CONTROL SCHEME OF MULTISTAGE FLASH PLANTS

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Contents

Summary

In this paper, the principals of large-scale desalination plants have been briefly introduced. Based on this, the essential aspects of obtaining a mathematical model of an MSF plant were presented in Section 3. This step of defining the main system variables and decomposing the large-scale system into its main subsystems is most important, whether the model is used for simulation or model-based control design. Moreover, the successful applicability of the controller designed depends directly on the validity of the model with respect to the actual plant.

Considering the control strategies of modern MSF plants, one must recognize a big discrepancy between the control philosophies used, on the one hand and the numerous new control schemes, on the other hand. In Section 4, an overview of the actual advanced control strategies is given, where each one is certainly superior to classical PID control.

1. Introduction

The availability of potable water in the Gulf region is one of everyday undertaking, commanding the highest priority in the development of these countries. It is undeniably the most fundamental element in all places and at all times: human consumption, irrigation systems for agriculture, transport media for heating or cooling purposes, or as a solvent for chemical processes are but a few examples. Although the greater part of the Earth's surface is covered with water, the salt content of this water is so high that it cannot be directly used as a source of fresh water supply. The only water with a low salt concentration is rainwater. Due to the limitations of the underground water, low precipitation, rapid economic growth, etc., in several regions of the world, desalination units are needed more than ever.

To ensure constant fresh water production in the desalination plants and quality of the potable water, maximal availability is one of the strongest objectives to be met. Another aim of the optimization of desalination plants should be the minimization of the environmental pollution produced. For these purposes, a well-tuned automation and control scheme is necessary for reduced long-time maintenance shut-downs, optimal operation conditions, minimized chemical consumption, and lower risk of human errors.

A useful tool in the investigation and optimization of multistage flash (MSF) plants is computer-based derivation and simulation of the mathematical models of these plants. Obtaining a mathematical description of a real plant can be done in different ways. Two of them are steady-state and dynamic modeling. The steady-state description can be chosen in cases where, for instance, the plant parameters or the static behavior of the plant are the objectives of interest. For transient behavior or control design and validation, dynamic models are the most suitable choice. In the case of MSF desalination plants, which are large and complex systems, a mathematical model that describes every detail of the static and dynamic characteristics cannot be exactly derived. Considering this, when modeling complex plants one should bear in mind the ultimate purpose for which the entire job is performed. The following are some of these purposes for which one requires dynamic models (Unbehauen et al. 1987).

(a) Investigation of system behavior under various special conditions.
(b) Forecasting of quantitative trends useful in systems planning and management.
(c) Application of modern control methods to industrial and general systems.
(d) Need for better understanding of the influence of complexities in systems.
(e) Creation of simulation facilities for the purpose of training operation personnel for systems.
(f) Failure detection, fault diagnostics, and dynamic condition monitoring.

In other words, before creating the mathematical description of a model one must investigate the system and appreciate its main characteristics, while neglecting the unnecessary ones in relation to the model's objective.

In this paper, control of MSF desalination is considered. Based on this, the focuses of interest are the following topics. First, an introduction is given to the principles of MSF desalination. To obtain a realistic model of a real plant, it is very important to define the system properly, i.e. the degrees of freedom and correct selection of the variables. Note that this step must be done very carefully because all conclusions obtained from investigations based on the mathematical model depend on this definition. This will be discussed in detail in Section 2. Section 3 gives an overview of the control schemes for these large plants actually used and discussed. A short summary will close this introduction to the control schemes of MSF desalination plants.

2. Principles of MSF Desalination

Desalting in general describes a process where salty waster is divided into two streams: one with a low concentration of dissolved salts, the fresh water stream and the other with a higher salt concentration as the input stream, the brine stream. This separation can be done in several ways for example, using the membrane process (e.g. electrodialysis or reverse osmosis) and thermal processes (e.g. multieffect or MSF distillation). Over 60 per cent of the world's desalinated water is produced by thermal processes which mimic the natural method of water desalination. The water is heated at a determined temperature, it changes its phase to vapor and, after cooling down, it condenses to fresh water with low concentration of dissolved salt. For the phase change from liquid to vapor and vice versa two parameters of the water must fit together. The ambient pressure must correspond to the temperature. The relation between the water vapor pressure and the water temperature for fresh and seawater is given in Figure 1. Additionally, another special amount of energy is needed for vaporization. This energy is called the latent heat of vaporization and is needed during the phase transition. When the vapor is condensed the latent heat is released. Of the thermal processes, the MSF desalination is the process most used for large desalination plants all over the world. The idea of MSF distillation is based on the fact that water can be boiled at different temperatures if the ambient pressure is adapted to the corresponding value. This means, for example, that water at normal atmospheric pressure boils at a temperature of 100°C. If we halve the ambient pressure the boiling temperature is reduced to 80°C. Reducing the ambient pressure to restart boiling can be continued downwards and, if carried to the extreme with the pressure reduced enough, the point will be reached when the solid phase will shift to the steam phase without passing through the normal liquid phase.

