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Spray flash evaporator for low-temperature saline water desalination application

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Abstract: A new spray-type flash evaporator is suggested for the application of saline water desalination. The flash evaporator is 1000 mm in height and 1200 mm in diameter, with a water injection arrangement inside. The evaporator design is based on experiments conducted at vacuum pressures between 10 and 18 mm of Hg, and at saline feed water temperatures between 26°C and 32°C. The saline water is injected into a vapouriser through a pair of high-flow swirl injectors with a nominal flow rate of 1.5 litre/sec. per jet and the distance between the injectors is taken as 200 mm for design. The influence of the different thermal, hydrodynamic and geometric parameters on the evaporator performances was investigated. The results obtained are presented, which prove the validity of the proposed system.

Keywords: desalination; flash evaporation; spray-flash vapouriser design; water spray.

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1 Introduction

The developing nations are waking up to the crisis of finding good potable water caused by the population explosion combined with the growth of the industrial and agricultural sectors. The oceans, spreading over 71% of the Earth's surface, contain enormous quantities of water but it is not suitable for consumption. Hence the development of a reliable and economic technique for desalination of ocean water is a challenge pursued over the years (Muthunayagam, 2003).

2 Literature review

Muthunayagam (2003) introduced a new concept for the production of fresh water using the spray-flash evaporation technique, where warm ocean water from the upper strata of the ocean at the ambient temperature is flash-evaporated in a vapouriser, maintained at low pressure. The resulting water vapour is condensed in a condenser, also maintained at low pressure, using the cold ocean water taken from the depth of the ocean. The vacuum in the vapouriser and condenser is maintained by means of a vacuum pumping system and barometric seals. The barometric seal, provided by the long duct connecting the vapouriser to the ocean, allows the maintainance of the vacuum in the vapouriser and also the discharge of a large volume of water, which is not vapourised in the vapouriser without any pump. Similarly, the barometric seal provided by another duct connecting the condensate side of the condenser to the fresh-water collection reservoir allows the maintainance of the vacuum in the condenser and also the discharge of all condensed fresh water from the condenser without any pump. Later, Muthunayagam and Paden (2005) extended this concept to produce fresh water in thermal stations without affecting their normal operations. The warm seawater discharged to the sea, carrying waste heat from thermal stations, is injected into a vapouriser at low pressure and vapourised. This vapour is condensed as fresh water in a condenser, using the cold seawater intake to the thermal station, also maintained at low pressure. The temperature of the warm sea water discharge to the sea is reduced by this process and promotes preservation of marine ecosystems.

According to the principle of flash evaporation, when a liquid at a given temperature is exposed to a sudden pressure drop below the saturation pressure at that temperature, all the heat is unable to be contained in the liquid as sensible heat, and the surplus heat reduces to latent heat of evaporation, causing momentary boiling – the so-called flash evaporation or flashing phenomenon (Saury *et al.*, 2002). As a result, the liquid temperature drops to the saturation temperature corresponding to the lowered pressure, but flash evaporation is supposed to terminate at more or less non-equilibrium conditions because of the potential required for the growth of vapour bubbles, the static pressure rises owing to liquid depth (in pool flash-evaporation). The pressure difference between the saturated vapour pressure at the average liquid temperature and the equilibrium pressure is considered as the major driving force for vapourisation, *i.e.*, ($P_{\text{sat}} - P_{\text{vac}}$).

The literature in the area of spray-flash evaporation is limited. The spray-flash evaporation technique developed by Miyatake *et al.* (1981a–b), is adopted for the generation of process steam in which the hot working fluid from the heat storage column is injected directly downward into a low-pressure vapour zone inside the flash chamber through a tubular nozzle of small diameter, and as the working fluid attains a superheated condition (40°C, 60°C and 80°C), a portion of it suddenly vapourises to regain equilibrium and the steam is formed. In this phenomenon of spray-flash evaporation, the temperature descent of the water jet was measured with various nozzle diameters, flow velocity and the degree of superheat. Based on the results of the measurements, an empirical formula about the dimensionless temperature of a water jet, which suits the characteristics of spray-flash evaporation was obtained.

