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Thermal analysis for system uses pressurized hot water for seawater desalination (pressurized multistage)

Ahmed A.A. Attia [1], Ahmed A. Abdel-Rehim

Mechanical Engineering Department, Benha University, Faculty of Engineering at Shoubra, 108 Shoubra Street, Cairo, Egypt

HIGHLIGHTS

- The system consists of pump, heat exchanger and discharge tank.
- The heat adds to pressurized water in form of sensible heat.
- Thermal analysis was done to estimate the productivity of the system.
- The analysis shows promising energy consumption for each kilogram of fresh water.
- The optimum operating is pressure of 30 bar with final stage pressure of 3 bar when system consists of 45 stages.

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ABSTRACT

The present work is a description of a proposed system for seawater desalination. The suggested system operates basically the same as the MSF system operates but uses high pressurized saturated water. The system operating pressure through all stages of the system and the final stage pressure are higher than atmospheric pressure. The system is simple and easy to construct. No need for high operation maintenance or high technical stuff in operation. No need for vacuum pumps because it operates at pressure higher than atmospheric pressure which also makes the system starts to operate fast and easy. The seawater could be with any quality or grade even brackish water could be used so no need for seawater pretreatment. The system could also be run by solar energy through replacing heat exchanger with a solar collector according to operating pressure and assigned saturated temperature. Energy consumption and production cost are promising even if system uses electricity as heat source.

1. Introduction

According to the type of energy, desalination systems are divided into two main types, thermal and non-thermal. Thermal-type desalination plants such as multistage flash (MSF), multiple effect evaporation (MEE), single-effect evaporation (SEE), humidification–dehumidification (HDD), solar distillation and freeze desalination use heat either by direct heating or indirect heating. Other systems are classified as non-thermal system such as reverse osmosis (RO), capacitive deionization technology (CDT). This type uses electrical energy. There are three types of energy used, thermal energy, mechanical energy (pumping work), and electrical energy (electric potential).

A description of several desalination technologies in commercial and pilot stages of development is introduced in Ref. [3]. The primary focus is on those technologies that are suitable for use in remote areas, especially those which could be integrated into solar thermal energy systems.

A state-of-the art review on membrane processes associated with renewable energies for seawater and brackish water desalination is introduced Ref. [6]. The membrane processes include reverse osmosis, membrane distillation and electro dialysis. They are coupled with renewable energies such as solar, wind, wave, and hydrostatic pressure. This article presents the main results in this field including principles, plant design and implementation, mathematical models and economic feasibility.

The economic performances expressed in terms of cost of water production have been based on different system capacity, system energy source, system component, and water source. These differences make it difficult, if not impossible, to assess the economic performance of a particular technology and compare it with others. Reverse osmosis

E-mail addresses: Ahmed_attia72@yahoo.com, Ahmed.attia@feng.bu.edu.eg, Ahmed.azim@bue.edu.eg (A.A.A. Attia).
[1] Tel.: +20 2 22050175 4111; fax: +20 2 2202336.

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is becoming the technology of choice with continued advances being made to reduce the total energy consumption and lower the cost of water produced [9].

An overview of R&D activities and outlines of future prospects for the state-of-the-art seawater desalination technologies is provided. The present review is made with special emphasis on the MSF and RO desalination technologies because they are the most successful processes for the commercial production of large quantities of fresh water from seawater [4].

A study presenting a detail engineering and economics of an MVC system operating at 172 °C is introduced by Ref. [11]. The literature that performed through the study indicates that high overall heat transfer coefficients for the evaporator are possible at high temperatures with dropwise condensation on the steam side and pool boiling on the liquid side.

Energy is a critical parameter for economic development and of vital importance in social and industrial development, as well as quality of water. Numerous low-density population areas lack not only fresh water availability, but in most of the cases electrical grid connection or any other energy source as well, except for renewable energy sources, mostly referring to solar radiation. For these regions desalination is a moderate solution for their needs. In using RE desalination there are two separate and different technologies involved: energy conversion and desalination systems. The real problem in these technologies is the optimum economic design and evaluation of the combined plants in order to be economically viable for remote or arid regions. Conversion of renewable energies, including solar, requires high investment cost and the intensive R&D effort technology is not yet mature enough to be exploited through large-scale applications [10].

The thermal desalination process almost is the process that uses heat to separate water from salts. This separation mostly happens through evaporation of water then condensing it again in a separate zone and rejecting the remaining brine water. Thermal methods are used mainly in medium- and large-sized systems, while membrane methods, mainly RO, are used by medium- and low-capacity systems. Yet, during the last years, RO is the optimal choice in even larger units. RO methods, which are dominant in the desalination of brackish water, have the lowest cost, mainly due to much lower energy consumption and the recent technological advances that have been achieved in membranes. Under special conditions hybrid systems can offer increased and more stable production of fresh water [5],

The single-effect evaporation desalination (SEE) system has very limited industrial applications. The system is always used in marine vessels. This is because the system has a thermal performance ratio of less than one, i.e.; the amount of water produced is less than the amount of heating steam used to operate the system. The multiple effect evaporation (MEE) system is formed from sequence of single-effect evaporators, where the vapor formed in one effect is used in the next effect. The vapor is reused in the multiple effect system which allows reduction of the brine and low temperature values and prevents rejection of large amount of energy to the surrounding, which was the main drawback of the single-effect system. MSF processes always use waste heat from power plants either traditional or nuclear. So the level of temperature is not higher than 110 °C or 120 °C. This is related to the cooling system of power station. MSF system does not include moving parts, rather than conventional pumps. Construction of the MSF plants is simple and contains a small number of connection tubes, which limit leakage problems and simplify maintenance works. In the light of the above, they strongly believe that the MSF system will remain the main desalination process, especially in the Middle East [8].

