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A study of the bubble column evaporator method for improved thermal desalination

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A B S T R A C T

A bubble column evaporator (BCE) was used to study the enhanced evaporation of water from 0.5 m NaCl solutions, using a range of pre-heated carrier gases (air, CO_2, Ar and He), each at an inlet temperature of 150 °C. Surprisingly, the use of hot helium as a carrier gas substantially improved water evaporation efficiency, by a factor of about 3 times, compared with, for example, dry air. It is suggested that this higher efficiency could be due to a slightly reduced water hydrogen bonding, and hence enthalpy of vaporisation, due to the continuous sparging of hot He gas atoms into the aqueous solution. These results suggest that this process could form a basis for the development of a more efficient, sub-boiling desalination process. The effect of added cationic and anionic surfactants on BCE water evaporation rate was also studied. The cationic surfactant myristyltrimethylammonium bromide (MAB) and the anionic surfactant Sodium dodecyl sulfate (SDS) each gave a slightly enhanced water evaporation rates, in agreement with previous studies, probably due to enhanced water vapor retention within surfactant coated bubbles.

1. Introduction

Seawater desalination is an effective approach being used worldwide to cope with the global problem of fresh water scarcity, which is considered the main challenge facing humanity, due to rapid population growth and economic growth [1]. Seawater desalination has a long history and many ancient civilisations largely used boiling and filtration methods to produce fresh water [2]. Desalination techniques mainly can be categorised into two sections: 1) thermal methods, which requires heating water to the boiling point to obtain water vapor; and 2) high pressure membrane processes, which involve a membrane that forms a barrier between two different concentration zones to separate water from ions and eventually to produce fresh water.

Thermal methods because of employing high quantities of fuel are costly so that poses a main challenge for their commercial applications in desalination processes. This problem was solved by emerging membranes, mainly RO, which needs high pressure to separate salt ions from water rather than high thermal energy. However, this technique also requires extensive pre-cleaning of the feedwater to prevent continuous membrane fouling [3,4].

It is also possible to obtain fresh water without the need for seawater boiling, by using the fact that the water–air interface acts as a natural semi-permeable membrane, since it allows water vapor to escape but not dissolved ions. The bubble column evaporator (BCE) [5] method uses this idea and offers a simple process which can be further enhanced using a remarkable but still unexplained property of salt in water, which was first discovered by Russian mineral flotation engineers in the 1930s. They found that adding salt to a flotation chamber significantly reduced bubble size and hence improved its efficiency [6].

Most salts prevent bubble coalescence when added to water, but there is still no theoretical model to explain this phenomenon [7]. Dissolved salt (NaCl) at 0.5 m (i.e. seawater levels) when used in the BCE process makes dense bubble columns, with bubbles in the range of 1–3 mm diameter, by inhibiting bubble coalescence. This produces higher mass and heat transfer between the increased interfacial area of the gas and the water, enhancing the evaporative effect [8].

The rate of thinning of the intervening water film formed as two bubbles collide must determine whether coalescence will occur. This rate is controlled by several factors, such as, the viscosity of the intervening solution, the size of the bubbles and the presence of solutes, such as salts and surfactants, in the intervening solution. In chaotic bubble columns, collisions occur within fractions of a second; if the film can drain during these collisions, the bubbles will coalesce [9]. The situation is quite complex, for example, it is expected that the film drainage rate between approaching bubbles should be increased by raising the column solution temperature, which causes significant drop in the viscosity. This will also enable the film to drain before the bubbles are rebounded by the high turbulence in the column solution [10].

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However, it was observed [11] that bubbles were less likely to coalesce as the solution temperature was increased. Further complications occur when the sparging gas bubbles are transiently hot but the bubble column solution itself has a more modest, steady state temperature. Therefore, the combined effect of a rise in column solution temperature with sparging hot gas bubbles should produce significant local heating around the bubbles, which should further reduce film viscosity [9].

In the BCE method, there are basic heat and mass transfer processes, in which hot gas transfers its heat to the aqueous solution and consequently mass transfer takes place in the form of transfer of water vapor but not dissolved inorganic ions. Dynamic diffusion enhances capture of water vapor into the rising bubbles and they are rapidly saturated with water vapor and travel upward to the top of BCE column, where they can then be collected and condensed in the form of fresh water [12]. Bubbles in the 1–3 mm size range are optimal because they are the smallest bubbles rising at the fastest rate [13].

The BCE method has opened up a new direction for fresh water availability, especially for low energy sub-boiling seawater desalination and offers a new approach for tackling fresh water shortage in a cost-effective and environmentally friendly way [14].

The thermal and mass (i.e. water vapor) transfer balance within the BCE can be described by the relation [15]:

$$[\Delta T \times C_p(T_e)] + \Delta P = \rho_v(T_e) \times \Delta H_v(T_e) \qquad (\text{In units of J/m}^3) \tag{1}$$

where in this equation, ΔT is the difference between inlet and outlet gas temperature; C_p (T_e) is the inlet gas specific heat capacity (in J/m^3·K); ΔP is the pressure difference between the gas entering the sinter and atmospheric pressure, at which it is released. This term corresponds to the work done by the gas flow which must be absorbed by the bubble column. The water vapor density and enthalpy of vaporisation, both at equilibrium column temperature (T_e), are defined as ρ_v and ΔH_v, respectively. This model represents the steady state thermal balance in the BCE process as heat supplied by incoming hot bubbles passing through the solution in the column carry away the evaporated water vapor. Released bubbles, at a given inlet temperature above the steady state temperature of the column, cause capture of water vapor and so maintain a steady state column temperature [15]. Eq. (1) leads directly to the surprising fact that even very hot bubbles continuously passed into an aqueous bubble column will not cause boiling because of the evaporative cooling effect of the BCE. This has led to the use of hot gas bubble columns for many other applications, such as low temperature sterilisation of contaminated water [15,16].