Ikegami *et al.* (2006) made a comparative study of a spray-flash desalination process with the direction of injection of feed water in a depressurised chamber. Experiments conducted with superheated liquid at 24°C, 30°C, and 40°C through a cylindrical nozzle is compared with the phenomenon of a downward jet-flash evaporation method. The tube-type nozzle was used with an internal diameter of 20 mm and a length of 81.3 mm. The range of the mean velocity of the superheated liquid inlet was from 1.74 to 3.62 m/s. The temperature decrease of the superheated liquid inlet along the nozzle axis was measured by thermal resistance. Furthermore, Ikegami *et al.* (2006), compared the experimental results on the upward jet method with the data and empirical equation for the downward jet method previously reported (Miyatake *et al.*, 1981a–b). The results obtained in Ikegami *et al.* (2006) show that the upward jet method needs a shorter distance to complete the flash evaporation than the downward jet method, and the upward jet method has the possibility of making the spray-flash desalination system more compact and efficient.

The present work deals with the design of flash evaporator for spray flash system. In the literature we find single and multieffect evaporators most of which deal with evaporation with the help of coils (tubes). The present system deals with evaporation of water without the aid of any coil or tubes. Water is injected into the vapouriser through a pair of impinging conical swirl jets, which leads to the production of fine droplets. No such work has been reported previously.

3 Estimation for vapourisation rate

A simple energy balance model for percentage vapourisation of warm water at low-pressure evaporation is reported in Muthunayagam and Nicholas (2003), the warm saline water is assumed to be dispersed as a cloud of droplets in a vapouriser column maintained at subatmospheric pressures. The choice of the level of vacuum pressures to give sufficient vapourisation and the requirements of the critical parameters to achieve certain targets of performance are determined from the model. Vapourisation from a single representative droplet is considered and the energy balance at the surface of the droplet is modeled. If the average mass of a water droplet formed in the spray is m kg, the heat balance at the droplet–vapour interface is given by Muthunayagam *et al.* (2005):

$$m_{\mathrm{d}} C \frac{\mathrm{d}T_{\mathrm{d}}}{\mathrm{d}t} = \frac{\mathrm{d}m}{\mathrm{d}t} h_{\mathrm{fg}} + \underbrace{h\pi D^2 (T_g - T_{\mathrm{d}})}_{\text{Convection}} + \underbrace{\pi D^2 k \varepsilon_{\mathrm{d}} (T^4{}_{\mathrm{g}} - T^4{}_{\mathrm{d}})}_{\text{Radiation}}. \tag{1}$$

here:

h = the heat-transfer coefficient at the droplet interface in W/m^{2}K
h_{fg} = the enthalpy of vapourisation in kJ/kg
D = the droplet diameter in m
T_{g} = the ambient temperature in °C
T_{d} = the droplet temperature in °C
C = the specific heat of water in kJ/kgK
k = the Stefan–Boltzmann's constant (5.67×10^{-8} W/m^{2}K^4)
ϵ_{d} = the emissivity of the droplet.

In the present investigation, water is not significantly heated over the ambient temperature, so lumped mass assumption is used since the Biot modulus $<< 0.1$. Therefore, convective term and the radiation term are neglected. The initial value of droplet temperature is the same as the feed water temperature T_{feed}, the vapourisation results from the superheat of the liquid owing to the low pressure, *i.e.*, because the ambient pressure is lower than the saturation pressure at the given temperature of the saline water droplet, the evaporation can be considered to be driven by the pressure difference between the saturation pressure P_{sat} at the surface temperature of the droplet and the ambient low pressure P_{vac} (Paden *et al.,* 2006). The heat of vapourisation of water and specific heat is significant and is reasonably constant at about 2450 kJ/kg and 4.2 kJ/kgK respectively, in the temperature range between 26°C and 32°C. The main contributing factor for the variation of droplet temperature with time in Equation (1) is the evaporation at the surface. Therefore Equation (1) can be simplified as:

