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Allocation of thermal vapor compressor in multi effect desalination systems with different feed configurations

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ABSTRACT

Multi-Effect Desalination system with thermal vapor compression (MED-TVC) is a promising large-scale thermal water production technique. In MED, multiple evaporators are used where vapor is formed in each one using the heat generated from condensing steam/vapor in the previous effect, resulting in high Performance Ratio (PR). A thermal Vapor compressor is used with the MED system to extract a portion of the formed vapor formed in an effect and mix it with motive steam to reduce the rate of steam from a power plant and decrease the pressure in the effects. The top brine temperature of MED system is limited to a value around 65 °C to avoid scale formation on the outer surface of tubes in the evaporator.

In this study, a mathematical model is developed to identify the optimum location of the thermal-vapor-compressor (TVC or ejector) attached to the Multi Effect Evaporation system. Both forward and parallel feed configurations are investigated. The performance of the system is evaluated using the main performance indicators such as performance ratio (PR), surface area of the evaporators and condenser, and the specific cooling water flow rate needed for condensing the vapor that reaches the down condenser.

Locating the TVC at the middle effect resulted in the best unit performance regardless of the number of effects. That is, the highest PR, lowest specific cooling water flow rate are resulting from placing the ejector (TVC) at N/2 where N is the number of effects. Changing the TVC location did not affect the specific heat transfer area, which means that the plant capital cost is not affected by placing the TVC in its optimum location within the practical range of TBT.

1. Introduction

Desalination of seawater and brackish water is receiving increased attention due to the scarcity of water in many places in the world. Due to increase of population rate around the world and the constant amount of fresh water in the planet, the need arises to develop new sources for fresh water. Desalination can be basically classified into two main types: thermal and membrane. The thermal desalination methods are classified into two types, heating and evaporation followed by cooling and condensation that is a widely used technique. The second one involves freezing seawater followed by melting it.

The Multi Effect Desalination processes fall under the former category where seawater is evaporated to pure vapor and then condensed at reduced pressure through a series of effects/stages. A number of evaporators generate water vapor at progressively low pressure, as the pressure decreases, water boils at lower temperature. Then, the vapor of an effect works as a heating source for the next effect; releasing its latent heat of condensation that is used to heat the sprayed seawater in that effect. As the number of evaporators increases, the performance ratio, PR (defined as the ratio of desalinated water flow rate to the steam flow rate used in the first effect) rises depending on the heat exchanger tube arrangement. Desalinated water is collected as vapor condenses in each effect. The main features of Multi-Effect evaporation system (MED) include

- It is a combination of single effect evaporators connected together
- Formed vapor in one effect is the heat source in the next effect releasing latent heat as it condenses.
- The drawback of the single effect system of high energy brine rejected to the environment is avoided since this brine stream is reused in at least two configurations of MED systems.

MED system is known to have low specific energy consumption and relatively low steam temperature admitted to the first effect to operate the system.

Fig. 1 shows a simplified sketch of the forward feed MED system in

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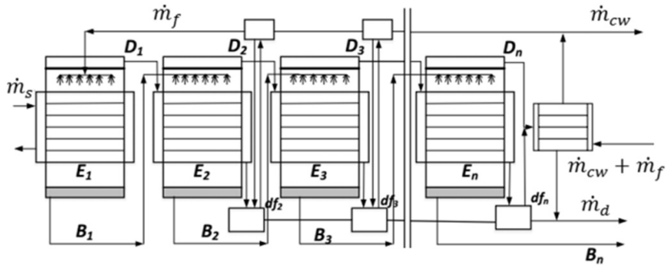

Fig. 1. Forward feed multi effect evaporation system.

which feed water stream leaving the condenser is forwarded to be sprayed in the first effect. Brine leaving an effect is sprayed in the next one. In this arrangement, both the feed stream and the vapor are flowing from the first effect to the last one. Although the multi stage flashing system (MSF) is more widely used as a thermal desalination technology for large scale production in the Arabian Gulf region, the MED system is reported to be better thermodynamically due to lower energy consumption compared to MSF systems. The ability to operate at low temperature and the use of steam from a power plant turbine as a source of heat for MED system result in low specific energy costs for desalinating seawater [1].

Therefore, MED are merged with power plants in a combined water-power cogeneration system [2] to reduce the energy cost in producing large quantities of fresh water. Darwish et al. [3] reported that the normal Multi Effect Boiling system has the benefit of exploiting a low-temperature source of heat when it works at relatively low top brine temperature (TBT), leading to lower consumed energy consumption compared with the more dominating MSF systems. The decrease in ΔT to $< 2\,^{\circ}C$ increases the heat transfer areas considerably [4]. It is important to state that the relatively low TBT is to avoid scale formation that may occur on the outer surface of evaporator tubes. On the other hand, the lowest brine temperature is dictated by the environmental (ambient) conditions and hence is set to a value close to 40 °C. Nevertheless, the increase in Gain Output Ratio (GOR) is due to the use of feed heaters, that would also complicate the system and rise its initial cost. Pumps also increase the system energy requirements. MED systems are reported to consume about 50% of the pumping power compared to MSF systems. MED desalination systems provide higher overall heat transfer coefficients utilizing only latent-heat transfer. They also have low specific heat transfer surface area compared to MSF systems [5]. In another comparison with MSF, Darwish and El-Dessouky [6] showed that the MED-TVC system is superior to the MSF system in terms of better sensitivity to the inlet steam variation, less pumping power, and a better ability to run at various modes.

