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Development and optimization of ME-TVC desalination system

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ABSTRACT

Significant and rapid developments have taken place recently in the multi-effect thermal vapor compression (ME-TVC) desalination system of SIDEM Company, particularly in enlarging the unit capacity. The new trend of combining ME-TVC with conventional multi-effect has allowed this unit capacity to increase from two to eight million imperial gallons per day (MIGD) in the last decade. This considerable increase in capacity, poses a real competition to the multi stage flash system (MSF) as a large-scale production plant with lower operation temperatures.

A steady state mathematical model of the ME-TVC desalination system is developed in this paper using Engineering Equations Solver (EES) to evaluate the model system performance. The model validity is examined against three commercial ME-TVC units which showed good results. The main improvements in the performance during the past ten years are also outlined and discussed. Another purpose of this paper is to determine the optimum operating and design conditions of the ME-TVC desalination system through mathematical modeling optimization. A MATLAB algorithm solution is developed and used to solve model equations, where a different number of effects were tested to maximize the gain ratio using (1) Smart Exhaustive Search Method and (2) Sequential Quadratic Programming. Results showed that the maximum gain ratio varied between 8.5 and 18.5 for 4 and 12 effects with the optimal top brine temperature ranging between 55.8 and 67.5 °C and a reasonable specific heat transfer area. The optimal ranges of compression and entrainment ratios are between 1.81 to 3.68 and 0.73 to 1.65 respectively. The optimal results of 4-effect TVC unit are also compared with three commercial 4-effect units having almost the same input, which showed that further improvement in the distillate output production, compression and entrainment ratio can be achieved by combining the ME-TVC system with conventional multi-effect unit.

1. Introduction

Rapid developments have occurred recently in the Multi-Effect Thermal Vapor Compression (ME-TVC) desalination system, which makes this technology competitive enough to the multi stage flash (MSF) desalination system. It becomes available in large units up to 8 MIGD; operates at low top brine temperatures around 60 °C, has high gain ratio (GR) up to 16 and lower expenditures (Table 1). The strong competition between manufacturers led to improved designs based on technical optimization along with their experiences in the previous projects [2].

The French company SIDEM commissioned several plants of Multi Effect (ME) desalination system since 1890 [3]. Lately, it developed the thermal vapor compression system in several projects around the world, particularly in the United Arab Emirates (UAE). The first two ME-TVC units were introduced in 1973 at Das Island in UAE with a 125 m^3/d unit capacity; each unit consisted of two effects. The unit capacity increased to 1500 m^3/d in 1979 where four units were installed in Ruwais Refinery [4]. The first ME-TVC desalination unit of 1 MIGD capacity was commissioned in the remote western areas of UAE in December 1991 at Jabal Dhana and Sila, followed by 2 units of 1 MIGD capacity at Mirfa. Each of these units had four effects with gain ratio close to 8. A boiler was used to supply the motive steam at 25 bars [5]. The next unit capacity was 2 MIGD which started up in 1995 in Sicily (Italy). It consisted of four identical units; each had 12 effects, with gain ratio of 16. The steam was supplied from two boilers at 45 bars to the plant [6]. Due to the adequate performances of the plants, more units of 1, 1.5 and 2 MIGD were ordered from SIDEM and commissioned in UAE between 1996 and 1999 [4]. The next range in size was achieved with two units, each of 3.5 MIGD in 2000 in Umm Al-Nar and 14 units of 3.77 MIGD in 2002 in Al-Taweelah A_1. Each unit had nine effects with gain ratio close to 8. The steam was extracted from a steam turbine at 2.8 bars to supply two steam ejectors in each unit [7]. The next unit that was commissioned was in Layyah with a nominal capacity of 5 MIGD using medium pressure motive steam [4]. The largest unit ever built to date for ME-TVC was 8 MIGD, which was built for a contract with Sharjah Electricity and Water Authority in 2005 [8]. Now, this technology is starting to gain more market shares in Saudi Arabia and SIDEM has been selected to build one of the largest ME-TVC desalination plants with a total capacity of 176 MIGD, (6.5 MIGD × 27 units) in Al-Jubail Industrial City [9].

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Table 1
Several projects of ME-TVC with different capacities commissioned by SIDEM.

Year	Location	Country	Unit capacity	No. of units	TBT, °C	GR	Unit capital cost, $/m^3/day [1]
1991	Jabal Dhana, Mirfa, Sila	UAE	1 MIGD	4	58.8	8	NA
1995	Trapani	ITALY	2 MIGD	4	62.2	16	NA
2000	Umm Al-Nar	UAE	3.5 MIGD	2	62.8	8	1100
2001	Layyah	UAE	5 MIGD	2	NA	NA	990
2002	Al-Taweelah A_1	UAE	3.77 MIGD	14	62.8	8	750
2005	Sharjah	UAE	8 MIGD	NA	NA	NA	NA

Although several studies have been published concerning ME-TVC desalination system in literatures, to the best of our knowledge, optimization of ME-TVC desalination system has not been tackled through mathematical modeling, and thus a mathematical model will be developed in this paper for designing a ME-TVC unit using a simple optimization procedure. The MATLAB program will be used to determine the optimum operating and design conditions of a different number of effects to maximize the gain ratio using two methods: (1) Smart Exhaustive Search Method and (2) Sequential Quadratic Programming. The results of this optimization will be compared with some of the existing ME-TVC plants through some case studies. The main improvements in ME-TVC will also be outlined and discussed.