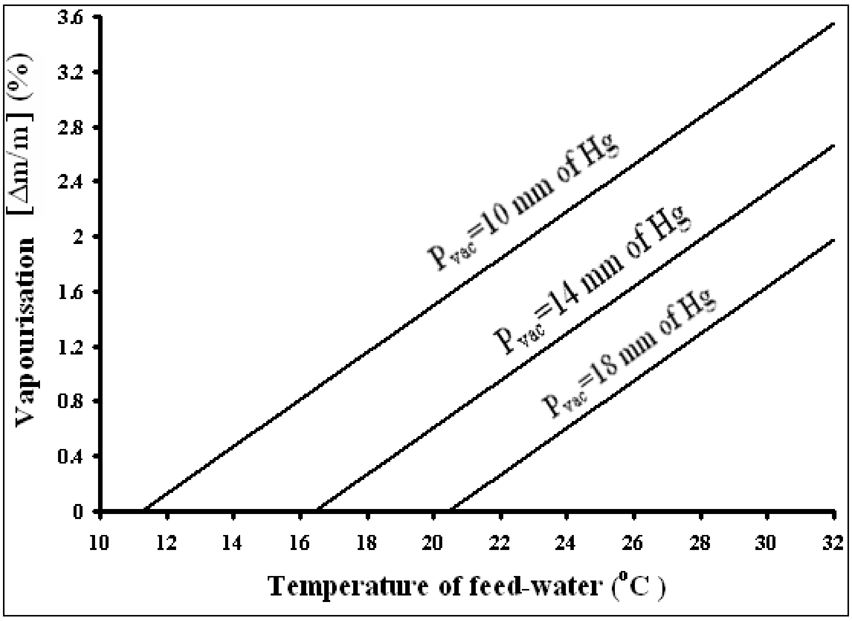
$$\frac{\Delta m}{m} = \frac{C\,\Delta T_d}{h_{fg}}. \tag{2}$$

Here, Δm is the mass of water vapourised when the temperature of the droplet of mass m falls by ΔT_d ($= T_d - T_{sat}$). Since the convective transport at the surface is neglected in Equation (1), the fractional mass evaporated ($\Delta m/m$) is seen to be independent of diameter. On substituting the values of h_{fg} and C in Equation (2), it will reduce to:

$$\Delta m/m = 1.71 \times 10^{-3} \times \Delta T_d. \tag{3}$$

Vapourisation is possible only when the saturation vapour pressure at the droplet temperature exceeds the ambient vacuum pressure in the vapouriser. Stated differently, for a given value of vapouriser pressure, the vapourisation of the water droplets would be possible only when the temperature of the droplet exceeds the value of the saturation temperature corresponding to the pressure in the vapouriser. Using Equation (3) the fractional mass of injected water Δm/m that vapourises is estimated for feed water temperature varying from 26°C and 32°C and vapouriser pressures from 10 to 18 mm of Hg.

Figure 1 Fractional mass of feed water vapourised (Δm/m) as a function of feed-water temperature

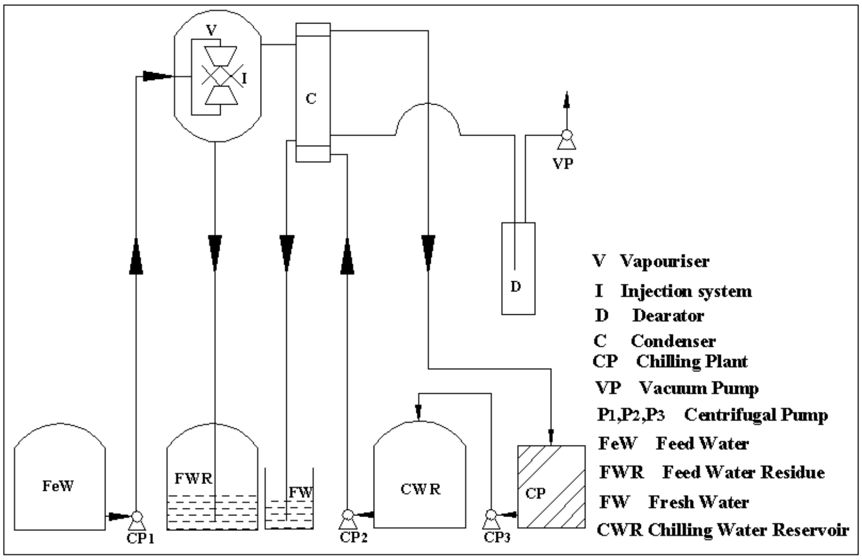


It is seen that the evaporation is very sensitive to the level of vacuum in the vapouriser. The evaporation rapidly falls as the pressure in the vapouriser increases, especially at reduced temperature of water. Also, as the initial temperature of water increases, the percentage of evaporation increases for a given vapouriser pressure. The desirability to operate the system at higher feed-water temperature and lower vapouriser pressure is seen from the plots. It is seen that the yield increases with reduction in vapouriser pressure and increase in the feed-water temperature with a strong influence of vapouriser pressure at lower values.