Desalination plants integrated with compression heat pumps along with steam compression desalination plants can be considered to produce distillate from seawater. They can maintain water supply of high quality for small fixed and mobile consumers of fresh water [1].

There are also a lot of methods still under development as stated by Ref. [2]. EDI is a combination of ion exchange and electro dialysis. MD uses a temperature difference that occurs on opposing sides of the membrane. In CDI salt water passes through plates coated with carbon aerogel material. Carbon aerogel absorbs ions, thus producing potable water applicable to special needs. In RSE saltwater is sprayed through nozzles at high velocity. As it exists, it is vaporized and salt is not, thus producing potable water, potential to process brine and high salinities, can use waste energy. Freezing with hydrates a saltwater vapor/gas mixture is cooled. Hydrates are formed and separated from the brine. Hydrates are decomposed to form potable water and the hydrate former gas, potential for future use because of research of hydrates developing. In vacuum distillation the saltwater is subject to vacuum, the boiling temperature is reduced. Saltwater is vaporized at lower temperatures and is condensed to form potable water. Low amounts of energy, ability to run off of waste energy, no scaling because of low temperatures.

An overview of the studies performed on the gained output ratio (GOR), specific energy consumption (EC) and the water production costs (WPC) of different MD systems is presented together with comparisons to other desalination processes [8].

Actual cost for each method depends mainly on the type of physical process of salt removal (i.e. evaporation, filtration, freezing or electrostatic potential difference). The efficiency of each type depends on the total energy required to remove the salt particles which depends on some extent on the method of operation, the purity of the required fresh water and also on the type of saline water used.

In thermal desalination MSF, the applied pressures on water surface play a critical role where all the water properties are related to it. Most thermal desalination plants especially MSF plants work at low pressure. Low pressure is related to low saturation temperature which is the mean phenomena of parts of heat that rejected from thermal power and nuclear power plants, which ranges between 100 °C and 120 °C. So the MSF plants are always designed to work at pressure lower than atmospheric pressure.

With the increase of using solar energy (photovoltaic) as source of electricity and trends to use renewable energy, the rejected heat from thermal plant will not satisfy the required quantity to produce required fresh water especially with the population growing. Also with constrains on CO_2 emissions, we should find another trend to increase the productivity and reduce fresh water production cost for MSF plants.

The main idea of the suggested system depends on raising the inlet pressure of the MSF plant to be higher than atmospheric pressure. This will increase the percentage of dryness fraction at plant stages which will cause an increase in productivity and consequently reduce the production cost for each kg of fresh water.

2. System description

The system is similar to MSF but replacing vacuum pump by traditional water pressure pump. The pump raises the pressure of seawater to the required operating pressure. The heat added to seawater through the boiler raises its temperature to saturation temperature of inlet pressure of first stage. After that seawater is injected into the first stage which is always kept at pressure lower than injection pressure. The first stage outlet is used as injection into next stage. This sequence is repeated for the next stages. The pressure of the final stage may be higher than or equal to the atmospheric pressure.

In each stage injection pressure is higher than stage pressure. Part of seawater is divided into two parts, vapor phase and water phase at stage saturation pressure and temperature with dryness fraction according to ratio of injection pressure to stage pressure (dryness fraction). Each stage is supplied by a condenser section at the upper part which condensed the vapor phase, that forms fresh water production rate for stage. This condensate (fresh water) is collected by the upper tray of stage and then fed to the upper tray of the next stage. The water phase (brine) is used as feeds for the next stage. As shown in Fig. 1.

After the final stage the produced fresh water has temperature equal to saturation temperature of the final stage pressure. To recover heat that is coupled with it, the produced fresh water should pass through a heat exchanger. The same should be done for the rejected brine. So it passes also through another heat exchanger. The supplied seawater is divided into two paths of flow, one goes through fresh water heat exchanger and the other goes through the heat exchanger of rejected brine. After that the two flows from the two paths mixed again forming the cooling inlet to the stage number "*n*" of the system (cooling flow for final stage).

3. System analysis and performance

At the first stage the pressurized seawater comes out from boiler at saturation conditions and is then injected into first stage. Due to difference between injection pressure and stage pressure, the injected flows of seawater are separated to two parts, first is vapor part and the second is water part. The vapor part is condensed in the upper tray of the stage, which forms the stage production rate of fresh water. The other part is saturated water at stage pressure, which is used as a saturated salt water for the next stage. This process is repeated up to stage number "*n*". The first stage is assigned as stage No, "1" directly after the boiler and the final stage is assigned as stage No. "*n*". For each stage we should determine, inlet water saturation pressure and temperature (stage inlet pressure and corresponding saturation temperature), the stage pressure (outlet pressure), mass of hot pressurized brine that flows into the stage, input mass flow rate of cooling water (the cooling salt water that flows to through the stage), and inlet fresh water from previous stage. Process layout of the system is plotted on water pressure enthalpy diagram (see Fig. 2).

3.1. Heat and mass balance for stage No. (*i*)

For each stage the saturation pressure is well known so the thermal properties of water could be accurately determined. From Fig. 3 and for steady-state operation for the stage assigned as stage No. (*i*) mass balance and energy balance are stated as follows.

