A HYBRID METHODOLOGY FOR OPTIMIZATION OF MULTI-STAGE FLASH-MIXER DESALINATION SYSTEMS

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***Abstract*— In this paper, a new strategy involving an evolutionary algorithmic procedure for the optimization of Multiple Stage Flash (MSF-M) Systems is presented. A "detailed model" of an MSF-M System is developed according to rigorous material, momentum and energy balances for each stage. The model of the MSF-M System is represented as a complex NLP, which incorporates a high number of nonlinear constraints that difficult the global optimum determination. Here we present a hybrid methodology that uses optimal solutions obtained from a "thermodynamic method" to find the "economic global optimal solution". A pre-processing stage (solving successive NLPs) is used to initialize the final NLP problem. A Case Study and a discussion of the results are presented.**

***Keywords*— MSF-Mixer Desalination System. Optimal Synthesis and Design. Hybrid Methodology.**

I. INTRODUCTION

In previous papers (Scenna, 1987a,b; Scenna *et al.*, 1993), a simplified model was presented using a Thermodynamic Based Methodology, which allows finding optimal solutions involving both structural and operational conditions of MSF-M systems. In practical designs, models with a more detailed description become necessary (for example pressure drops, inter-stage flowrates and liquid levels are critical due to operative conditions), but generally they are very difficult to solve using the above-mentioned approach.

From the Mathematical Programming point of view, we can use NLP models (Mussati *et al.* 2001) for system description. In this paper, a strategy to determine the optimal design for the MSF-M System is presented. It involves solutions obtained in a first step involving a thermodynamic model. Thermodynamic solutions are used to initialize an MSF-M rigorous model when an economic objective function is considered (which includes the capital and operation costs).

This idea is based on previous work (Scenna and Aguirre, 1993) to solve the synthesis of dual-purpose desalination plants. Indeed, several researchers (Gundersen and Grossmann, 1990; Bek-Pedersen *et al.*, 2000) have used thermodynamic functions in different ways to make the MINLP or NLP solution easier, proposing a "physical insight" to solve complex synthesis problem.

Here, we introduce a formal context for using of thermodynamic models for solving a complex optimization problem based on previous experiences and results. Also, a discussion about the global optimality of the achieved solution is presented. In addition, a general procedure to handle the link between "thermodynamic" and "economic" based solutions will be approaches.

II. RIGOROUS NLP FORMULATION FOR THE MSF-M SYSTEM OPTIMIZATION

Figure 1.a shows the flow-sheet of an MSF-M System. A typical flash stage is shown in Fig. 1b. The evaporator is divided into stages; each stage has a seawater condenser, a brine flash chamber, a demister, distillate collecting and a transfer system.

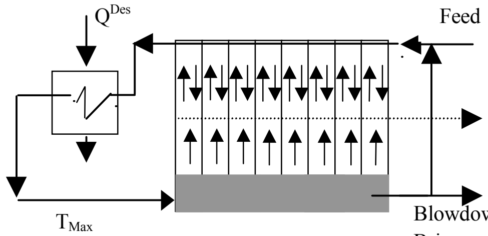

Figure 1a. Diagram of MSF-M Desalination Process.

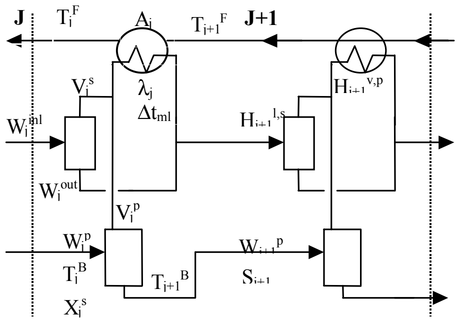

Figure. 1b. Schematic Representation of the jth stage.

The seawater (feed) enters at temperature T0 and it is heated at the maximum temperature (Tmax) as it flows in series through the condenser tubes of each stage and brine heater. It then flows into the first stage inlet box and is evenly distributed across the width of the evaporator. It enters the first stage through an orifice that controls its flow rate and flashing contour characteristics. The flashed vapor flows through a demister, which removes any entrained brine, then over a condenser that condenses it. The condensate, referred to as distillate, is collected in a distillate collection. The seawater, now referred to as brine, because its salinity has increased, then flows through the evaporator stages in turn, releasing flashed vapor in each stage in the same manner. The brine is rejected from the last stage evaporator by a brine blow down pump to the sea. Part of this stream is recycled and mixed with the feed to enter on the pre-heater tubes as was described previously.