4 Experimental set-up

The feed-water system consists of a 10 m^3 Sintex storage tank with facility to condition (heating/cooling) the feed water to required temperature. The water is pumped into the vapouriser through a pair of conical swirl jets. The cooling water system consists of 20 TR chilling plant with storage facility. A 6-pass shell and tube condenser was used for condensation with heat transfer area 26.5 m^2. The vacuum pumping system consists of a deareator and two vacuum pumps to maintain vacuum in the vapouriser and condenser. The barometric seal, provided by the long High Density Polyethylene (HDPE) pipe connecting the vapouriser with a 10 m^3 Sintex tank allows the maintainance of the vacuum in vapouriser and also the discharge of a large volume of water, which is not vapourised in the vapouriser without any pump. The freshwater system consists of two storage tanks each of 200-litre capacity. The freshwater tank is located in such a way that the barometric seal is maintained during operation. With the help of an overflow pipe in the freshwater barometric well, the freshwater is collected in a storage tank. The instrumentation system in the plant consists of sensors for measuring the flow rates of feed water and cooling water, pressures and temperatures at different locations.

Figure 2 Experimental set-up



Thus several experiments were conducted by varying feed-water temperatures, flow rates, vacuum in the vapouriser, the distance between the injectors and the vapouriser volume to determine the influence of these parameters on freshwater produced as a percentage of the feed water. Since the major content in seawater is NaCl, it was decided to mix only NaCl in the water to prepare artificial sea water for our experiments; therefore the feed water used for experiments is mixed with common salt with 35 g/l (35 000 ppm).

5 Selection of parameters for experiments

A series of experiments is carried out with different combination of parameters so that the data would be useful for scaling up the desalination process. The desalination plant could be barge-mounted and moored in the deep sea around 1 m depth, where the cold water at 6°C could be available. The desalination plant could also be shore-based for which the cold sea water at 12°C and 15°C could be available from depth around 350 m and 20 m at distance less than 1000 m from the shore. The above bathymetry data is for the Cheyur coast near Pondychary in India. The distance from the shore to where cold water is available depends on the bathymetry of the coast and varies from place to place.

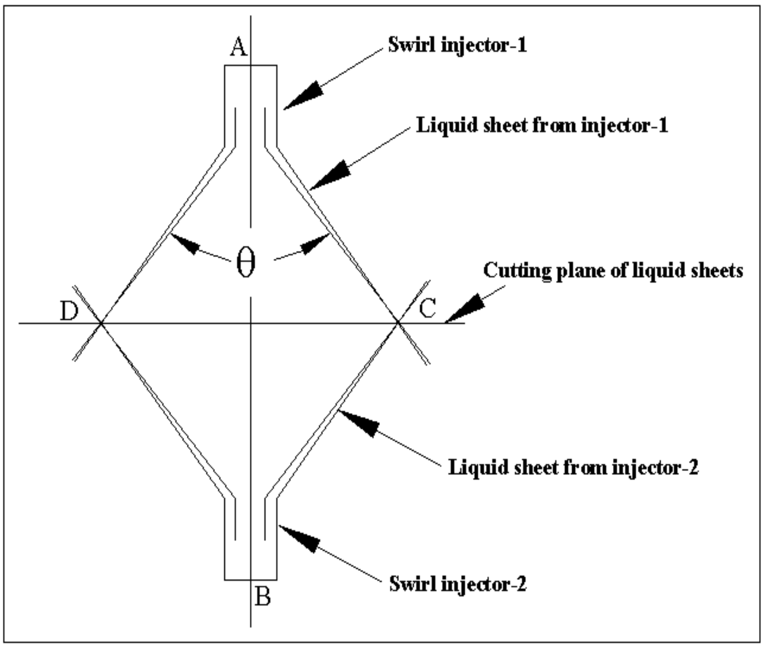
A desalination plant could also be established with cold water drawn from the deep sea for condensing the vapour and with feed water drawn from the upper strata of the sea around 3°C, so that a temperature difference of about 15°C is possible. For effective condensation, a temperature difference of 5°C is planned between the cooling water inlet temperature and the saturation temperature corresponding to the vapouriser pressure, *i.e.*, vapour temperature. Therefore 1, 14 and 18 mm of Hg vapouriser pressures are chosen, for which the saturation temperatures are 11.25°C, 16.42°C and 2.43°C, respectively, which are approximately 5°C higher than the cooling water temperature for the above three cases.

