Experimental studies on Solar Multi - Effect Desalination system

Thilagan Kannappan[1] and Mani Annamalai[1]

[1]Department of Mechanical Engineering

Indian Institute of Technology Madras, Chennai, Tamil Nadu, 600036 (India)

Abstract

A Multi – Effect Desalination system with a capacity of 10 m^3 has been designed, erected and tested to convert seawater into potable water using solar energy. This solar desalination will produce drinking water for a small community. The steam is flashed initially from a flash chamber of the desalination plant, using hot water from a solar flat plate collector field and fed to the first stage of the multi-stage evaporator. The average hot water outlet temperature from the collector field is in the range of 60ºC - 65ºC. In a multi-stage evaporator, seawater is sprayed parallelly to produce water vapor. This water vapour loses heat and forms condensate by losing the latent and sensible heat through the tube surface. The brine and condensate is carried to the last stage of the multi-effect desalination (MED) system. It is observed that during peak production of potable water, maximum temperature difference between inlet and outlet of cooling water is 10ºC in the condenser. Experimental studies on the solar MED system are made to understand the performance of the system using solar energy alone. The solar MED system with a maximum production rate of 1.008 $m^3\ h^{-1}$ is observed during peak sunshine hours. The distillate TDS is tested and is in the range of 1 ppm - 5 ppm.

Keywords: Multi - Effect Desalination, Solar energy, Sea water, Ejector

1. Introduction

Water naturally occurs and is a basic need for all forms of life. Among the total water availability in the world, 2.5% of water is potable for drinking. The scarcity of potable water is increasing day by day due to the increase in population and increase in industrial activities. The conversion of sea or brackish water into potable water will meet the demand through desalination techniques. Converting sea or brackish water into potable water is an energy-intensive process and can be made viable using accessible renewable energy sources like solar energy, geothermal, ocean thermal gradient, etc.

Among the available forms of renewable energy, solar energy is abundantly, distributed form and freely available throughout the year. There are different techniques of desalination using solar energy. Solar still is one of the oldest and most famous techniques in desalination. The detailed experimental studies are carried out on single sloped solar still (Mani, 1982a, 1982b). The researchers have developed a vacuum-based desalination system to commercialize desalination technology. In 1991, Low and Tay developed and tested the vacuum based desalination process using sea water (Low and Tay, 1991). Later, this experiment is extended using waste heat from a steam turbine for desalination (Tay et al., 1996).

In the desalination system, vacuum pump plays a significant role in maintaining the system's vacuum pressure. The vacuum pump will consume high-grade energy. The researchers later started working for alternate solutions and found an ejector to maintain the desalination system's vacuum pressure. Lot of simulations and experimental trials have been conducted for different configurations of ejector to replace vacuum and reduce the electrical power cost (Arun et al., 2017; Parveen Banu and Mani, 2019). Simulation studies for desalination systems have been validated with experimental results for a lab-scale desalination test rig (Kudish et al., 2003).

In this paper, experimental studies have been carried out at Vivekananda Kendra, Kanyakumari, India [Latitude : 8.08ºN and Longitude : 77.53ºE], by designing, fabricating, erecting and testing a solar multi - effect desalination plant with a capacity of 10 m^3 per day. This paper presents the design details and experimental performance of the

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plant.

2. Principle of operation

Figure 1 shows the schematic view of the Solar Multi - Effect Desalination (MED) system. The system consists of solar flat plate collector (FPC) field, flash chamber, multi - effect evaporator (MEE), condenser, solar photovoltaic power plant, ejector, hot water recirculation pump, brine pump, distillate pump, MED pump and seawater intake pump. The ejector is used for the creation of a vacuum in MED to maintain the system at the saturation state. The pressurized hot water from solar FPC field enters the flash chamber. Hot water is flashed to steam at saturation pressure of the flash chamber, and the remaining water is recirculated back to the solar FPC field. The generated steam is sent to the first stage of MEE by pressure difference.

The sea water is sprayed and flashed in MEE over the tubes of MEE, where it gets vaporized by taking heat of condensation. Also, due to flashing at the corresponding evaporator pressure, steam flows to the next stage of the evaporator in MEE. The condensed steam and the remaining brackish sea water are collected at the distillate box and brine box, respectively and are sent to the next stage of MED by manometric effect. This process continues till the distillate reaches the condenser. At the condenser, incoming sea water is used to condense the steam and reduce the temperature of distillate from the last stage of MEE. The condensed water is sent to the distillate storage tank by pump and the brackish seawater collected at the last stage of MEE is pumped back to sea. The entire Solar MED plant is powered by a solar photovoltaic power plant with a battery backup of half an hour. The MED plant is operated solely using solar energy.

