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A Comparative Study of Evaporator Sizes and Condenser Temperatures used in Different Barometric Distillation Type Desalination Systems

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***Abstract* - In the present time, drinking water shortages from natural sources has forced almost all the countries to think of desalination which uses less energy and least hazardous to ecosystem. Clean water scarcity is heightened in hot regions of the world especially in the Arabian Gulf, where desalination is the main source for meeting drinkable water demands. These countries are desalting seawater in a large amount and require cheaper techniques which could consume less energy. Barometric distillation type desalination is also such a unique concept which evolved few years back. It requires very small amount of energy with least maintenance but gives enough water to support a family for a day. This is specifically useful for remote areas where bigger plants are not feasible to install because of limited demand and non-availability of maintenance personnel. Many investigations have been done to understand different aspects of this innovative technique. In this process, barometric height of water column is used to create natural vacuum in the space above the water column. This generated vacuum makes desalination possible at low temperature and reduced pressure, which can be obtained from low level heat sources. This paper outlines a review of the two major factors that influence the production rate of freshwater in barometric distillation type desalination.**

Keywords— Barometric distillation; saline water; evaporator size; condenser temperature; Direct evaporation; Flashing evaporation;

I. INTRODUCTION

A Barometric distillation type desalination system is one of the recently proposed and demonstrated concepts having many advantages for obtaining fresh water from saline water **[1].** In this type of desalination system the evaporation of seawater can be made to occur at sub atmospheric pressures using nearly passive vacuuming technique. A low cost pump can be used without employing an expensive energy intensive vacuum pumps, and as a result the corresponding evaporation temperatures at the low pressures achieved are at just above normal ambient temperatures. The principle behind the barometric distillation process can be understood by assuming two columns at barometric height of water (~10.3 m) at ambient temperature, one filled with freshwater and other with saline water. The vapors of the respective fluids will occupy the head space of the columns at their particular vapor pressures. If these head spaces are joined together, then water vapor will distill, due to vapor pressure difference, from the freshwater column to the sea water column. However, if the temperature of the sea water column can be kept marginally higher than that of the freshwater column, to raise the vapor pressure of the saline water side above that of the fresh water side, then water vapor will distill into the fresh water column from the saline water column. About 15ºC temperature difference between two columns is sufficient to vanquish the vapor pressure differential and drive this distillation process [1]. Therefore, this method can also utilize the low-grade heating sources such as solar and thermal energies, heat rejecting from power plants, and refrigeration systems.

Some experimental and theoretical studies have been conducted to investigate the characteristics of desalting saline water using the vacuum distillation concept where vacuum has either been created by employing vacuum pumps or by using a barometric column. Different investigators have used different cooling mechanisms to condense vapors evaporated from boiling of saline water at reduced pressure and temperature. These cooling arrangements in barometric desalination system resulted in variable amount of condensed fresh water. One of the earliest studies in this context used superheated vapor from a steam turbine exhaust, to carry out a lab scale study to investigate the feasibility of using a vacuum desalination process for desalting seawater [2]. The experimental results were obtained by boiling water between 40-90°C and obtaining low pressures between 10-70 kPa, respectively. Al-Kharabsheh and Goswami [3-5] were the first to concept and investigated this idea both theoretically and experimentally in 2003.

II. DIRECT EVAPORATION TYPE BAROMETRIC DESALINATION SYSTEMS

In direct boiling barometric systems low grade energy source heats saline water in evaporator placed at barometric height of water. This is basically single effect distillation process. Al-Kharabsheh and Goswami [3-5] investigated theoretically and experimental a low pressure barometric desalination unit, as shown in fig. 1. System performance was studied by four parameters. These were brine taking out rate, water depth in evaporator, heat source temperature and condenser temperature. The evaporator area was 0.1 m^2 with a

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cylindrical outline and a cross sectional area of 0.2 m^2. The 0.2 m height evaporator also had a truncated cone on the top. The condenser was air cooled made of half a meter long, four inch diameter copper tube of 2.5 mm thickness. Ten circular fins of 25 cm diameter and 0.635 mm thickness were joined 40 mm apart along the condenser length. It was found that the system output increased with the decrease of depth of water in the evaporator chamber, the brine removal rate and the temperature of condenser. The condenser temperature was changed by changing the condenser area or heat loss. They simulated solar energy by using an electric heater with six hours of operation a day. Evaporation rates were calculated by a model developed by Bemporad [6] for the evaporator. Optimum working conditions were determined by this model. They established that system works very well at 0.08 m water depth in evaporator with 0.1 kg per hour brine removal from the evaporator. There was 6 W difference of power consumed in experimental and theoretical investigation with 109 W and 103 W, respectively, at the steady state. Output rates was 0.115 kg per hour compared to 0.108 kg/h obtained in experimentation.

