LARGE SCALE MSF AND MED THERMODYNAMIC MODELING AND DESIGN

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Contents

Summary

Water is essential for human life and activities such as agriculture and industry. The World Health Organization (WHO) has estimated that 1000 cubic meters per person per year is the benchmark level below which chronic water scarcity is considered to impede development and harm human health. Access to safe drinking water has improved steadily and substantially over the last decades in almost every part of the world. Despite this development, it is estimated that by 2025 more than half of the world population will still be vulnerable to severe water shortage, a situation that has been called a water crisis by the United Nations according to which annual renewable resources of less than 1000 cubic meters per capita per year indicate water stress. Desalination provides an alternative source, offering water for irrigational, industrial, and municipal uses. Desalination technologies can be classified by their separation mechanisms into thermal and membrane-based systems. Thermal desalination separates

salt from water by evaporation and condensation. Thermal desalination includes multi-stage flash, multi-effect distillation, mechanical vapor compression, and thermal vapor compression. Among these techniques, multi-stage flash and multi effect distillation are most widely used in the world for large-scale water production. This chapter introduces the reader to several major topics in design and simulation of large-scale thermal desalination plants (multi stage flash & multi effect distillation). After a brief introduction to the process principles, modeling and simulation issues for each type and configuration are discussed. Special emphasis is placed on design aspects for optimization. Towards the end a conclusion and perspective section summarizes the chapter.

1. Introduction

Water and its natural resources are important for life on the earth. Water is particularly important for activities such as domestic use, agriculture, and industry. However, during the last few decades water shortage problems appeared in many countries, especially developing countries. Many remote areas of the world such as coastal desert areas in the Middle East or some Mediterranean and Caribbean islands are suffering from acute shortage of drinking water (El-Nashar, 2001). By the year of 2025, about 60% of the world population will be suffering from serious water shortages. Moreover, common use of unhealthy water in developing countries causes 80-90% of all diseases and 30% of all deaths (Fath, 2000). Due to the rapid growth of the worldwide demand for potable water, several scientists even consider such resource is more crucial than energy for the future (Dong, 2019). Desalination is a process of removing dissolved minerals from salty water for producing fresh water. Nowadays, thermal desalination processes account for more than 65% of the entire capacity of desalination industry (Dong, 2019).

Seawater desalination is and will be a fundamental process to deal with fresh water shortage in many regions of the world. Desalination technologies can be classified by their separation mechanisms into thermal and membrane systems. Thermal desalination separates salt from water by evaporation and condensation, whereas in membrane desalination water diffuses through a membrane, while salts are almost completely retained. Thermal desalination includes multi-stage flash, multi-effect distillation, mechanical vapor compression, and thermal vapor compression while membrane desalination contains reverse osmosis, ion exchange, and electro-dialysis processes. Multi effect distillation and multi-stage flash are the techniques that are most widely used in the world (Sharaf et al, 2011). Multi-stage flash (MSF) desalination process has been used for decades for making freshwater from seawater and is now the largest sector in desalination (Al-Hamahmy et al, 2016).

Multi-Stage Flash (MSF) evaporation process is currently the workhorse of the desalination industry with a market share close to 60% of the total world production capacity (El-Dessouky et al, 1999). Multi Stage Flash (MSF) process has also a possibility for use with solar power. Operation temperatures of multi-stage flash distillation systems allow the use of different solar collectors in solar powered plants (Garcia-Rodriguez and G6mez-Camacho, 1999). A conventional multi effect distillation (MED) process uses about half of the MSF pumping energy, and almost the same amount of thermal energy used by the MSF, if both have the same gain ratio (Sharaf et al, 2011). However, a recent trend of using low-temperature MED allows the use of low temperature (in the range of 70^{o}C) steam as heat source, and consequently of low exergy and low equivalent work. This can bring the MED consumed equivalent mechanical energy close to that consumed by an efficient RO system. An example construction in Abu Dhabi of an MED plant with a 240,000m^3/day capacity shows a breakthrough in large-scale MED plants (Bernhard and Zarza, 1996).

