Design and Simulation of a Multiple EffectEvaporator System

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***Abstract*—The objective of this report is to develop a model and an algorithm to design a multiple effect e evaporator system. Also, it is required to make to evaluate the amount of steam saved by the use of vapour compression. The use of vapour compression allows us to use the energy in the vapour leaving the last effect. Since evaporators are energy intensive system, use of vapour compression can considerably reduce steam consumption, but at the cost of electrical energy needed to run the compressor.**

To achieve above targets a model based on nonlinaer equations is developed to design the multiple effect evaporator system of seven effects to concentrate black liquor. For this system, first the live steam requirement will be evaluated for the evaporator without any vapour compression. Then vapour compression will be used and the live steam requirement will be calculated. Also the cost for compression of the steam should been taken into account. This gives us a thermo- economic solution wherein both energy and money is being saved.

To select the best solution total 17 combinations of placing the compressor in the multiple effect system are identified. The best combination in terms of thermo- economic criterion is vapour from the sixth effect being compressed and sent into the second effect. The cost for running the equipment without any vapour compression is found out to be 4009 $/hr. however, for best combination cost is reduced to 3886 $/ hr and the savings made are 23 $.hr.

I. Introduction

Evaporation falls into the concentration stage of down-stream processing and is widely used to concentrate foods, chemicals, and salvage solvents. The goal of evaporation is to vaporize most of the water from a solution containing a desired product, or in the case of drinking water from seawater, an undesired product. After initial pre-treatment and separation, a solution often contains over 85% water. This is not suitable for industry usage because of the cost associated with processing such a large quantity of solution, such as the need for larger equipment. If a single evaporator is used for the concentration of any solution, it is called a single effect evaporator system and if more than one evaporator is used in series for the concentration of any solution, it is called a multiple effect evaporator system. Unlike single-stage evaporators, these evaporators can be made of up to seven evaporator stages or effects. Adding one evaporator to the single effect decreases the energy consumption to 50% of the original amount. Adding another effect reduces it to 33% and so on. The number of effects in a multiple-effect evaporator is usually restricted to seven because after that, the equipment cost starts catching up to the money saved from the energy requirement drop. [1]

1.1 Application of evaporators

Evaporators are integral part of a number of process industries namely Pulp and Paper, Chlor-alkali, Sugar, pharmaceuticals, Desalination, Dairy and Food processing, etc. Evaporators find one of their most important applications in the food and drink industry. The goal of

evaporation is to concentrate a target liquid, and this needs to be achieved for many different targets today. One of the most important applications of evaporation is that on the food and drink industry. Many foods that are made to last for a considerable amount of time or food that needs a certain consistency, like coffee, need to go through an evaporation step during processing. It is also used as a drying process and can be applied in this way to laboratories where preservation of long-term activity or stabilization is needed (for enzymes for example). Evaporation is also used in order to recover expensive solvents such as hexane which would otherwise be wasted. Another example of evaporation is in the recovery of sodium hydroxide in Kraft pulping. Cutting down waste handling cost is another major application of evaporation for large companies. Legally, all producers of waste must dispose of the waste in a method that abides by environmental guidelines; these methods are costly. If up to 98% of wastes can be vaporized, industry can greatly reduce the amount of money that would otherwise be allocated towards waste handling. Evaporation is also used in pharmaceutical industry as to get a concentrated product and to improve the stability of the products.

1.2 Problems associated with multiple effect evaporators

The evaporators being a highly energy intensive system offer a great scope for reduction of costs by reducing the live steam requirements. In order to cater to this problem, efforts to propose new operating strategies have been made by many researchers to minimize the consumption of live steam in a multiple effect evaporator system in order to improve the steam economy of the system. Some of these operating strategies are feed-, product- and condensate- flashing, vapour compression, feed- and steam- splitting and using an optimum feed flow sequence, vapour bleeding, vapour compression.

One of the earliest works on optimizing a multiple effect evaporator by modifying the feed flow sequence was done by Harper and Tsao in 1972 by developing a model for optimizing a MEE system by considering both forward and backward feed flow sequence. This work was extended by Nishitani and Kunugita (1979) in which they considered all possible feed flow sequences to optimize a MEE system for generating a non inferior feed flow sequence. All these mathematical models are generally based on a set of linear or non- linear equations and on changing the operating strategy, a whole new set of equations were required for solving the new

- is with

operating strategy. This problem was addressed by Stewart and Beveridge (1977) and Ayangbile, Okeke and Beveridge (1984) . They developed a generalized cascade algorithm which would be solved again and again for the different operating strategies of a multiple effect evaporator system.

