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Simulation of flat falling film evaporator system for concentration of black liquor

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ABSTRACT

In the present investigation, a non-linear mathematical model is developed for the analysis of Septuple effect flat falling film evaporator (SEFFFE) system used for concentrating black liquor in a nearby paper mill. This model is capable of simulating process of evaporation considering variations in boiling point rise (τ), overall heat transfer coefficient (U), heat loss (Q_{loss}), flow sequences, liquor/steam splitting, feed, product and condensate flashing, vapor bleeding and physico-thermal properties of the liquor. Based on mass and energy balance around an effect a cubic polynomial is developed and solved repeatedly in a predetermined sequence using generalized cascade algorithm.

For development of empirical correlations for τ, U and Q_{loss}, plant data have been collected from SEFFFE system. These correlations compute τ, U and Q_{loss} within average absolute errors of 2.4%, 10% and 33%, respectively, when their results are compared with the plant data.

1. Introduction

Evaporators are integral part of a number of process industries namely Pulp and Paper, Chlor-alkali, Sugar, Pharmaceuticals, Desalination, Dairy and Food processing, etc. The Pulp and Paper industry, which is the focus of the present investigation, predominantly uses the Kraft Process in which black liquor is generated as spent liquor. This liquor is concentrated in multiple effect evaporator (MEE) house for further processing. Earlier, long tube vertical (LTV) type of evaporators were employed in India (Bhargava, 2004). However, with development of flat falling film evaporators (FFFE), which claim many benefits over its counter parts LTV evaporators, most Indian paper mills have already switched to FFFE systems. In fact, it operates under low temperature drop (about 5 °C) across the film and thus, more evaporators can be accommodated within the total temperature difference available ($T_S - T_{Le}$) for evaporation to offer higher steam economy.

Rao and Kumar (1985) pointed out that the MEE house of Indian paper mills alone consumes around 24–30% of the total steam required in a large paper mill. Therefore, it calls for a thorough investigation into its analysis and various energy reduction schemes.

For the analysis of MEE system mathematical models have been reported in the literature since last seven decades. A few of these were developed by Kern (1950), Itahara and Stiel (1966), Holland (1975), Radovic, Tasic, Grozanic, Djordjevic, and Valent (1979), Nishitani and Kunugita (1979), Lambert, Joye, and Koko (1987), Mathur (1992), El-Dessouky, Alatiqi, Bingulac, and Ettouney (1998), El-Dessouky, Ettouney, and Al-Juwayhel (2000), Costa and Enrique (2002), Agarwal, Alam, and Gupta (2004), and Miranda and Simpson (2005). These models are generally based on a set of linear or non-linear equations and can accommodate effects of varying physical properties of vapor/steam and liquor with change in temperature and concentration.

These models offer limited flexibility as far as handling of operating strategies is concerned. For example, if feed sequence has to be changed or any flash term (product, feed, condensate, etc.) is to be added or deleted or the streams are to be splitted or joined the whole set of equations of the model needs to be reframed. This offers considerable rigidity for use of the model, especially when one is exploring an optimum operating strategy from a number of feasible ones (Mathur, 1992).

To overcome this difficulty, Stewart and Beveridge (1977) developed cascade algorithm in which model equations of an effect is solved repeatedly in a predetermined sequence to simulate different operating strategies of a MEE system. The cascade simulation-based model of Stewart and Beveridge (1977) was improved by Ayangbile, Okeke, and Beveridge (1984). Their algo-

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Nomenclature

A	heat transfer area (m^2)
B	Boolean matrix
CFV1–CFV3	primary condensate flash tanks
CFV4–CFV7	secondary condensate flash tanks
CO	condensate flow rate (kg/s)
C_P	specific heat capacity (J(kg/K))
F	feed flow rate (kg/h)
FFT	feed flash tank
h	specific enthalpy of liquid phase (J/kg)
H	specific enthalpy of vapor phase (J/kg)
k	iteration number
L	liquid flow rate (kg/s)
MEE	multiple effect evaporator
n	number of total effects
n_s	number of effects supplied with live steam
OS	operating strategy
P	vapor body pressure (N/m^2)
PFT	product flash tank
Q_{loss}	heat loss (W)
SC	steam consumption (kg/h)
SE	steam economy
SEFFFE	Septuple effect flat falling film evaporator
T	vapor body temperature (K)
U	overall heat transfer coefficient ($W(m^2/K)$)
V	vapor flow rate (kg/s)
x	mass fraction
Yf	flow fraction matrix