The distillate formed in each stage passes through the transfer system into the succeeding lower temperature stage, where a proportion is flashed to vapor similarly to the seawater. This vapor flows over the condenser of the stage, together with the vapor flashed from the sea water and is condensed and transferred to the next stage. The distillate accumulates as it flows through succeeding stages and is discharged from the last stage to a product water tank by the distillate pump.

The model (see Appendix 1) considers rigorous material, momentum and energy balances for each stage. The stage area is calculated taking into account chamber length and width, gate height and total chamber height. The flow between two adjacent chambers is given by the pressure gradient, which is related with the pressure in the vapor space, the liquid level in the two adjacent chambers and the pressure drop along the orifice. Also, the Boiling Point Elevation (BPE) that depends on the salinity and flashing temperature at each stage, and the Non-Equilibrium Allowance (NEA) that represents a measure of the thermal flashing process efficiency are taken into account.

Finally, the variation of the overall heat transfer coefficient is considered according to brine velocity in the condenser tubes, tube diameters, fouling factor and condensation temperature.

The modeling system General Algebraic Modeling System GAMS (Brooke *et al*., 1988) is used to implement the model and the solution method. The generalized reduced gradient algorithm CONOPT 2.041 is employed.

III. THE PROPOSED METHOD FOR SOLVING THE NLP PROBLEM

In order to determine the optimal design for the MSF-M Systems (minimum Total Annual Cost TAC), we propose the use of the optimal solutions obtained from the formulation of an associated "thermodynamic model" as a guide to solve the original NLP problem ("economic" problem). Before describing the methodology, the two main NLP models will be presented.

A. Cost based Model (P1)

The cost associated to an MSF-M process consists of operating and capital costs. Operating costs include steam cost, pretreatment of the saline feed stream and pumping. Capital cost includes condenser and heat exchanger tubes and the flashing chambers with the associated piping cost. The most representative costs are steam cost and the capital costs associated to the heat transfer area and the flashing chambers.

In this way, the problem is defined as follows:

$$Minimize\, f(x) = \sum_{j=1}^{NS} CRF\,[A^j tubing + F\ A^j stage] + C_{Q^{Des}} Q^{Des}$$

subject to:

model constraints (1-30) presented in Appendix I.

Factor F can be calculated (the minimum value) as a ratio between the tube and the wall-chamber thickness. It depends on the resistance corrosion, tendencies to form scale and mechanical strength of the material used for the construction and the chamber geometry. Also F must consider the necessary instrumentation and others factors charged to chamber cost (Genthner *et al*., 2000). Assuming the above-mentioned hypothesis the minimum value for factor F is 25.

B. Thermodynamic based Model (P2)

Here, we consider an NLP problem, similar to the above-defined one, with a "thermodynamic" objective function. In this way the optimization problem is:

Prob. 2.1 (P.2.1)

$$Minimize\ Q^{Des}(x) \equiv Minimize\ \sigma$$

subject to:

$$\sum_{j=1}^{NS} \left(A^j{}_{tubing} + F\ A^j{}_{stage}\right) = Atotal$$

and the constraints of the model (1-30) presented on the Appendix I. Atotal is a model parameter.

The above-defined problem is equivalent to the following:

Prob. 2.2 (P.2.2)

$$Minimize \sum_{j=1}^{NS} [A^j{}_{tubing} + F\ A^j{}_{stage}]$$

subject to:

$$Q^{Des} \geq Q_0$$

and model constraints (1-30) presented in Appendix I. Q_0 is a model parameter.

The basic idea of the methodology is to use the solution of the thermodynamic based NLP models P.2.1 or P.2.2 as a starting point for solving P1. Since both problems differ from each other only in the objective function, they are generally equally complex to solve. The advantage of using a thermodynamic model is that it always allows us to find physical insight of the process Mussati *et al*. (2001, 2002). As it will be described in the next section, it also provides relationships associated to the original problem (P1) and the "thermodynamic" based one (P2).

