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Steady state and dynamic models of multistage flash desalination: A review

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ABSTRACT

This article focuses on a review of literature studies on steady state and dynamic modeling of the multistage flash desalination process (MSF). The review shows that both steady state and dynamic models are based on lumped parameter approach. Differences in literature models are found in the assumptions used to model the flashing stage in addition to the correlations used to determine the heat transfer coefficients, thermodynamic losses, thermodynamic and transport properties. Interestingly, literature indicates a rapid progress made in software used for coding and solution of the model equations. The review shows a limited number of literature models for the internals of the flashing stage, which includes the brine orifice, the demister, and the condenser tube bundle. The review of models for lumped analysis and the process internals focuses on evaluation of the quality of the predictions of these models, their functionality and suitability to perform the desired process simulation. A special section of this review focuses on the current status of MSF simulators, which includes modular and equation oriented simulators. This evaluation focuses on simulator simplicity and flexibility in order to take into account possible different process elements.

Keywords: Desalination; Multistage flashing; Modeling; Steady state; Dynamics; Control

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1. Introduction

The desalination industry continues to grow and expand across the world. Currently, the industry is adopted by more than 155 countries and with a total capacity of 47 × 106 m3/d. This amount is sufficient to provide the daily needs of 470 million inhabitants at a rate of 100 L/person/day [1]. Currently, the desalination industry is the life line in the Gulf countries, Malta, Cyprus, and the Caribbean islands. Also, desalination is vital in Singapore, Southern Spain, Southern Italy, Western Australia, Western Florida, and Southern California. This is to offset continuous increase in urban growth, decrease in annual rain fall and associated reduction in underground water reserves. On the other hand, desalination in Japan, South Korea, and many parts in the US is used to produce water for industrial applications. This is dictated by strict environmental regulations to prevent reduction in underground water reserves as well as depletion or pollution of small rivers and lakes.

The desalination industry started on commercial scale during the 1950s with small scale thermal evaporation processes [2]. Success and reliability of the early units paved the way to further increase in the number and capacity of installed units. Growth of the desalination industry is also attributed to the introduction of the reverse osmosis process on commercial

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scale in the 1970s. The first generation of reverse osmosis (RO) membranes was susceptible to various forms of scaling and membrane fouling. Also, the RO energy consumption at this early stage was not fully optimized. Irrespective of these drawbacks the RO process provided the users with a modular configuration that can be tailored to meet the required consumption rate and product quality. In addition, the RO process consumes smaller amount of energy than thermal desalination processes, this being more suitable for countries with limited energy resources. Over the years, the RO process progressed and expanded to reach more than 40% of the entire seawater desalination market. Progresses included the development of lower cost membranes with better chemical and mechanical properties as well as higher permeate flux and salt rejection properties [3]. In addition, use of energy recovery units reduced the specific energy consumption for desalination of sea and brackish water [4]. On the other hand, survival of thermal desalination processes was a result of the massive field experience, which have been accumulating since the early 1950s, as well as the continuous advances in unit design and associated process and the increase in the unit capacity, where a single MSF unit can produce more than 75,000 m3/d. In addition, production plants with capacities of 500,000 m3/d are quite common. Similar trends are found in RO plants, where capacities of newly installed plants have exceeded 200,000 m3/d [5].

It is worth noting that the development of various desalination technologies has been performed also thanks to the use of mathematical models and process simulators. Indeed, these are inexpensive tools that can be used for system design and analysis of process performances. Mathematical models can be used to obtain, streams’ features profiles, power consumption, and, eventually, product cost. This article reviews technical-scientific literature relevant to various aspects of MSF modeling, which include simple and detailed steady state models, and dynamic models. Also, focus is made on modeling of specific elements of the process, which includes orifice weirs, condenser tubes, and demisters.

The following section includes a brief description of the MSF system. This is followed by review of steady state and, then, dynamic models. The review provides a critical assessment on the status of various models and defines areas that require further developments in order to improve ability and functionality of the models. A special section is devoted to discuss simulating details within the flashing stage, i.e., brine orifice, demister, and condenser tubes. The review also includes an assessment of available MSF simulators, which focuses on their ease to use and their flexibility to modify simulation parameters, model correlations, or process elements.