The reported literature considers a number of energy reduction methods such as flashing, steam and feed splitting, vapours bleeding and using an optimum feed flow sequence. In connection to these in the present work vapour compression is applied to an existing industrial multiple effect evaporator and overall cost computations will be made. Thus to achieve this target following objectives are to be met:

- To develop governing equations for multiple effect evaporator system with the induction of vapour compression.

- To develop computer program for solution of equations.

- To compute the operating cost as well as capital cost of the modified system

- To define a number of combinations in multiple effect evaporator and compressor to choose best combination based on total annual cost.

DEVELOPMENT OF A MODEL & SOLUTION

TECHNIQUE

Model for MEE system

To develop a basic model for the system of septuple effect evaporator negligible boiling point elevations is considered. Also the variation in physical properties of liquor is neglected. These assumptions will be further relaxed. The governing equation of first effect is derived as follows:

Fig 4.1 Single effect with all input and output stream with temperatures

An enthalpy balance on the process fluid stream is as follows:

In the following expression the vapour is eliminated using appropriate total material balance. Also the enthalpies are approximated by taking them equal to those of the pure solvent. Thus enthalpies depend on temperature alone. For the first effect

Therefore equation (1) becomes

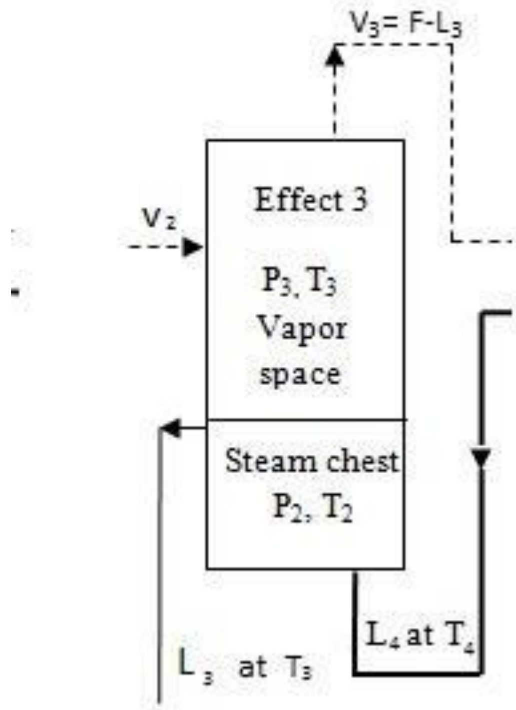

Fig. 1.

TABLE I

$$Fh_f + Q_1 - (F - L_1)\, H_1 - L_1\, h_1 = 0 \qquad (1)$$

TABLE II

$$V_1 = F - L_1 \qquad (2)$$

$$F\,(h_f - h_1) + Q_1 - (F - L$$

$$Fh_f + Q_1 - (F - L_1) H_1 - L_1 h_1 = 0 \quad (1)$$

In the following expression the vapour is eliminated using appropriate total material balance. Also the enthalpies are approximated by taking them equal to those of the pure solvent. Thus enthalpies depend on temperature alone. For the first effect

$$V_1 = F - L_1 \quad (2)$$

Therefore equation (1) becomes

$$F (h_f - h_1) + Q_1 - (F - L_1) \lambda_1 = 0 \quad (3)$$

Where $\lambda_1 = H_j - h_j$, the latent heat of vaporization of the solvent form the thick liquor at

temperature T_j and pressure P_j (j=1, 2, 3, the effect number) Alternately, the result give by equation (3) may be obtained by taking the enthalpy reference for the first effect to be enthalpy of the thick liquor leaving the effect at the temperature T_1.

The enthalpy balance on the heating medium is given by

$Q_1 = V_0 (H_0 - h_o) = V_0 \lambda_0$

And the rate of heat transfer by

$Q_1 = U_1 A(T_0 - T_1)$

Substituting for Q_1 final equation of first effect are found as

Enthalpy balance;	**f1**	**(4)**
Heat transfer rate; $f_2 = U_1$	**$(T_0 - T_1)$ - $V_0 \lambda_0$**	**(5)**

These equations will be followed for the second, third and so on till the seventh effect.

