



A study of the bubble column evaporator method for thermal desalination



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HIGHLIGHTS

- High temperatures do not affect inhibition of bubble coalescence in salt solutions.
- Enhanced bubble column evaporation was observed using high inlet gas temperatures.
- Surfactant monolayer coatings were found to improve the evaporation rate.
- Latent heats of vaporization can be obtained even at high inlet gas temperatures.

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ABSTRACT

A simple bubble column evaporator can be used to evaporate water from concentrated salt solutions without boiling. The process is made more effective by the inhibition of bubble coalescence caused by the presence of some concentrated salts, such as NaCl. This work examines the effects of high bubble temperatures on this coalescence inhibition and its effects on the efficiency of water vapor collection. A continuous flow of hot dry air, at 275 °C, produced about 10% higher rate of water vaporization than that expected from the equilibrium vapor pressures. Also, the use of a non-ionic surfactant monolayer bubble coating further improved the evaporation efficiency, by up to 18%, apparently due to supersaturation. In addition, the steady state temperature of the bubble column evaporator can be used to estimate the latent heat of vaporization even for inlet air temperatures of up to 275 °C.

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1. Introduction

Producing drinking water from seawater has a long history. Aristotle (384–322 BCE) commented that pure water can be made by the evaporation of seawater. In ancient times, many civilizations used distillation to produce drinking water on their ships. Aristotle also carried out some experiments on removing salt from seawater by filtration and ion exchange, by flowing it through a high surface area porous material such as sand and clay. Simply by digging a hole near the seashore and allowing the seawater to percolate through the sand reduce the salt level [1]. The availability of water has been a major influence on culture in the Middle East, for thousands of years [2]. They support habitation and agriculture, in some parts of the Middle East, until very recently, when pumped bores began to significantly deplete the water table [3, 4]. The Arab states of the Persian Gulf were among the first to adopt industrial-scale desalination, and have the largest proportion of the world's installed desalination capacity. This is partly because of the availability of abundant fossil fuels, proximity to the sea, and the limited

natural fresh water [5,6]. Other countries, such as Singapore [7], Australia [8] and Spain [9], also have increasing levels of investment in seawater desalination. Demand for water in Asia and the Middle East is expected to increase sharply in the long term, due to rapid population growth and economic growth. Much of this demand is expected to be met by desalination [10]. Predicted climate change may also have a significant impact on the availability of conventional water supplies. Water stress is expected to increase in the future, due to population growth alone [11].

The most cost and energy effective production of drinking water comes from the collection, storage and treatment of natural rainfall [12]. However, this source of water is not always readily available next to regions of high population and so for coastal regions two main processes have been developed for seawater desalination, which are based on the ancient methods of boiling and filtration. These methods are called thermal desalination and reverse osmosis (or membrane filtration) desalination [12,13]. Thermal desalination methods are severely limited by their high thermal energy demand and so multi-stage flash (MSF) and multi-effect distillation (MED) have been developed [12] to re-use the psychrometric (or vapor potential) energy which must be collected from the water vapor on condensation.

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More effective methods of obtaining this heat through the vapor compression process [14] have recently been developed.

In large scale, commercial thermal desalination processes, boiling is usually carried out under a reduced pressure to depress the boiling point. This process is very effective at producing clean water but it is costly in terms of energy requirements and is usually only cost effective when combined with an available source of waste industrial heat, for example from a power station. The second process of increasing importance is called reverse osmosis (RO) filtration [14]. In this process an asymmetric filtration membrane is used which contains a thin surface layer of pores so fine that only water molecules can pass through. Unfortunately, high pressures, in the range of 50 to 80 bar have to be used to force the seawater through the pores at a reasonable rate and the pores easily become clogged and so this process is also fairly costly as care has to be taken to pre-filter and clean the seawater prior to RO filtration [14]. Ion exchange is normally used for the desalination of brackish water [15].

Thermal evaporative methods have some advantages in terms of a reduced need for high quality feed water (compared with RO, where the membranes are readily fouled) and also the rejected salt can have a much higher concentration. In addition, evaporative methods can be used to treat heavily contaminated industrial waste water and hypersaline feed water. The cost of desalinated water is considerable, compared with that of treated reservoir water. MSF and MED desalination requires about 150–300 MJ m⁻³ for stand-alone units where waste heat is not used [13] and falls to about 17–43 MJ m⁻³ when using waste industrial heat [16]. These figures should be compared with the enthalpy of vaporization of water, of about 2.26 GJ m⁻³ at 100 °C and 2.45 GJ m⁻³ at room temperature [17], which clearly demonstrates the importance of thermal energy recovery in these evaporative methods. This enthalpy of vaporization values is not altered much by the addition of NaCl. Hence, the thermal recovery efficiency has to be about 90% or better. Even with this energy demand, the cost of water production, per cubic meter, is modest, at typically between US\$0.5 and \$2 [18]. These costs are largely determined by the efficiency of the plant, and are not affected substantially by feed water quality.