2. MSF process

The most adopted MSF process configuration is constituted by four main parts (see Fig. 1). These are the brine heater, the flashing chambers (separated in heat recovery and heat rejection sections), feed pretreatment, and venting line/system. The brine heater has a shell and tube configuration, where the brine recycle flows through the tube side and the heat steam on the shell side. In large plants, the heating steam is introduced through several ports along the length of the heater. This is to ensure uniform temperature distribution within the brine heater. Flashing stages (see Fig. 2) include a brine orifice, brine pool, demister, distillate tray, condenser tubes, and venting tubes. In the heat rejection section, a seawater stream flows inside the condenser tubes, where the vapour produced in the stages is condensed and part of the excess heat added to the system in the brine heater is rejected with a portion of this stream, namely the cooling seawater stream. Simultaneously, the remaining part of the stream circulating inside the tubes, namely the feed seawater, increases its temperature to the same temperature as the rejected brine stream from the last flashing stage. This is to prevent thermal shock and possibilities of precipitation of calcium carbonate upon the mixing of the feed seawater in the brine pool of the last flashing stage. Prior to the mixing process, the feed seawater is deaerated and dosed with a mixture of antiscalants, anticorrosion, and antifoaming chemicals. Part of the brine leaving the last flashing stage is rejected to the sea, thus constituting a blow down of excess salts and heat, while the remaining part is mixed with the pre-heated seawater make-up stream and recycled into the condenser tubes of the heat recovery stages. At the end of this section (exiting from the tube bundle of the first flashing stage) brine recycle temperature is only few degrees lower than the design value of the top brine temperature. Temperature increase of the brine recycle or the feed/cooling seawater in the condenser tubes is caused by absorption of the latent heat of the flashed off vapor in each flashing stage. On the other side, condensed vapor accumulates and flows in the distillate tray across the stages. All stages are vented to the ejector units in order to continuously remove and prevent accumulation of the noncondensable gases found in the brine recycle (oxygen, nitrogen, and carbon dioxide). Additional details on the MSF process as wells as its features and operating parameters can be found in most of the references cited in this study.

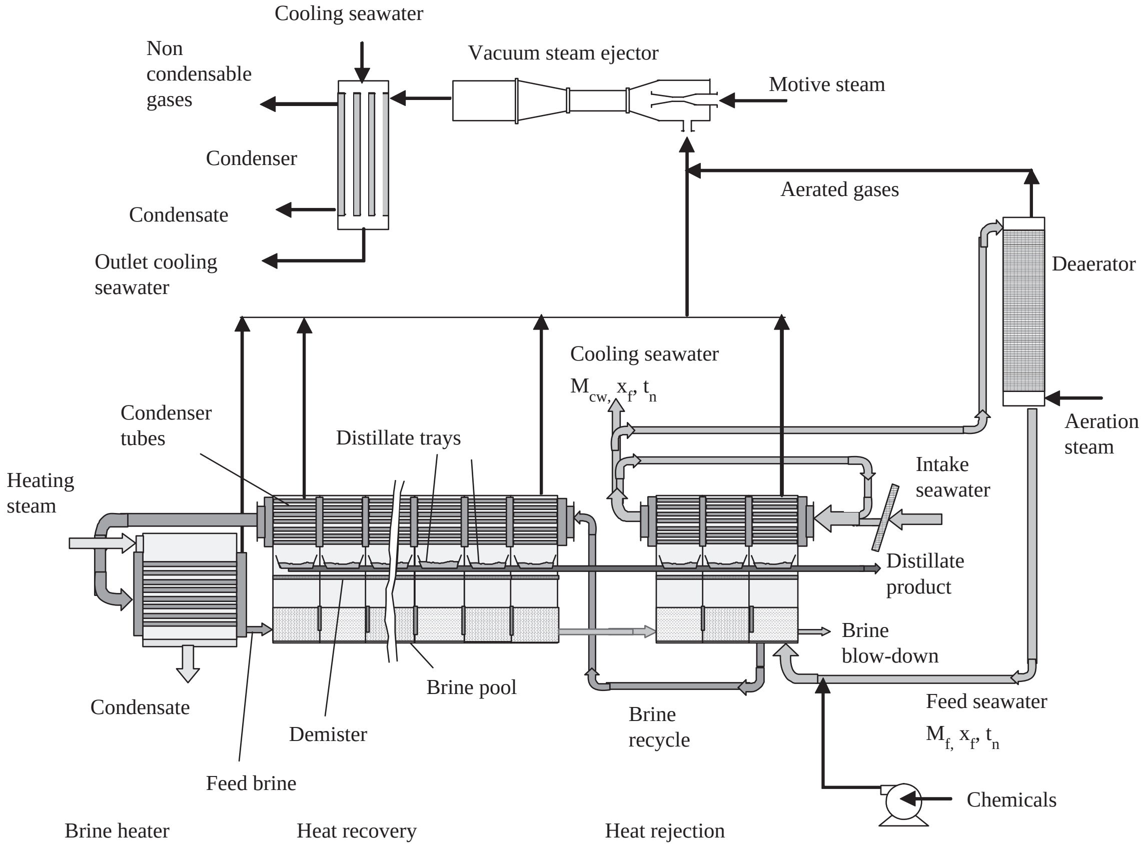

Fig. 1. Schematic of the MSF process with Brine Circulation configuration.