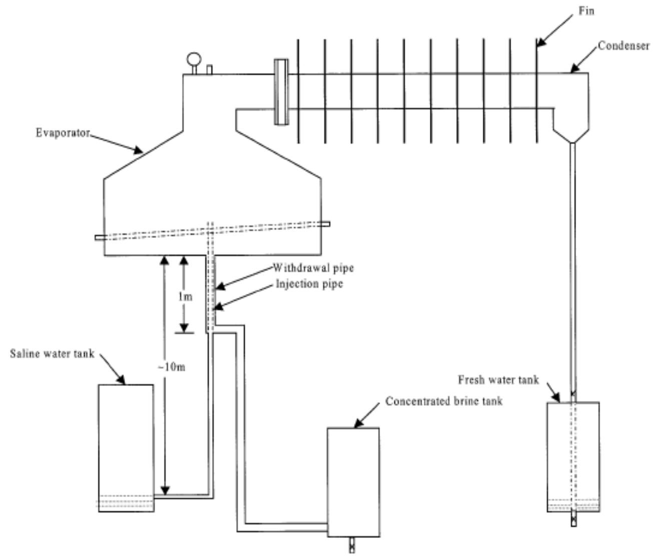

Fig. 1. Schematic of barometric desalination system adapted from Al-Kharabsheh [5].

Midilli and Ayhan [7] in 2004 developed a barometric desalination system based on single effect distillation process similar to Al-Kharabsheh and Goswami [3-5]. There were two variations in design, one was that they installed a 3 kW fan to draw vapors from evaporator to condenser chamber and other was their evaporator area was 0.16 m^2. After doing a thermodynamic analysis with and without fan in operation, an experimental setup was built in 2007 [8]. The maximum fresh water production rates was 3.96 and 7.79 kg per hour measured experimentally and theoretically, respectively. The power used by their test rig was 2.6 kWh per kg of distillate produced. It was three times higher than they had calculated theoretically. These gaps were justified by losses of heat and pressure in the piping.

Reali et al. [9] presented another barometric system research based on single effect distillation (SED) which took sea water directly as feed. A unique venting arrangement was employed to outwit gases which were not condensing with a demister to segregate water vapors from saltwater droplets. They designed the plant for 100 m^3 per day considering ten hours of operation time in a day. The total power consumed was calculated to be 2.162 kWh per m^3.

Gude and Nirmalakhandan [10] documented in 2008 another system with modifications by utilizing low grade heating sources like solar energy, thermal energy along with waste heat from different processes. Experimentation was simulated by electrical power to get a production rate 0.33 kg per hour of fresh water consuming 3.122 kJ energy for each kg of freshwater with an evaporator area of 0.2 m^2. They continued this investigation by introducing a heat storage tank having solar photovoltaic (PV) modules installed and heat coming out of an Absorption Refrigeration System (ARS). They were able to produce desalinated water at a rate of 4.5 kg/h with 3.25 kW power of ARS and adding 208 kJ of energy per kg of produced water [10].

Gude et al. [11] in another study reported production of 4.17 kg/h of fresh water in night duration by using a thermal energy storage system (TES) with one effect distillation system. They used flat plate solar collectors with an area of fifteen meter square and one cubic meter of TES volume. Ayhan and Al-Madani [12] documented a possibility of barometric desalination using SED process in Bahrain. They found out very encouraging outcomes with a production rate of 5.42 kg/h keeping one meter square area of evaporator. They inserted another unique feature by creating cavitation with evaporation to enhance the output. They adjusted seawater supply within the chamber to cause bubbling which improved evaporation rates [13]. Jitsuno and Hamabe [14] have simulated a barometric system by vacuum pump and conducted experiments. They were able to produce 0.42 kg per hour of fresh water for each square meter of evaporator area.

Another variant of vacuum distillation based desalination system was reported by Moore et al. [15]. In which water can be desalinated at reduced temperatures by low energy input. The schematic of the system is shown in fig. 2. The investigator has documented that this system is efficient than reverse osmosis desalination system. It has two columns of water, one containing freshwater other seawater, at 10 meters height. Vapors from hot and cold pipes was allowed to go in a chamber at 10 m height, named vacuum chamber. To avoid thermal equilibrium, higher amounts of liquid to be pumped uninterruptedly. To produce 1 kg of fresh water per hour, 100 kg of saline water needs to be propelled. Big storage facilities are required to run system for longer time.