For second effect: $f_3 = L_3(h_2 - h_3) + (L_3 - L_2)\lambda_2 - (L_2 - L_1)\lambda_1$ (6)

$f_4 = U_2A_2(T_1 - T_2) - (L_2 - L_1)\lambda_1$ (7)

for third effect: $f_5 = L_4(h_3 - h_4) - (L_4 - L_3)\lambda_3 + (L_3 - L_2)\lambda_2$ (8)

$f_6 = U_3A_3(T_2 - T_3) - (L_3 - L_2)\lambda_2$ (9)

for fourth effect: $f_7 = L_5(h_4 - h_5) + (L_4 - L_3)\lambda_3 - (L_5 - L_4)\lambda_4$ (10)

$f_8 = U_4A_4\ (T_3 - T_4) - (L_4 - L_3)\lambda_3$ (11)

for fifth effect: $f_9 = L_6(h_5 - h_6) + (L_5 - L_4)\lambda_4 - (L_6 - L_5)\lambda_5$ (12)

$f_{10} = U_5A_5\ (T_4 - T_5) - (L_5 - L_4)\lambda_4$ (13)

for sixth effect: $f_{11} = L_7(h_6 - h_7) + (L_6 - L_5)\lambda_5 - (L_6 - L_7)\lambda_6$ (14)

$f_{12} = U_6A_6\ (T_5 - T_6) - (L_6 - L_5)\lambda_5$ (15)

for seventh effect: $f_{13} = F(h_f - h_7) + (L_7 - L_6)\lambda_6 - (F - L_7)\lambda_7$ (16)

$f_{14} = U_7A_7\ (T_6 - T_7) - (L_7 - L_6)\lambda_6$ (17)

These nonlinear equations are solved using Newton-Raphson method which required scaling of each equation. For this purpose each functional equation is divided by the product $F\lambda_0$ and

the new

The fourteen independent equations can be solved for the fourteen unknowns. In addition to these fourteen independent equations, seven additional equations that contain seven additional independent variables,

$$FX = L_j x_j = 0$$

These fourteen equations may be stated in compact form by means of the following matrix equation

$$J_k \Delta X_k = -f_k$$

Where is called the Jacobian matrix and

$$\Delta X_k = X_{k+1} - X_k = [\Delta V_0\ \Delta T_1\ \Delta T_2 \Delta T_3 \Delta T_4 \Delta T_5 \Delta T_6\ \Delta I_1 \Delta I_2 \Delta I_3 \Delta I_4 \Delta I_5 \Delta I_6\ \Delta A]^T$$

- is with

The subscripts k and k+1 that elements of the matrices carrying these subscripts are those given by the kth and k+1st trials, respectively. In the interest of simplicity, the subscript k is omitted from the elements of X_k, J_k *and* f_k. On the basis of an assumes set of values for the elements of column vector

(or column matrix) X_k, which may be stated as the transpose of the corresponding row vector (or row matrix)J_k *and* f_k are computed. Adisplay of the elements of the J_k *and* f_k *follows*:

If the function $f_1, f_2, \ldots, f_{14}$ and their partial derivatives which appear in$J_k$are continuous and the determinant of $J_k$is not equal to zero, then the Newton Raphson method will converge, provided a set of assumed values of the variables which are close enough to the solution set can be found .

The nonlinear equations are solved using Newton-Raphson method which required scaling of each equation. For this purpose each functional equation is divided by the product $F\lambda_0$ and the new expression so obtained was denoted by g_j where $g_j = f_j/F\lambda_0$ (where j=1,2,3..14) and $L_j = l_j F$ and $V_j = v_j F$, $T_j = u_j T_0$. Differentiating $g_1, g_2, \ldots, g_{14}$ with respect to $v_0, u_1, l_1, u_2, l_2, u_3, l_3, u_4, l_4, u_5, l_5, u_6, l_6$,a and keeping the expressions obtained in matrix forms. [9]

The steam requirement $V_0$is calculated. Now, the cost of the steam is calculated.

4.2 Empirical relation for overall heat transfer coefficient

The correlation given in equation 4.18 is used to evaluate the overall heat transfer coefficient of each effect of the evaporator. It is considered from Bhargava et al. (2008) . From the correlation it can be seen that the overall heat transfer coefficient of each effect is a function of the temperature gradient and the average values of concentration and liquor flow rate obtained from the input and output parameters.

$$\frac{U}{2000} = a\left(\frac{\Delta T}{40}\right)^b \left(\frac{x_{avg}}{0.6}\right)^c \left(\frac{F_{avg}}{25}\right)^d \qquad (18)$$

Here a, b, c, d are empirical constants. These values are assumed to be same for the first and second effect and same for rest of the five effects. Their values are as given in the Table 4.1.

Table 4.1 Empirical constants to find out overall heat transfer coefficient

Effect no.	a	b	c	d
1 and 2	0.0604	-0.3717	-1,227	0.0748
3,4,5,6 and 7	0.1396	-0.7949	0.0	0.1673
..				