2. Process description

A simplified schematic diagram of a ME-TVC desalination system with n effects is presented in Fig. 1. It consists of (1) a steam jet ejector which acts as a thermal compressor, (2) horizontal falling film evaporators (effects), (3) distillate, feed, condensate and brine disposal pumps to circulate the streams, (4) an end condenser, (5) feed heaters and (6) flashing boxes. The motive steam D_s is directed at relatively high pressure P_s into the steam ejector. Part of the vapor formed in the last effect (D_r) is entrained and compressed by the steam ejector along with the motive steam (D_s+D_r) into the first effect where it condenses. The latent heat of condensation is used to heat the feed F_1 from T_{f1} to the boiling temperature T_1 and evaporates part of that feed by boiling equal to D_1. Part of the condensate (D_s) returns to its source and the other part (D_r) enters the first flashing box where a small amount of vapor flashes off due to pressure drop. This flashing vapor is passed through the first feed heater along with the vapor formed in the first effect to heat the feed F_1 from T_{f2} to T_{f1} and it then flows as a heating source to the second effect and so on. The brine leaving the first effect (B_1) is directed to the next effect which is at a lower pressure, so that flashing occurs releasing additional vapor. This process is continued up to the last effect n. The vapor produced in the last effect D_n is split into two streams. The first stream D_r is entrained by the steam ejector and the remainder D_f flows into the end condenser where it condenses by the cooling seawater stream M_c. The latent heat of condensation is used to heat the seawater temperature from T_c to T_f. Part of the cooling stream flows to the effects (F) and is heated in a series of feed heaters, before it splits into each effect and the remainder (M_c-F) is rejected from the system [10].

3. Mathematical model

A mathematical model of the ME-TVC desalination system (Fig. 1) is presented in this section. The model is developed by applying mass and energy conservation laws to the evaporators, steam ejector, feed heaters and end condenser. The following assumption were used to simplify the analysis: steady state operation, negligible heat losses to the surrounding, equal temperature difference across feed heaters, salt free distillate from all effects and variations of specific heat as well as boiling point elevation with the temperature and salinity are negligible.

The brine temperature in an effect is less than that of the previous one by ΔT. So, if the brine temperature in the effect i is assumed to be T_i, then the brine temperature in the next effect $i+1$ can be calculated as follows:

$$T_{i+1} = T_i - \Delta T, \quad i = 1, \quad 2, \ldots n \tag{1}$$

The temperature of the vapor generated in the effect i, T_{vi} is lower than the brine temperature by the boiling point elevation plus non

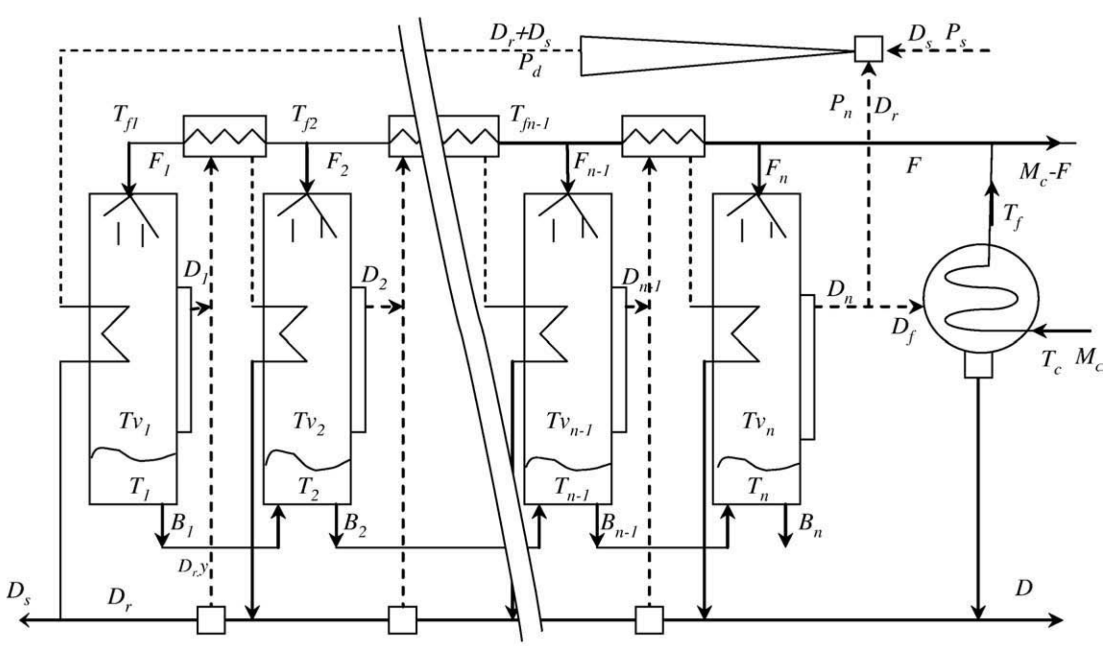

Fig. 1. Multi Effect Thermal Vapor Compression system with n effects.