3. Simple steady state models

Simple mathematical models of the MSF process are very useful to provide quick estimates of the main process characteristics, i.e., performance ratio (defined as the amount of distillate product per unit mass of heating steam), heat transfer areas for the brine heater and condensers, and profiles of the temperature, pressures, salinity, and flow rate along flashing stages [6]. Examples of applications of such ‘‘short-cut’’ equations include plant design, process synthesis, modeling and simulation, energy conservation, flow sheet analysis, and of water desalination. The simplicity of the model equations makes it easy to grasp and understand various relations governing the systems. Also, simple models can be coded on hand calculators or spread sheets. Simple models only provide major design and operating features of the system; however, care should be taken in interpreting the model results. This is because of the simplifying assumptions used to develop the model. Another useful application of the simple models is to develop initial guesses to solve more detailed models.

Common assumptions among simplified mathematical models for the MSF system include the following:

- Constant physical properties: This assumption is invoked to simplify the solution of the energy balance equations. Therefore, assuming constant values for the specific heat at constant pressure for the

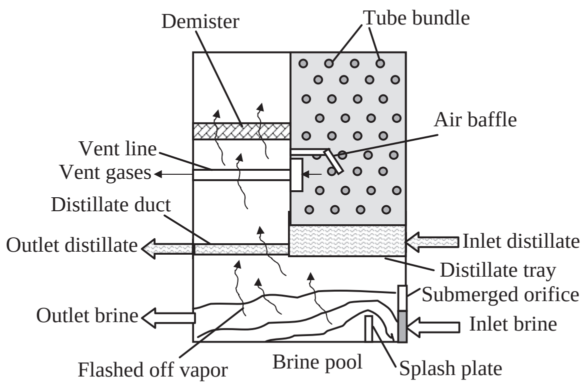

Fig. 2. Schematic of an MSF flashing stage.

flashing brine, the latent heat for evaporation, and the flow rate of the flashing brine results in a linear temperature profile for the flashing brine and inside the condenser tubes [7]. This assumption is motivated by the fact that variations in the specific heat of flashing brine, water flowing inside condenser tubes, and latent heat are relatively small between a flashing range of 30–110 °C [8].
- Constant overall heat transfer coefficients: Heat transfer coefficients for brine flowing inside condenser tubes or for vapor condensing on the outside surface of the tubes would actually depend on the physical properties of the streams, which include viscosity, density, and thermal conductivity, and on the flows fluid dynamic conditions.
- Constant thermodynamic losses: Keeping the thermodynamic losses constant throughout the flashing stages, which includes the boiling point elevation, non-equilibrium allowance, demister losses, and friction losses, simplifies calculations of the temperature of the flashed off and condensed vapor. On average, the thermodynamic losses vary between 1 and 2 °C per flashing stage [9].

The simple models developed by Soliman [10], Darwish [7], El-Dessouky et al. [6], Al-bahou, et al. [2], Al-Sahali and Ettouney [11] are proposed to be used for the determination of various system features, which include temperature and flow rate profiles, performance ratio (distillate mass per unit mass of heating steam), specific heat transfer area (ratio of the total condenser and brine heater areas and product flow rate), stage dimensions, and product cost. Main outcomes of these studies include the following:

- Efficient MSF units require the use of a large number of flashing stages. This is illustrated through the analysis of a single stage unit, which has a performance ratio of less than one, i.e., the amount of distillate product is less than the amount of heating steam. Increasing the number of stages to two gives a performance ratio higher than one, however, the required heat transfer area will be very large because of the small temperature difference between the temperature of the flashing brine and the feed water inside the condenser tubes. Optimum design conditions are obtained upon the increase in the number of flashing stages to a range of 20–24, where the specific heat transfer and the performance ratio would vary over a range of 300–500 m2/(kg/s) and 8–10, respectively, El-Dessouky et al. [6].
- At constant number of stages and constant brine blow down temperature, increase in the top brine temperature improves the system performance ratio and reduces the required specific heat transfer area. Increase in the performance ratio is a result of increase of the flashing range, i.e., the difference between the top brine temperature and the brine blow down temperature. This is due to the general increase in the temperature drop per stage, which results in larger amount of flashed off vapor and consequently of distillate product. Also, increase in the temperature drop per stage results in enhancing the driving force for heat transfer thus reducing the specific heat transfer area. Also, operation at higher temperatures results in the increase in the value of the overall heat transfer coefficient. However, an upper limit for the top brine temperature is set to approximately 110–115 °C, in order to avoid calcium sulfate scaling.