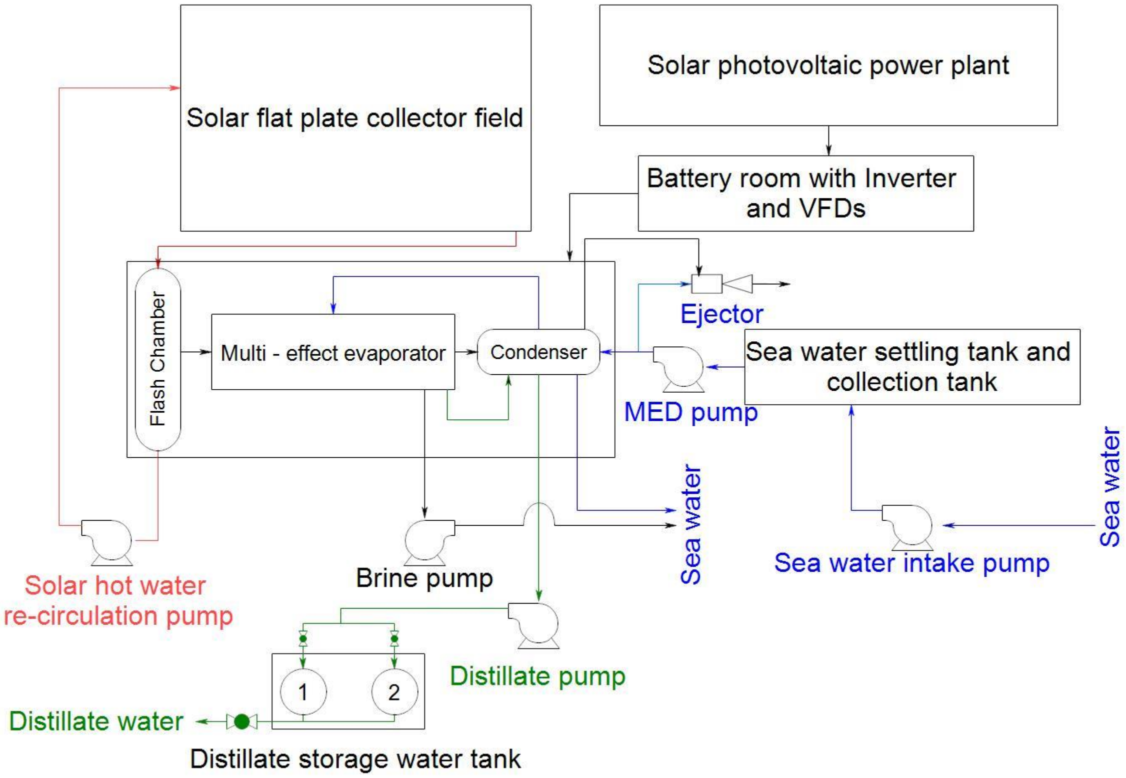

Fig. 1: Schematic diagram of Solar Multi - Effect Desalination (MED) system

3. Design of the system

Solar MED plant layout diagram is shown in Fig. 2. The plant component details are narrated below.

3.1. Solar flat plate collector field

Solar flat plate collectors are used to raise the water temperature from 60°C to 70°C at a varying flow rate ranging from 26,800 kg hr^{-1} to 29,800 kg hr^{-1}. A large area of solar collector field is required to raise the water temperature.

Based on Eq. 1, the total number of solar flat plate collectors required to raise the temperature of water from 60ºC to 70ºC is 315 (Duffie and Beckman, 2013). The area required for the solar flat plate collector field is 630 m^2. The specification of a single flat plate collector is given in Table 1.

$$\dot{m}\, C_p\, \Delta T = I \eta N \qquad \text{(eq. 1)}$$

where, $\dot{m}$ = Mass flow rate of solar FPC (kg hr^{-1}) ; C_p = Specific heat of water (J kg^{-1} K^{-1}) ; ΔT = Temperature difference between inlet and outlet of solar FPC (ºC) ; I = Incident Solar Radiation (W m^{-2}) ; η = Efficiency of solar FPC (%) ; N = number of collectors.

The collector field is installed in such a way that every seven collectors are connected in series to form an array. The array arrangements will enhance heat transfer. There are 45 arrays in parallel, and they are arranged in seven rows in parallel. A ball valve operates each row to ensure a uniform flow rate in all the rows. The entire field is oriented to face south with an inclination angle of 8º to maximize solar energy falling on the collectors.

Tab. 1: Details of solar flat plate collector

Area	2 m^2 ± 0.1 m^2
Absorber Material	Copper
Fin Material	Aluminium
Reflector	Aluminium foil
Max. pressure	6 bar
Collector box	Extruded aluminium L : 2050 mm x B : 1040 mm x H : 100 mm ± 0.2 mm
Back insulation	Rockwool

3.2. Flash chamber

The hot water from solar FPCs is fed into the flash chamber. The hot water is made to flash using upward spray flashing mode (Goto et al., 2008). At saturation pressure of the flash chamber, hot water is flashed to steam. The remaining water is sent back to the solar field for recirculation using a solar hot water pump. The steam is sent to the first stage of the MED system by a difference in vacuum pressure.

Based on Eq. 2, the efficiency of the flash chamber is computed

$$FC = \frac{H_{IN}^{L} - H_{OUT}^{L}}{H_{OUT}^{V} - H_{OUT}^{L}} \qquad \text{(eq. 2)}$$

where, FC = Flash chamber efficiency (%) ; H_{IN}^{L} = Flash chamber inlet liquid enthalpy at temperature and pressure (J kg^{-1}) ; H_{OUT}^{V} = Flash chamber outlet flashed vapour enthalpy at pressure and corresponding saturation temperature (J kg^{-1}) ; H_{OUT}^{L} = Flash chamber outlet unflashed liquid enthalpy at pressure and corresponding saturation temperature (J kg^{-1}).

3.3. Multi-Effect Evaporator (MEE)

In the first stage of MEE, seawater is sprayed over the tubes of each evaporator using spray nozzle parallelly. The water from the spray nozzle gets atomized and absorbs the heat of condensation from the tube wall. At saturation pressure of each effect of MEE, water gets flashed, and the remaining concentrated brine solution is sent to the next effect of MEE by manometric effect. The condensed steam is collected and carried to the next effect by manometric effect. This process is continued until the distillate reaches the condenser and the brine solution is ejected from the system using the brine solution pump.