IV. RESOLUTION METHODOLOGY

In previous works Scenna (1987b) and Mussati *et al.* (2001), some properties of the solution of this problem obtained from a thermodynamic point of view and some physicals insights were analyzed. In Mussati *et al.* (2001) using mathematical programming, a detailed model considering mass and energy balances and the physicochemical properties was presented. The Hydraulic calculations and the chamber geometry, which in turn permit an exhaustive evaluation of the chamber cost, were not considered in that model. From this point of view, the previous model (Mussati *et al.*, 2001; 2002) is a special case of our model presented in Section 2) of this paper (considering F = 0). For example, if we not consider the chamber cost (F=0) the solution of P.2.1 and P.2.2 stated in section 2 corresponds to a number of stages tending to ∞.

According to the methodology considered in this paper, and due to consider an implicitly chamber cost considering F, at difference with that paper, the optimal stage number can be achieved.

In order to solve the problem P1, we can summarize our procedure in the following steps:

1) Obtain Q^{Des} vs. Atotal curves solving the optimization problem P.2.1 or P.2.2. Figures 2a and 2b show the optimal solution achieved solving the P.2.2 problem. Given the Q0 value (Q^{Des}) for each number of stage NS the minimum total heat transfer area value has been determined. For example, Fig. 2a shows Atotal vs NS for Q^{Des}= 140 Gcal/hr.

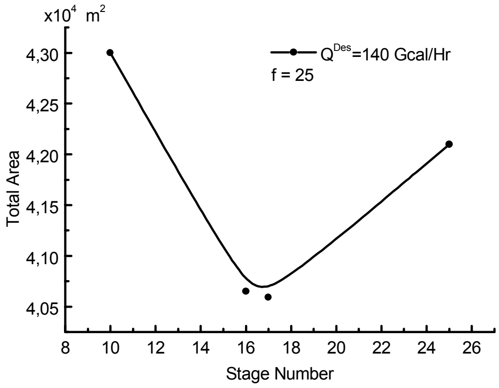

Figure 2a. Atotal vs. NS for Q^{Des}=140 Gcal/h

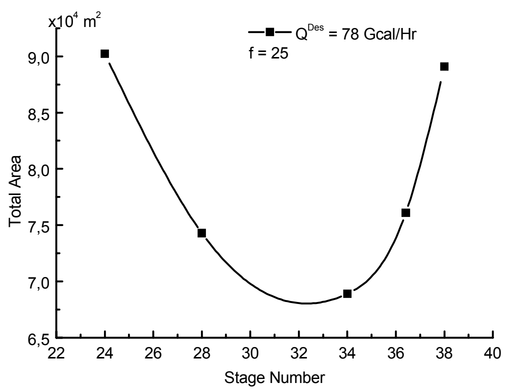

Figure 2b. Atotal vs. NS for Q^{Des}=78 Gcal/h

2) Determine from 1) the values NSoptim and Atotal$_{min}$ corresponding to a minimum for each Q^{Des}. Obtain the curve Q^{Des} and NSoptim in terms of total area Atotal$_{min}$ (Fig. 2c).

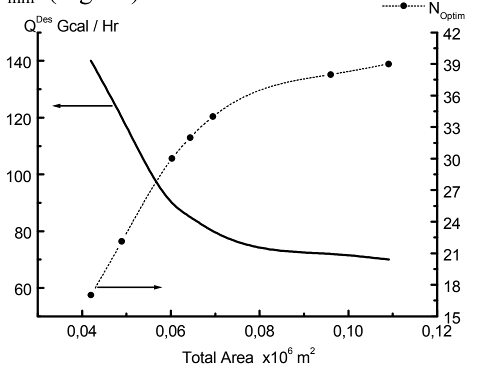

Figure 2c. Minimum total area corresponding to Noptim vs Q^{Des}.

3) Given the data costs (CA, CQ^{Des}, CRF) solve the NLP problem P1 using the relation dAtotal / dQ^{Des} = - RCF CQ^{Des}/CA and Figs. 3 and 2c to determine the initial point. So, we determine Q^{Des}*, the tubing area and the chamber area associated to each stage and NS* to be used as initial values to solve the problem P1.

