HEAT AND MASS BALANCES IN THE EVAPORATOR COMPONENTS GROUP: STAGE HEAT AND MASS TRANSFER BALANCE

M.A. Darwish and Faisal Al-Juwayhel
Mechanical Engineering Department, Kuwait University, Kuwait

Keywords: flash chamber, transfer orifice, separator height, shell load

Contents

Summary

This chapter discusses the analyses of heat and mass transfer in a single stage of a multi-stage flash (MSF) desalting system. The stage is a unit of stages connected in series forming the once through multi-flash stage (MSF) evaporator, or the heat recovery section, or the heat rejection section of the re-circulation MSF evaporator.

1. Introduction

Analyses of heat and mass transfer in a single stage of a multi-stage flash (MSF) desalting system are presented in this article. A flash stage is a key unit of the MSF process. It should be realized that performing a stage by stage calculation, instead of calculations for the stages based on averaged values, is essential to understand what is happening within a stage. Stage by stage calculation is also a necessary step for better analysis and simulation of the MSF process resulting in better design and operation of the system. Such calculations are also deemed effective in determining the effect of the operating variables on the characteristics of a stage.

The flow sheet of an MSF desalting system is shown in Figure 1 (Darwish 1995). An MSF plant consists of a heat-input section (HIS) known as the brine heater, a heat recovery section (HRS), and a heat rejection section (HJS). The HRS and HJS are made up of stages. Each stage consists of a flash chamber with inlet and out flow controlling devices (usually sluice gates) to control the flow of the flashing brine to and from the stage. As shown in Figure 2, this stage contains the bulk of flashing brine, a vapor space, a mist separator (a demister), condenser tube bundle (a pre-heater), and distillate tray. The distillate tray receives the condensate of the vapor generated in the stage and the accumulated distillate from the upstream stage and conveys the distillate to the downstream stage.

