Study on Design of Heat Integrated Multiple Effect Evaporator System

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Abstract— Evaporators can minimize the production of regulated waste residues, and increase the potential for recovering valuable materials from those wastes. Multiple-effect evaporators (MEEs) are common to industries that concentrate different products, regenerate solvents, or separate solid-liquid mixtures. Process integration can help to choose the best configuration of MEE in order to achieve a more efficient process in the sense of energy use. Economic evaluation to optimize the number of flash tanks is carried out for seven effect evaporator system. The two different types of configuration of vapor bleeding are considered and comparison of both configurations is done. Considering the optimum number of flash tanks and the best configuration of vapor bleeding, a system was designed.

Key words: Heat Integrated Multiple Effect Evaporator System

I. Introduction

Evaporators are integral part of a number of process industries namely Pulp & Paper, Chloralkali, Sugar, Pharmaceuticals, Desalination, Dairy and Food processing, etc. The Pulp and Paper industry, which is the focus of the present investigation, uses the Kraft Process to convert wood chips into pulp. The Kraft process consists of multiple effect evaporators (MEE) system as one of the major section. The evaporator house of a Pulp and Paper industry consumes about 24-30% of its total energy and makes it as an energy intensive section. The energy efficiency of MEE system can be enhanced by inducting flashing, splitting and vapor bleeding.In the present work seven effect evaporator system of typical Indian pulp and paper industry isconsidered for analyses based on above configurations. Based on the above discussions the present work has been planned with following objectives:

- These models also use complex transport phenomena based mathematical models or empirical models for the prediction of overall heat transfer coefficients (U) of evaporators as a function of liquor flow rate, liquor concentration, physico-thermal properties of evaporating liquor and type of evaporator employed. On the other hand, Khanam and Mohanty (2011) proposed linear model based on principles of process integration. This model worked on the assumption of equal ΔT in each effect and thus, eliminated the requirement of U in the model.
- Though all these models account complexities of real MEE system such as variation in physical properties, flashing, splitting and bleeding these do not propose methodology to optimize the performance of the system considering flashing as well as vapor bleeding. In other words, these models were developed with condensate flashing in which positions of flash tanks were fixed.
- These did not account optimum number of flash tanks, its position in the MEE system, performance of each flash tank, etc. These also did not consider different configurations for vapor bleeding to optimize the economy of the system.

1) To develop model for seven effect evaporator system with variation in physical properties of liquor, condensate and vapor, boiling point rise and for different operating configuration such as steam splitting, condensate flashing, vapor bleeding, etc.
2) To compute contribution of different flash tanks towards total evaporation and thus to optimize number of flash tanks in the system based on economic analysis.
3) To extract steam data from seven effect evaporator system and apply pinch analysis to these data.
4) To compare the steam economy predicted by models of different configurations and to propose modified design for seven effect evaporator system.

II. Literature Review

A. Thermo Physical Properties of Black Liquor Solution

There are several physical and thermal properties that are important to black liquor evaporator design and operation. These properties are boiling point rise, specific heat, latent heat of vaporization and density. Black liquor is typically about one-third inorganic and two thirds
organic materials.

B. Heat Transfer Coefficient of Falling Film Evaporator

Falling film evaporators are especially popular in the food and paper industry where many substances are heat sensitive. A thin film of the product to be concentrated trickles down inside of heat exchanging tubes. Steam condenses on the outside of the tubes supplying the required energy to the inside of the tubes.

C. Modelling of Multiple Effect Evaporators

Lambert et al. (1987) presented a model which was based on the nonlinear enthalpy relationships and boiling point rise. Curve fitting techniques and interpolation were used to reach these relationships.

D. Energy Reduction Schemes (ERSs)

The steam consumption for the MEE system can be reduced by incorporating different ERSs. These ERSs are induction of flashing, vapor bleeding, heating up liquor using condensate, etc., in the MEE system.

III. Development of Model

A model for seven effect evaporator system, used for concentrating black liquor solution and described in chapter 3, is developed. For the present investigation as most of the models use temperature dependent physico-thermal properties of liquor/fluids a number of correlations for the prediction of physico-thermal properties of black liquor solution and condensate (in present case water) are developed.

A.

As steam/vapor enters different effects at different temperature, the properties of steam/vapor and condensate also vary with temperature. Thus, temperature dependent expressions of heat of vaporization and enthalpy are required to be developed. For this purpose data of heat of vaporization, enthalpy of water and enthalpy of steam over the temperature range of 52-148°C, obtained from steam table, are plotted. A second order polynomial and linear trends are fitted on heat of vaporization and enthalpy curve as shown in Figure 1and 1.1 respectively.