Desalination plants could also be established with warm water drawn from the upper strata of the sea, The temperature of the upper strata of sea around India varies over the year between 26°C and 32°C. The feed-water temperature derived from the sea would therefore be between 26°C and 32°C. Experiments are planned for four temperature levels for the feed water; *viz*, 26°C, 28°C, 30°C, and 32°C.

It was decided to keep two swirl injectors in the opposite direction for the impinging of the water film coming out from the injectors. Different distances between the injectors were experimented to produce different droplet size distribution, whereby the influence of size of water droplet on vapourisation was studied. The fine water droplets formed by the swirl nozzles give larger surface area for vapourisation and help to enhance the vapourisation rate. The distance between the injectors (AB in Figure 3) varies between 100, 200, 300, and 400 mm.

The swirl injector used in the present study was slope bottom-type whirl jet spray (Spraying systems (India) pvt.ltd, 2000), which is generally used in cooling towers, spray ponds and evaporation ponds. These injectors can produce 1 mm droplets at a far away distance from the injector exit. In the experiments, two such swirl injectors were taken and the water sheet produced by the injectors was allowed to impinge each to produce fine droplets at a shorter distance from the nozzle exit shown in Figure 3.

Figure 3 Impingement of pair of injectors



The influence of vapouriser volume on the vapourisation rate was studied by varying the vapouriser volume. This was done by reducing the vapouriser diameter by means of fixing non-reacting objects along the inner wall without affecting the impinging and vapourisation process. The vapouriser volume is indirectly a function of the residence time, so the experiments are conducted by varying the diameter of the vapouriser from 1200 mm (100%) to 480 mm (40%).

The *range and parameters* studied are:

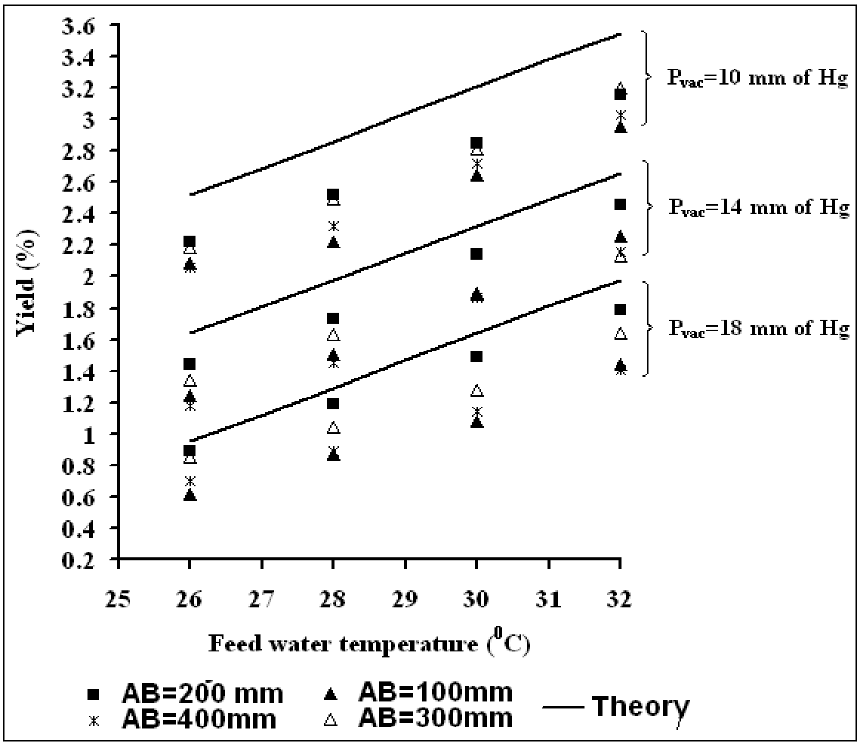
Feed-water temperature	26°C, 28°C, 30°C and 32°C
Feed water flow rate	2 to 3 litre/sec
Vapouriser pressure	10, 14 and 18 mm of Hg
Distance between injection planes	100, 200, 300 and 400 mm
Volume of the vapouriser by keeping D_i as 1200, 960, 720 and 480 mm.	100%, 80%, 60% and 40%

6 Results and discussions

The experiments are conducted to study the influence of feed-water temperature, pressure in the vapouriser, distance between the injectors and the vapouriser volume on vapourisation. The feed water flow rate is 2 litre/sec, when a pair of nozzles N_1 is used for injection in the vapouriser and similarly for a pair of N_2 nozzle is 3 litre/sec.