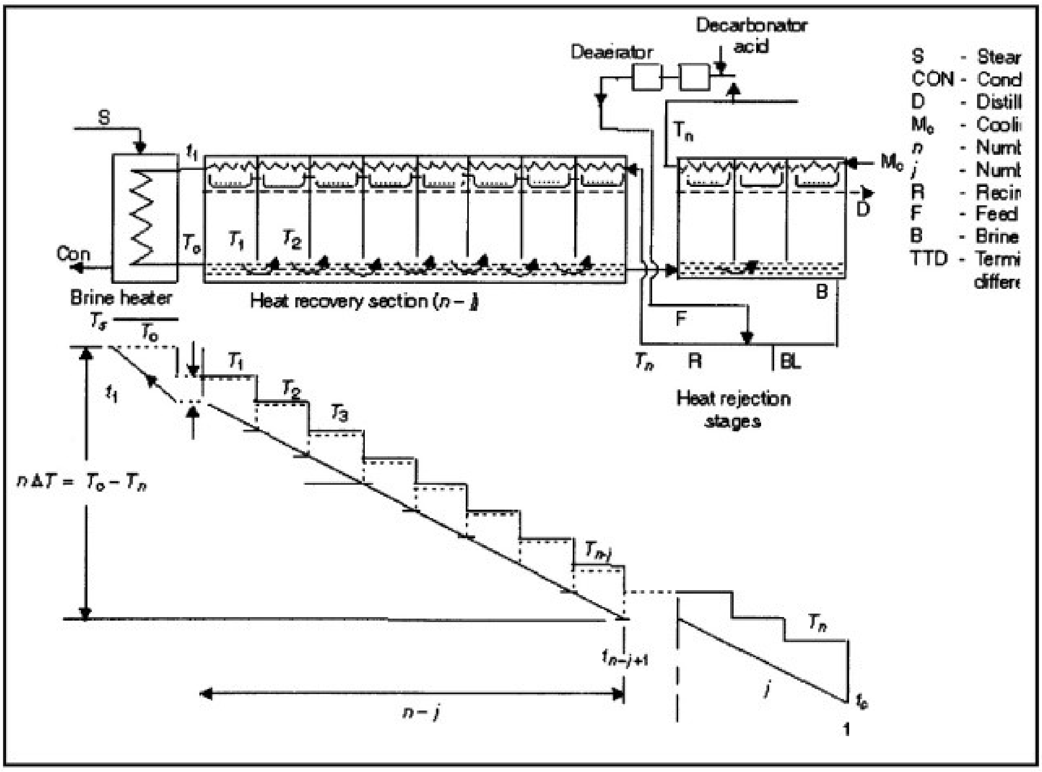

Figure 1: Flow Sheet of a brine Recirculation MSF Desalting System

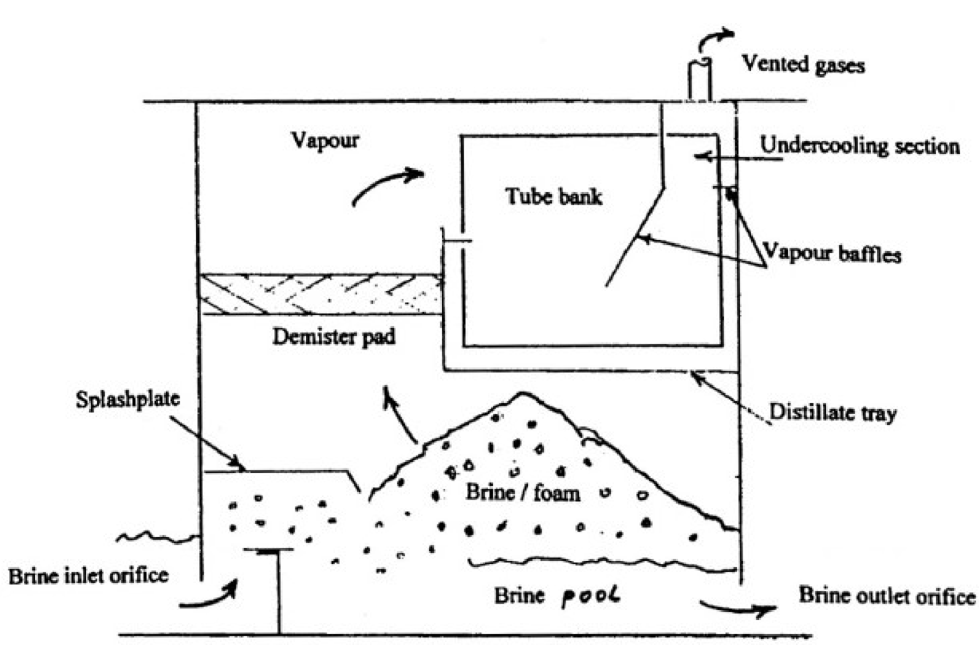

Figure 2: A typical MSF Stage

Consider a flashing brine of a flow rate B_{i-1}, a temperature T_{i-1}, and a pressure P_{i-1} entering a stage that is kept at a pressure $P_i < P_{i-1}$ and a saturation temperature $T_i < T_{i-1}$. The brine will become unstable and part of it will spontaneously vaporize (i.e. flash) resulting in a drop in the brine temperature to T_i which will cause the brine to reach thermal stability. The vapor released by flashing flows upward in the vapor space, through the mist eliminator, to the condenser tubes in the upper space of the chamber. Here, the vapor condenses to form the product. Similarly, the accumulated distillate flowing from the upstream stage i-1, ΣD_{i-1}, suffers pressure and temperature drops as it enters stage i. Part of this distillate is evaporated by flashing and condensed on the condenser tubes. The heat released by condensation of vapors generated from the flashing brine and from the distillate is gained by the re-circulation stream flowing inside the condenser tubes. The temperature of the vapor generated from the flashing brine suffers some losses as it condenses to form the product of this stage. This temperature loss (DT) is due to boiling point elevation (BPE), pressure loss in the mist eliminator, and pressure loss in the condenser tubes.