Mass balance

$$\left(\dot{m}_{\text{salt in}_i} + \dot{m}_{\text{fresh in}_i} + \dot{m}_{\text{cool in}_i}\right) = \left(\dot{m}_{\text{salt out}_i} + \dot{m}_{\text{fresh out}_i} + \dot{m}_{\text{cool out}_i}\right) \tag{1}$$

where

$$\dot{m}_{\text{cool in}_i} = \dot{m}_{\text{cool out}_i} = \dot{m}_{\text{cool}} \tag{2}$$

$$\dot{m}_{\text{fresh in}_i} = \dot{m}_{\text{fresh out}_{i-1}} \tag{3}$$

$$\dot{m}_{\text{fresh out}_i} = \dot{m}_{\text{fresh in}_i} + \Delta\dot{m}_{\text{fresh}_i} \tag{4}$$

$$\Delta\dot{m}_{\text{fresh}_i} = X_i * \left(\dot{m}_{\text{salt in}_i}\right) \tag{5}$$

$$X_i = \frac{h_{\text{salt in}_i} - h_{\text{salt out}_i}}{h_{\text{fg (at stage pressure } e)_i}} \tag{6}$$

Energy balance

$$\left(\dot{m}_{\text{salt in}_i} * h_{\text{salt in}_i} + \dot{m}_{\text{fresh in}_i} * h_{\text{fresh in}_i} + \dot{m}_{\text{cool in}_i} * C_p * T_{\text{cool in}_i}\right) = \left(\dot{m}_{\text{salt out}_i} * h_{\text{salt out}_i} + \dot{m}_{\text{fresh out}_i} * h_{\text{fresh out}_i} + \dot{m}_{\text{cool out}_i} * C_p * T_{\text{cool out}_i}\right) \tag{7}$$

where

$$Q_{\text{condenser}\,i} = X_i * \left(\dot{m}_{\text{salt in}_i} + \dot{m}_{\text{fresh in}_i}\right) * h_{\text{fg}_i} \tag{8}$$

$$h_{\text{fresh in}_i} = h_{\text{salt in}_i} = h_{\text{f}}\ \text{Atp}_{i-1} \tag{9}$$

$$h_{\text{fresh out}_i} = h_{\text{salt out}_i} = h_{\text{f}i}\text{At}\ p_i \tag{10}$$

$$T_{\text{cool in}_i} = T_{\text{cool out}_{i-1}} \tag{11}$$

$$T_{\text{cool out}_i} = \frac{Q_{\text{condenser}_i}}{\dot{m}_{\text{cool out}_i} * C_p} + T_{\text{cool in}_i} \tag{12}$$

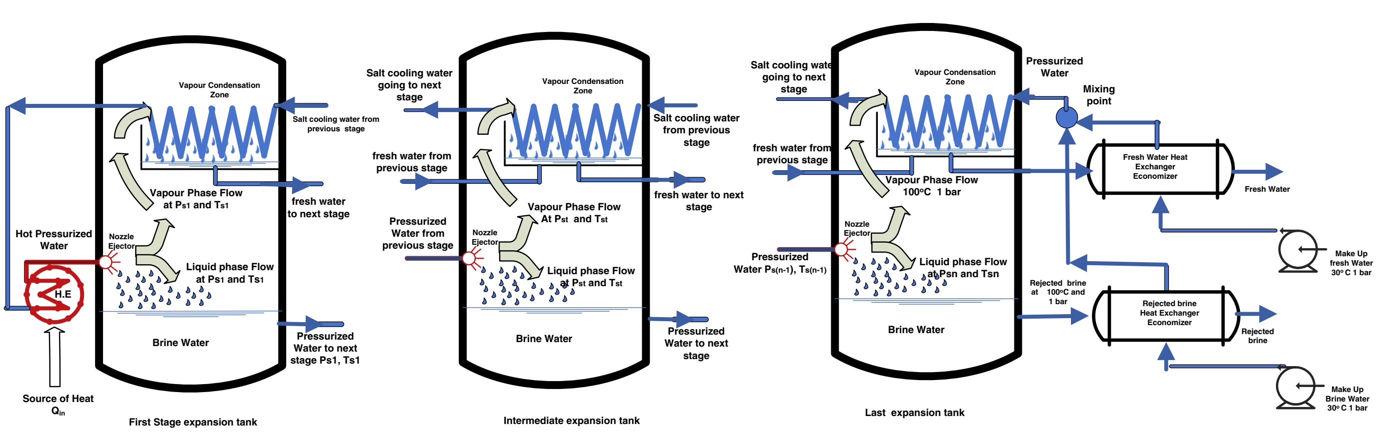

Fig. 1. System layout.

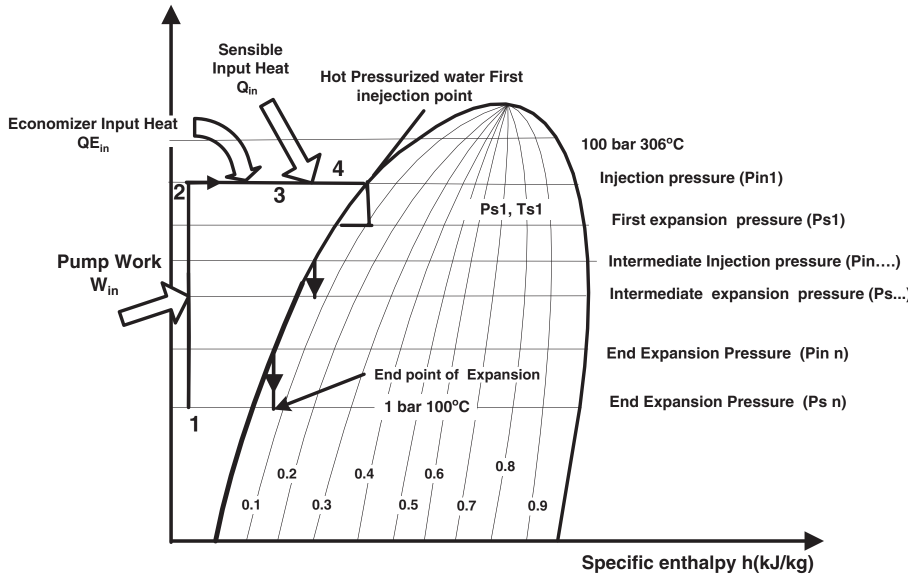

Fig. 2. Process layout of the system on water pressure enthalpy diagram.

