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Dynamic modeling of multi-effect desalination with thermal vapor compressor plant

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HIGHLIGHTS

- Multi-Effect Desalination (MED) is one of the most common techniques that provides a considerable quantity of potable water.
- The aim is to obtain a dynamic model for MED plants in such a way that the behavior of the system in different working conditions is predicted.
- The model is simulated with the MATLAB/SIMULINK software to simulate the transient behavior of the MED plants under various conditions.
- This model is validated with actual data from an industrial plant that operate in the South of Iran.

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ABSTRACT

This paper aims to develop a mathematical dynamic model for multi-effect desalination (MED) with thermal vapor compressor plant. The developed model is based on coupling the dynamic equations of material, salt and energy balance of the system. Towards this, the plant is divided into three main subsystems; evaporators (effects), condenser and thermo-compressor. Moreover, each effect is considered to be a dynamic system of order three that represents the dynamic behavior of the evaporator. Using material, salt and energy balance physical relations, three dynamic equations are obtained for each effect where they are modified to get the state equation of the effect. This procedure is repeated for the condenser while in the thermo-compressor only static equations are considered due to its fast dynamic. The proposed model is validated by actual data of an operating plant in Kish Island (in south of Iran). The transient and steady state behavior of the model is more investigated by simulating some conditions like applying disturbance and changing the operating point which can be happened in real conditions. Due to high performance of the proposed model, it can be used in optimal designing of the MED plants and control applications as well.

1. Introduction

Energy conservation has been intensively studied since years ago. Climate change, population growth and industrial development have caused water shortage as a comprehensive crisis in many countries especially in the Middle East and North Africa (MENA). Therefore, the Persian Gulf countries such as Iran are confronted with the water shortage crisis insofar as the International Water Management Institute predicted that many of these countries would face with high water shortage by 2025 [1]. This issue has encouraged these countries to use desalination technology in the recent years.

There are several methods for water desalination. Multi-effect desalination (MED) is one of the most common techniques that provide a considerable quantity of potable water. This type of thermal desalination plants due to its advantages like low capital requirements, low operating costs, simple operating and maintenance procedures, high thermal efficiency, high heat transfer coefficient, lower energy consuming and higher performance ratio than other thermal desalination methods like MSF has been used more in the recent years [2,4]. Therefore, MED has been considered by many researchers and several works have been presented regarding performance evaluation and optimization of these systems during the past years.

Slesarenko [3] made a comparison between vertical and horizontal types of MED. He showed that the heat transfer area for the horizontal is almost twice as the vertical type of MED. In 1997 it was presented that by increasing top brine temperature (TBT) the heat transfer area of evaporator reduces (due to increasing the temperature and heat transfer coefficient of evaporator) [4]. This reference also showed that the performance of the system can be improved by increasing the value of TBT, although this increment is limited by some physical constraint such as corrosion, scaling and maintenance cost.

In order to improve the performance of the system, it is essential to obtain a dynamic model to simulate and predict the behavior of the plant. Whereas some researchers have studied performance

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improvement of desalination plants, but there are a few references that investigate the desalination plant from dynamic modeling point of view, especially for MED. The steady state modeling of the MED desalination plant, of course, has been the subject of various studies in the past.

Al-Juwayhel, El-Dessouky and Ettouney [5] performed a comparison for four types of single effect evaporator desalination systems. They developed mathematical models for the proposed systems in steady state conditions. The analysis was based on comparison of the performance ration, specific power consumption, specific heat transfer area and specific cooling water flow rate. In 2009 a MATLAB algorithm was developed and used to solve a mathematical model optimization problem, where different numbers of effects were tested to maximize the gain of output ratio [6]. Ettouney in [7] described a computer package for simulation of different types of multi-effect desalination systems. This package intended to serve as an educational tool to study the MED coupling to nuclear reactors or fossil energy sources such as gas turbine combined cycle. Hanbury [8] presented a steady-state solution to solve equations of a MED plant. The simulation was based on steady state behavior in boiling heat transfer coefficient, unequal inter-effect temperature differences. In [9] a comparison was made between four different types of single effect desalination systems. For each one, the steady state mathematical equations were written. Finally, performance ratio and heat transfer area and cooling seawater flow rate were compared. Results showed that energy consumption of MED with mechanical vapor compressor (MVC) decreased by reducing the boiling temperature of water. Hatzikioseyian and Vidali [10] developed a mathematical model that predicted the performance of MED plant, assuming horizontal tube film evaporator. The model was based on mass and energy balance in the steady state conditions. Aly and El-Figi [11] presented a mathematical model to analyze the steady state behavior of the multi-stage and multi-effect desalination systems. These models show the role of fouling and its effect on the plant performance ratio.