Several researchers modeled MED system performance [3,6,8,11,12–14,18,31]. Some considered different layouts including forward feed FF, backward feed BF, and parallel feed PF [2,12,21], or through focused analysis of a certain layout (feed forward), [8] and stated that the performance ratio mainly depends on the number of effects more than its dependence on the top brine temperature. Al-Sahali and Ettouney [7] developed simple simulation model for MED-TVC that was based on sequential solution rather than iterative procedure and assumed constant temperature drop, specific heat and heat transfer coefficient.

Mistry et al. [9] developed a model of MED system that is flexible enough to be used in cogeneration systems optimization to produce both water and power. The developed model is capable of studying both forward and parallel feed arrangements. It is important to state that, in this model, it is assumed that all the vapor leaving an effect passes first by a feed preheater associated with this effect to preheat the feed seawater. The two-phase flow (vapor and condensate) leaving the preheater is directed to the next effect to act as a heat source to generate vapor through releasing the remainder of the latent heat of condensation. In contrast, other models such as [7,10,11,31] divide the vapor stream formed in an effect to a potion that is driven to condense in the feed preheater and then flows to the product pipe whereas the remainder of the vapor is driven to the next effect to generate a new portion of vapor.

Ameri et al. [12] investigated the effects of operating parameters on the MED system performance. They studied the influence of number of effects, inlet steam pressure to the first effect, temperature difference between the effects, and the temperature of feed seawater. They illustrated that there is an optimum number of effects for the system at constant production rate. It depends on the seawater salinity effect-to-effect temperature difference and inlet seawater temperature. They also reported that increasing steam pressure leads to higher performance ratio and heat transfer area and decreasing cooling water flow rate. Kamali and Mohebini [15] analyzed a multi effect desalination system, thermal vapor compression MED-TVC. They reported that condenser temperature and pressure affect the system temperature and pressure. Increasing the condenser surface area leads to lower top brine temperature. Therefore, increasing both gain output ratio and the system lifetime. They used a simulation model to optimize the performance of actual MED producing 1500 ton/day.

Bin Amer et al. [16] examined analytically MED-TVC (thermal vapor compression) system. Results showed that GOR ranged from 8.5 for a system comprised of 4 effects to 18.5 for 12 effect-system at TBT that ranges from 55.8 °C to 67.5 °C. The optimal compression ratio was reported to be between 1.81 and 3.68 whereas the optimal entrainment ratio varies from 0.73 and 1.65. Minich et al. [17] developed an analytical model to examine variation of GOR, steam pressure with heat transfer surface area for a TBT of 60 °C. They reported an optimum GOR and TBT of 14 and 110 °C, respectively. They reported that the limitation of TBT for MED systems is 60 °C. This value prevents MED system from taking full advantage of potentially higher heat transfer coefficients and the constant temperature difference that drives the heat transfer. El-Allawy [18] studied the impact of changing TBT and number of effects on the GOR of a MED system with and without thermal-vapor compression. The TBT was varied between 58 °C and 70 °C and the number of effects increased from 3 to 6. They reported that the increase of number of effects from 3 to 6 results in an increase of the GOR by nearly two-folds. Hamed [19] reported that the performance ratio increased with inlet seawater insignificantly. Then, Hamed, et al. [20] compared thermal performance of the MED-TVC system with these of the conventional multi-effect boiling (MED) and mechanical vapor compression (MVC) desalination system. They reported that that MED-TVC system has the least exergy destruction among the three systems. They also indicated that Increasing the number of effects and decreasing the TBT can reduce the exergy losses. Al-Najem [21] conducted a parametric thermodynamic analysis for TVC and MED-TVC. The study reveals that the steam ejector and the evaporator are the main source of exergy destruction in the TVC system. Greogorzewski and Genthner [22] reported that MED with parallel feed arrangement with preheater is yielding slightly better thermal performance compared to forward feed with preheaters, due to lower exergetic losses.

Recently, AlMutaz and Wazeer [23] developed a mathematical model of multi effect Desalination, parallel cross arrangement with thermal vapor compression (MED-TVC-PC) system and compared the results with the available existing plants. They reported that GOR for each simulated plant is close to the GOR of the actual plant. Kouhikamali and Sharifi [24] investigated the performance of a MED-TVC system and reported that better thermocompressor performance is attained at higher entrainment ratio. In addition they indicated that the geometry of the thermocompressor also affects the entrainment ratio.

Esfahani et al. [25] and Padillaa and Rodriguezb [26] proposed integrated absorption heat pump and a MED with vapor compression refrigeration cycles to generate cooling effect and pure water simultaneously. The latter [26] indicated the importance of optimizing such system for better performance.