3.4. Condenser

The distillate and flashed steam from the last stage of MEE is condensed in the condenser by using incoming seawater at the flow rate of 20.6 m^3 h^{-1}. The condensed distillate is pumped to the distillate tank using a distillate pump. During the process of flashing in the flash chamber, water level reduces and part of the distillate is redirected to the flash chamber outlet (or) suction of solar recirculation pump as makeup water to the solar heating system. During the condensation process, most of the seawater is sent back to sea, which acts as a sink and the remaining seawater is sent to the spray nozzles of MEE in parallel mode at the rate of 1.2 $m^3 h^{-1}$.

3.5. Ejector

The ejector system is used to maintain vacuum pressure of the MED system during operation. In ejector, primary stream is admitted with a given flow rate of seawater. The non-condensable gases from the condenser of the MED system is entrained through the secondary stream of the ejector. The ejector is powered by seawater at the primary stream.

Based on Eq. 3, the entrainment ratio of the ejector is computed (Arun et al., 2019)

$$Entrainment\ ratio = \frac{\dot{m}_s}{\dot{m}_p} \qquad \text{(eq. 2)}$$

where, $\dot{m}_s$ = Mass flow rate of secondary stream (kg h^{-1}) ; $\dot{m}_p$ = Mass flow rate of primary stream (kg h^{-1}).

3.6. Pumps

In the solar MED system, six pumps as shown in Table 2 are used to run the plant.

Tab. 2: Details of pumps

Sl.No.	Pump	Make	Details
1.	Solar recirculation pump	Grundfos	Power – 10 hp / 7.5 kW 3 Phase ; 380-415 V ; 50 Hz Max. discharge – 30 $m^3 h^{-1}$
2.	Brine pump	Grundfos	Power – 1.5 hp / 1.10 kW 3 Phase ; 380-415 V; 50 Hz Max. discharge – 5.8 $m^3 h^{-1}$
3.	Distillate pump	Grundfos	Power – 0.37 kW / 0.5 hp 3 Phase ; 380-415 V; 50 Hz Max. discharge – 1.8 $m^3 h^{-1}$
4.	Ejector pump	PSG	Power – 3.7 kW / 5 hp 3 Phase ; 380 V ; 50 Hz Max. discharge – 24 $m^3 h^{-1}$
5.	MED pump	Kirloskar Brothers Ltd	Power – 5.5 kW / 7.5 hp 3 Phase ; 415 V ; 50 Hz Max. discharge – 25.6 $m^3 h^{-1}$
6.	Seawater intake	Johnson Pump	Power – 2.2 kW / 3 hp 3 Phase ; 415 V ; 50 Hz Max. discharge – 40 $m^3 h^{-1}$

3.7. Solar Photovoltaic panels

The pumps of solar MED plant require 20 kW of power to run the plant. The installed solar photovoltaic power plant is 20 kW with a battery backup of half an hour. Batteries are used to start and run the motors at lower solar radiation in the morning and evening hours. Inverters are used to convert DC to AC current. The specification details of solar photovoltaic panels, batteries and inverters are shown in Table 3.

Tab. 3: Details of solar PV panels and subsystems

Sl.No.	Materials	Numbers	Details
1.	Solar Photovoltaic Panels	100	PV panel capacity – 200 W Type of PV cell – monocrystalline silicon cell
2.	Batteries	14	Type of battery – Tubular battery Voltage – 12 V A.H. capacity – 75 Ah
3.	Inverters	3	Capacity – 10 kWh [Two Nos.] Capacity – 3 kWh