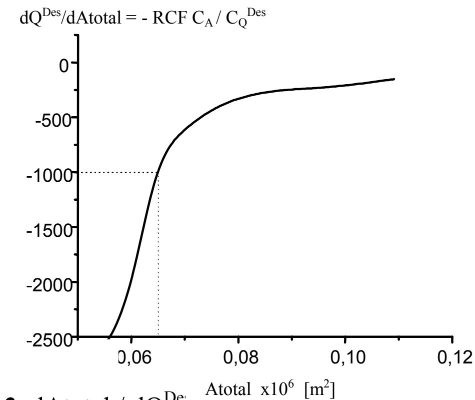

Figure 3. dAtotal / dQ^{De}

4) Solve the objective function value for NS*-1, NS* and NS+1* (according to 3), and then determine the optimal number of stages according to the objective function values.

In order to obtain the Q^{Des} vs. Atotal$_{min}$ curve for the P2 (Fig. 2c), first we must solve successive NLP problems to determine the values of NSoptim and Atotal$_{min}$ for each Q^{Des}. As it can be seen in Figs. 2a and 2b, for a fixed value of external heat consumption Q^{Des} , there exists a solution which characterizes the number of stage (NSoptim) for which the total area (Atotal) is the minimum (Atotal$_{min}$). It is then possible to draw (Fig. 2c) the relationship Q^{Des}, Nmin in terms of the minimum total area (Atotal$_{min}$).

Each point of this curve represents an optimal solution of P2 and allows us to determine a cuasi-optimal initial point to solve P1. Then, given the complete space of "thermodynamic" optimal solutions, we must relate them with the optimal solutions of the "equivalent" NLP problem P1. According to the Kuhn-Tucker conditions for both problems it follows that the optimal solution of the cost based problem represents one of the optimal solutions of the "thermodynamic problem". The thermodynamic solution that corresponds to the cost based optimal solution can be found when the values CQ^{Des}, CArea and CRF are given. Selecting the dual multiplier u*=CA CRF/CQ^{Des}, it can be shown that the Kuhn-Tucker conditions for both problems are identical (Mussati *et al.*, 2002). Furthermore, from the duality theory, the following condition is established:

$$-d(Q^{Des})/d(Atotal) = CRF\ C_A / C_{Q^{Des}} = u^*$$

Since for a given problem we know u*, it is possible to relate the optimal values for Q^{Des} and Atotal according to the optimal thermodynamic curve (see Fig. 2c and Fig. 3). In turn, these values allow us to specify "optimal critical variables" at each stage by applying simple relationships. These variables are a sort of optimal initialization for the problem P1.

V. CASE STUDY

Given the following data and parameters: C_A= 50$/m2, CQ^{Des}=0.076/$10^6$$/Kcal ,RCF=0.182$/year, we will apply the above-describe procedure in order to determine the optimal MSF-M conditions representing the minimum total annual cost. Solving the first problem according to step 1) and step 2) of the above-proposed method, the optimal solution family indicated in Fig. 2c was obtained. For this case the following parameters have been considered: Tmax = 387 K, Tfeed = 295 K, F = 25, production = 1,000 tn/hr, xi=45,000 ppm. In order to limit scale formation, the brine concentration, which is the ratio of the recirculating brine concentration to the feed concentration is kept at 1.5.

Using eq. (A) and Figs. 3 and 2c (that are universal in the sense that their have general validity), the critical variables to initialize P1 were established. It is important to stress that P1 was solved in few iterations using this initialization. Also the "optimal economic solution" was checked satisfying eq. (A) and the appropriate point in Fig. 3. Finally, according to step 4) the optimal number of stage NS value is determined. A good agreement is found between the data of a real plant in operation and those obtained from the model.

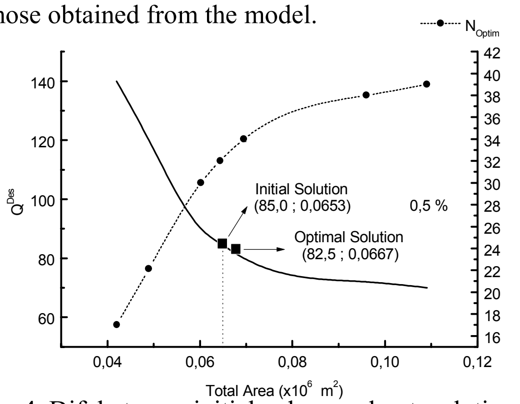

Figure 4. Dif. between initial values and opt. solution

Some of the results of the optimal solution are shown in Figs. 5, 6, 7 and 8.