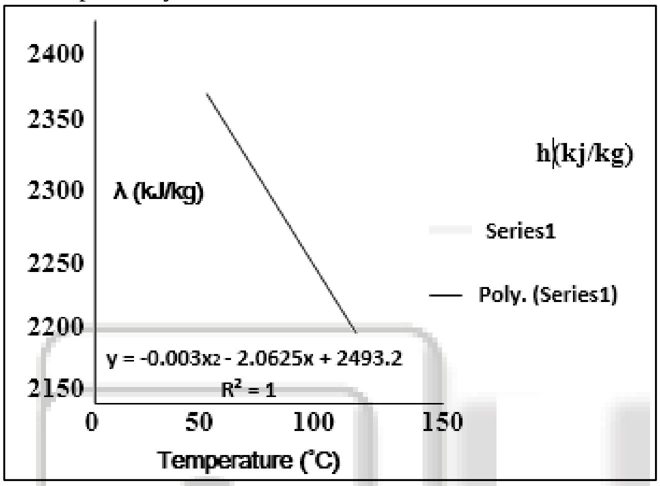

Figure 1: Correlation of heat of vaporisation

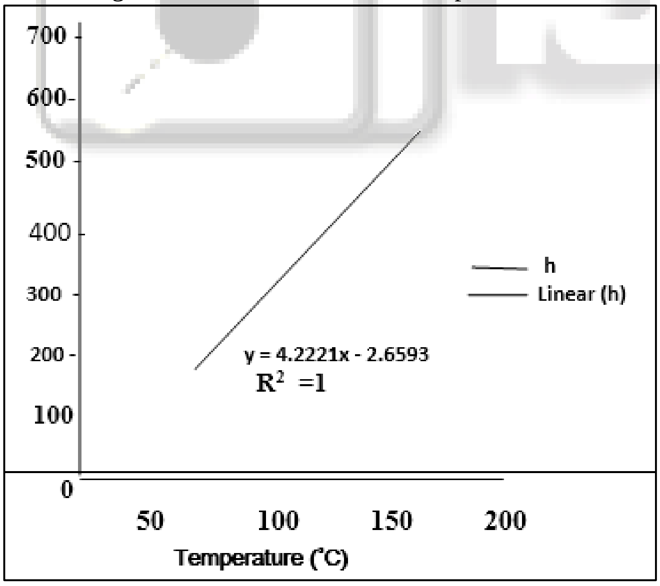

Figure. 1.1: Correlation of enthalpy of condensate

B. Model for Overall Heat Transfer Coefficient

The mathematical model of overall heat transfer coefficients of different effects is developed by Bhargava et al. (2008) based on plant data of seven effect evaporator system.

C. Model Development of MEE System

In the present section mathematical model is developed for seven effect system shown in Fig.3.1. The model is developed in different stages. The first stage considers the simple system with variation in physical properties, BPR and steam splitting. Further, this model is modified considering condensate flashing. Finally, the model is improved to include vapor bleeding from effects to use it in liquor preheating.

IV. SOLUTION TECHNIQUES

The solution of these models requires an iterative approach as number of parameters such as variable physical properties, BPE, overall heat transfer coefficient, etc., are involved in the models which depend on unknown intermediate temperatures. The set of non-linear equations developed in chapter 4 is solved using Systems of Non-Linear Equations Software. A detailed algorithm explaining the series of steps performed for solution of developed models is given as follows:

- Step 1: Values of known parameters are collected from Table 4.1.
- Step 2: Equal temperature drop and equal vaporization in each effect are assumed initially to calculate temperatures and liquor flow rates for each effect. An initial guess of overall heat transfer coefficient for each effect is made to start the calculation.
- Step 3: The overall component balance is used to determine the product stream flow rate. The component and material balance is used to get estimates for the flow rates and the compositions of the intermediate streams within the system.
- Step 4: The compositions are used to estimate BPEs and specific heat of the solution. The temperature and composition estimated in Step 2 and 3 are used to get enthalpy values. 37
- Step 5: The inclusion of variations such as steam splitting, variation in specific heat capacity, BPE, latent heat of vaporization, condensate flashing preheating of liquor using condensate and vapor bleeding are considered.
- Step 6: Based on values of U set of nonlinear equations are developed which are solved to obtain the revised values of temperatures and liquor flow rate of each effect using solver ‘system of nonlinear equations’.
- Step 7: Revised values of U are computed considering temperature, flow rate and concentration of each effect.
- Step 8: Revised values of U are compared with the previous iteration values. If difference of U is not within ±40% the calculation from Step 3 to 10 are repeated with revised values of temperature, liquor flow rates and U until the system converges.
- Step 9: Steam economy is computed.

V. RESULT AND DISCUSSION

The results obtained from the theoretical investigation carriedout in the present work. The MEE system considered in this work is seven effect evaporator which is utilized for concentrating black liquor in typical Pulp and paper Industries as described in problem statement. For this system different models are developed for different configurations such as steam splitting, vapor bleeding and condensate flashing. These models consist of non-linearequations are developed in development of model. Temperature dependent physico-thermal properties and BPR are determined using the correlations developed in development of model .The set of non- linear equations developed is solved using Systems of Non-Linear Equations Software. The results obtained are discussed in the subsequent paragraphs:

A. Seven Effect Evaporator System with Vapour Bleeding

Vapor bleeding is done to preheat the liquor near to the temperature of the effect before it isentering into the effect so that the liquor can quickly attain the boiling temperature inside the effect. A portion of stream of vapor extracted from the stream entering as a heating medium to one of the effects is used to preheat the liquor that is coming out from one effect. In the present work two configurations are considered. In both cases four pre heaters are placed between effects3 and 7