Heat and mass balance for fresh water heat exchange

Mass balance

$$\dot{m}_{makeup\ \ fresh} = \dot{m}_{fresh\ out\ \ n} \tag{13}$$

Heat balance

$$\dot{m}_{makeup\ \ fresh} * C_p * \left(T_{makeup_{fresh\ out}} - T_{makeup_{fresh\ in}}\right) = \varepsilon * \dot{m}_{fresh\ out\ \ n} C_p * \left(T_{fresh\ \ out_n} - T_{fresh_{out}}\right) \tag{14}$$

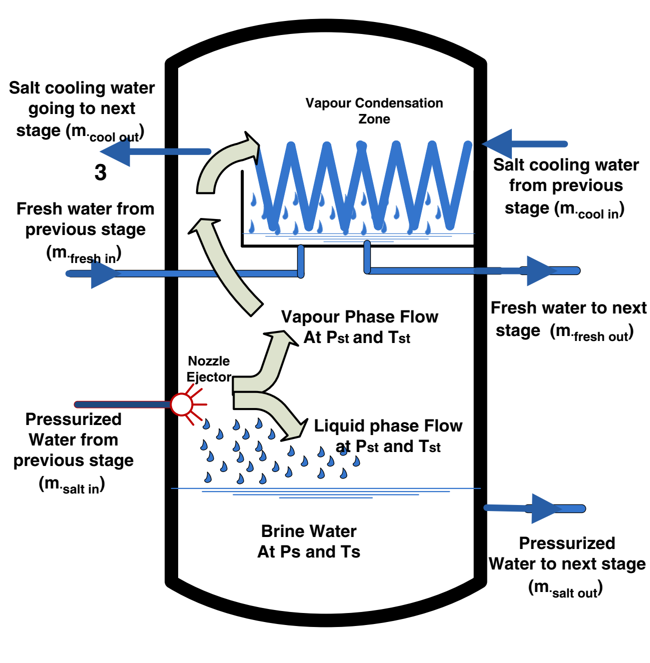

Fig. 3. Selected stage assigned as stage No. "*i*."

where

$$T_{makeup_{fresh}\ \ in} = 30\,^{\circ}\mathrm{C}$$

ε Heat exchanger effectiveness for cross flow heat exchanger; the value of it may reach 0.95.

Heat and mass balance for rejected brine heat exchanger

Mass balance

$$\dot{m}_{makeup\ \ brine\ \ in} = \dot{m}_{Brine\ \ out_n} \tag{15}$$

Heat balance

$$\dot{m}_{\ makeup\ \ brine} * C_p * \left(T_{makeup_{brine\ out}} - T_{makeup\,brine\ in}\right) = \varepsilon * \dot{m}_{\ brine\ out\ \ n} C_p * \left(T_{Brine\ out\ \ n} - T_{Brine_{out}}\right) \tag{16}$$

where

$$T_{make\ \ up\ \ brine\,in} = 30\ ^{\circ}\mathrm{C}$$

ε Heat exchanger effectiveness for cross flow heat exchanger; the value of it may reach 0.95.

Mixing point

Mass balance

$$\dot{m}_{cool\ \ in} = \dot{m}_{makeup\ \ total} = \dot{m}_{makeup\ \ brine} + \dot{m}_{makeup\ \ fresh} \tag{17}$$

Heat balance

$$\left(\left(\dot{m}_{makeup\ \ fresh} + \dot{m}_{make\ \ up\ \ brine}\right) * C_p * T_{makeup_{out}}\right) = \left(\dot{m}_{make\ \ up\ \ brine} * C_p * T_{makeup_{brine\ out}} + \dot{m}_{makeup\ \ fresh} * C_p * T_{makeup\ \ fresh_{out}}\right) \tag{18}$$

$$T_{\text{makeup}_{\text{out}}} = \frac{m^{\cdot}_{\text{makeup}\ \ \text{brine}}}{\left(m^{\cdot}_{\text{makeup}\ \ \text{total}}\right)} * T_{\text{makeup}\ \text{brine}_{\text{out}}} + \frac{m^{\cdot}_{\text{makeup}\ \ \text{fresh}}}{\left(m^{\cdot}_{\text{makeup}\ \ \text{total}}\right)} * T_{\text{makeup}\ \text{fresh}_{\text{out}}} \quad (19)$$

Boiler

$$Q_{\text{boiler}\ \ \text{in}} = m^{\cdot}_{\text{cool}} * C_p * \left(T_{\text{salt in}\ _1} - T_{\text{cool out}_1}\right) \quad (20)$$

where

$$T_{\text{salt in}\ _1} = T_{\text{saturation}}\ \text{At}\ p_1 \quad (21)$$

$$T_{\text{cool out}_1} = T_{\text{makeup}\ \ \text{out}} + \sum_{i=1}^{n} T_{\text{cool out}\ \ i} \quad (22)$$

Pump

$$W_{\text{pump}} = m^{\cdot}_{\text{salt in}} * g * H \quad (23)$$

where

$$H = \frac{P_{\text{Boiler}} - P_{\text{stage}\ n}}{\rho_{\text{water}} * g} \quad (24)$$

System energy consumption

$$E = \frac{Q_{\text{boiler in}} + W_{\text{pump}}}{m_{\text{fresh out}\ \ n}} \quad (25)$$

A computer program using lab-view software had been constructed to evaluate the performance of the suggested system. The thermal properties of water were evaluated using equation for data which is represented in Ref. [7]. The program allows studying the effect of the number of stage at different inlet pressure at any flow rate of input salt water. The program has the ability to change the system outlet pressure. The program uses the following procedure to perform this task.