It is clear that MSF and MED are considered dominant in large-scale desalination industry; however, the processes need some improvements in order to compete with the other desalination technologies such as reverse osmosis and electro-dialysis. Therefore, modeling and simulation are considered a vital option in order to save time and cost. The simulation type is considered a very important dimension because it can decide the direction of the program. Henghua et al (2019) adopted a mathematical model of multi-stage flash (MSF) chamber based on the volume of fluid (VOF) multiphase modeling. Tanvir and. Mujtaba (2008) used gPROMS model builder optimal design and operation of MSF desalination process. Mabrouk et al (2006, 2007a, 2007b) created a software library by the use of graphical user interface (GUI) model created by the aid of visual basic toolbox. Thomas et al (Thomas et al, 1998) presented a mathematical model and its solution procedure to simulate the steady state and dynamic behavior of multistage flash desalination plants. Gambier and Badreddin, (2004) used Matlab/Simulink for properties of the flashing process. Al-Hamahmy et al (2016) modeled a special design for MSF by applying a method named “brine extraction”. The technique involves extracting a part of the cooling brine from the water boxes and re-injecting this extracted brine directly into the flashing chambers; i.e., the extracted brine will not pass through the brine heater or high-temperature flashing stages. Economically speaking, brine extraction is expected to reduce the surface area of condenser tubes at the brine heater and high temperature flashing stages, and shift the vapor condensation heat load to lower temperature flashing stages, where a cheaper condenser tube material is used. Hamid Rezvani Dastgerdi et al, (2016) developed a new distributed boosted multi-effect distillation process to effectively harness low-grade “waste heat” in the temperature range 65°C-90°C. Palenzuela et al (2014) introduced a steady-state mathematical model of a vertically stacked forward feed multi-effect distillation (MED) plant. The model has been developed taking into consideration the same design and operational characteristics as the pilot MED plant at Plataforma Solar de Almería (PSA), in the southeast of Spain. Seungwon Ihm et al, (2016) introduced and energy cost comparison between MSF, MED and SWRO in order to investigate energy consumption.

Peyman Talebbeydokhti et al, (2017) presented a Low Temperature-MED system integrated with a novel Parabolic Trough Concentrated Solar Power plant. The study explored the use of the waste heat in CSP-DES plant to feed a Low Temperature-MED technology. Nannarone et al (2017) investigated an accurate and flexible model of the MED desalination process, implemented within the CAMEL-Pro^{TM} Process Simulator. The model validation embraced some case studies, to prove the reliability of the tool. A remarkable result returned by the code, in terms of process variables and plant operational parameters, guaranteed an effective support in each design step. Zhe Dong et al (2019) introduced a lumped-parameter dynamic model for MED-TVC process. The plant control design is deployed as a program on Matlab/Simulink platform. It is quite clear from the literature that modeling techniques are diverse.

Modeling techniques and simulation studies are considered a vital tool for design and optimization for both MSF and MED. As mentioned in the previous paragraph, a number of computer programs have been developed for desalination processes simulation, design and optimization. The available software packages of HOMER, Hybrid2, RETScreen, iHOGA, INSEL, TRNSYS, HYBRIDS, SOMES, SOLSTOR, IPSYS, ARES, and SOLSIM can only solve special cases of solar thermal or desalination systems. Some of these programs are focused only on Renewable Energies (RE) and the rest focus only on desalination without any combination between the two technologies. Moreover, most of these codes have no more than one or two modeling dimensions i.e., some focus on performance and others focus on cost calculation—not thermo-economic analysis that includes both energy and exergy with optimization routines.