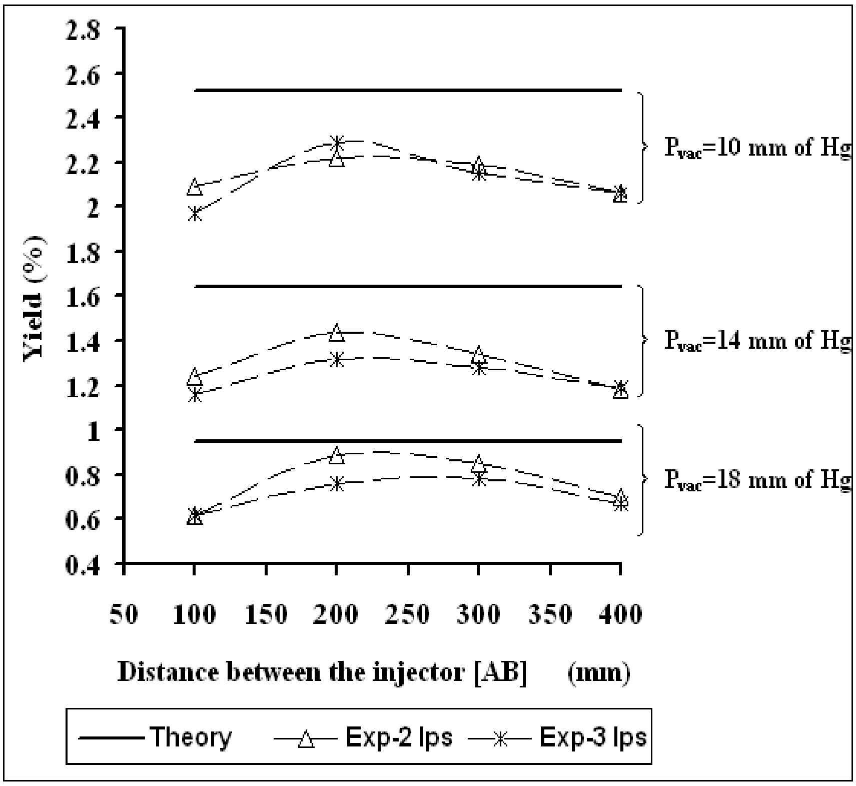
To study the influence of temperature of feed water (T_{feed}) for different pressures in the vapouriser (P_{vac}), distances between the injectors (AB), diameters of vapouriser (D_{i}) and flow rates of feed water, a series of experiments was conducted and the results of yield as a function of temperature of feed water are plotted for three different pressures in the vapouriser, four different distances between the injectors, two different flow rates of feed water and three different diameters of vapouriser. A particular case is shown in Figure 4, where AB = 200 mm, m = 2 litre/sec and D_{i} = 1200 mm, and it is seen that the yield increases as the pressure in the vapouriser decreases; also, the yield increases as the temperature of feed water increases, as predicted by the theory. Also for a particular diameter of vapouriser, the yield (percentage of conversion) slightly decreases as the flow rate of feed water increases.

Figure 4 Experimental yield as a function of temperature of feed water



To study the influence of distance between injection planes of impinging jets and the influence of the droplet sizes and distribution of injected feed water on the rate of vapourisation, a series of experiments was conducted and the results of yield as a function of distances between the injectors for four different temperatures of feed water, three different pressures in the vapouriser, three different diameters of vapouriser and two different flow rates of feed water are plotted in Figure 5. It is seen that the yield is higher when the distance between the injectors (AB) is 200 mm; this is because at higher and lower value of AB (*i.e.*, AB >200 mm and <200 mm), the droplets produced after jet impingement are bigger in size and the time required for the evaporation of bigger drops is longer, which leads to the reduced yield. From the theory of atomisation, at the injector exit, the flow through the orifice becomes a free sheet that later forms the spray. It is also seen that the thickness of the water sheet near the exit of the injector is more than the thickness far away from the injector (Paden *et al.*, 2006).