In the simple case where BPE and ΔH_{dil} are negligible (i.e for inorganic colloids).H_f *and* H differ from the enthalpy of the saturated liquid only in sensible heat , To the extent that sensible heat is negligible, we can substitute the enthalpy of saturated liquid for H_f *and* H

$$q = (m_f - m)H_v - m_f H_L + mH_L$$
$$= H_v - (m_f - m)H_L$$
$$= (m_f - m)(H_v - H_L)$$
$$= (m_f - m)\lambda$$

Heat to boil vapour: This heat duty is partially offset by the latent heat recovered by condensing the compressed vapour. The remainder comes from makeup stream:

$$q = = (m_f - m)\lambda_s + m_s\lambda_s$$

where we are compressing the vapour to the same pressure as the make up steam .Eliminating q, we can solve for the steam requirements :

$$m_s = (m_f - m)\left(\frac{\lambda}{\lambda_s} - 1\right)$$

I. Result and Discussion

Cost Computation without Vapour Compression

Considering the operating parameters shown in Table 3.1 and 3.2, the model shown through Eq. 4 to 17 is solved using MATLAB. This model is without vapour compressor. In this model the values of heat transfer coefficients are taken from equation 4.18. As the solution of the model is based on iterations the results of all iterations are shown in Table 5.1.

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Also, the steam requirement is 7520 kg/hr. So, using the cost of steam at $ 0.3/ of steam according to Al-Sahali et al. (1997) the cost for this operation is $ 4095.

5.2 Solution of model with Vapour Compression

Considering the operating parameters shown in Table 3.1 and 3.2, the model shown through Eq. 4.19 to 4.32 is solved. This model is with vapour compressor. Here the values of heat transfer coefficients are taken same as considered for model without compressors. The results of all iterations are shown in Table 5.3.

5.2.1 Cost Computation with Vapour Compression

When the vapour from the 7^{th} effect is compressed and sent to the 1^{st} effect and the Jacobian matrix is solved, we get the steam requirements to be 3492.18 kg/ hr and the steam costs to be 1977.45 $/hr.

But also some cost is required to compress the steam from its pressure of 0.7009 bar to 2.8195 bar, this cost can be computed using equation for energy consumption of a compressor given by Al-Sahali et al. (1997) :

Using this equation we get the work done to be 8154 KWh and again using the cost of electricity given by Al-Sahali et al. (1997) , we get the costs to be $ 2446. This results in a total cost of 4423 $/ hr which is greater than the cost for the operation without vapour compression. So, even though the steam required is vastly reduced, the high cost of compression makes this configuration unviable

Now we compress the vapour from the 7^{th} effect and send it to other effects and compute the total costs.

For each configuration the equations are altered and Jacobian Matrix is formed again. Now the matrix is iterated and the variables are calculated. After the calculation of the variables the total steam requirement is calculated. Then, from the pressure values in each effect, the total cost of compression is computed and the resultant total cost is compared.

I t can be seen that while in the first two cases the steam cost is drastically reduced, the cost from compression is high and thus there are no savings made by vapour compression and the method is not viable

Also, the 4^{th} and 5^{th} case even though the cost is very low in compressing but also, the saving made on compression are not enough to counter the higher steam requirements.

II. CONCLUSION

In the present work, simulation of a flat falling film seven effect evaporator is done in order to apply vapour compression to the system and to find of the most thermo-economically viable route of compressed vapour. A generalized solution technique is developed so that the same algorithm maybe used for different vapour compression routes with only slight modification in the inputs. Hence there is no need of different codes for different routes of vapour compression.

Taking the results into account, the conclusions that can be drawn from the work are as follows:

1. Pumping back compressed vapour we can reduce the live steam requirement, but also the cost of compressing the vapour is very high and so all the vapour compression routes are not economically viable even though thermally they save a lot of energy. Thus the most thermo-economically viable route has been chosen.

2. In the present work, first the live steam requirement is evaluated for the evaporator without any vapour compression. Then vapour compression is used and the live steam require- ment has been calculated.

3. The cost for running the equipment without any vapour compression is found out to be 4009 \$/hr. With the vapour from the sixth effect being compressed and sent into the second effect the cost of running is reduced to 3886 \$/hr. The savings made are 23 \$.hr.

4. The initial investment of compressor, the cost of installa- tion and the salvage value of the compressor were taken into account to calculate the payback period for the arrangement and it was found to be 1 year and 8 months. As this arrangement reduces both live steam requirement and the cost of the process and thus is viable.

$$W = \frac{\gamma}{\left(\eta\left(\gamma-1\right)\right)} P_v V_v \left(\left(P_s / P_v\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1 \right)$$