3.2. Solution procedure

A first basic module was constructed to calculate the saturation properties of water at different pressures or temperatures. This basic module could use the saturation pressure or saturation temperature, which allows to use it in a different situation in program procedure and all saturation properties are calculated using this basic module. This module is used to construct a program to evaluate the performance of the system. The program has an ability to run at different input conditions such as, number of stages, different injection pressure, and output pressure at specified inlet seawater flow rate. The program had been constructed according to the following procedure of calculations and assumptions.

$T_{\text{sw}\ \ \text{in}} = 30^{\circ}\text{C}$

$C_{\text{p}} = 4.2\ \text{kJ/kg.K}$

Step 1 Input parameters

P_{Boiler}	Maximum system pressure
$P_{\text{stage}\ n}$	Minimum system pressure
N	Number of expansion stages of the system.
$m^{\cdot}_{\text{sw}\ \ \text{in}}$	Mass of makeup salt water flow (total mass flow through the cooling system).

Step 2

$$\Delta P_{\text{stages}} = \frac{P_{\text{Boiler}} - P_{\text{stage}\ n}}{N}$$

$$m^{\cdot}_{\text{cool}} = m^{\cdot}_{\text{sw}\ \ \text{in}}$$

Step 3 For $i = 0$ up to n

{

If $i = 1$ then $P_{i\ -\ 1} = P_{\text{Boiler}}$

$P_i = P_{\ i-1} - i * \Delta P_{\text{stages}}$

Get the value of $h_{\text{salt}\ \ \text{in}_i} h_{\text{fg}_i}, h_{\text{salt}\ \ \text{out}\ \ i}, T_{\text{saturation}\ \ i}$

where $h_{\text{salt}\ \ \text{in}_i} = h_{\text{salt}\ \ \text{out}_{i-1}}$

h_{fg_i} The latent heat of water at stage pressure

$$h_{\text{salt out}\ _i} h_{\text{liquid at stage}(i)\ \text{pressure}_i}$$

$$X_i = \frac{h_{\text{salt in}_i} - h_{\text{salt out}_{i+1}}}{h_{\text{fg}\ \ i}}$$

$$m^{\cdot}_{\text{salt in}_i} = m^{\cdot}_{\text{salt out}\ \ i+1}$$

$$m^{\cdot}_{\text{fresh in}_i} = m^{\cdot}_{\text{fresh out}_{i+1}}$$

$$\Delta m^{\cdot}_{\text{fresh}_i} = X_i * \left(m^{\cdot}_{\text{salt in}_i} + m^{\cdot}_{\text{fresh in}\ _i}\right)$$

$$q^{\cdot}_i = \Delta m^{\cdot}_{\text{fresh}_i} * h_{\text{fg}\ \ i}$$

$$\Delta T_{\text{cool}_i} = \frac{q_i}{C_p * m^{\cdot}_{\text{cool}}}$$

}

Step 4

$$m^{\cdot}_{\text{makeup}\ \ \text{fresh}} = m^{\cdot}_{\text{fresh}} = \sum_{i}^{n} \Delta m^{\cdot}_{\text{fresh}_i} m^{\cdot}_{\text{makeup}\ \ \text{brine}} = m^{\cdot}_{\text{brine}} = m^{\cdot}_{\text{cool}} - m^{\cdot}_{\text{fresh}}$$

Step 5

$$T_{\text{makeup}_{\text{brine out}}} = \varepsilon * \left(T_{\text{Brine out}_n} - T_{\text{Brine}\ \ \text{out}}\right) + T_{\text{makeup}_{\text{brine}\ \ \text{in}}}$$

$$T_{\text{makeup}_{\text{fresh}\ \ \text{out}}} = \varepsilon * \left(T_{\text{fresh out}_n} - T_{\text{fresh}_{\text{out}}}\right) + T_{\text{makeup}\ \ \text{fresh in}}$$

$$m^{\cdot}_{\text{makeup}_{\text{total}}} = m^{\cdot}_{\text{makeup}_{\text{brine}}} + m^{\cdot}_{\text{makeup}_{\text{fresh}}}$$

$$T_{\text{mixture}} = T_{\text{makeup}_{\text{out}}} = \frac{m^{\cdot}_{\text{makeup}_{\text{brine}}}}{\left(m^{\cdot}_{\text{makeup}_{\text{total}}}\right)} * T_{\text{makeup brine}_{\text{out}}} + \frac{m^{\cdot}_{\text{makeup}_{\text{fresh}}}}{\left(m^{\cdot}_{\text{makeup}_{\text{total}}}\right)} * T_{\text{makeup fresh}_{\text{out}}}$$

For $i = n$ down to 1

{

If i = n $T_{cool\ \ in\ \ i} = T_{mixture}$ Else $T_{cool\ \ in_i} = T_{cool out_{i-1}}$