Subscripts

avg	average of inlet and outlet conditions
out	exit condition
F	feed
f	flashing
i	effect number
L	black liquor
Le	last effect
P	product
S	steam
T	target
V	vapor
ph	re-heater

Greek letter

τ	boiling point rise (K)

rithm was capable of handling any number of feed splitting/joining operations. However, it has limitation, as it did not account operating strategies like reheating, flashing, etc. Bremford and Muller-Steinhagen (1994) proposed an iterative method for the simulation of MEE system but did not include the provision of vapor bleeding and also considered constant value of U.

Under the above background the present work has been planned to provide a model which has the flexibility of model of Ayangbile et al. (1984) but do not have the limitations. Thus, the model of above authors has been modified and improved in the present work. It accounts for different operating strategies such as steam and liquor splitting, feed sequencing, condensate, feed and product flashing, vapor bleeding for re-heaters, etc. In this paper the model for an effect is represented by single cubic polynomial, which utilizes the value of U supplied to it through an empirical correlations developed from the plant data. The model also accounts for Q_{loss} from effects and τ. It will be validated against plant data and used to study the effect of variations of different operating parameters such as T_S, x_F, T_{Le}, T_F and F on steam consumption (SC), steam economy (SE) and product concentration (x_P).

2. Problem statement

The MEE system selected for above investigation is a Septuple Effect Flat Falling Film Evaporator (SEFFFE) system operating in a nearby Indian Kraft pulp and paper mill for concentration of non-wood (straw) black liquor. Black liquor is a mixture of organic and inorganic chemicals. The proportion of organic compounds in the liquor ranges from 50 to 70%. Table 1 shows the inorganic constituents of Kraft black liquor found in Indian paper mills.

The schematic diagram of a SEFFFE system with backward feed flow sequence is shown in Fig. 1. The first two effects of it require live steam. This system employs feed, product and condensate flashing to generate auxiliary vapor, which are then used in vapor bodies of appropriate effects to improve overall SE of the system. The last effect is attached to a vacuum unit. The base case operating and geometrical parameters for this system are given in Table 2 which shows that steam going into first effect is 7 °C colder than that into second effect. This is an actual scenario and thus it has been taken as it is during simulation. The plausible explanation is unequal distribution of steam from the header to these effects leading to two different pressures in the steam side of these effects.

3. Model development

3.1. Boiling point rise (τ)

For development of a correlation for τ of black liquor, the functional relationship is taken from well established TAPPI correlation (Ray, Rao, Bansal, & Mohanty, 1992). For ith effect where concentration of black liquor is x_i, τ is given as

$$\tau = C_3(C_2 + x_i)^2 \quad (1)$$

To develop Eq. (1) different samples were collected from the SEFFFE system and experiments were conducted under controlled conditions in the R&D section of the industry to determine τ as a function of temperature as well as concentration of black liquor. It should be noted that plant data (such as liquor temperature and concentration) used in the present study were measured after calibrating the sensors. Additional measurements of temperature and concentrations were also performed in those places where routine measurements were not performed. Based on value of τ, obtained

Table 1
Weak kraft black liquor constituents

S. No.	Organic compounds	
1	Alkali lignin and thiolignins	
2	Iso-saccharinic acid	
3	Low molecular weight polysaccharides	
4	Resin and fatty acid soaps	
5	Sugars	
	Inorganic compounds	gpl
1	Sodium hydroxide	4–8
2	Sodium sulphide	6–12
3	Sodium carbonate	6–15
4	Sodium thiosulphate	1–2
5	Sodium polysulphides	Small
6	Sodium sulphate	0.5–1
7	Elemental sulphur	Small
8	Sodium sulphite	Small