4. Detailed steady state models

Detailed steady state models provide more accurate and useful information for system design and simulation. Accurate performance charts can be generated and used to guide the designer, the operator, and to interpret plant data. Detailed mathematical models take into consideration variations of the physical properties of various streams as a function of temperature, pressure, and salinity. Also, they include comprehensive correlations for evaluation of physical properties, thermodynamic losses, and heat transfer coefficients. All of the detailed models found in previous literature studies are based on lumped parameter analysis for the variables in each flashing stage. They are constituted by a set of non-linear algebraic equations, which requires iterative solution of the material and energy balance equations as well as the heat transfer equations in each flashing stage.

The most common assumptions among detailed steady state models include the following:

- MSF plants are operated at steady state conditions to maintain the output production rate at the design value. Therefore, it is necessary to adjust the heating steam flow rate due changes caused by seasonal variations in the intake seawater temperature as well as continuous fouling and scaling of the condenser tubes. Cycles of on-line tube cleaning are applied at frequent intervals to continuously remove soft scale. In addition, off line acid cleaning is applied at less frequent intervals to restore clean conditions. Over long periods of operation, 3–5 years, increasing the amount of heating steam as well as various cleaning procedures are no longer effective and the system must be shut down for an overhaul.

- The distillate product from every stage is free of salt. This assumption is valid due to the fact that the distillate salinity on average is below 20 ppm. On the other hand, the brine and feed salinity varies between 40,000 and 70,000 ppm. Therefore, the effect of the distillate salinity on the salt balance equation is negligible. This assumption implies that entrainment of brine droplets in the flashed off vapor is negligible.
- Subcooling has negligible effects on the energy balance and heat transfer equations in the brine heater and the condensers. This is because of the larger magnitude of the latent heat of condensation.
- Negligible heat and vapor losses due to venting of non-condensable gases: Approximately, 2.5% of the total amount of vapor formed in all flashing stages is vented away in order to prevent accumulation of non-condensable gases [8]. Therefore, part of the product water vapor is lost in addition to heat losses. If these losses are not factored into the final system design, the temperature of the brine stream leaving the condenser tubes from the heat recovery section will be reduced and will affect the system production rate or its overall performance. Therefore, it is necessary in the final system design to increase the heat transfer area of the condenser tubes to account for these losses and to insure increase of the temperature the brine stream to the desired design value.

Omar [12], Helal et al. [13], and Al-Mutaz and Soliman [14] developed comprehensive MSF models, which have similar features. However, the main difference among these studies was the solution method. This in part was motivated by limitations of the computational facilities during that period and the need to develop an efficient solution scheme that requires low computer memory and small computational time. It should be noted that all these studies were coded in the Fortran language. Omar [12] used the stage to stage calculations to solve the model equations. Helal et al. [13] developed a new solution approach for the system model using the tri-diagonal matrix algorithm. Al-Mutaz and Soliman [14] used the orthogonal collocation method to calculate the stream profiles across the stages. Subsequently, Rosso et al. [15] presented a model similar to that previously developed by Helal et al. [13], however, several performance charts were included in their study. El-Dessouky and Bingulacl [16] solved a more comprehensive MSF model using a fixed point solution scheme that solves the equations iteratively using the stage-to-stage algorithm.

A similar MSF model was developed by Hussain et al. [17], where an advanced computational platform (SPEEDUP) was used to solve the model equations. The SPEEDUP code is an equation oriented simulator that provides the user with more flexible and efficient programming platform. New additions in the MSF model were made by El-Dessouky et al. [18]. These additions included taking into accounts effects of fouling s and non-condensable gases on the heat transfer coefficient in the condensing zone. Also, calculations of the gate height were included in the model. Thomas et al. [19] added to the material and energy balance equations extra terms that account for the mass flow rate of the non-condensable gases. It should be noted that, in El-Dessouky et al. [18] model, non-condensable gases concentration was defined as a percentage of the total amount of flashed off vapor. Abdul-Jabbar et al. [20] solved the MSF model using Newton's method and the visual basic computer coding. Focus was made on obtaining design details within the stage, which include weir loading and dimensions of the flashing stage, tube bundle, and demister.