$T_{cool out_i} = T_{cool in_i} + \Delta T_{cool_i}$

$T_{cool\ \ out\ \ max_i} = T_{saturation\, i} - 2.5$

If $T_{cool\ \ out_i} < T_{cool\ \ out\ \ max_i}$ then $T_{cool\ \ in_{i-1}} = T_{cool\ \ out_i}$

If $T_{cool\ \ out_i} > T_{cool\ \ out\ \ max_i}$ then $T_{cool\ \ in_{i-1}} = T_{cool\ \ out_i} = T_{cool\ \ out\ \ max_i}$

If i = 1 then $T_{boiler_{in}} = T_{cool\ \ out_i}$ and $T_{boiler_{out}} = T_{saturation\ \ i}$

}

Step 6

$$Q_{\text{Boiler in}} = m^{\cdot}_{\text{cool out}\ _1} * 4.2 * \left(T_{\text{boiler}\ \ \text{out}} - T_{\text{boiler}\ \ \text{in}}\right) \text{kJ}$$

$$H = \frac{P_{\text{Boiler}} - P_{\text{stage}\ n}}{\rho_{\text{water}} * g}$$

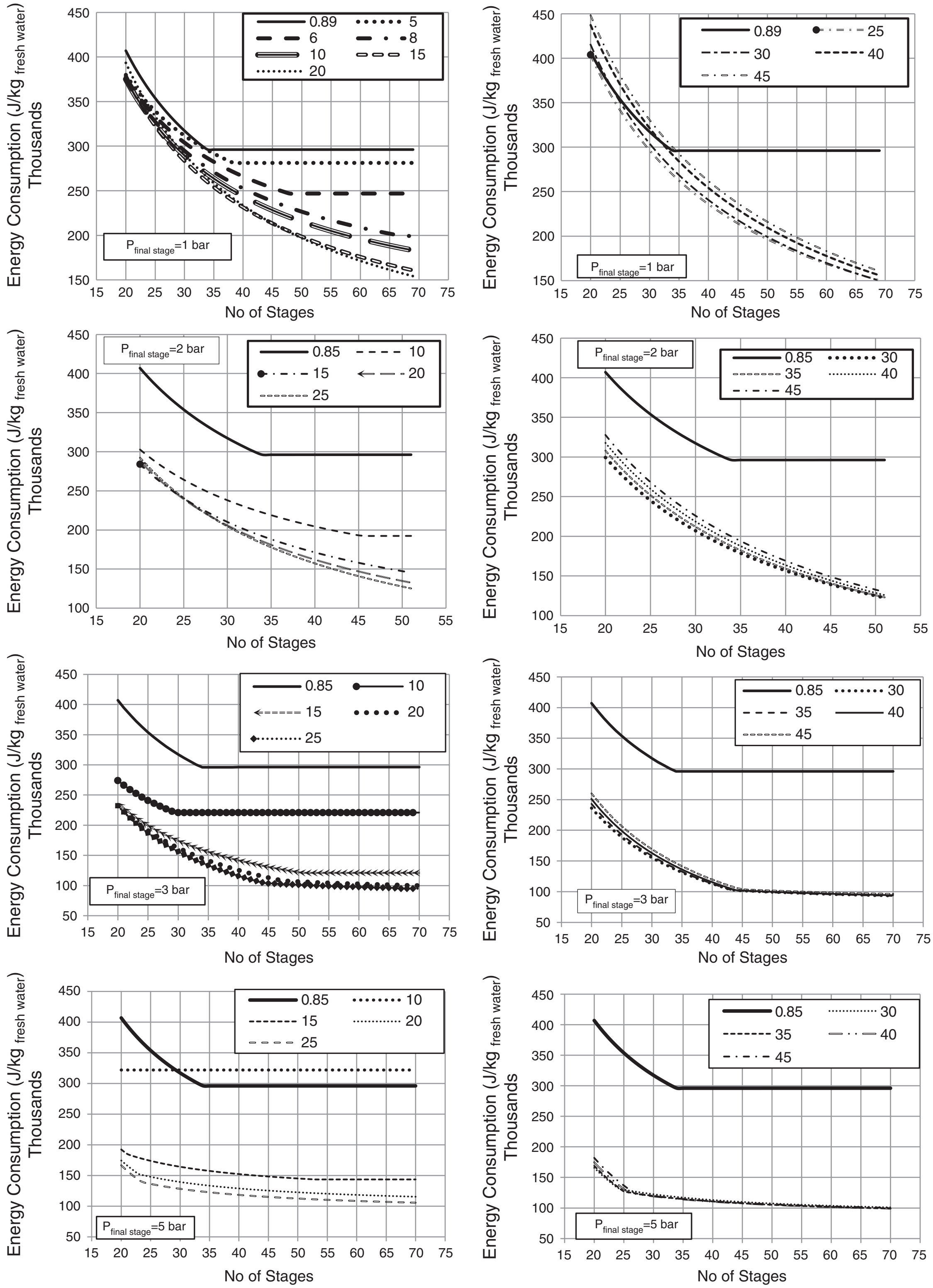

Fig. 4. Effect of number of stages on the energy consumption for different inlet stage pressure at different final stage pressure (exit pressure).

$$W_{pump} = m^{\cdot}_{sw\ in} * g * H$$

$$E = \frac{\left(Q_{Boiler\ in} + W_{pump}\right)}{m^{\cdot}_{fresh\ out}} \text{kJ/kg}_{fresh\ water}$$