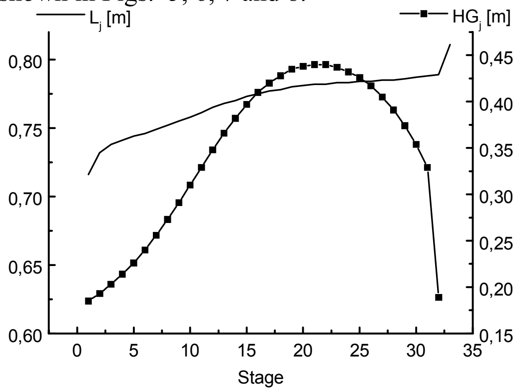

Figure 5. Stage Length and Width Stage distribution through the flashing chambers

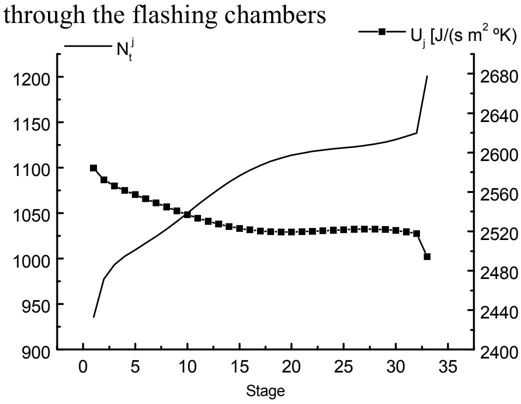

Figure 6. Tube Number and U distribution through the flashing chambers.

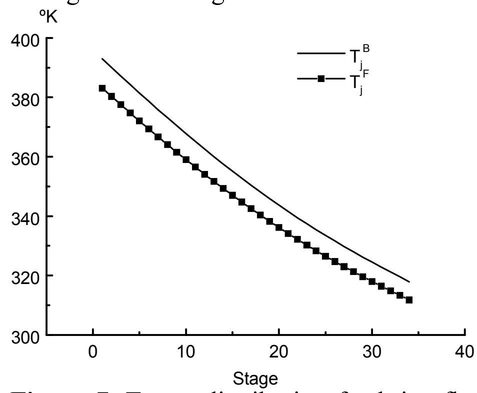

Figure 7. Temp. distribution for brine flowing in the pre-heaters and through the flashing chambers.

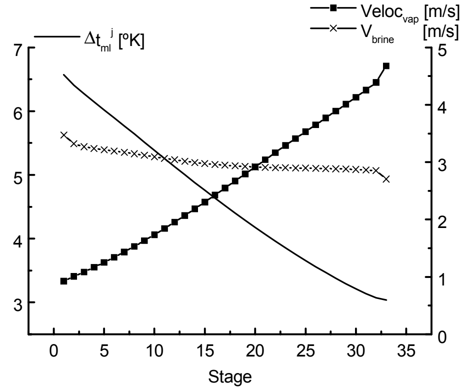

Figure 8. V_{brin}^{j}, Δtmlj and Vel_{vap}^{j} distribution through the flashing chambers

It is important to mention that our procedure determines a good (quasi-optimal) initial feasible point (IP) to be used for the resolution of P1. Figure 4 shows that the difference between the initial point and the optimal solution is only 0.5%. The initial point determined by this procedure is always in the neighborhood of the real optimal solution. This is very important in order to facilitate convergence, generally obtaining the optimal solution in few iterations.

VI. CONCLUSIONS AND FUTURE WORK

In this paper an algorithm for the optimal design of an MSF-M System is presented. A rigorous NLP model has been developed based on a thermodynamic preliminary approach; it is shown that it is possible to establish a link between our called "thermodynamic solution" and the solution considering "real costs". From this relationship, we can estimate the optimal solution when the total annualized costs are given. As was depicted in Fig. 4 the difference between the initial point and the estimated optimal solution is only 0.5%.

The optimal solution family reported on Fig. 2c and Fig. 3 are universal because this is not a function of geographical and contingent factors, having a general validity. Then, these solutions constitute a basis for the designer´s selection when the economic objective function is considered.