This method offers an effective vapor transfer process with continuous water collection from seawater at the bubble interface, below the boiling point, to improve the efficiency of seawater desalination. As discussed above, salt solutions also inhibit the coalescing of bubbles and therefore increases their efficiency in carrying water vapor, which is absorbed into relatively small and uniform bubbles [7]. The bubble coalescence inhibition effect facilitates efficiency of heat transfer in the BCE and consequently increases the performance of evaporation in the desalination application [9].

Francis and Pashley [16] reported that heating seawater solution to 70 °C and passing room temperature air bubbles through it with a glass sinter, porosity No. 2, decreases the temperature of the solution to 52 °C in the column after 60 min of air bubbling. By using the initial and final temperature in the system, the theoretical yield of water vapor in the column was calculated and the electrical conductivity of the column solution was decreased from 49 mS cm^{-1}, for seawater, to 6 µS cm^{-1} for the condensed water, which meets the criteria for drinking water.

Some recent studies show that increasing the temperature of inlet gases cause improvement in the efficiency of the BCE system for seawater desalination. For example, in [17] dry and hot air bubbles with temperatures ranging from 150 to 250 °C were passed at a flow rate of 23 L/min into empty columns which were then quickly filled with 200 g of 0.5 m salt solution. The temperature of the solution was recorded every 30 min of bubbling and the weight of the water vapor removed from the solution was weighed by detaching the column. Results obtained showed that by increasing the inlet gas temperature from 150 to 250 °C, the vaporisation increased from 6.2% to 8.3%, respectively, above the expected water vapor carryover rate, which demonstrates that raising the inlet gas temperature in the BCE improves the water vapor saturation levels within bubbles.

In a similar study [9], it was found that adding a non-ionic surfactant, octaethylene glycol monododecyl ether ($C_{12}EO_8$), improved water vapor transfer in the BCE, apparently by creating a mono-layer coating on the surface of the bubbles. It was suggested that the adsorbed soap layer around the bubbles facilitates the water vapor evaporation into the rising bubbles in the BCE but once inside the bubbles, its interior hydrophobic surface could potentially acts like a molecular diode and inhibit vapor transfer back into solution [9].

The BCE method offers a more controllable operation, compared with boiling, it is also a simple technique, highly resilient to feed water quality and salinity and should therefore be cost and energy-effective and more sustainable given the lower temperature of the operating column solution [18].

This work is aimed at further improving the BCE system for seawater desalination through the study of the effects of different input parameters to improve vaporisation efficiency. The effects of different input carrier gases (e.g., Air, CO_2, Ar and He) have been studied as well as the effects of two different added surfactants, sodium dodecyl sulfate (SDS) and myristyltrimethylammonium bromide (MAB) on the performance of BCE seawater desalination.

2. Materials and methods

In this work, different gases including CO_2/Ar/He and air were used by cylinder (Coregas Pty Ltd., Australia) and air pump (Hiblow HP40, Philippines), respectively. The gases were flowed through a 1000 mL filter funnel with sinter No. 2 (Büchner type, Pyrex® Borosilicate, VWR) and the flow rate was measured, for most of the gases, using a BOC flowmeter and a Dwyer flowmeter (Dwyer Company, Pty. LTD). Fig. 1 shows the schematic diagram of the BCE setup used for these studies. A bypass metallic valve was used to divert gas flow to atmosphere, which was required to enable weighing of the remaining column solution after 30 min of bubbling time. The temperature of inlet gas was controlled using an AC Variac electrical supplier monitored with a thermocouple temperature detector. Another thermocouple was positioned at the centre of the column to maintain the same inlet gas temperature just above the column sinter (i.e. 150 °C for all of these experiments). High gas inlet heater temperatures, up to 600 °C, were required to produce the required temperature on the surface of the glass sinter. The gas inlet system was made of metallic connectors, which were insulated with Rock Wool to prevent heat loss. In all of these experiments, the volume flow-rate of inlet gas at the same temperature (150 °C) and pressure was measured and maintained constant during the evaporation runs.

Variable flowmeters are scaled between zero and full-scale range mostly in Metric units at standard conditions. These types of flowmeter are known as Rotameters, which are simple, economical and precise to indicate the rate of flow for a known gas. They are designed to be positioned vertically in the system with an engineered glass tube and spherical stainless-steel bobbin or ball, which floats depending on the inlet gas pressure flow.

The significant correction factor needed for He gas flow using a rotameter was of some concern and so for He the gas flow rates were measured by weighing the He cylinder over a known time, with flow rate maintained constant using a rotameter. Mass loss for He cylinders was monitored with digital balance (Excel FBTW Series Platform Scale, South East Queensland Scales, Brisbane). For example, the mass loss of helium gas with molecular weight of 4 g mol^{-1} after 30 min was found to be about 40 g; Therefore, the volume flow can be obtained by