It is possible to obtain high quality drinking water from seawater without the need for boiling using the fact that the water–air interface is a natural semi-permeable membrane, since it allows water vapor to escape but not dissolved ions. It turns out that this simple process 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 [19]. The formation of a bubble in water requires some work because of the surface tension of the water. We can see this for ourselves when we use our lungs to blow bubbles in water through a straw. When two air bubbles are forced together in water, they tend to coalesce to form one bigger bubble. This is what we would expect because a single bubble has a smaller total surface area than two small bubbles of the same volume. However, within a bubble column containing large numbers of continuously colliding bubbles it becomes clear that salt has the ability to inhibit bubble coalescence, hence allowing the formation of a high volume fraction (>50%) column of bubbles [20,21].

A suitable high density bubble column can be produced by pumping air continuously through a 40–100 µm pore size glass sinter (sinter size 2) to produce a continuous stream of bubbles within a column filled with water or salt solution. When using an aqueous NaCl solution of about 0.15 M, or more, finer bubbles are produced (of about 1–3 mm diameter) giving an opaque column, because of the salt inhibition effect [20,21]. These bubbles rise at a limited rate of between about 15 and 35 cm/s in quiescent water because they undergo oscillations in shape and rise trajectory, which dampen their rise rate [22,23]. These oscillations also increase the rate of transfer of water vapor into the bubbles and enhance the rate of water vapor collection. Equilibrium vapor pressure within the bubbles is therefore attained quite quickly, within a few tenths of a second [22] and the bubbles will therefore reach

saturated vapor pressure within a travel distance of about 5–10 cm. Larger bubbles are limited at a similar rise rate and so the use of larger bubbles has no advantage and has the disadvantage that they will take longer to reach water vapor equilibrium, simply due to their larger size [22–24]. Smaller sized bubbles, below about 1 mm, have increasingly slower rise rates, which will significantly reduce the efficiency of the vapor transfer process [23,24]. The relatively short travel distance for optimum sized (1–3 mm) bubbles to rapidly reach water vapor saturation will have a significant influence on the design of any larger scale vapor separation process based on a bubble column evaporator.

This bubble column evaporator process can be described by Eq. (1), which is based on the energy balance within the column at steady state equilibrium [25].

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

$C_p(T_e)$ is the specific heat of the gas flowing into the bubble column at constant pressure; T_e is the steady state equilibrium temperature of the column; ρ_v is the vapor density at T_e ; ΔT is the temperature difference between the gas entering and leaving the column; and ΔP , the additional correction term, is equal to the hydrostatic differential pressure between the gas inlet into the sinter and atmospheric pressure at the top of the column, which represents the work done by the gas flowing into the base of the column until it is released from the solution. Eq. (1) describes the process by which heat is supplied from warm bubbles for vaporizing water in solutions in units of Joule per unit volume.

These combined factors mean that a simple bubble column can be used to efficiently collect water vapor over a modest distance and time period. Unfortunately, however, only very limited data is currently available on the rise rate at different bubble sizes and for higher column temperatures. Although there is a lack of detailed information on the fundamental processes involved in the bubble column evaporator, the technique has recently been used in the development of several new applications. These include sub-boiling desalination [26], measurement of the latent heat of vaporization of concentrated salt solutions [25], evaporative cooling [25] and, most recently, low temperature sterilization [27]. The bubble column evaporator (BCE) method also has great potential for applications in the treatment of heavily contaminated industrial water and high salinity water. This is because the evaporation surfaces are continually being produced and destroyed, that is, the fresh bubbles. The buildup of scale in conventional thermal desalination processes presents a major problem [28] which is almost completely removed by the use of the BCE process.

When no other materials are present, air bubbles in water readily coalesce with each other and break at the surface of the water because of the release of their surface energy/tension. However, bubbles can be stabilized by adding soap to the water. Soap molecules adsorb at the bubble surface and form a monolayer film, which is often charged and lowers the surface tension. Colliding bubbles are prevented from coalescing by the adsorbed soap molecules and instead form a foam. This is one of the most important and well known characteristics of soap solutions and is the basis of the 'bubble persistence test'. When water is vigorously shaken, the bubbles break in less than a second, unless there is soap contamination. Even a very low level of residual soap will extend bubble lifetimes to several seconds. This is the basis of the simple and practical 'bubble persistence test'.

The ability of monomolecular soap layers to reduce evaporation rates is also well known and used to reduce water loss in arid areas [29]. However, we also know that lipid bilayers in biological cells readily (and importantly) allow the transport of water across membranes in both directions [29], hence water can be transmitted along hydrocarbon chains within bilayers. In the experiments reported here we have studied the effects of high temperature gases on water vapor collection in a bubble column evaporator combined with a study of the additional effect of surfactant monolayer coatings at the bubble surface.

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