The mass flow rate of the flashing brine to stage i, B_{i-1}, depends on the stage pressure, P_i, the temperature (T_{i-1}) and pressure (P_{i-1}) of the incoming brine, the discharge coefficient of the sluice gate, and the brine level upstream and downstream the gate. Meanwhile, the pressure (P_i) in stage i depends on the rate of generation and condensation of vapors in this stage. So, the mass flow rate of the brine (B_{i-1}) to stage depends indirectly, but significantly, on the factors affecting the condensation process. These factors include the overall heat transfer coefficient of the condenser tubes, U, the heat transfer area, the concentration of non-condensable gases around the condenser tubes (as it affects both U and P_i), and the temperature of the re-circulating brine flowing inside the tubes.

The above discussion shows how the variables interact with each other. No simple formula exists that represents the interaction of those variables. Several models were formulated (e.g. Aly et al. (1995), Bourouis et al. (1995), El Dessouky et al. (1995)) to simulate the flow to a flash stage and the interactions within it. The main objective here is to present the equations which will help the reader to understand the interaction of the variables in the stage.

It is appropriate here, before presenting the mass and energy balance, to give the terms and variables generally used in the characterization of a stage. A stage consists of a flash chamber, a mist separator, heat transfer area, and distillate collection tray, along with water boxes, piping, etc., pertaining to a particular stage. The stage is a unit of stages connected in series forming the once through multi-flash stage (MSF) evaporator, or the heat recovery section, or the heat rejection section of the re-circulation MSF evaporator.

The following are definitions of the various parts of a stage:

The flash chamber is the part of the stage where flashing occurs. It is bound by the inter-stage walls and the lower side of the separator, and contains the inter-stage brine transfer orifices.

The separator is fitted to the roof of the flash chamber to separate the droplets being carried by the upcoming vapor flashed from the brine.

The brine transfer orifice is usually a system of orifices and weirs used to regulate the flow brine from one stage to another. The widely used configurations in large MSF units are the simple slot, and the slot and weir shown in Figures 3 and 4.