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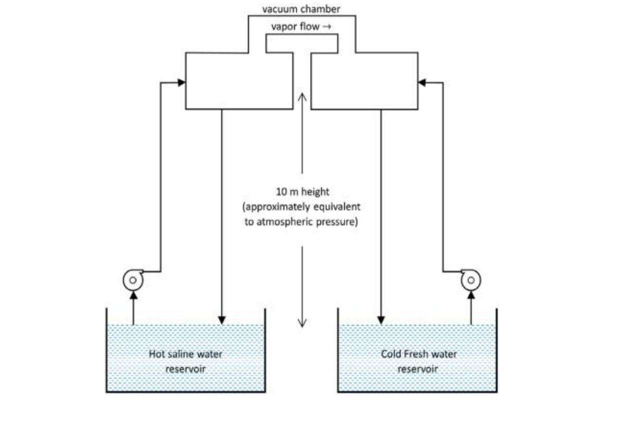

Fig. 2. Schematic representation of NVD system adapted from Moore et al. [15].

III.FLASHING EVAPORATION TYPE BAROMETRIC DESALINATION SYSTEMS

Eames et al. [16] investigated barometric desalination system by employing single stage flashing process with solar energy. An evacuated Flash chamber has been made as shown in fig.3. Saline water is preheated in condenser, where it also acts as a coolant, and then sent to solar collector module to raise its temperature. After that, it is gushed by a nozzle to flash chamber. Vapors are carried to condenser by vapor pressure difference of evaporator and condensing chamber. A flash evaporation technique has been used in this desalination system at temperatures which can be achieved by solar collectors. This flash type barometric system was capable of producing 1.25 kg of fresh water by consuming energy gathered by 4.727 m2 of solar thermal collector. This concept has been tested by Maidment et al. [17, 18] in Cyprus utilizing waste heat from a power plant.

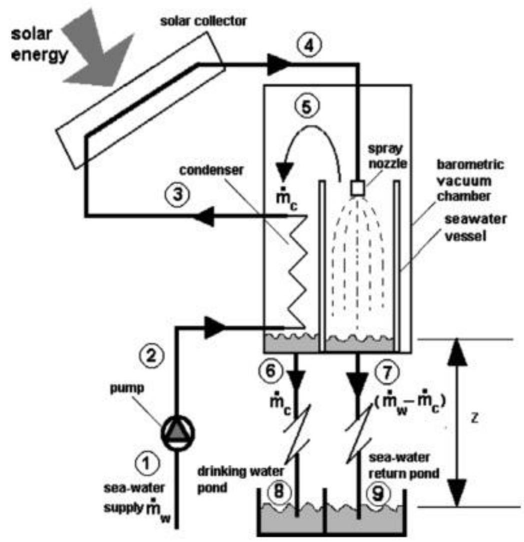

Fig. 3. Barometric Desalination Unit with Single Stage Flashing adapted from Eames et al. [16].

To enhance performance of this type of desalination system many investigators have come forward with multi-stage process employment. In the multi-stage system, like conventional two or more effect evaporators, saline water from first stage is sent to second stage to increase produced fresh water. Reali [19-21] has suggested a multi stage flash evaporation barometric system based on his earlier investigation [9]. As a result, he attributed that two stage process needs lower energy than a single stage unit. He found that two stage system consumed 2.1 kW for one m^3 of produced water while a single stage took 1 kWh for the same amount of water. Abutayeh and Goswami [22-24] came up with a multi stage flash barometric system as recommended by Al-Kharabsheh and Goswami [3] in an earlier work. Solar heater is used to heat the concentrated water then allowed to go to barometric distillation flash chamber. This arrangement used vapor of first stage to evaporate saline water in second stage and onwards. This fine energy management produces 1.66 kg of fresh water in one hour when saline water feed temperature was kept 80°C. In another investigation Abutayeh et al. [25] have reported production rate to be more than 42 kg/h for an experiment duration of three hours on the same system by reducing pressure to 16 kPa. Gude et al. [26] have also studied the same multi stage by proposing another two level low temperature process. The system was based on their earlier system of single stage with same components doubled for two stages. Vacuum was created by keeping three columns at a height of ten meters. This arrangement disregards any mechanical energy for operation. The vapors generated in first stage by low grade heat source used to preheat the feed for the coming stage. The reported a production rate of 21 kg/hour with energy utilization of 1500 kJ/kg. Gude [27] mentioned several methods to store energy for this type of system to run without disturbance. A thermal energy storage (TES) system is the suitable option for storing energy. Gadhamshetty et al. [28] has calculated optimum waste heat needed to run a desalination unit by TES.