4. Results

For the purpose of comparing, performance of MSF plant—with first stage inlet pressure 0.85 bar and final stage pressure 0.156 bar—is studied with the same program at the same number of stages that will be studied for the suggested system. From the results, which is presented in Fig. 4, it could be concluded that the energy consumption decreases

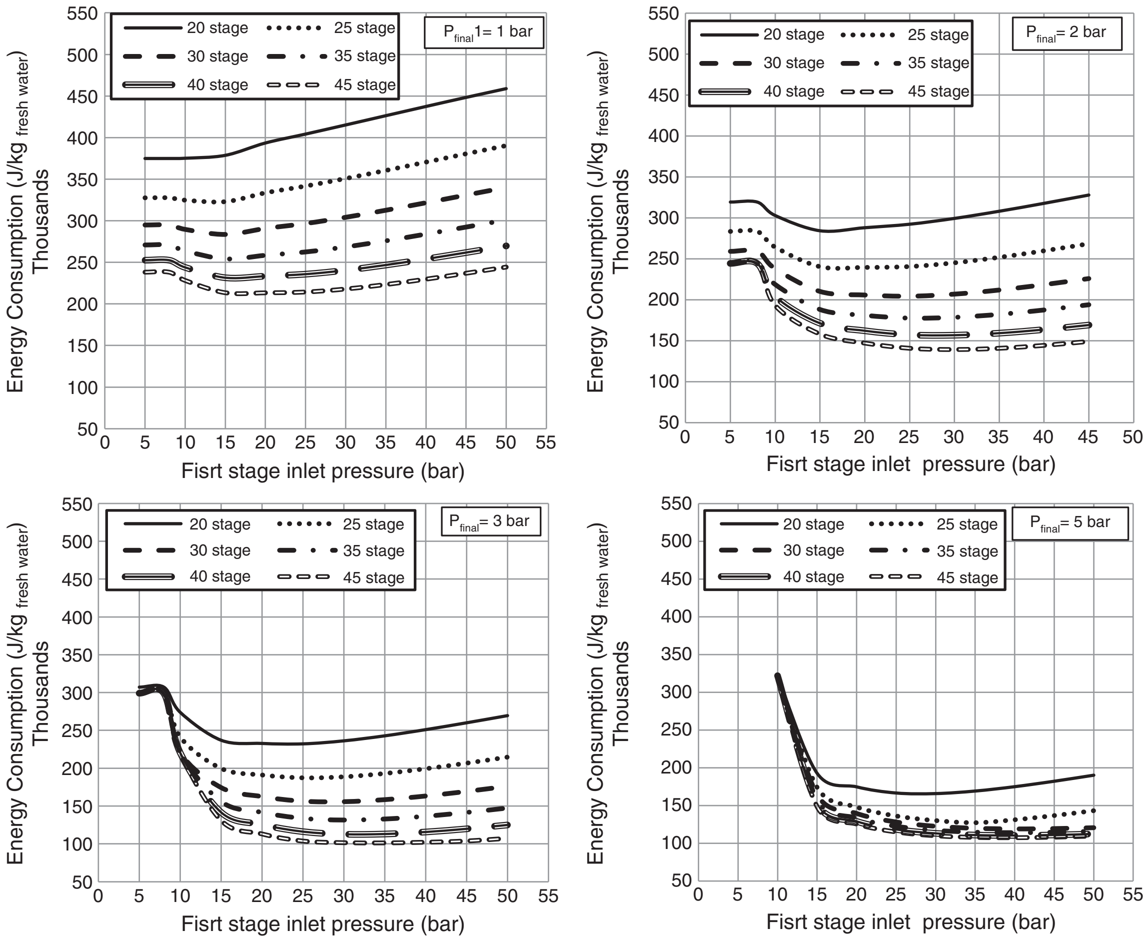

Fig. 5. Effect of input pressure on energy consumption at different number of stages for different exit pressure.

with the increase in number of stages, this is due to the increase in ability of catching back the lost energy with the increase in number of stages. A significant decrease is noticed in energy consumption with the increase in the number of stages up to 33 stages. After this number of stages the increase in number of stages has no great effect on the energy consumption which means that the optimum number of stages is around 33 stages. The energy consumption for MSF with this number of stages is 289 kW/kg fresh water, which is consistent with values listed in Ref. [5].

The effect of the number of stages—from 20 up to 70 stages—at different inlet stage pressures, on the energy consumption for each kilogram of produced fresh water with different final stage pressure (1, 2, 3 and 5 bar), was plotted in Fig. 4. The performance of MSF plant—which works with the same salt water flow rate—with inlet pressure of 0.89 bar and exit pressure of 0.156 bar at the different number of stages is plotted to compare with suggested system performance at different operating conditions. The MSF performance was plotted using bold line.

For exit pressure of 1 bar (final stage pressure), the results show that, with increase in number of stages, the energy consumption decreases. This is for all inlet pressures that were studied. Also the more inlet pressure increases, the more energy consumption decreases. This is for inlet pressures that ranged from 5 up to 15 bar. After that with the increase of inlet pressure up to 30 bar the energy consumption starts to increase but still lower than the energy consumption of MSF plant for all the number of stages that were studied. With an inlet pressure increase of higher than 30 bars up to 45 bars the energy consumption increases more than MSF plant for a number of stages lower than 35 stages. Generally the energy consumption for the suggested system is lower than the value of energy consumption of MSF plant for a system that operates with the same number of stages. For exit pressure of 1 bar, the energy consumption may reach to be about 200 kJ/kg of fresh water with 50 stages when inlet pressure was 20 bars which is considered as a promising feature for cost production.

