See also: IDA Desalination Yearbook, 2007–2008, p. 83.
[4] J.E. Miller, Review of water resources and desalination technologies. Sandia National Laboratories, SAND 2003-0800, 2003.

[5] V.S.J. Craig, B.W. Ninham and R.M. Pashley, Nature, 364 (1993) 317–319.
[6] V.S.J. Craig, B.W. Ninham and R.M. Pashley, J. Phys. Chem., 97 (1993) 10192–10197.
[7] I. Leifer, R.K. Patro and P. Bowyer, J. Atmosph. Ocean Technol., 17 (2000) 1392–1402.
[8] R. Clift, J.R. Grace and M.E. Weber, Bubbles Drops and Particles. Academic Press, New York, 1978, 380 pp.
[9] J.N. Israelachvili, Intermolecular and Surface Forces, Academic Press, 1992.
[10] J.N. Israelachvili and R.M. Pashley,. Nature, 300 (1982) 341–343
[11] H.K. Christenson and P.M. Claesson, Adv. Coll. Int. Sci., 91(3) (2001) 391–436.
[12] V.S.J. Craig, Current Opinion Colloid Interf. Sci., 9(1–2) (2004) 178–184.
[13] B. Donaldson, J.Genin and M.S. Lavery, System and method for desalination of brackish water from an underground water supply. US Patent no: 7037430, issued 2006.