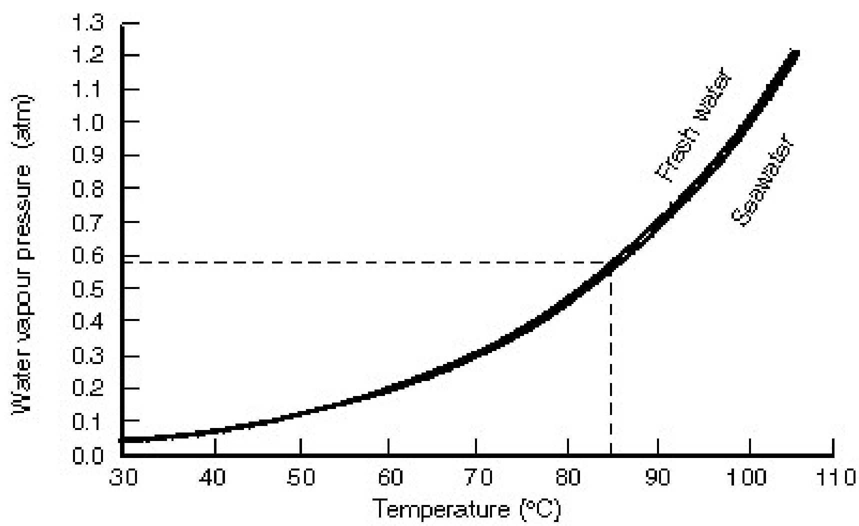

Figure 1. Increase of water vapor pressure of pure water and of seawater with temperature.

In MSF plants the salty water, which is called the brine, is heated in the brine heater to its start temperature, the top brine temperature (TBT), for instance 95°C (left-hand side in Figure 2). To prevent boiling of the brine in the transport tubes the ambient pressure lies above the vapor pressure. After heating, the brine is pumped to the first stage where the ambient pressure is reduced. This causes the brine to flash into steam immediately, which is condensed in the brine tubes (condenser) and fresh water precipitates in the distillate tray. Because of the high amount of latent heat needed for vaporization, only a small fraction of the water is evaporated before the brine temperature falls under the boiling point. It is important to note that the latent heat released during condensation is not wasted but used for the pre-heating of the brine. From the first evaporator stage the feedwater is passed to the next stage where the pressure is again lower than the previous stage and the procedure starts again. In MSF plants the feedwater (brine) passes from one stage to another and is boiled repeatedly without adding more heat. Typically, an MSF plant can contain from four to 50 stages.

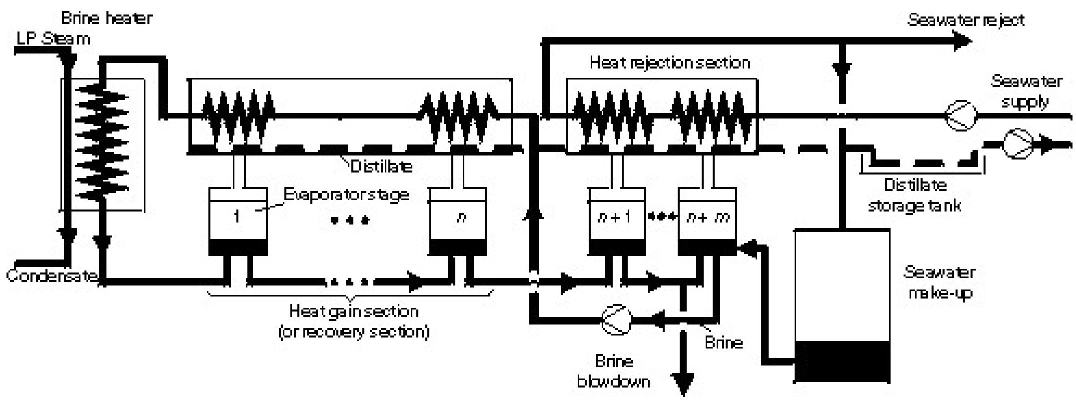

Figure 2. Schematic diagram of an MSF desalination Plant.

A schematic diagram of an MSF desalination plant with brine recycling is shown in Figure 2. It consists of three major sections: the heat rejection section, the heat gain section, also known as the heat recovery section, and the brine heater section, shown in this order from right to left. The heat rejection and heat recovery sections contain several flash stages. The number of these stages in the rejection sections varies between two and three and the number of stages in the heat recovery section is usually ten and can grow up to 50 in large plants. Every stage is a closed unit which contains a flash chamber at the bottom, cooling tubes at the top, and a distillate tray in between them, in which the desalinated water (distillate) is collected. A cross-section through a single stage is shown in Figure 3. In practical plants, each stage is additionally connected to a vent system where any infiltrated air or any non-condensable gases are continuously withdrawn in order to maintain the pressures in the different stages at their prescribed levels. Before the vapor enters the vapor space it is passed through demister screens. A demister screen is a wire netting device where entrained water droplets are separated from the vapor.