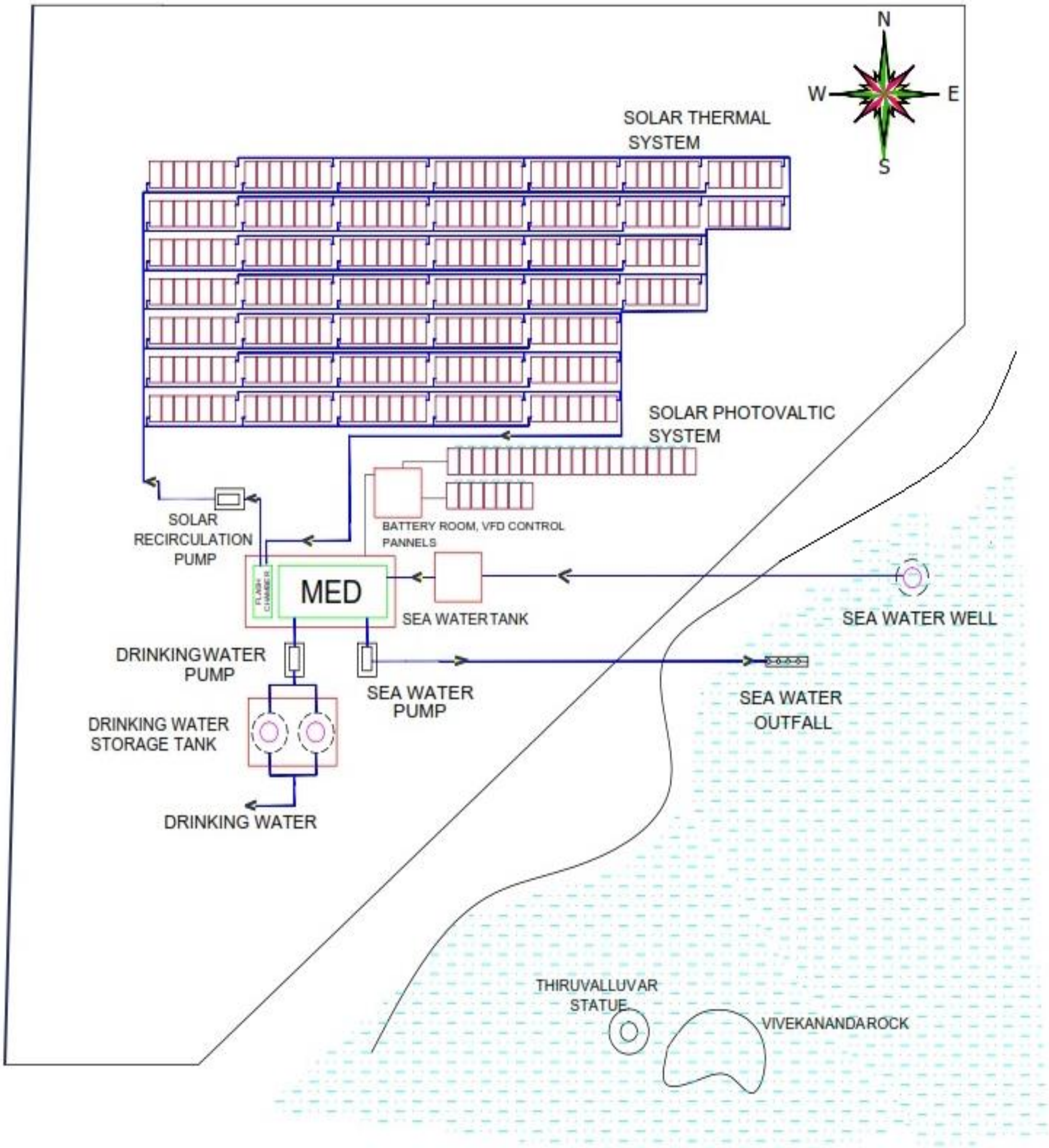

Fig. 2: Schematic diagram of Solar Multi - Effect Desalination (MED) system

4. Experimentation

Solar MED plant components are successfully designed, fabricated, erected and integrated at the project site at Vivekananda Kendra, Kanyakumari, India. The solar thermal FPC field is tested for pressure up to 4 bar in order to check leakage. Entire MED plant is tested under vacuum pressure up to 30 mbar to check vacuum leakage.

Calibrated bourdon type pressure gauges are installed at the inlet of solar FPC field, sea water inlet and primary stream of ejector. Calibrated bourdon type vacuum gauges are used at flash chamber, each effect of MEE and condenser of MED plant. Temperatures of solar MED plant are measured at different locations using calibrated T - type thermocouples. Calibrated orifice plates are used at solar FPC field inlet, brine discharge, distillate discharge and seawater inlet and are used to measure differential pressure across the orifice plates using digital differential manometer. Using the measured differential pressure readings, flow rates are calculated. Level indicators are installed at flash chamber, distillate line and bine line in order to maintain the level during operation of the plant. Solar radiation and wind speed are measured using calibrated pyranometer and anemometer respectively. The details of measuring instruments used for experimentation are shown in Table 4.

Tab. 4: Accuracy and range of measuring instruments

Sl.No.	Instrument	Accuracy	Range
1.	T type thermocouple	± 0.1 ºC	-60 ºC to 120 ºC
2.	Pressure gauge	± 1% FS	0 to 10 bar
3.	Vacuum pressure gauge	± 1% FS	0 to -1 bar
4.	Differential pressure manometer (digital)	± 0.5% FS	0 to 200 psi
5.	Pyranometer	± 10 W m^{-2}	0 to 1999 W m^{-2}
6.	Anemometer	± 3%	0 to 30 m s^{-1}

Seawater is drawn from the sea, 20 m away from the desalination plant. Sand and other particles are made to settle in the settling tank and collected in collection seawater tank. The collected seawater is sent to the plant by MED pump. Before entering the condenser, fine meshes are kept to avoid chocking of fine particles at the spray nozzles of MEE. During experimental days, sea water flow rate is maintained at 20.6 $m^3 h^{-1}$ with the pressure of 0.8 bar.

The entire MED plant is kept below 150 mbar using an ejector. In solar FPC, water is circulated until it reaches the required temperature. The average temperature of water is maintained between 65ºC - 70ºC. The water is flashed and sent to the first stage of MEE by pressure difference. The remaining water in flash chamber is recirculated to the solar FPC field using solar recirculation pump. Seawater is sent to each stage of MEE from the spray nozzles. The sprayed seawater forms steam by taking the heat of condensation and flashing, and carries to the next stage of MEE by differential pressure. The condensed steam and brine water are carried to the next effect by using manometric effect and continues till it reaches the last effect of MEE. The brine water from the last effect of MEE is pumped back to the sea using brine pump. The steam and distillate water from the last effect of MEE are condensed in the condenser and pumped to distillate tank using a distillate pump. During condensation, the ejector rejects the non-condensable gases (NCGs). The level of distillate, brine and flash chambers are monitored continuously for effective operation.

5. Results and discussion

Solar MED plant is tested for different operating conditions on different days. This paper discusses a typical operation condition for a given single day. The plant is operated between 8:00 h to 17:00 h of IST.

5.1. Experimental investigation of collector performance

Solar flat plate collector (FPC) field performance curves are shown in Fig. 3. It is observed that the temperatures of inlet and outlet increase initially and later decrease. This is due to the incident solar radiation falling on solar FPC. The maximum hot water outlet temperature is realized in the range of 74ºC - 76ºC with solar radiation variation in the range of 1050 W m^{-2} - 1100 W m^{-2}. The average differential temperature between inlet and outlet of the collector field is maintained above 10ºC with solar radiation variation in the range of 900 W m^{-2} - 1100 W m^{-2}. At least solar radiation, the collector filed is able to maintain the temperature difference in the range of 6ºC - 8ºC.