Although it is necessary to solve a set of parametric thermodynamic problems (solving P2 for different area values) to obtain Fig. 2c, this task can be easily done using a continuation algorithm (Mussati *et al*., 2002).

Moreover, we can state that by using universal thermodynamic properties for heat transfer operations (Scenna and Aguirre, 1993) for this case, we can find a set of very useful thermodynamic heuristics to make P2 problem solution easier. In this way, the construction of the optimal curve will be also easier. In fact, we have achieved an appropriate approximation to the optimal curve employing these heuristics by using only a hand calculator (only solving algebraic equations), thus achieving a tremendous simplification for implementing the proposed methodology. The explanation of this procedure will be the object of a future work.

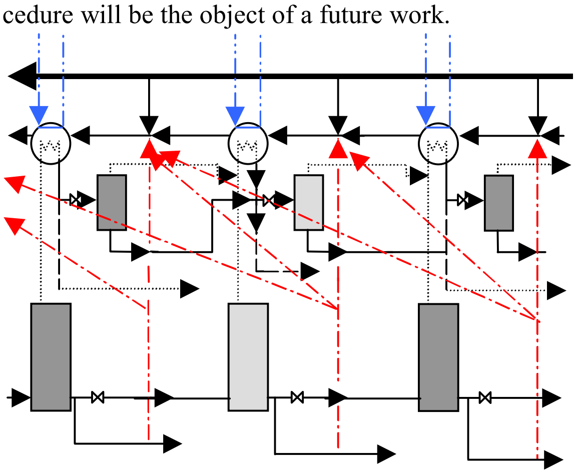

Figure 9. Superstructure for Multi-Stage Flash Desalination System.

In order to develop new configurations for the MSF System, we will propose in a future work a superstructure in which the flow-pattern of the distillate and the recycle are variables of the problem (see Fig. 9).

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Notation

Parameters:

CA	Area Transfer Unit Cost, \$/m2
Cd	Orifice discharge coefficient
CQ^{Des}	Heat Consumption Unit Cost, \$/Kcal
CRF	Capital Recovery Factor
D_s	Shell Diameter of pre-heater j, m
di	Interior diameter tube
FF	Fouling Factor
g	Gravitation constant, m/seg2
TinlF	Inlet feed temperature, K
Tref	Reference temperature, K
TMax	Top brine temperature, K
MWNaCl	Molecular weight, Kg/mol
NS	Number of Stage
Production	Distillate production flow rate, Kg/hr
Pt	Pitch
Q^{Des}	Heat consumption, Kcal/hr
RR	Recycle ratio
Xf / Xa	Concentration Factor

Variables:

A^j_{tubing}	Heat Recovery Transfer Area , m2
A^j_{stage}	Stage Area , m2
BPE	Boiling Point Elevation, K
B_j	Width of flashing chamber j, m
HG_j	Height of the gate in the flashing chamber j, m
$H_j^{l,F}$	Liquid enthalpy inlet to pre-heater j, Kcal/Kg
$H_j^{s,F}$	Solid enthalpy inlet to pre-heater j, Kcal/Kg
$H_j^{l,p}$	Liquid enthalpy inlet to stage j of primary chamber, Kcal/Kg
$H_j^{l,s}$	Liquid enthalpy inlet to stage j of secondary chamber, Kcal/Kg
H_j^{S}	Solid enthalpy inlet to stage j, Kcal/Kg
$H_j^{v,p}$	Vapor enthalpy inlet to stage j in the principal chamber, Kcal/Kg
LS_j	Length of Stage j, m.
L_j	Height of brine in the flashing chamber j, m
NEA_j	Non-Equilibrium Allowance, K
Nt_j	Total numb of tubes in the preheater j
Nj	Number of rows of horizontal tubes in the pre-heater j
NS	Number of Stage
P^j_v	Sat. Vap. Pres. of chamber j, Kgf/m 2
S_j	Solid flow rate inlet to stage, Kg/hr
Sfeed	Solid flow feed rate, Kg/hr
$Sinl_j^F$	Inlet solid flow rate to pre-heater j, Kg/hr.
$Sout_j^F$	Out solid flow rate from pre-heater j, Kg/hr
$S_{blowdown}$	Solid blow-down flow rate, Kg/hr
S_{Recir}	Solid flow rate recirculation, Kg/hr
T_j^{Brine}	Brine Inlet temperature to stage j, K
T_j^{F}	Feed outlet temperature of stage j, K
T_j^{Cond}	Condensation temperature of stage j, K
U_j	Overall heat transfer coeff. foul, Kcal/(m2 K Hr)
V_{brin}^{j}	Brine velocity on the condenser tubes of stage j, pie/s
Velocvapj	Vapor velocity in the chamber j, m/s
V_j^p	Vapor production of primary chamber of stage j, Kg/hr
V_j^s	Vapor production of secondary chamber of stage j, Kg/hr
W_j^p	Water flow rate inlet to primary chamber of stage j, Kg/hr
$W_j^{s,inl}$	Water flow rate inlet to secondary chamber of stage j, Kg/hr
$W_j^{s,out}$	Water flow rate leaving secondary chamber of stage j, Kg/hr
$Winl_j^{F}$	Inlet water flow rate feed to pre-heater j, Kg/hr
$Wout_j^{F}$	Outlet water flow rate feed to pre-heater j, Kg/hr
W_{feed}	Feed water flow rate, Kg/hr
$W_{blowdown}$	Water blow-down flow rate, Kg/hr
W_{Recirc}	Water flow rate recirculation, Kg/hr
X_j	Salt Concentration
λj	Latent heat evaporation, Kcal/Kg
Δtmlj	Log. mean temperature difference, K