5. Dynamic models

There are several studies on dynamic modelling of the MSF process. They are based on a detailed physico-chemical representation of the process including all the fundamental elementary phenomena, in particular the description of mass and energy accumulation in the different stages and the use of fluid-dynamic correlations to determine the fluids behavior between stages. This is used to analyze the stability of steady state regimes, to choose the proper start up and shut down procedures, and to study the system transient behavior (related to activities such as control strategies, stability assessment, process interactions, trouble shooting, startup, load changes and shut down scheduling) and to optimize and develop system controllers for industrial units. That is because the successful development of a control system requires an appropriate definition of the control structure (i.e., selection of output, input and disturbance variables) and an efficient dynamical model on which the design, analysis and evaluation can be carried out [19,21,22].

As mentioned by Cipollina [23], an early work on dynamic modelling of MSF was done by Glueck and Bradshaw [24]. This model includes a differential energy balance combining vapor space and distillate in the flash stage given as consequence an over-specified model. Drake [25] applied empirical correlations for the evaporation rates but the non-condensable gases in the vapor were not taken into consideration. Rimawi et al. [26] developed a dynamic model for the once through configuration. Husain et al. [21] presented a model with flashing and cooling brine dynamics. The model was improved by Husain et al. [17] and by Reddy et al. [27] considering the system dynamics and including the brine recirculation.

The model contains differential equations for the mass and heat balances in all phases (liquid and vapor). And contains constitutive equations to calculate physical properties, equilibrium relations between pressure and temperature and heat transfer coefficient in the condensing zone. More constitutive equations are used to calculate the brine flow rate through the orifices depending on the pressure drops and on the brine level, whereas vapor flowing in the venting line is considered constant.

The dynamic simulation can be carried out either off-line (no connection to the real plant; the input data are fed from a file) or on-line (the input data are directly received from the actual operating plant). Solution methods can be with a simultaneous approach (equation oriented), where the whole problem is treated as a global set of equations pertaining to all process unit, and with a stage by stage (sequential) approach, where the analysis proceed from module to module. Presently, the use of a combination of sequential and simultaneous approaches (in which the equations are solved simultaneously and iteratively) is becoming more popular [21].

Table 1 shows a summary for most of the previous literature study on process dynamics of the MSF process. Critical evaluation of these studies shows the following:

- All of the studies used lumped parameter analysis and ignored spatial variations. This assumption simplifies the system model because it reduces the model to an algebraic form for steady state analysis and a set of ordinary differential equations for dynamic analysis. Although the lumped parameter analysis does not allow for a description of spatial details within the flashing stage, it still provides sufficient and useful information for design purposes and analyzing the system performance and dynamics. On the other hand, distributed systems provide insights into variations within the flashing chamber. This might reveal areas of high turbulence within the flashing brine or dead zones within the condensing vapor. Such information can be used to improve the internals layout.
- Distillated flashing is ignored in the condensate duct. Taking this parameter into consideration results in 10% increase in the amount of flashed off vapor and as a result increases the temperature of the brine inside the condenser tubes. In turn this will reduce the thermal load of the brine heater and result in the increase of the performance ratio.
- Models for the flashing efficiency vary widely among various studies. The flashing efficiency is expressed in terms of empirical relations describing the boiling point elevation and non-equilibrium allowance. Use of different correlations would result in different flashing rates. In turn, this would affect the heat transfer area and the system performance ratio.
- Non-condensable gases in the flashing stage have a strong effect on the flashing and condensation process. Most of the literature studies have neglected the presence of the non-condensable gases, except for the works by Cipollina [23] and Bogle et al. [28]. Non-condensable gases have a similar effect as fouling, since they reduces heat transfer coefficients on the surface of condenser tubes and ... the vapor partial pressure, thus decreasing condensation temperature and worsening the heat transfer between condensing vapour and recirculated brine.
- Demister losses also result in a reduction of the temperature of the condensing vapor, thus leading to and increase in condenser heat transfer area and a decrease of the system performance ratio [29]. Most of the literature studies ignore demister losses as they vary over a range of 0.01–0.6 °C. However, a reduction of 0.6 °C in the low temperature effects would have indeed significant effects.
- Vapor blow through has been discussed in some literature studies, but it was modeled only by Cipollina [23] and Bogle et al. [28]. The phenomenon is associated with the reduction of the brine level below the orifice height. As a result, the system operation becomes unstable because of difficulties in regulating brine heights and pressure distribution along the stages. This might put the system in cyclic or runaway operating conditions.

6. Computer simulators

The most powerful software packages for mathematical modeling of industrial processes are listed in Table 2 [21]. Simulators are divided between modular and equation oriented. The modular simulators are originally developed for chemical process industry.[1] Most of these packages have modular elements for commonly known unit operations, which include distillation, absorption, heat exchangers, etc. Although these simulators have sufficient resources to simulate desalination processes, their use is quite complex. This is because flow chart development would require extensive work. Moreover, it would be necessary to provide the simulator with proper correlations of heat transfer coefficients and thermodynamic losses. Another difficulty is the need to break down each desalination unit

Table 1
Summary of literature studies on detailed dynamic models of MSF plants.