The solar flat plate collector field's efficiency is calculated and shown in Fig. 3. The collector field's efficiency is low during the initial period due to the cold start of solar FPC with water. As solar radiation increases, efficiency of the solar FPC field increases and later decreases when solar radiation decreases.

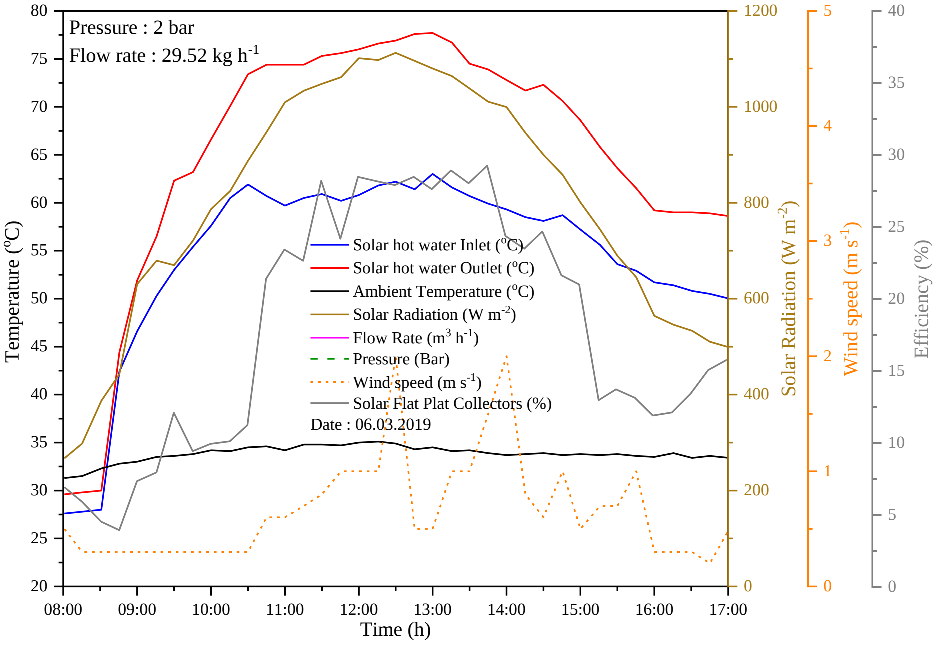

Fig. 3: Performance of solar flat plate collectors

5.2. Experimental investigation of Flash chamber performance

Figure 4 shows the performance of flash chamber. It is observed that the temperatures of flashed steam, hot water inlet and outlet of flash chamber increase and later decrease. This is due to varying hot water inlet temperature from solar field. The hot water from solar FPC is flashed to steam at saturation pressure of flash chamber. The maximum steam temperature is realized in the range of 60ºC - 65ºC at the corresponding flash chamber pressure of 0.13 bar - 0.18 bar.

The efficiency of flash chamber is calculated and is shown in Fig. 4. Initially the temperature of hot water is lower and does not match with the saturation pressure of flash chamber. So, the efficiency of flash chamber is lower and increases as time progresses. After reaching the flashing point of hot water, the flash chamber efficiency is in the range of 65% - 75%. The decreasing trend in the efficiency of flashing is due to lower hot water temperature of the flash chamber.

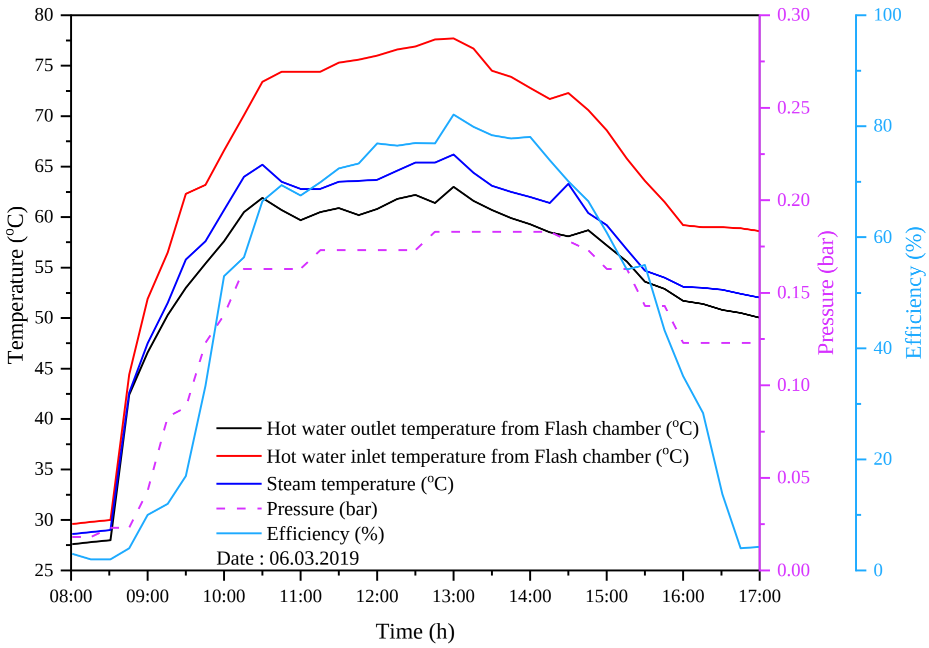

Fig. 4: Performance of Flash Chamber

5.3. Experimental investigation of Multi-stage evaporator performance

Multi Effect Evaporator performances are studied based on the temperatures of flashed steam, brine water, distillate water and non - condensable gases (NCGs) in each effect.