The seawater feed to the plant enters the tube bundle of the last stage (stage $N = n + m$) where it is allowed to pass through the heat rejection section. The heat rejection function is to reject the surplus thermal energy from the plant and to cool the product and brine to the lowest possible temperature as they emerge from the last rejection stage. On leaving the first rejection stage (the warmest; stage $n + 1$), the seawater feed stream is split into two parts: reject seawater, which passes back to the sea and a make-up stream which is added to the brine in the last stage. From this mixture, a combined brine recycle stream enters the tube bundle of the last recovery stage (stage n) where it is passed through the heat recovery section. It is progressively heated in each stage, due to condensation of vapor. At the very first stage of the heat gain section (stage 1), the heated water is passed to the brine heater where it is further heated by condensing low-pressure steam to the optimal TBT.

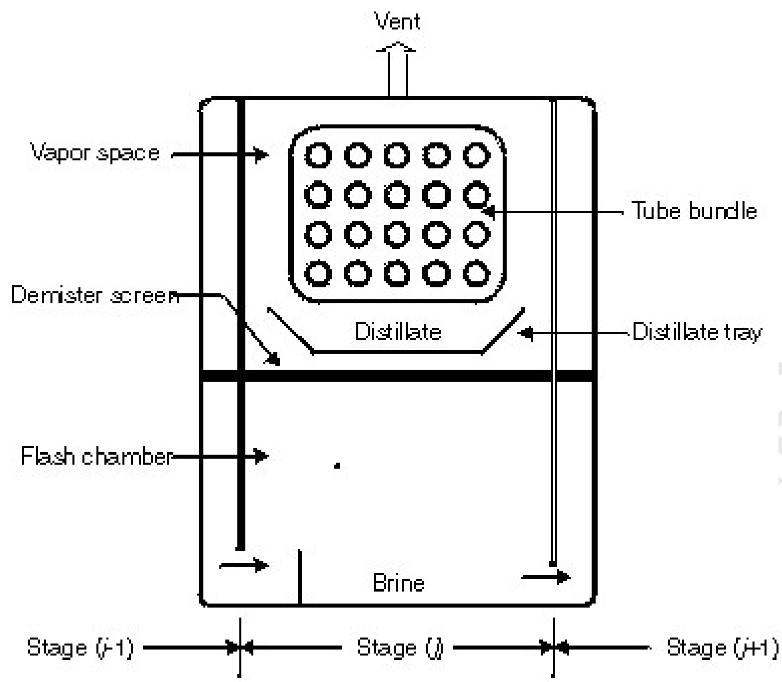

Figure 3. Cross section through a single distillation stage.

The flashing brine and the distillate flow from stage to stage in a countercurrent direction with regard to the flow of the combined brine stream inside the tube bundles. The pressure is gradually reduced from stage to stage until it reaches its lowest pressure in the last stage (stage *N*). At the last stage the distillate is pumped away to a storage tank. Some of the brine is mixed with the make-up stream again and fed back through the plant. This warm brine is recycled to prevent its salt concentration from increasing beyond acceptable limits. The rest of the brine is rejected back to the sea.

The MSF plant described is a familiar recirculation plant, because the brine flow through the distillation stages is mixed with the make-up flow and then recycled to the distillation process. The reason for this construction was the high consumption of chemicals used for preventing scale formation on the heat exchanger tubes. This type of plant is actually the most used form of MSF desalination plant.

The early MSF plants were once-through plants. In these plants the brine passes the distillation stages once and is then pumped back to the sea. As the salt concentration of the brine is much lower in once-through plants than in recirculation plants, the boiling point is also lower (see Figure 1). This naturally yields to a smaller heat exchange surface, which is the main factor in the size and cost of a distillation plant. Another main advantage of a once-through plant is the reduced complexity of the installation. Several pumps such as the recirculation pump and valves are not needed and, as a consequence of this, less pipes need to be installed. From that, a reduced cost for the installation and maintenance of a once-through desalination plant follows. These are the reasons why nowadays the discussion has started to build future plant as once-through processes. However, further calculations and simulation must show which one will be the better construction for large plants.

3. Defining the System for Control

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 dynamic model on which the design analysis and evaluation can be carried out. Thus, the reliability of the results obtained depends on the validity of the control structure and the model used.