Reference	Summary
[26]	Used a combination of the method of lines and Gears of the IMSL library. The model is applied for the MSF-OT process. Limited system analysis is presented in the manuscript; therefore, it is difficult to discern the model efficiency.
[17]	Used the SPEEDUP code to solve the steady state and dynamics of the MSF with brine recycle. In addition, a TDM FORTRAN program is used to obtain the steady state performance of the system. The SPEEDUP code is used to study system control using PI, PID, and Lag controllers. Detailed analysis is provided for system dynamics as a function of operating parameters. Calculations are made for long operating times through which new steady conditions are achieved.
[55]	Used a combination of Newton-Raphson and Runge-Kutta method to obtain the transients of the system profiles. The system analysis is limited to very short transient periods. This makes it difficult to assess the model efficiency.
[19]	Simulation code written in C and implemented in a UNIX-based system. The model is very detailed and comprehensive as well as the simulation results. However, review for some of the simulation data reveal that absence of pressure control in the last stage causes unlimited increase in the brine level.
[56]	Used the CAMEL modular simulator. Steady state analysis is made against plant data. Dynamic analysis is made against literature data. It is difficult to critique this work because the manuscript does not include details of the mathematical model or a reference to previous work in the open literature. However, the authors have used in their model a linear function to simulate the gate height because of lack of knowledge about interstage hardware arrangements. In reality the gate height fluctuate in non-monotonic manner across the stages. The authors state in the manuscript that this affected the simulation results, which includes the brine levels and temperature.
[22]	Lumped parameter dynamic analysis. The model equations are solved by LSODA routine. The model includes detailed account of variations in physical properties as a function of temperature and concentration as well as thermodynamic losses. Model results show non-linear response to variations in steam and sea water temperatures. This indicates the necessity of using this type of models for development of an optimal control strategy.
[57]	Used Delphi 5.0, a computer visual language to simulate the MSF process. The model is comprehensive and the manuscript includes detailed system analysis. Discussion is given for various forms of probable system faults, which might be caused by pumps, valves, heaters, controllers, and heat exchangers.
[58]	Used Fortran 95 and the Runge-kutta method to simulate and model the startup characteristics of an MSF unit. The main assumptions in this model are the use of a constant brine holdup in all stages and knowledge of the ejector extraction profile. This reduced the model to simulation of the energy transients within the brine heater and flashing stages. Therefore, it was possible to determine the startup time to reach steady state conditions.
[28]	Comprehensive dynamic model of the MSF. The model details include temperature losses, blow through mechanism, and correlations for the heat transfer coefficients, transport properties, and thermodynamic properties (except for the specific heat of the brine stream, which is assumed constant). The model does not account for demister losses and distillate duct. Also, values for the discharge coefficient are defined as a function of the stage pressure. Correlations for the discharge coefficient are more complex and depend on the orifice dimensions, pressure drop between the two stages, inlet brine flow rate, stage temperature, brine height, densities of the vapor and brine, and flashing rate.

into smaller parts known by the simulator; i.e., a flashing stage must be divided into a condenser and a non-equilibrium flashing unit. Furthermore, the use of these packages needs special training and experience in dealing with the intrinsic of the simulator. Finally, the program source code of these packages is inaccessible to the user, which makes it difficult to refine or upgrade the existing models adopted by the simulator.

Several process simulators were used to model the MSF process. Among these, a very popular tool in the academic and industrial communities is gPROMS of Process System Enterprise Ltd. This modeling tool was developed specifically for chemical engineering systems. The system mathematical description is introduced in a specific language which is very close to the natural mathematical language. gPROMS interprets model equations and links together all the variables in order to solve the equations by a powerful mathematical solver [28]. gPROMS is a complete software package for modelling and simulating processes in both lumped and distributed systems. It has many features such as the possibility of implementing models at different levels, which are included in a hierarchical structure, thus allowing the easy simulation of

Table 2
Types of computer packages for modeling and simulation of chemical process units