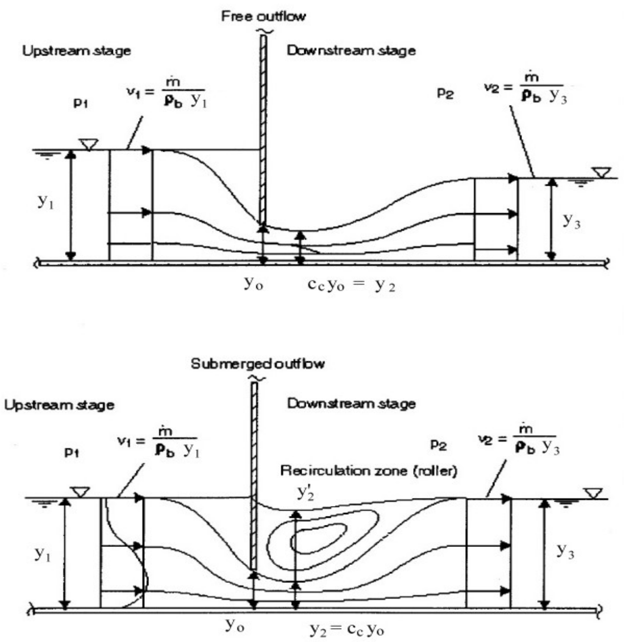

Figure 3: Sluice gate, free/submerged flow

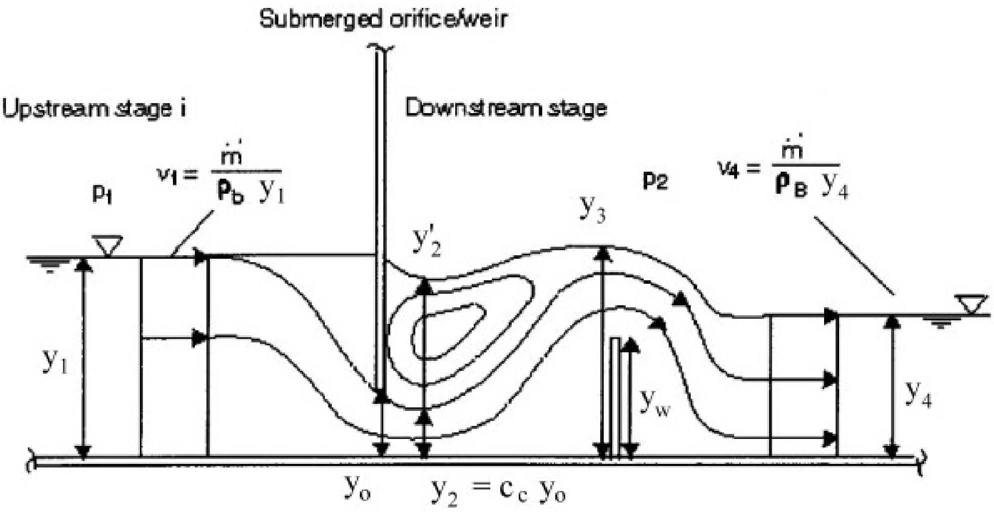

Figure 4. Combination orifice/weir

The brine level is the height of the brine surface above the floor of the flash chamber.

The foam height is the maximum height of the foam jet above the surface of the brine.

The separator height is the dimension from the floor of the flash chamber to the lower side separator.

The separator area is the area through which the vapor flows, neglecting the space taken by vanes, mesh, etc.

The flash chamber width is the dimension of the chamber across the flow of the brine.

The shell load is the mass flow rate per unit width of the flash chamber in kg s^{-1} m.

The stage distillate production rate is the mass flow rate of the vapor leaving the brine in the stage. This vapor will condense on the heat transfer area in the upper section of the stage. It can be calculated from $D_i = B_i\, C\Delta T/L$, where ΔT is the brine temperature difference between the upstream and the present stages.

The vapor release rate is the mass flow rate at which the vapor leaves the brine surface per unit area, in kg s^{-1} m^2, based on the plan stage area. This is equivalent to D_i/stage area.

The mist separator loading is the vapor mass flow rate through the separator. It is equivalent to D_i/separator area.

2. Factors Affecting the Brine Flow to the Stage

The flow of the flashing brine to a stage is a complex process since it depends on a large number of inter-related variables. This is in addition to the complex nature of flashing occurring at the orifice. The operating variables directly affecting the inter-stage brine flow are the level of the brine in the stage, the pressure drop and brine level differences between the upstream and the stage in question, and the amount of flashing taking place at the orifice. The flashing in the orifice region causes abrupt acceleration of the brine and represents an additional energy loss that must be compensated for by an increase in the available head upstream.

The liquid level greatly affects the brine flow to the stage as well as the operation of that stage. The rise of the brine level can increase the entrained droplets carried over by the upcoming vapor to the distillate tray and thus deteriorates the distillate product quality. Also the rise of the brine level in a stage can impede the thermal equilibrium of the brine before it leaves the stage, especially in low temperature stages. Meanwhile the decrease of the brine level below the height of the exit orifice allows the vapor to escape to the downstream stage. This deteriorates the efficiency of the stage.

The brine level depends on the net flow to the bulk brine in the stage. This is equal to the incoming brine flow from the upstream stage, less the brine leaving the downstream stage and vapor release from the brine. Equilibration is satisfied when the net flow is zero while other variables remain constant. The liquid level in a stage tends to regain equilibrium very rapidly. When the brine level is increased, due to a positive net flow to the brine bulk, the head and the flow at the downstream orifice are increased to arrive at equilibration. Similarly if the brine level is decreased, due to negative net flow to the brine bulk, the head and the flow at the downstream orifice are decreased. Such processes will lay the ground for steady-state, steady flow (SSSF) conditions if all other factors remain constant, as mentioned above. However, keeping those factors constant is questionable.

The net head across an orifice depends on the pressure difference ΔP_v across the orifice. The value of ΔP_v is a direct function of the flash down (the temperature drop due to flashing), and the temperature of the stage. It should be mentioned here that the value of ΔP_v varies significantly with the stage temperature for the same temperature difference (flash down temperature). As an example, for the same temperature difference between two consecutive stages, say 2°C, the value of ΔP_v is equal to 788 Pa at a stage temperature of 40°C, and is equal to 9636 Pa at a stage temperature of 110°C. Thus ΔP_v at 110°C is more than 12 times ΔP_v the pressure difference at 40°C. This fact makes the flow in the top temperature stages different to the flow in the low temperature stages for the same temperature drop and stage opening.