Steam temperatures of the first and the last effects of MED at the corresponding pressure are shown in Fig. 5. It is observed that the steam temperatures of all the effects are initially at lower temperatures. This is due to cold start of the system. As time progresses, the steam temperatures are in the increasing trend till reach peak production rate and later decrease due to decrease in chamber pressure of MEE.

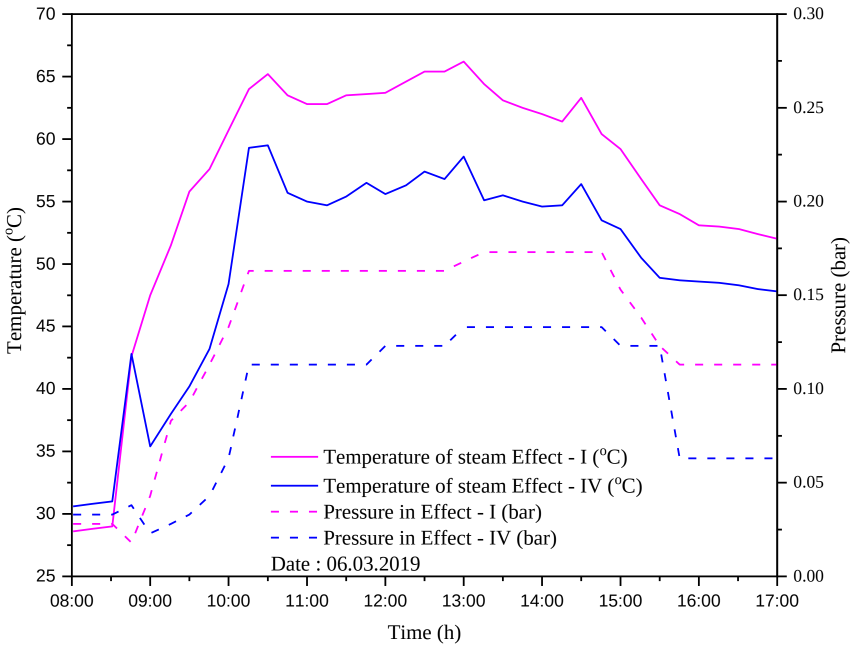

Fig. 5: Variation of steam parameters in MED

Brine water temperatures of all the effects in MED are shown in Fig. 6. The temperature profiles of brine water increase initially and later decrease. It is also observed that the brine water temperature in the first effect is higher when compared to the other effects. This is due to sea water's temperature after the steam generation at saturation pressure of the chamber. The average brine water temperature from the last effect of MEE is in the range of 45°C - 47°C, with chamber pressure in the range of 0.09 bar - 0.13 bar.

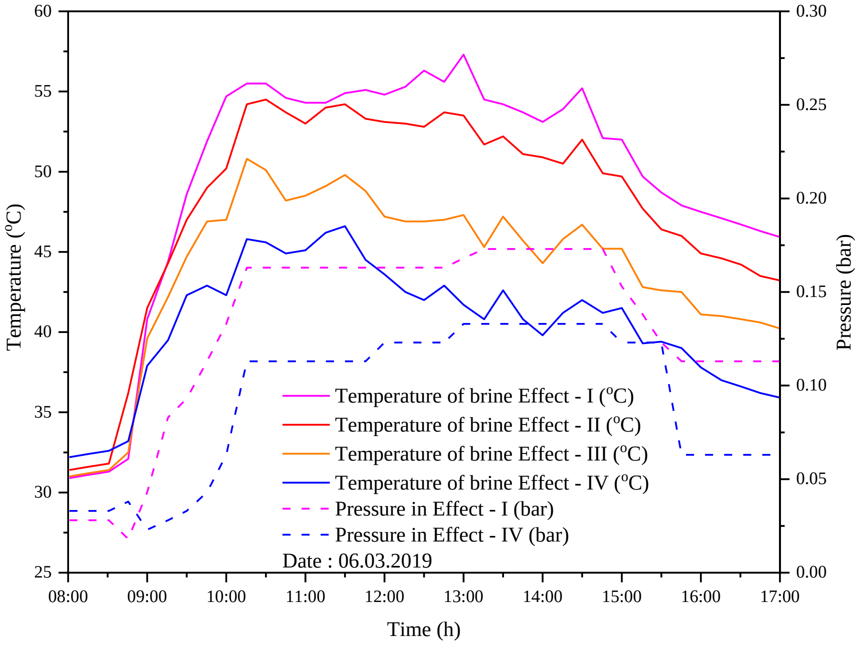

Fig. 6: Variation of brine parameters in MED

Distillate water temperatures of all the effects in MED are shown in Fig. 7. The temperature profiles of distillate water increase initially and later decrease. It is also observed that the distillate water temperature in the first effect is higher when compared to the other effects. The average distillate water temperature from the condenser is in the range of 40°C - 45°C.