Appendix 1

With the notation above mentioned, the model formulation can be presented.

Mass conservation equations for primary stage:

$$W_j^{p} - W_{j+1}^{p} = V_j^{p} \qquad j = 1,\ldots.NS \qquad (1)$$

$$S_j = S_{j+1} \qquad j = 1,\ldots.NS \qquad (2)$$

Energy balance for primary stage:

$$W_j^{p} \cdot H_j^{l,p} + S_j \cdot H_j^{s} - W_{j+1}^{p} \cdot H_{j+1}^{l,p} - V_j^{p} \cdot H_j^{v,p} - S_{j+1} \cdot H_{j+1}^{s} = 0$$

Mass and energy balances for secondary stage:

$$W_j^{s,\,inl} - W_j^{s,\,out} - V_j^{s} = 0 \qquad j = 1,\ldots.NS \qquad (4)$$

$$W_j^{s,\,out} + V_j^{s} + V_j^{p} - W_{j+1}^{s,\,inl} = 0 \qquad j = 1,\ldots.NS \qquad (5)$$

$$W_j^{s,\,inl} H_j^{l,\,s} - W_j^{s,\,out} H_{j+1}^{l,\,s} - V_j^{s} H_j^{v,\,p} = 0 \qquad (6)$$

Mass balance in preheater:

$$Wout_j^{F} = Winl_j^{F} \qquad j = 1,\ldots.NS \qquad (7)$$

$$Sout_j^{F} = Sinl_j^{F} \qquad j = 1,\ldots.NS \qquad (8)$$

Energy balance in preheater:

$$(V_j^{p} + V_j^{s})\lambda_j = Wout_j^{F}(H_j^{l,F} - H_{j+1}^{l,F}) + Sout_j^{F}(H_j^{S,F} - H_{j+1}^{S,F}) \qquad (9)$$

Relations associated to brine recirculation:

For j = NS+1, we have:

$$W_j^{p} \cdot RR = W_{Recir} \qquad (10)$$

$$S_j^{\,p} \cdot RR = S_{\text{Recir}} \tag{11}$$

$$W_j^{\,p} = W_{\text{Recir}} + W_{Blowdown} \tag{12}$$

$$S_j^{\,p} = S_{\text{Recir}} + S_{Blowdown} \tag{13}$$

$$Winl_{(j-1)}^{\;F} - W_{feed} - W_{recirc} = 0 \tag{14}$$

$$Sinl_{(j-1)}^{\;F} - S_{feed} - S_{recirc} = 0 \tag{15}$$

Design equations

Heat exchange area for each stage:

$$(V_j^{\,p} + V_j^{\,s}) \cdot \lambda_j = U_j \cdot A_j \cdot \Delta tml_j \tag{16}$$

Chamber length:

$$LS_j \cdot B_j = \frac{V_j^{\,p}}{Vel^{j}_{vap} \cdot \delta^{j}_{vap}} \qquad j = 1,\ldots NS \tag{17}$$