Effect	1	2	3	4	5	6	7
U, kW/m2ºC	0.263	0.3526	0.39	0.644	0.786	0.819	0.9499
L, kg/s	5.321	6.458	7.174	8.9	10.64	12.177	13.707
X	0.3462	0.2852	0.2568	0.257	0.1731	0.1573	0.1344
τ, °C	3.9818	2.9643	2.5458	1.834	1.492	1.2628	1.0988
Vapor from cond. flashing, kg/s	_	_	_	0.213	_	0.1767	0.1299
Amount of vapor bled, kg/s	_	_	0.054	0.0606	0.0743	0.0729	_
T, °C	105.37	118.307	95.08	81.73	71.02	60.76	52

B. Seven Effect Evaporator System with Vapour Bleeding And Condensate Flashing

In the present section seven effect system is considered which includes steam splitting, variation in physical properties, condensate flashing and vapor bleeding together. The part of vapor that enters to the next effect is bled to preheat the liquor entering the following effect and after that vapor is also used for flashing. It is observed from section 6.2.1 that the seven effect evaporatorsystem with condensate flashing using five flash tanks is optimum. Hence five flash tanks system with vapor bleeding is considered in the present section to study the enhancement in steam economy.

Results of system with vapor bleeding and condensate flashing-

Effect	1	2	3	4	5	6	7
U, kW/m2ºC	0.263	0.3426	0.39	0.644	0.786	0.819	0.9499
L, kg/s	5.321	6.458	7.174	8.9	10.64	12.177	13.707
X	0.3462	0.2852	0.2568	0.207	0.1731	0.1513	0.1344
τ, °C	3.9818	2.9683	2.5458	1.884	1.492	1.2628	1.0988
Vapor from cond. flashing, kg/s	_	_	_	0.213	_	0.1797	0.1299
Amount of vapor bled, kg/s	_	_	0.054	0.0606	0.0743	0.0729	_
T, °C	105.37	118.307	95.08	81.73	71.02	60.76	52

C. Seven Effect Evaporator System with Preheating Of Liquor Using Sensible Heat of Condensate

In this section the liquor is preheated near to the temperature of effect before it is entering into the effect. Under Section 6.3 preheating of liquor is done through bled vapor, however, in this case condensate of steam/vapor is used to preheat the liquor, which is entering into that effect using a counter current heat exchanger. Condensates of live steams and condensates of vapor chests of 3rd, 4th and 5th effect are utilized in the process to preheat the liquor coming from the 4th, 5th, 6th and 7th effect, respectively. The final results of the model of seven effect evaporator system with preheating of liquor using condensate

Effect	1	2	3	4	5	6	7
U, kW/m2ºC	0.263	0.3426	0.39	0.644	0.786	0.819	0.9499
L, kg/s	5.321	6.458	7.174	8.9	10.64	12.177	13.707
X	0.3462	0.2852	0.2568	0.207	0.1731	0.1513	0.1344
τ, °C	3.9818	2.9683	2.5458	1.884	1.492	1.2628	1.0988
Vapor from cond. flashing, kg/s	_	_	_	0.213	_	0.1797	0.1299
Amount of vapor bled, kg/s	_	_	0.054	0.0606	0.0743	0.0729	_
T, °C	105.37	118.307	95.08	81.73	71.02	60.76	52

VI. CONCLUSION

A phenomenological and heuristic mathematical model for a multiple effect evaporator is developed in present work. The mathematical model considers the variation of thermo physical properties within the process. The salient conclusions of the present work are as follow:

– The model considered which is based on set of nonlinear equations, directs almost all difficulties of real MEE system such as variation in physical properties, BPR, steam splitting, feed, product and condensate flashing and vapor bleeding.
– The economy of simple system is 4.334 which increase by 20.2%, 12.4%, 23.7%, 24.6 % and 29.05% by inducting condensate flashing, vapor bleeding, preheating of liquor with condensate, vapor bleeding and flashing and preheating of liquor with condensate and Flashing respectively.
– Based on economic analysis as well as steam economy it is concluded that the seven effect evaporator system can run effectively with five flash tanks instead of seven in actual flowsheet. Thus, this approach gives a less complex network for evaporator system.
– The two different types of configuration of vapor bleeding are considered and comparison of both configurations is done. It is observed that steam economy for configuration two is more compared to configuration one.
– Considering the optimum number of flash tanks and the best configuration of vapor bleeding, a system was designed. This system enhances the steam economy by 24.6% and reduces the steam consumption by 21.3% in comparison to simple system.
– Liquor heating using sensible heat of condensate contributes considerably to reduce steam consumption. Besides, it produces less complex MEE network in comparison to other model.
– Considering the maximum possible number of flash tanks and pre heating of liquor with condensate, a final system was designed. The steam economy was 23.77% more and steam consumption 36.76 % less in comparison to simple system.
– Pinch analysis of the MEE network has also been done using ASPEN Pinch software. It is found that the result obtained is very close to simulated values.

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