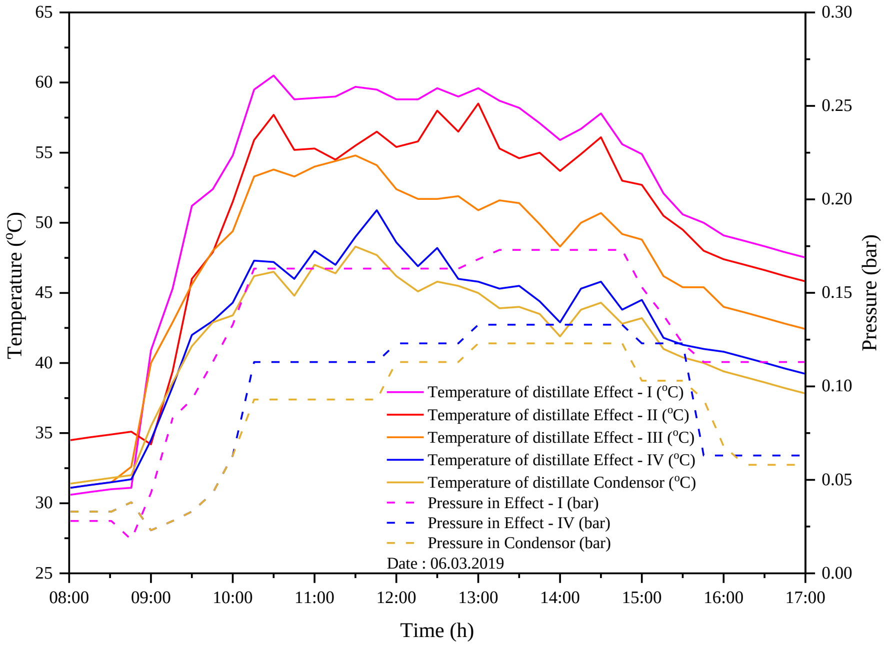

Fig. 7: Variation of distillate parameters in MED

Non – Condensable Gases (NCGs) temperatures of all the effects in MED are shown in Fig. 8. The temperatures of NCGs increase initially and later decrease.

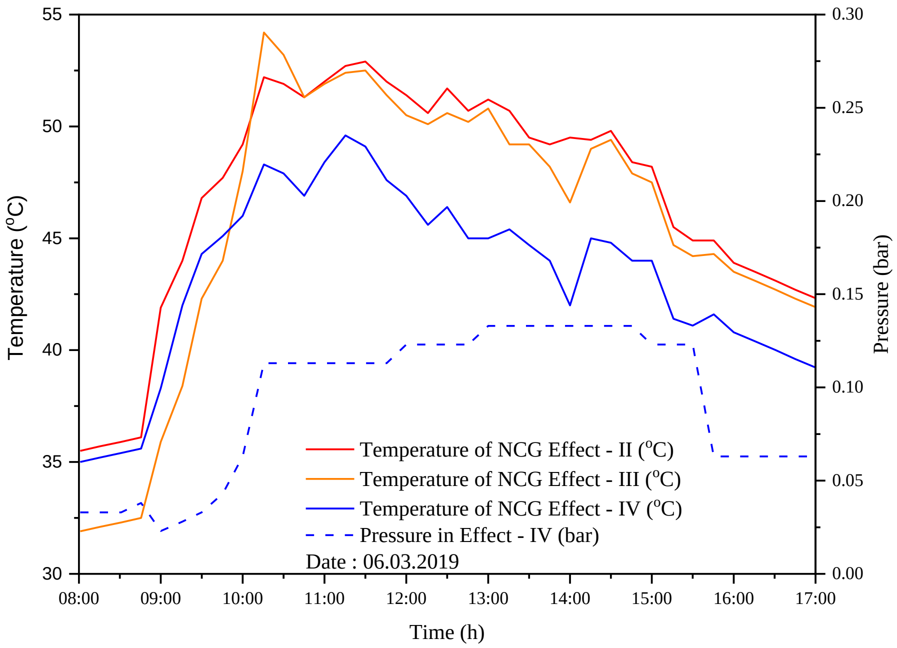

Fig. 8: Variation of NCGs parameters in MED

5.4. Experimental investigation of condenser performance

Figure 9 shows the performance of the condenser. In the condenser, sea water inlet flow rate is maintained at 20.6 $m^3 h^{-1}$ with a pressure of 0.8 bar. The average sea water inlet temperature is 30°C. It is observed that the average outlet temperature of sea water is in the range of 40°C - 43°C. During this period, the maximum outlet flow rate of distillate is observed, when the average condenser differential temperature is in the range of 10°C - 13°C. The average distillate water flow rate during the production period is l.04 $m^3 h^{-1}$.

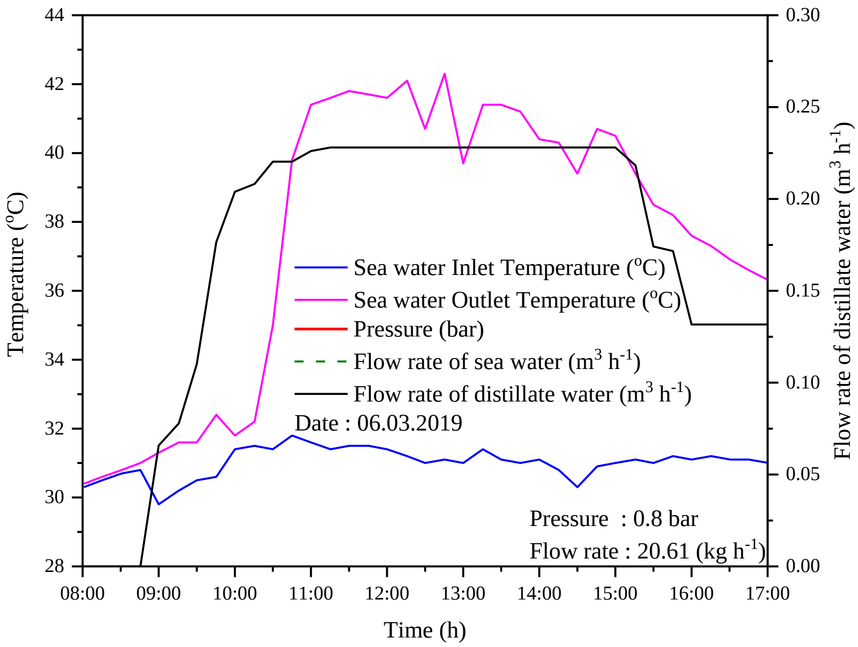

Fig. 9: Variation of parameters in condenser

5.5. Experimental investigation of ejector performance

The entrainment ratio of the ejector is studied for the performance of ejector of the solar MED plant as shown in Fig. 10. It is observed that the entrainment ratio of the ejector increases initially. Due to the initial starting condition, NCGs are accumulated at the condenser. As time progresses, distillate water production increases along with NCGs in the condenser. The entrainment ratio is maintained as constant at peak production rate of distillate. Later, the entrainment ratio decreases due to less distillate production rate.