2.1. The Hydrodynamic of Inter-stage Brine Transfer

Due to the complexity of the flashing flow through the inter-stage control devices, simple models assuming single phase flow were developed by different researchers. In such models the effect of flashing was neglected. Ball (1986), indicated that several possible single-phase flow regimes can exist when there is a pressure difference across an inlet orifice. Figure 5 shows four types of such flow regimes; they are the shooting flow, jump flow, submerged discharge flow, and blow-through flow. For both the shooting and jump flows, the flow down stream the orifice is supercritical and thus intensive to change in liquid levels further down stream. The flow is called critical when the Froude number, $Fr = V^2/gh$, is equal to 1. The Froude number is a parameter characterizing the flow when the gravity force is the dominant force affecting the flow, much like the Reynolds number to the flow when viscous forces are the dominant affecting ones. The flow is called supercritical when Fr > 1, and subcritical when Fr < 1.

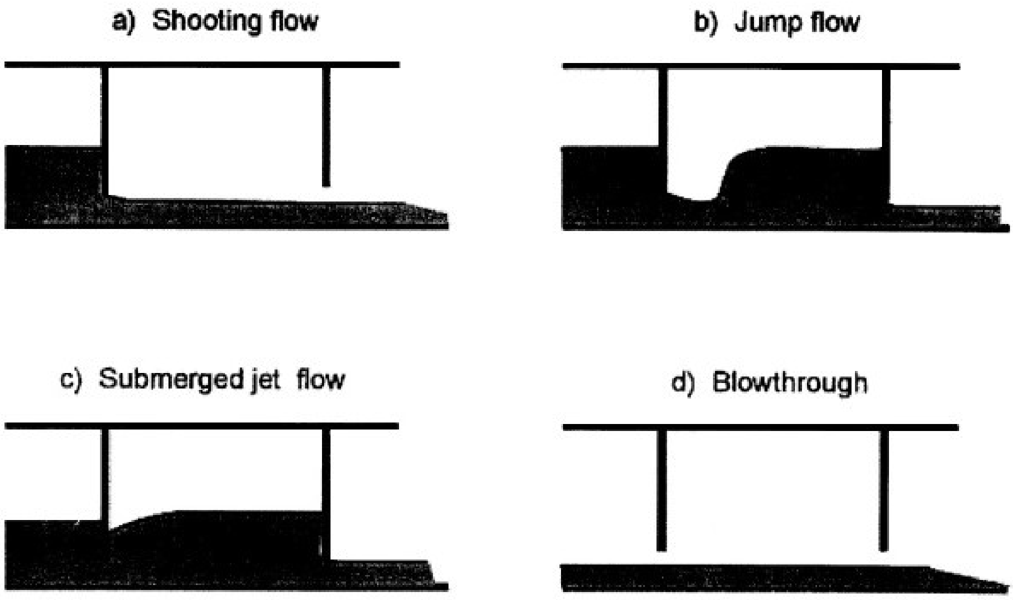

Figure 5: Flow Regimes prevailing in MSF chambers

In the blow-through flow case, supercritical flow occurs upstream from the orifice, and the downstream brine level has no effect on the flow. In the operational range of MSF plants, only jump and submerged flow regimes prevail, though non-submerged flow is considered desirable with internal mechanical arrangement, like weirs, Reddy (1996).

The flow through an orifice for the single-phase case is given by:

$$Q/A_o = C_d \sqrt{2g\Delta y}$$

The problem with using the above equation is specifying the net Δy. The head upstream of the orifice y_1, is usually taken as the brine level far before the orifice. The downstream velocity head is usually computed at the vena contracta (with a height $y_2 = C_c y_o$, where y is the orifice height), and the static head is taken at the level located approximately at the vena contracta. Some specialists in the field take y_2 as the brine height far after the orifice.

Kishi et al (1985) presented a flow model for a submerged sluice gate and weir which is widely used in the design of MSF evaporators. The flow model is subdivided into three flow regions as shown in Figure 6. These regions are from upstream to downstream the weir (weir over flow). The first two regions can be considered as the case of simple sluice gate, with no weir, as in the very last stages where ΔP across the stage is very low. The relationships for the interaction of the variables in the three stages are obtained by using the continuity, momentum, and energy equations. The procedure is outlined in the next section.