It is important to note here that the variables, which are shared in the control system, normally constitute a reduced subset of the total variables which can be defined in the process. Moreover, a dynamic model suitable for control is usually simpler than the model derived from the physics of the underlying process. Hence, the selection of variables and the model building from the point of view of control design presents a compromise between the indispensable information contained in the model and the total mathematical complexity of the design. It may be that a very complete model leads to an unsatisfactory control system, whereas simple models with a reduced number of controlled variables yield better control performance for the same process.

For MSF desalination processes, steady-state and dynamic models can be found in the control literature. The former consists of algebraic equations and is a useful tool in the design stage, helping in the appropriate dimensioning of the plant (Lammers el al. 1977), optimization aspects (Omar 1983), and calculation of the setpoints (Fumagalli 1994). Since steady-state models are normally used to design the plant, they can be used to determine fixed parameters and validate the dynamics for $t \to \propto$. However, they are not of use for control design and analysis purposes.

Dynamic models are based on differential equations and are required for solving problems in the transient phase (Rimawi et al. 1989), process interactions, and trouble shooting (Husain et al. 1993). Moreover, they are necessary to implement modern control strategies (Al-Gobaisi el al. 1991).

The first attempt to obtain a dynamic model of an MSF process has already been reported in (Glueck et al. 1970). However, this model was overspecified because of the differential energy balance included, combining vapor space and distillate in the flash stage. A second effort (Drake 1986) applied empirical corrections for the evaporation rates, but the non-condensables in the vapor were not taken into consideration. The simulations realized with this model showed significant deviations in the cooling water rate (Ulrich 1977). In (Rimawi et al. 1989), a model without brine recycle was proposed. Husain et al. (1993) proposed a model with flashing and cooling brine dynamics. The model was improved in (Husain et al. 1994) and (Husain et al. 1994) considering the distillate dynamics and in (Reddy et al. 1995) including the brine recycle. These models were oriented at completing and reproducing the properties of the plant as exactly as possible. However, a simplified verified model for control purpose is still not available in the literature.

The MSF plant belongs to the class of large-scale systems (in size and complexity), that is systems which can be described satisfactorily by normal, traditional mathematical tools, but this leads to large-scale models bringing into play more than 100 state variables. Thus, particular considerations should be taken into account when dealing with such systems. Hence, it is convenient to apply the typical techniques for large-scale systems such as, for example, decomposition and coordination (Bernusou et al. 1982, Mahmoud et al. 1985).

According to the characteristics of MSF plants, a spatio-temporal decomposition has advantages in plant organization. This technique consists of a combination of the physical, horizontal, or geographical decomposition and temporal or vertical decomposition. The former is based on interconnected subsystems along the physical coupling links according to the system structure. The temporal decomposition is given by several levels of phenomena which occur at different time points or different time scales. However, the literature presents different approaches to spatiotemporal decomposition. Thus, for example, a decomposition with physical predominance was presented in (Rao 1993) (e.g. a brine heater, condenser, evaporator, cooling section ejector, and venting), while in (Drake 1986) the predominance was functional (e.g. operational control section, protective devices, environment protection, safety features, and efficiency controls) and in (Al-Gobaisi et al. 1991) an extended but equilibrated decomposition was considered. This leads to different sets of variables and, therefore, to different subsystems for an MSF plant.

Finally, to obtain the control system as well as an effective model, it is very important to define the system properly, i.e. the degrees of freedom and correct selection of the variables. Note that all conclusions obtained from a design based on model and simulation results depend on this definition, since different selection of variables will bring about different results. Moreover, the successful applicability of the designed controller depends on the validity of the model with respect to the actual plant.

3.1. The Degrees of Freedom

When using a mathematical model, it should be ensured that the model equations provide a unique relation between all inputs and outputs. This is equivalent to requiring that the degrees of freedom be zero, i.e.

$$N_f = N_v - N_e = 0 \qquad (1)$$

where N_f is the degrees of freedom, N_v is the total number of variables including inputs and outputs, and N_e is the number of independent differential and algebraic equations. Note that $N_f = 0$ (exactly specified process) is the only satisfactory case because, if $N_f < 0$ (overspecified process) then additional independent model equations must be developed. If $N_f > 0$ (underspecified process), then sufficient variables have not been identified.

On the other hand, one effect of the feedback control is a reduction in the degrees of freedom of the process. Hence, in an underspecified process ($N_f > 0$) the degrees of freedom can be utilized to select manipulated variables and the variables fixed by the process environment, such that

$$N_f = N_M + N_S \tag{2}$$

where N_M and N_S are the number of manipulated variables and variables specified by the environment. Equation (2) leads to the fact that $N_f \geq N_M$ always.

It was shown in (14) that the total number of variables for an MSF process with N stages is $12N + 38$ and the total number of equations is $12N + 24$, i.e. $N_f = 14$. Thus, 14 variables should be specified to permit a consistent solution to this problem. Different numbers and selections of variables can be found in the literature (see, for example (Husain et al. 1993, Barba et al. 1973)).

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