Regarding the dynamic model of desalination systems there are some useful references for MSF plants. For example Bodalal et al. [12] developed a dynamical model and validated it by using data from an actual plant obtained from an operating MSF unit. But not much attention has been paid in the subject of dynamic modeling of MED plants. In this regard, Narmin and Marwan in [13] developed a dynamic model for the MED process based on mass and energy and salt balance equations, however without any validation by actual data.

In the present work the same procedure of [13] is used and the model is extended with more details and less assumptions. Compared to the developed model in [13], the proposed model in this paper considers distillate level of condenser, time delay between effects and the model of thermo-compressor. In addition, the proposed model has been validated by actual data of an operating plant.

The aim of this paper is to obtain a dynamic model for multi-effect desalination (MED) plants in such a way that the behavior of the system in different working conditions is predicted. MED process consists of three parts that are evaporators (effects), condenser and thermo-compressor where the governing physical relations are analyzed for each one and as a result mass, energy and salt balance dynamic equations are written for each effect. These equations are integrated and three nonlinear differential equations are obtained. The equations are given based on defining three state variables, namely, brine level, brine salinity and temperature of the effect that represents the dynamic behavior of each effect. The same procedure applies to the condenser but due to the absence of salinity in this part, we have two state variables, namely, distillate level and feed water temperature. The thermo-compressor has fast dynamic compared to the other parts, so it is considered in steady state situation. Finally all equations are combined together as physical system in which all parts are connected together in order to obtain the complete dynamic model of the MED. To have a more accurate model, the delays of the system are incorporated to the models. This model expresses relations between inputs and outputs as differential equations and can evaluate dynamic behavior in different working conditions. The model is simulated with the MATLAB/SIMULINK software to simulate the transient behavior of the multi-effect desalination plants under various conditions. Finally the model is validated with actual data from an industrial plant which operate in the south of Iran and the results and accuracy of the developed model are shown practically [24]. It should be considered that this reference is a confidential document obtained by the authors.

This paper is organized as follows: in the next section a description about the performance of MED is given and some main variables that affect the MED operation are explained. In Section 3, mathematical dynamic model of the plant is fully derived. In Sections 4 and 5, the proposed model is validated by the actual data from an operating plant and the results in different situations of the plant under disturbances are presented. Finally, Section 6 provides some concluding remarks.

2. Process description

MED process operates in a series of evaporator–condenser vessels called effects and uses the principle of reducing the ambient pressure in the various effects. There are some configurations of multi-effect desalination process. A process diagram for the horizontal parallel multiple effect desalination process is shown in Fig. 1. This process consists of six effects, main condenser and steam jet ejector. The steam jet ejector runs by the motive steam; due to design of ejector it entrains a portion of the output vapor from the other or last effect. Ejector compresses the entrained vapor by the motive steam to reach the desired temperature and pressure and also increases its flow rate [14]. The heating steam leaves the ejector and condensed in the first effect and provides energy required to evaporate seawater. The steam condensate is recycled to the power plant to its HRSG boiler feed water.

The seawater enters to the condenser and is preheated to desired temperature and then is forwarded to two directions; part of the heated seawater is used as the feed of evaporators and the remaining as cooling seawater is rejected back to the sea. The feed seawater is equally sprayed on the last four effects, due to the design of the first and second effects; the feed water flow rate which is sprayed on these effects is more than the other effects. In the first effect the feed seawater is sprayed onto the surface of all tubes of evaporator to raise rapid evaporation. The tubes are heated by externally supplied steam from a HRSG boiler in the power plant. Each effect has lower pressure and temperature than the previous effect. During this procedure, pressure drop and high temperature in the effects cause a part of the sprayed seawater on the tubes in the first effect to evaporate. Therefore, some water is evaporated and the remaining falls into the brine pool as brine. In the second effect the same procedure is carried out; the tubes of this effect are heated by the vapors created in the first effect. These vapors that run into the tubes are condensed to produce fresh water. This process of evaporation and condensation continues all the way to the last effect. On the other hand the collected brine stored in the brine pool from the first evaporator is flowed into the second effect through an orifice. This process is repeated for all effects up to the last one [15,16].

Usually some plants, due to their capacity, have been built to operate with 4 to 13 effects. The production of the MED plants is related to the number of effects. The total number of effects is limited by the total available temperature range and the minimum allowable temperature difference between two adjacent effects. Some plants have been built to operate with a top brine temperature (TBT) in the first effect of about 60–70 °C that reduces the potential for scaling of seawater [17].

Some important variables in the MED process that have role in design of control structure for the plant are listed as below:

- Top brine temperature (TBT) from the first effect; this variable affects the distillate production and the performance of plant directly.