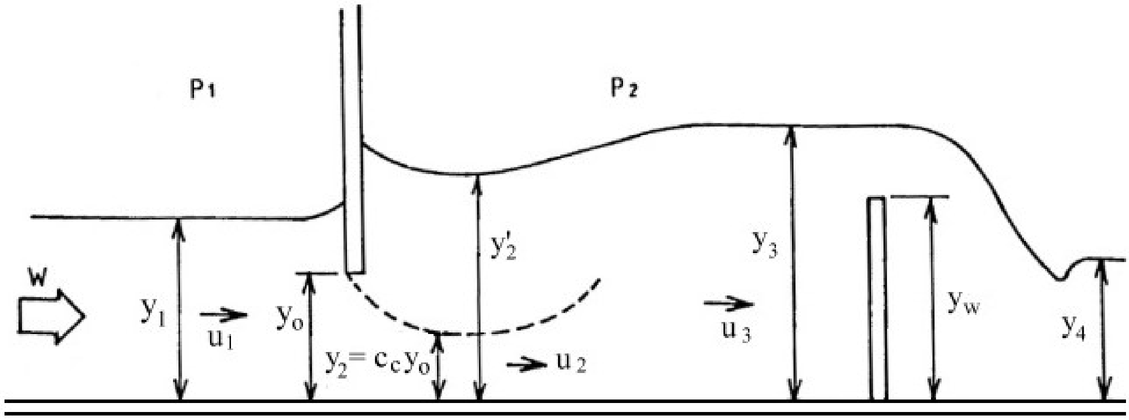

Figure 6: The Flow model for a submerged sluice gate and weir as developed by Kishi et al (1985)

-
-
-

Bibliography and Suggestions for further study

Aly S E and Fathalla K (1995) MSF - A mathematical model. IDA World Congress on Desalination and Water Science, Abu Dhabi, vol. V, 203-226.

Ball S J (1986) Control of two phase evaporating flows. *Desalination* 59, 199-218.

Bourouis M, Azzaro Pantel C, Floquet, P, Duverneuil P, Pibouleau L and Domenech S (1995) Steady state simulation of MSF by using an equation of oriented approach. IDA World Congress on Desalination and Water Use, Abu Dhabi, vol. IV, 167-184.

Darwish M A, El Refaee M and Abdul Jawad M (1995) Development in the multi stage flash desalting system. *Desalination* 100, 35-64.

Dempsey M C and Sarkodi Gyan T (1995) Modelling simulation of the processes in a single stage of MSF desalination plant. IDA Congress on Desalination and Water Reuse, Abu Dhabi, 295-310.

El Dessouky H and Bingulac S (1995) A stage-by-stage algorithm for solving steady state model of multi stage desalination plants. IDA World Congress on Desalination and Water Reuse, Abu Dhabi, vol. V, 251-278.

Homig H E (1978) Fichtner-Handbook on Seawater and Seawater Distillation.

Kishi M K, Matsumoto K, Takeuchi Y and Hattori (1985) Development of flow model for weir type orifice. *Desalination* 55, 481-492.

Marto P J (1991) Heat transfer in condensation, in boiler, evaporators and condenser. (ed. S. Kakaç), pp. 525-538, John Wiley and Sons.

Reddy K V, Husain A, Woldai A and Kurdali A (1995) Dynamic modelling of MSF desalination process.

IDA World Congress on Desalination and Water Reuse, Abu Dhabi, vol. IV, 227-242.

Reddy K V, Husain A, Woldai A and Kurdali A (1997) Holdup and inter stage orifice, flow model for MSF. Madrid, pp. 323-340.

Streeter (1979) *Fluid Mechanics*. McGraw Hill Pub. Co.

Wangnick K (1995) How incorrectly determined physical and constructional properties in seawater and brine regimes influence the design and size of an MSF desalination plant - stimulus for further thoughts. IDA World Congress on Desalination and Water Reuse, Abu Dhabi, vol. II, 201-218.