In addition, most of these programs are rigid, on-off simulators, fixed-point calculators and step forward. These computer programs were developed in three stages. In the first stage, a special purpose program (one-off program) is used to solve the problem. For a particular solar heating process (or unit) with a fixed configuration, it is possible to write a mathematical model describing the process in the form of an 'on-off' computer program. The structure of these programs is rigid, simple, and straightforward. All that the user has to do is to supply is the data and the executive handles the program in the same way, irrespective of the nature of the process simulated. The disadvantage of such programs is that a model exists for only one process and any changes made to that process might require extensive re-programming. However, the specialized program makes it much easier to produce mathematical models of sufficient realism. It is obvious from the literature that the modeling software packages are presented to solve a special case where some of it is focused on renewable and the rest are focused on only desalination without any combination between the two technologies. Moreover; most of it has no more than one or two modeling dimensions i.e., part focused on performance and other focused on cost not thermo-economic and/or energy not exergy. Therefore, the need for a general, flexible, accurate, and visualized software package for renewable desalination systems has become an urgent need. In this chapter, a new software package for modeling and simulation for MED and MSF desalination systems is presented. The technique of modeling, the process description, the modeling dimension, the software features, capabilities, and the interface explanation are also presented. The developed model should be implemented for some capabilities to overcome previous programming problems and limitations; such as the brine recycle streams. The developed model overcomes the problem that appears in other techniques of simulation such as sequential approach, and matrix manipulation technique. MSF brine recycle and MED parallel feed configurations are considered for study in this chapter.

2. Mathematical Modeling

Engineering processes (especially renewable energy combined with desalination processes) consist of a number of interactive units. Using these units in a wide range of processes and configurations can be obtained. To understand the behavior of these processes under different design and/or operating conditions, the proposed flexible computer program will manipulate large number of flow sheeting problems. The

process modeling technique will have some requisites such as the dimension of the technique utilized. The main modeling dimensions are:
• The mathematical technique environment (MTE).
• The simulation types.
• The data analysis type.

The MTE is normally decided by the programmer from the beginning by choosing the program language or technique. The MTE is also divided into three main categories: the first is called special purpose program (sequential or simultaneous marching), the second is a general-purpose program (sequential or simultaneous modular approaches), and the third is a new visual system program (subsystems are broken to physical, functional, or both concepts). The simulation type is considered a very important dimension because it can decide the direction of the program. This simulation type can be generally divided into three classes: (a) performance, (b) design, and (c) optimization. In the performance type (a), the variables associated with the feed streams to a process unit and all design parameters (such as PV module area, PV panel's dimensions, etc.) are assumed to be known. The variables associated with the internal and output streams are the unknowns. In the design problem (b) (the present work), some design parameters (areas, dimensions, voltage, current, number of cells, unit cost, etc.) and/or feed variables are left unspecified and become unknown. The known streams are the broader streams of the process such as the power of the PV module or the system productive. The optimization problem (c) differs from the design problem in that the number of equality constraints is smaller than that of the variables left unspecified. The unspecified variables are now calculated so as to minimize an objective function (usually the cost or specific power consumption), normally of economic nature. The data analysis dimension depends on the programmer's choice. More analyses mean more generality and more capabilities added to the developed code. For this work, the available analyses are: (i) energy, (ii) exergy, (iii) cost, and (iv) thermo-economic. The programmer has to decide the methodology from the beginning i.e., building the numerical model according to the dimension. Therefore, a new visual system program by the use of MatLab/SimuLink should be built to solve design, performance and optimization types of simulation and to run all possible types of output data analyses of energy, exergy, cost, and thermos-economic. The mathematical approaches that are used in the analysis for solar desalination plants are basically preformed according to the 1st and 2nd laws of thermodynamics. For any system under steady state, the mass, energy, and entropy balances equations under steady state condition should be developed as follows:

$$\sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{out}} = 0\left(\text{kg/s}\right), \tag{1}$$

$$\sum \dot{e}_{\text{in}} - \sum \dot{e}_{\text{out}} = 0\left(\text{kJ/kg}\right), \tag{2}$$

$$\sum \dot{s}_{\text{in}} - \sum \dot{s}_{\text{out}} = 0\left(\text{kJ/kg}^{\text{o}}\text{C}\right). \tag{3}$$