Also, it could be concluded that the energy consumption decreases with the increase in the final stage pressure of the system. The lowest value of energy consumption was achieved when the final stage pressure was 3 bar with the number of stages equal to 45 stages for system works with inlet pressure higher than or equal to 30 bar. The lowest system energy consumption was about 110 kJ/kg. A little enhancement was achieved with an increase in the number of stages which may reach to be about 100 kJ/kg of fresh water.

Fig. 5 shows the effect of inlet pressure on energy consumption for MSF plant with different numbers of stages. The results show that with the increase of number of stages the energy consumption decreases for the same system inlet pressure at different final stage pressure. The lowest value of energy consumption was achieved when pressures of inlet stage were at 25 bar up to 45 bar, with final stage pressure of 3 bar. With the increase in inlet pressure a little enhancement in energy consumption is achieved. It could be concluded that the lowest energy consumption achieved for plants works with inlet pressure of 30 bar, exit pressure of 3 bar, and 45 stages.

Fig. 6 shows the percentage of produced fresh water to the total salt water inlet. This ratio is very important to compare the effect of the process on the disposal brine salt concentration, which is very important to

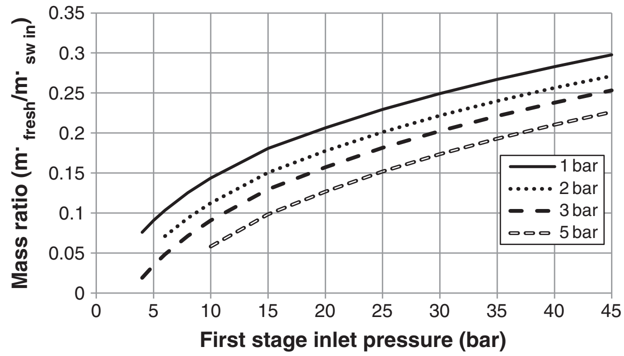

Fig. 6. Effect of inlet pressure on the production ratio ($\dot{m}_{fresh}/\dot{m}_{sw\ in}$) at different exit pressure.

study the effect of the system on the environment. The salt concentration of disposed brine is a very important environmental parameter. The results show that the more inlet pressure increases the more ratio increases consequently the salt concentration in rejected brine increases. For lowest energy consumption value (30 bar, 45 stages and 3 bar exit pressure) this ratio is about 0.18 which means that the slat concentration in the rejected brine is 1.18 of salt concentration in the inlet salt seawater. This is environmentally accepted. For MSF plants this ratio is about 1.66 which means that the concentration may be more that one an half of seawater concentration.

Table 1 shows energy consumption and cost consumption comparison between the suggested system and some other desalination methods. From the table it clearly shows that the system has a comparable and promising value of the required energy consumption compared with other types of desalination system. The cost is estimated for the system when using electricity as source of energy in work and heat form.

5. Conclusion

Desalination by suggested system increases the efficient usage of energy for thermal desalination process. The thermal energy consumption could be reduced to 90 MJ/m^3 for suggested system at first stage inlet pressure equal to 30 bar, when exit pressure is 3 bars when system consists of 45 stages. The system is suitable for any type of thermal energy, low- and high-quality energy. Moreover, the energy consumption of suggested system that may work in other range of operation at specified number of stages is always lower than the MSF plant energy consumption which operates at the same number of stages.

The concentration of salts inside the system does not exceed about 5–10% more than the seawater concentration. So no scale could be formed inside the tubes of the systems which means low maintenance cost. Also the rejected brine water has salinity not more than 5–10% of the seawater supplied, which consequently have a good effect on the environment.

The system always works at a pressure higher than atmospheric pressure so that the complication of the evacuation process as it was found in traditional MSF will no longer exist. This will achieve lower construction cost and fast starting in troubleshooting or maintenance.

Nomenclature
Symbol

P	Pressure N/m^2
N	No. of expansion stages of the system
$\dot{m}$	Mass flow rate kg/s
$\Delta\dot{m}$	Rate of mass flow rate change kg/s
h	Enthalpy J/kg. K
h_{fg}	Latent heat of vaporization J/kg
X	Dryness fraction
T	Temperature °C
C_p	Specific heat of water J/kg.K
Q	Quantity of heat J
W	Work J
E	Energy consumption J/kg
g	Gravitational acceleration m/s^2
ρ	Density kg/m^3

Subscript

in	Inlet
out	Outlet
s	Stage
B	Boiler
sw	Salt water
i	Stage index
f	Fresh
c	Coolant
sa	Salt
makeup	Make up
t	Total

Table 1
Comparison between energy requirements for different water desalination methods stated in Ref. [12], Ref [13] and that required for suggested system.

Energy used	Multistage flash	Reverse osmosis	Conventional vapor compression	Theoretical		Suggested system	
				High temperature vapor compression		Operating conditions	
				Case C \$5.00/GJ 5.5 Cent/kWh	Case A \$0.50/GJ 1.5 Cent/kWh	$P_{inlet} = 30$ bar, $P_{final} = 3$ bar, at 45 stages	
						5.5 Cent/kWh	1.5 Cent/kWh
Water cost (\$/m^3)	0.77–1.84	0.64–1.98	0.46–2.5	0.49	0.38	0.14	0.04
Heat (MJ/m^3)	145–290			30.8	54.3	75	
Work (MJ/m^3)	14.4	21.6–36.0	21.6–36.0	15.7	27.7	15	

brine Salt water
sat Saturation
cond Condenser
p Pump
w Water

Greek letter
ε Effectiveness of the heat exchanger

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