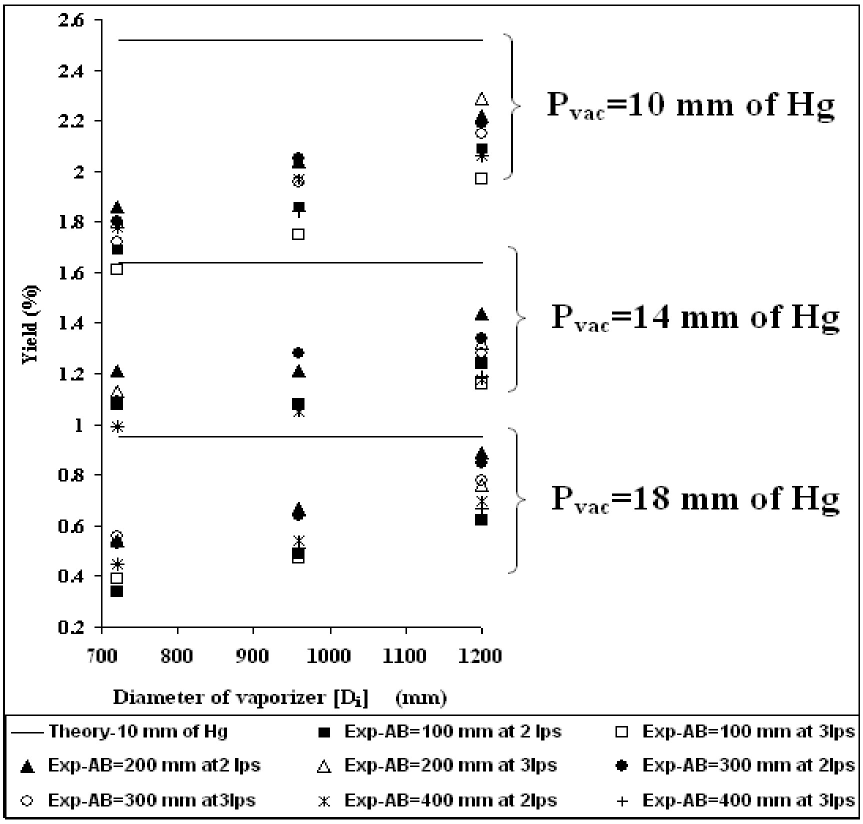
Figure 5 Experimental yield as a function of AB, for $T_{\text{feed}} = 26°\text{C}$, $P_{\text{vac}} = 18$ mm of Hg and $D_i = 1200$ mm



When AB >200 mm, the water sheets were in a stage of disintegrating into drops, so the jet impingement would not be effective, which leads to the production of bigger droplets. When AB <200 mm, the thickness of the water sheet is more, which leads to the production of bigger droplets after water jet impingement. The present injectors' performance may not be the same for other high-flow injectors, because of the variation in the film thickness with distance for different injection pressures. A variation in the yield when AB = 200 mm and 300 mm of less than 10% is also observed and this is within the experimental error. In general the distance between the injectors does not appear to significantly influence the yield.

To study the influence of the diameter of the vapouriser on the rate of vapourisation, a series of experiments was conducted and the results of yield as a function of the diameter of the vapouriser [D_i] are plotted in Figure 6 for four different temperatures of feed water, three different pressures in the vapouriser, four different distances between the injector [AB] and two different flow rates of feed water. A decreasing trend of yield is seen for both flow rates of feed water (2 and 3 litre/sec) as the diameter of the vapouriser is decreased from 1200 mm to 720 mm, so the diameter of the vapouriser [D_i] is not reduced below 720 mm for experimentation.