Unlike energy, which is conserved in any process according to the first law of thermodynamics, exergy is destroyed due to irreversibility taking place in any process, which manifests itself in entropy creation or entropy increase. The general form of the availability is defined by the following equation;

$$A_2 - A_1 = A_q + A_w + A_{fi} - A_{fo} - I \ , \qquad (4)$$

where $A_2 - A_1 = 0$ is the non-flow availability change in steady state condition,

$$A_q = \sum_j \left(1 - \frac{T_{amb}}{T_j}\right) Q_j$$

is the availability transfer due to the heat transfer between the control volume and its surroundings, $A_q = -W_{cv} + P_o\left(V_2 - V_1\right)$ is equal to the negative value of the work produced by the control volume but in most cases the control volume has a constant value; therefore A_w can be further simplified. And $I = T_{amb} \times S_{gen}$ is the availability destruction in the process. The flow availability expressed as

$$A_{fi} - A_{fo} = \sum_i \dot{m}_i a_i - \sum_o \dot{m}_o a_o$$

So the general form in steady state condition would become;

$$0 = A_q + A_w + A_{fi} - A_{fo} - I \ . \qquad (5)$$

Thermo-economics is the branch of engineering that combines exergy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations but is crucial to the design and operation of a cost effective system. In a conventional economic analysis, a cost balance is usually formulated for the overall system operating at steady state as follows:

$$\sum_{out} \dot{C} = \sum_{in} \dot{C} + Z^{IC\&OM} \ , \qquad (6)$$

where $\dot{C}$ denotes the cost rate for the inlet/outlet streams, and $Z^{IC\&OM}$ is the capital investment and operating and maintenance costs. In exergy costing a cost is associated with each exergy stream. Thus, for inlet and outlet streams of matter with associated rates of exergy transfer $E_{i,o}$, power W, and the exergy transfer rate associated with heat transfer E_q it can be written as follows;

$$\dot{C}_i = c_i \dot{E}_i \ , \ \dot{C}_o = c_o \dot{E}_o \qquad (7)$$

$$\dot{C}_{\mathrm{w}} = c_{\mathrm{w}}\dot{W}\,, \tag{8}$$

$$\dot{C}_{\mathrm{q}} = c_{\mathrm{q}}\dot{E}_{\mathrm{q}}\,, \tag{9}$$

where $c_{\mathrm{i,o,w,q}}$ denote average costs per unit of exergy in $/kJ for inlet ($_{\mathrm{i}}$), outlet ($_{\mathrm{o}}$), power ($_{\mathrm{w}}$), and energy ($_{\mathrm{q}}$) respectively. Figure 1 shows the flow diagram of the process energy flow.

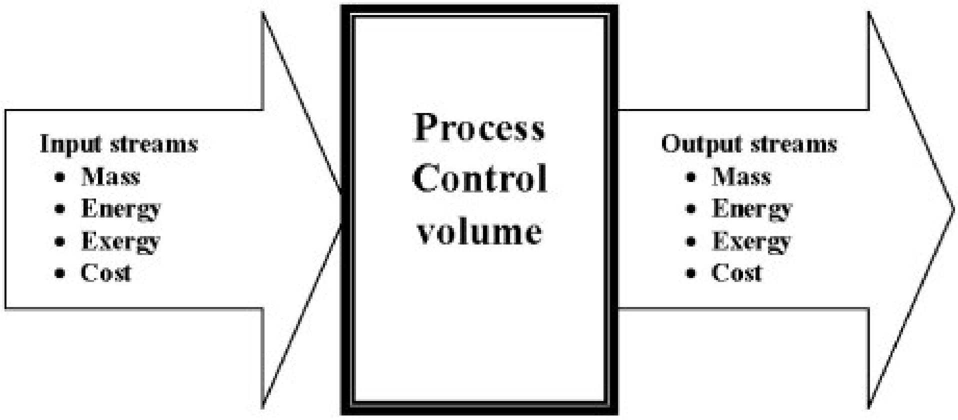

Figure 1. Flow streams considered across any process.