IV. DISCUSSION

The barometric distillation concept has been investigated by many researchers in previous one and half decade. This natural vacuum incurring technique has many favorable characteristics as compared to other distillation techniques used in thermal desalination. This system is very simple in construction and requires least maintenance, thus, very much suitable for remote locations where bigger plant installations are not feasible. In this new technique, boiling can be made to occur at reduced pressure and temperatures resulting in low scaling in plant, higher plant life and reduced heat losses. In barometric desalination systems, evaporator area and condenser temperature are among the very important factors to be taken care of for a specific production rate. Evaporator size defines evaporation rates and temperature in condenser regulates flow of vapors. Many equations for evaporation rate of pure water are available in literature derived from equation of physicist Irving Langmuir [29]. Later researchers have presented modifications in that equation. Knudsen [30] added a term in the equation named mass accommodation factor (α) to describe gap between experimental and theoretical evaporation rates. Mass accommodation factor has a range from 0 to 1.

$$\frac{dm}{dt} = \alpha (P_v - P_p) \sqrt{\frac{M}{2\pi RT}} \qquad 1$$

Bemporad [19] has presented widely accepted equation for rates of evaporation for water in barometric type systems with a correction factor (f(C)).

$$\dot{m_{ev}} = A \times \alpha_m \times \left(f(c) \frac{P_v(T_s)}{\sqrt{T_s+273}} - \frac{P_v(T_f)}{\sqrt{T_f+273}}\right) \qquad 2$$

$$f(C) = 1 - 0.0054\ C \qquad 3$$

Mass accommodation factor is an experimentally determined factor by Bemporad [19] with a range of 10^{-7} to 10^{-6}. Other investigators who studied vacuum distillation type desalination systems, have mentioned perhaps the same range. More experimentation is needed to have a better and precise result for mass accommodation range. Sharqawy et al. [31] presented formulations which can be used to get seawater properties. The evaporator size has a significant role in deterring production of barometric systems. Higher evaporation rates can be obtained by larger evaporator areas. Most of the work done by the different investigators have used fixed evaporator sizes while conducting theoretical or experimental studies. However, this effect needs to be investigated more by varying areas of evaporator. The temperature of condenser in vacuum distillation type desalination systems plays a very important role. Evaporation rates depend on pressure difference between the vapors above the evaporation chamber and condensed water. It can be verified from equation (2). High vapor pressure as a result of high temperature in condenser can reduce the driving push for evaporation. Therefore, having fresh water temperature as low as possible is a much needed attribute in these systems. The effect of this characteristic has been reported least in literature as maximum investigators have employed ambient temperatures or covered areas for condensing. However, having a lower temperature on the condenser side than ambient is even preferable to enhance the vapor pressure difference. This lowering of condenser temperature below ambient has not been reported except Moore et al. [38], in another way. He documented that production of fresh water was expected to increase exponentially with increase in temperature difference between evaporator and condenser.

V. CONCLUSION

This study compares the evaporator sizes and condenser temperatures of different barometric type desalination systems investigated in past decade both theoretically and experimentally. In barometric desalination systems, vacuum can be created by head of a barometric column of water and the process can work with minimum energy because of gravity. Low grade heat sources or renewable energy can be the best alternatives to power these desalination units without an environment hazard. These systems should be designed and operated very carefully as they require vacuum sustainability throughout the process. Evaporator coil size should be selected properly and heat losses from connections should be minimized. Almost all the investigations presented earlier have employed very small-scale or pilot plants with evaporator areas ranging from 0.1 m^2 and 0.2 m^2 and used ambient conditions to control condenser temperature. To understand this concept in a better way, bigger units need to be built and explored by increasing different evaporator sizes and minimizing condenser water side temperature with other important parameters.

SYMBOLS & ABBREVIATIONS

dm/dt	Mass evaporation rate (kg/m^2)
p_v	Vapor pressure of liquid (Pa)
p_p	Partial pressure of vapor in ambient (Pa)
M	Molar mass
R	Universal gas constant (m^3/mol K)
T	Absolute Temperature (K)
m_{ev}	Evaporation rate (kg/s)
A	Cross sectional Area (m^2)
T_s	Temperature of the surface (K)
C	Salt concentration
F(C)	Correction factor

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