Figure 6 Experimental yield as a function of D_i for T_{feed} = 26°C, P_{vac} = 18 mm of Hg and AB = 200 mm



A large deviation of theoretical yield from the experimental value is viewed as insufficient volume of vapouriser, which is large for 10 mm of Hg when compared with 14 and 18 mm of Hg, because the specific volume of the vapour corresponding to 10 mm of Hg is 98.38 m^3/kg, compared with 71.53 and 56.40 m^3/kg corresponding to 14 and 18 mm of Hg. Ikegami *et al.* (2006) used a bigger vapouriser (diameter = 1700 mm, height = 3184 mm) for vapourisation studies even for smaller superheat (ΔT = 8°C); this also substantiates the importance of vapouriser volume. When the diameter of the vapouriser is reduced, the purity of the fresh water is slightly affected, because the vapour velocity is high in the reduced diameters of the vapouriser, which leads to a carry-over of small droplets into the condenser. Also for a particular diameter of vapouriser, the yield (percentage of conversion) slightly decreases as the flow rate of feed water increases, because the volume of the vapouriser is insufficient to vapourise all the droplets.

7 Dispersions in the yield owing to experimental errors

All measurements are taken at steady state, which is achieved in less than 10% of the duration of the experiment. The duration of the experiments is 30 mins; the measurements in the system were noted for every 10 mins. The accuracy of the measured values depends on dispersions in measurement. An assessment of such dispersion was established. The dispersions in the yield are estimated owing to the measurement inaccuracies in temperature of feed water, pressure in the vapouriser, mass flow rate of feed water and mass flow rate of condensed water. The quantity of vapour generated in the vapouriser, which subsequently condenses, depends on the difference between the temperature of feed water and the saturation temperature corresponding to the pressure in the vapouriser. The net dispersion in the yield following the root sum square method given by Moffat (1988) considers all the variables in the predicted yield equation simultaneously while calculating the predicted dispersion:

$$\Delta m/m = \mathrm{f}(m_{\mathrm{feed}}, T_{\mathrm{feed}}, T_{\mathrm{sat}}, m_{\mathrm{cond}})$$

$$\Delta m/m = m^{a}{}_{\mathrm{feed}}\, T^{b}{}_{\mathrm{feed}}\, T^{c}{}_{\mathrm{sat}}\, m^{d}{}_{\mathrm{cond}}$$

$$\frac{\delta\left(\frac{\Delta m}{m}\right)}{\left(\frac{\Delta m}{m}\right)} = \pm\sqrt{\left(a\frac{\delta m_{\mathrm{feed}}}{m_{\mathrm{feed}}}\right)+\left(b\frac{\delta T_{\mathrm{feed}}}{T_{\mathrm{feed}}}\right)+\left(c\frac{\delta T_{\mathrm{sat}}}{T_{\mathrm{sat}}}\right)+\left(d\frac{\delta m_{\mathrm{cond}}}{m_{\mathrm{cond}}}\right)} \qquad (4)$$

where:

$$a = \frac{\partial(\Delta m/m)}{\partial m_{\mathrm{feed}}}, b = \frac{\partial(\Delta m/m)}{\partial T_{\mathrm{feed}}}, c = \frac{\partial(\Delta m/m)}{\partial T_{\mathrm{sat}}} \text{ and } d = \frac{\partial(\Delta m/m)}{\partial T_{\mathrm{cond}}}.$$

The net dispersion in the yield is seen to be between 4% and 15% when the feed water temperature increases from 26°C to 32°C.

8 Conclusion

A parametric study was conducted and the result gives a valuable output for developing desalination systems using the spray-flashing technique. The influences of the temperature of feed water and the pressure in the vapouriser on the rate of vapourisation show that the rate of vapourisation increases as the temperature of feed water increases, and decreases as the pressure in the vapouriser increases. The distance between injection planes of impinging jets was altered and thereby the droplet sizes and the distributions of injected feed water were modified to study the impact on the rate of vapourisation. Higher yield was seen when the distance between the injectors (AB) was 200 mm. The volume of the vapouriser had a large influence on the rate of vapourisation; higher yield was seen when the volume of the vapouriser was 100%. It was found that the purity of the water is slightly affected when the vapouriser diameter is reduced. Experiments conducted using the artificially prepared seawater adequately demonstrate the technical feasibility of the process for the application of desalination. The water standards meet the requirement of the Indian standard specifications of potable water. This demonstrates the feasibility and adequacy of the process for desalination application.

This technology could be extended and desalination plant could be established as an integrated plant with the OTEC system in various parts of the country, where favourable bathymetry is available and fresh water for community needs around that area could be met. This system can be implemented without affecting the operations at power stations, by utilising waste heat from power plants.

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