Solution method	Computer package
Modular sequential	ASPEN PLUS (Aspen Tech, Manuals) FLOWTRAN (developed by Monsanto Co.) PROCESS (simulation sciences, California) DESIGN II (Chemshare, Houston) HYSIS (Hypotech, Calgary-Canada)
Equation oriented	SPEEDUP (Aspen Tech, Manuals) gPROMS

multi-stage systems. It uses purely declarative language, with the order in which equations are written being irrelevant. Single or multi-dimensional arrays for both variables and equations are allowed when describing multi-component or multi-stage systems. It can be used also for describing distributed parameters systems, and thus systems with significant gradients of all variables along the physical domain [23]. Another important feature of gPROMS is its ability to be coupled and linked to other programs such as CAPE-OPEN, CFD, Matlab, Simulink. gPROMS is a true modelling tool, not just a process simulator. It is underpinned by a powerful modelling language, and its equation-oriented representation allows solution of the underlying in many different and important ways, meaning that you can use one model for many different activities. gPROMS also provides an easy and flexible platform to build a process flowsheet graphically and the corresponding master model connecting automatically individual unit model equations during simulation and optimization. In addition, gPROMS can be combined with optimization routines to minimize to annual operating cost [30].

7. Modeling of flashing stage internals

Modeling of details inside a flashing stage is not common in the desalination literature. The most studied element of the flashing stage is the flow dynamics of the brine orifice [31]. Review of these studies show the complexity of the orifice model. This is because it includes several interactive mechanisms, i.e., non-isothermal flow, bubble formation/growth/release, and vapor flashing. The following is a summary for the main features of these studies:

- Lior [32] reviewed the hydrodynamics and heat transfer equations in non-flashing flow for different regimes. The study includes quantitative explanation for the role of the hydraulic jump in the flash evaporation process. The review confirms the limited number of studies on orifice configurations in the MSF process, whereas a larger number of correlations and design equations are found for the isothermal orifice flow in civil engineering applications.
- Bodendieck et al. [33] presented a semi-empirical model for two types of MSF orifices, which include a single slot and the orifice/weir configuration. The model is integrated in an MSF model to determine the brine heights across the stages. Analysis is based on strategies of stable operation for summer, winter, and partial load operating conditions. The analysis indicates suitable operating ranges for the two types of orifices, also showing that a larger possible operating range is predicted for the orifice/weir configuration.
- Miyatake et al. [34] presented a hydrodynamic model for the isothermal flow through the simple orifice and the orifice/weir configurations. The model results are validated against experimental measurements for loading range of 4.3×10^5–8.7×10^5 kg/(m hr) and liquid level of 0.4 m. The weir is found to promote the evaporation rates through propelling the entering liquid to the free surface and in generating low pressure regions near the top edge of the weir.
- Seul and Lee [35] developed a two dimension, non-isothermal, two phase fluid dynamic model. An Eulerian approach for the continuous liquid phase and a Lagrangian approach for the dispersed vapor phase. In addition, the model takes into considerations bubbles interaction. The model is applied to the simple orifice configuration. Results show that the evaporation rate increases at lower brine levels.
- The previous study was followed by a semi-empirical evaluation for the non-isothermal system, [36]. In their study, an empirical model is used for the temperature field and is combined with the two-dimensional hydrodynamic model developed by Miyatake et al. [34]. The results show good agreement with the experimental measurements as long as the flow is not disturbed by boiling or separation.
- Reddy et al. [37] proposed a model for simple orifice and orifice/weir configuration. The model is based on a set of empirical correlations previously developed in the reports of Oak Ridge National Laboratories (ORNL) and by Chow [38] and Subramanya [39]. A solution procedure for the proposed model is outlined for steady-state and transient conditions. However, no results are reported for the proposed model.
- Rautenbach and Schafer [40] constructed a full scale experimental system to test various design

configurations for the MSF orifices. Several configurations are tested, which include rectangular orifice, orifice/weir, siphon/sieve, and siphon with self-adjusting plate. The system allows for visual observations and measurements of pressure and temperature distribution Experimental measurements and resulting correlations show less than 10% deviations from the measured data for the pressure drop.

- Al-Fulaij [41] developed empirical correlations for the non-equilibrium allowance and the discharge coefficient for box and weir type orifices using actual field data. The analysis also included development of correlations for the overall heat transfer coefficient. The correlations were obtained from test data of six large scale MSF plants.

The most critical point in the above literature studies seems to be the difficulty in finding a full analytical or numerical solution for the modeling of non-isothermal flow in orifice/weir configuration of MSF stages. As discussed in the above quoted references, the flow is highly turbulent and is associated with generation of low pressure regions and discontinuity in the flow regime near the orifice opening and the weir. As a result, the only problem solution so fare identified is related to the combination of empirical correlations and numerical solution for the isothermal flow regime.