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http://www.mathworks.com/index.html

Biographical Sketches

Mohamed A. Sharaf Eldean is a specialist in modeling, design, and simulation of renewable desalination systems. He is awarded the PhD in design and simulation of solar desalination systems. His master's degree was in the field of manufacturing a small solar desalination unit (solar-MSF type). He was awarded his B.Sc degree in mechanical engineering. Currently, he is a full-time teacher at the University of Suez-the College of Petroleum and Mining - Energy Engineering Department. He is also a member of the Board of Suez and Engineers Association official of the Cultural Committee. He is a permanent reviewer (Editorial Board Member) of *Modern Applied Science Journa*l-Canadian Center of Science and Education and Editorial Board of our journal, entitled *Insight - Energy Science*. He also participated in several international projects with the European Union in the field of solar energy and water desalination. Moreover, he has many of the research papers in the field of solar desalination. He has awarded a top reviewer certificate in 2011 and 2012 from *Desalination* Journal. He is the creator and owner of REDS software library (www.redslibrary.com).

Abdelnasser Mabrouk is currently working at Qatar Environment and Energy Research Institute in desalination technology development from prototype to pilot scale. He is leading the advanced MED desalination technology using pilot plant facility which is based on novel ideas to reduce energy consumption and reduce water cost. He is also working at the College of Science and Engineering, HBKU to teach desalination technology and rolling scientific advisory for MSc and PhD students. He has worked at the Desalination R&D Center based company (Doosan Heavy industries, South Korea, UAE and KSA) and contributed to the development of the commercial desalination plants in the GCC countries through pilot programs including Multi Stage Flash (MSF), Multi Effect Distillation (MED), Reverse Osmosis (RO). During his work at Suez University, Egypt, he has participated in several EC funded projects in solar desalination (CSP, PV, Wind, MSF, MED, NF) in direct collaboration with several European institutes (Spain, Italy, Germany, Swiss, and France). He has published about 39 journal papers and 34 conference papers. He authored one book and 2 book-chapters. He has 4 GCC patents-pending and 1 PCT patent. He developed a Visual Simulation Software (VSP) for process design and techno - economics of desalination processes.

A. M. Soliman is a specialist in modeling, design, and simulation of renewable desalination systems. He was awarded a PhD in Energy Engineering Systems. Currently he is a full-time Asst. Prof. in Mechanical Engineering Department, Engineering College, Jouf University, KSA. He is also a member of the American Society of Mechanical Engineers (ASME) Board of Suez and Engineers Association, official of the Cultural Committee. He also participated in several international and local projects in the field of solar energy and water desalination.

Hassan E.S. Fath is a well-known expert in desalination and energy technologies with wide academic and industrial experience in solar thermal desalination systems. Prof. Fath got his B.Sc. & M.Sc. from Alexandria University (Egypt) and M. Eng. & Ph.D. from Mc Master University (Canada). His Academic experience was in different Middle East universities including; Egypt-Japan University of Science and Technology (E-JUST), Egypt, American University of Sharjah, UAE, Masdar Institute (MI) of Science and Technology, UAE, Alexandria University (AU), Egypt, King Abdul Aziz University, KSA. His industrial experience includes; Leader of New Thermal Desalination processes in Doosan Heavy Industries, Korea, Senior Engineer and Head of Efficiency and Statistics Dept., Saline Water Conversion Corporation (SWCC), KSA, Process Engineer, Atomic Energy of Canada Limited (AECL), Ontario Hydro (Canada). Prof. Fath has established different desalination laboratories, e-learning institute, Water & Energy associations, and centers. Prof. Fath has lead (as PI, Co-PI and consultant) many R&D funded projects, authored a Book “Desalination Technology”, Co-authored for Encyclopedia of Desalination & Water Resources (DESWARE), filed two patents in integrated MSF/MED thermal desalination and published over 150 papers, in desalination & energy technologies.