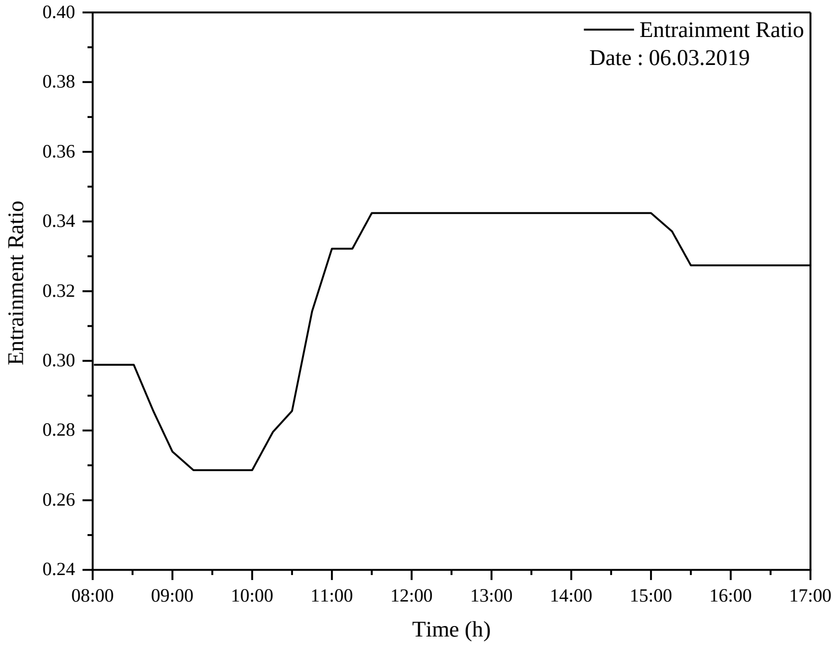

Fig. 10: Variation entrainment ratio

5.6. Quality analysis of water

The quality of distillate water is tested in terms of Total Dissolved Salts (TDS) and the unit of TDS is ppm. The distillate TDS from the plant is tested every 15 minutes of time interval on all the experimental days. Figure 11 shows the variation of distillate TDS from the plant. It is observed that the distillate TDS is 20 ppm initially and as time progresses, the average quality of distillate TDS is realized in the range of 1 ppm - 5 ppm.

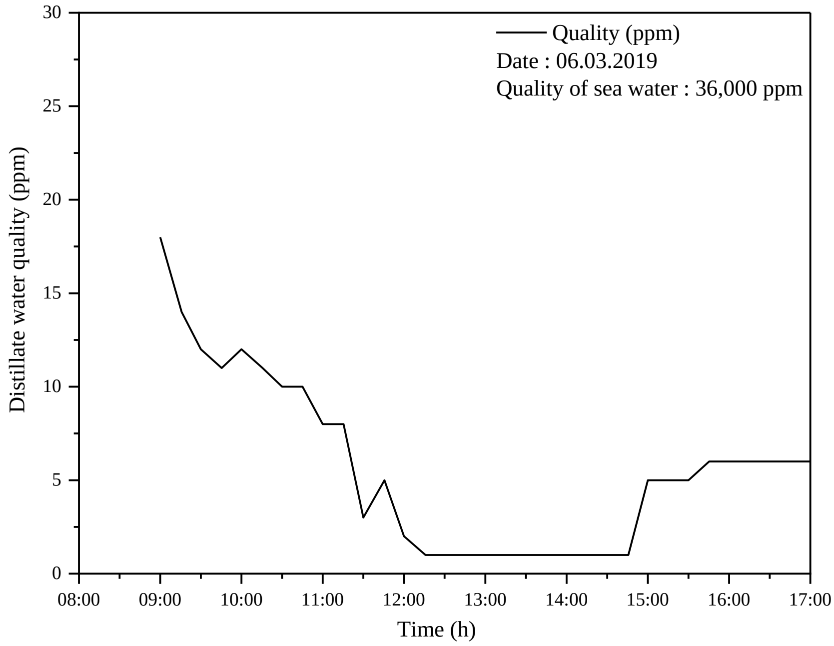

Fig. 11: Variation of distillate TDS in the desalination system

6. Conclusions

Solar Multi-Effect Desalination plant components are integrated and tested using sea water at Vivekananda Kendra, Kanyakumari, India. Solar MED plant performance is studied by varying the flow rate of solar flat plate collector field and keeping plant inlet sea water flow rate and vacuum pressure at condenser as constant on all the experimental days. The solar flat plate collector performance is studied and observed that the maximum efficiency of solar FPC is in the range of 30% - 35%. The maximum hot water outlet temperature from solar FPC is realized in the range of 70ºC - 76ºC. During the operation of the plant, vacuum pressure is maintained by using an ejector. The average entrainment ratio is in the range of 0.3 - 0.35 during peak operational hours. The desalination plant produces 6,400 liters per day using solar energy. The maximum production rate of 1.008 $m^3 h^{-1}$ is observed during peak sunshine hours. The distillate TDS is tested and is in the range of 1 ppm - 5 ppm.

7. Acknowledgments

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