Other models are focused on the mathematical description of phenomena related to demisters. The most common design procedure of demisters is based on estimation of the vapor velocity within the demister. This relation is given by

$$v_v = k\left(\frac{\rho_\ell - \rho_v}{\rho_v}\right)^{0.5} \tag{1}$$

Values of the k constant are around to 0.078 [42]. Knowledge of the vapor velocity as well as the vapor flashing rate can be used to determine the demister dimensions. On average, vapor velocity in the demister varies over a range of 4–5 m/s. An empirical correlation is developed by El-Dessouky et al. [29] for removal efficiency of large mist droplets. A better approach for demister design is found in the study by Brunazzi and Paglianti [43]. They have presented a semi-empirical model for the demister design. The model builds on previous analysis presented by Langmuir and Blodgett [44] and Pich [45] who evaluated the inertial capture efficiency for a single wire, expressed in terms of a dimensionless Stokes number. The analysis for industrial wire mesh packing is presented by Carpenter and Othmer [46] as a function of the demister pad thickness, the demister specific area, the stokes efficiency, and the number of mesh layers. The semi-empirical approach is further revised by Brunazzi and Paglianti [43]. They performed experimental and mathematical analysis for the removal of fine mist particles. The analysis is presented as a function of various design and operating parameters. The equation presented by Brunazzi and Paglianti. [43] fits well the experimental data; however, it is limited to the range of droplet capture as in the empirical approach by El-Dessouky, et al. [29]. The correlation does not take into account effects of very large vapor velocity, were droplet detachment and re-entrainment into the vapor stream takes place. Ettouney [42] developed a simplified model for design and performance analysis of the wire mesh demister. The literature shows that empirical or semi-empirical models are the most feasible means for system simulation and design. In either case, experimentation requires careful execution, detailed measurements for a number of parameters that include droplet radius, vapor velocity, temperature, and other characteristics of the demister pad (length, packing density, wire diameter, and specific area).

The literature review reveals limited published studies on vapor condensation around tube bundles. Karlsson and Vamling [47] developed a 2-D CFD model to study shell-and-tube condensation pure and binary refrigerants. The results show fundamental differences in the flow fields of pure and binary mixtures. Also, adjustments in the inlet geometry are found to affect the rate of heat transfer by up to 24%. Similar conclusion is reported by Sajjan [48] who used CFD simulation of vapor flow in a shell-and-tube condenser for some different geometry modifications. He concluded that changes in geometry can have an influence on heat transfer. Other CFD studies for heat exchangers and flow fields can be found in the work by Perrotin and Clodic. [49]), Liu et al. [50], Watterson et al. [51], Mohr and Gelbe [52], Schroder and Gelbe [53] and Longatte et al. [54]. The list of CFD work can be made long, but no work using CFD for investigating condensation in tube banks could be found in the recently published literature, except for the study of [47]. This motivates further the need to study the heat transfer and flow field around the condenser tube bundle in the MSF system.

8. Conclusions

Review of the MSF lumped parameter models, including simple and detailed steady state and dynamic models, reveals that most of the essential elements of the process are captured in the literature models. This is illustrated in several studies through validation of the models' predictions against field data. There are two main areas that still require further development to improve existing MSF models. The first area concerns the correlations for predicting physical and thermodynamics parameter which characterize the MSF process such as Non-Equilibrium Allowance (NEA), demister losses, friction losses, and heat transfer coefficients. In this regard, it might be necessary to develop new correlations more accurate and suitable for the novel configurations and geometries proposed by the recent developments of MSF desalination industry. These developments include changes in the layout of the flashing stage, increase in the stage capacity, and use of new material of construction. The second area for development should focus on providing the user with a simulator that allows for easy modifications of physical parameters, model correlations, and process layout of the simulated system. Most the available process simulators adopted for MSF process modeling are limited to a single process configuration and allow the user to modify system parameters only within pre-specified ranges.

Review of models for the design and simulation of MSF stage internals shows a limited number of studies. This is mainly caused by the complexity found in modeling phenomena related to specific elements of a typical flashing stage, such as brine orifice, demisters and condensing tube bundles. One way to avoid this difficulty is the development of empirical correlations from experimental data collected from prototypes and small scale units, as well as from data obtained in operating MSF plants. Progresses in computing should allow for the development of more accurate models, which could provide valuable insights on several physical phenomena taking place inside the flashing stage. Such models could also be useful for further improvement and development of the process.

Note

1. ASPEN Plus User's Guide, Aspen Technology, Inc., Cambridge, MA, http://www.aspentech.com. HYSYS User's Guide, Aspen Technology, Inc., Cambridge, MA, http://www.aspentech.com.

List of abbreviations

ORNL	Oak Ridge National Laboratory
MSF	Multi stage flash
NEA	Non equilibrium allowance
RO	Reverse osmosis
IDA	International Desalination Association
BPE	Boiling point elevation
gPROMS	General process modeling system
CFD	Computational fluid dynamics

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