Gate height (from momentum balance):

$$W_j + S_j = C_d \cdot B_j \cdot HG_j \sqrt{2 \cdot g \cdot (L_j - L_{j+1} + \frac{(P_v^{\,j} - P_v^{\,j+1})}{\rho_{brine}})} \tag{18}$$

Number of tubes for each pre-heater:

$$N_t^{\,J} = \frac{A_j}{2 \cdot \pi \cdot B_j} \qquad j = 1,\ldots NS \tag{19}$$

Total number of tubes (from momentum balance):

$$N_t^{\,J} = \frac{4 \cdot (Wout_j + Sout_j)}{\pi \cdot d_i^{\,2} \cdot \delta^{j}_{brine} \cdot V^{j}_{brine}} \tag{20}$$

For an equilateral triangular pitch arrangement, the equivalent number of tubes in a vertical row (N) can be predicted from the equation (El-Dessouky *et al.* (1995)):

$$N^{J} = 0.481 \cdot (N^{j}{}_{t})^{0.505} \qquad j = 1,\ldots NS \tag{21}$$

Also, the number the tubes in the vertical direction (N) is related to the shell diameter and pitch by:

$$N^{J} = \frac{D_S^{\,j}}{\sqrt{2} \cdot P_t} \qquad j = 1,\ldots NS \tag{22}$$

Approximate stage area:

$$A^{J} Stage = 2\ LS_j\ B_j + 2\ LS_j\ HS_j + B_j\ HS_j \tag{23}$$

where:

$$HS_j = 2\,L_j + D_S^{\,j} \qquad j = 1,\ldots NS \tag{24}$$

Temperature constraints:

$$T_j^{Brine} \geq T_{j+1}^{Brine} \qquad j = 1,\ldots NS \tag{25}$$

$$T_j^{F} \geq T_{j+1}^{F} \qquad j = 1,\ldots NS \tag{26}$$

$$T_j^{Cond} \geq T_j^{F} \qquad j = 1,\ldots NS \tag{27}$$

Property correlations:

For the Boiling Point Elevation [K]:

$$BPE = \left(\sum_{i=0}^{2} a_i\, m^i \right) \frac{m}{a_3} \tag{28}$$

where:

$$a_0 = \frac{565.757}{T} - 9.81559 + 1.54739\, ln(T)$$

$$a_1 = -\frac{337.178}{T} + 6.41981 - 0.922753\, ln(T)$$

$$a_2 = \frac{32.681}{T} - 0.55368 + 0.079022\, ln(T)$$

$$a_3 = \frac{266919.6}{T^2} - \frac{379.669}{T} + 0.334169$$

$$m = 19.819 \frac{X}{1 - X}$$

For the overall heat transfer coefficient [BTU/(hr ft^2 °F)] (Griffin and Keller, 1965):

$$U0 = \frac{U}{1 + U\,FF} \text{ ; where: } U = \frac{1}{z + y} \tag{29}$$

$$y = \frac{(v_{brine}\ Di)^{0.2}}{(160 + 1.92\ Tb)\, v_{brine}} \quad \text{and} \quad z = \sum_{i=0}^{4} a_i\, Tc^i$$

where a_0 = 0.1024768 x 10^{-2}, a_1 =-0.7473939 x 10^{-5}, a_2 = 0.999077 x 10^{-7}, a_3 =-0.430046 x 10^{-9}, and a_4 = 0.6206744 x 10^{-12}. z is the sum of vapor side resistances, y is the brine-side film resistance. The Fouling Factors FF [(hr ft^2 °F/BTU] is considered as: 8.54439 x 10^{-4} .

For the Non-Equilibrium Allowance [K], there are several empirical correlations developed, we adopted for our model the correlations developed for Oak Ridge National Laboratory (ORNL):

$$NEA_{10} = (0.9784)^{T_0} (15.7378)^{H} (1.377)^{w\,10^{-6}} \tag{30}$$

$$NEA = \left[\frac{NEA_{10}}{0.5\ \Delta T_s + NEA_{10}} \right]^{0.3281\,L} (0.5\ \Delta T_s + NEA_{10}) \tag{31}$$

where ΔT_S is the flashing range, W is the mass flow rate of recirculated brine per unit of chamber width, H is the brine level inside the flashing chamber.

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