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Research Paper

Optimization of multiple-effect evaporation in the pulp and paper industry using response surface methodology

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HIGHLIGHTS

- The evaporation plant has high energy demand in a pulp and paper industry. Any changes made to increase the efficiency of this process are of great industrial interest.
- We modeled the concentration of black liquor using a central composite rotational design.
- The mathematical model was validated through a comparison with data reported in the literature.
- Surface responses were used for the optimization of the process.

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ABSTRACT

The steady-state evaporation process was modeled by means of a phenomenological model based on mass and energy balances. The Newton method for nonlinear systems was adopted and then statistical methods were used for the preparation of an empirical model. The mathematical model was validated through a comparison with data reported in the literature. Surface responses were used for the optimization of the process by considering the output composition of the black liquor and the coefficient performance of the evaporator system (COP) as the response variables. The variables evaluated in the planning were the live steam ratio and the temperature of the live steam in evaporators 1 and 2. The temperature of the live steam entering the second evaporator was shown to be the most influential variable for the output composition, followed by the live steam flow ratio. For COP, the live steam flow ratio was the most influential variable, followed by the temperature of the live steam entering the first and second evaporators. The maximum value of the COP was achieved for a live steam flow ratio of 0.47 with the temperature of the live steam in evaporator 1 at 128.24 °C and the temperature of the live steam in evaporator 2 at 137.52 °C with a desirable function of 5.29.

1. Introduction

Falling film evaporation is a robust technology used in various industrial applications [1]. According to Ding et al. [2], evaporation has wide applications in nuclear and conventional power generation, refrigeration and air-conditioning, chemical and food processing, etc. In evaporation, the working fluid evaporates to extract heat from the surrounding media.

The black liquor evaporation process is very important in pulp mills [3] as a means of recovering heat and chemicals [1]. This process produces concentrated black liquor [3]. Black liquor is a mixture of organic and inorganic chemicals [4]. It is a residue of the digestion of wood chips in the cellulose and paper production via the kraft process [5]. The organic chemicals come from the wood and consist of a complex mixture of the products of lignin and cooking chemicals. The composition of this mixture is not well known. The inorganic chemicals are mainly sodium hydroxide, sodium sulfide, sodium acetate, and sodium carbonate, which come from the cooking chemicals and other mineral salts natural to wood [3]. This fluid is concentrated in a multiple effect evaporator system and burned in recovery boilers. The concentration of the liquor leaving the evaporator system influences the efficiency of the recovery of important chemical species in the recovery boiler [5].

The main advantage of multiple-effect evaporator systems is their energy economy, as the vapor generated in one effect can be used as the heating medium of another effect [5].

The evaporation process is widely used in a variety of industrial sectors, notably the pulp and paper industry. The phenomenological models for this type of process are based on a set of mass balance

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equations and energy and equilibrium relationships which must be solved simultaneously.

The evaporation process is employed in amusement branches of industry such as in the production of paper, sugar and alcohol, pharmaceuticals, chlorine, dairy products, and others [6]. The pulp and paper industry typically employs hull tube evaporators, using multiple-effect evaporation systems [7].

The pulp and paper industry is an energy-intensive industry [4,8]. According to Rao and Kumar (1985, cited in Kumar et al. [8]), the multiple-effect evaporator system alone consumes around 24–30% of the total steam consumed in a large Indian paper mill.

In the pulp and paper industry, the evaporation plant is in many cases the unit of operation that has the highest energy demand [9]. Thus, any changes made to increase the efficiency of this process are of great industrial interest [4]. As a result, mathematical models have been widely used as an alternative to achieve operating conditions that favor a reduction in energy consumption [6].

The mathematical models used for this process consist of nonlinear systems of equations that take into account the supply conditions, steam, and structure [4]. In the literature, there are several mathematical models for evaporation sets, such as those proposed by Ray et al. [10], Stefanov and Hoo [3], Agarwal et al. [11], Miranda and Simpson [12], Kaya and Sarac [13], Bhargava et al. [6], Ding et al. [2], Khanam and Mohanty [4], and Kumar et al. [8]. The complexity of the mathematical model may impose a compromise between its accuracy and the possibility of validating it practically in a real plant. Normally this compromise forces the engineer to develop a macroscopic model [12].

According to Khanam and Mohanty [4], the input and output of a given effect changes mathematically as operating strategy changes. While the cascade algorithm addresses these weaknesses of the general simulation models, it is not free from convergence and stability problems.

The modeling of steady-state multiple-effect evaporation has been widely reported in the literature [8], but the studies on optimization are scarce. Thus, the present study aims to evaluate the influence of the process variables in the model answers through statistical analysis with central composite rotatable design and response surface analysis.

The coefficient of performance of an evaporator system (COP) is used as a response variable. It is defined by Kaya and Sarac [13] as:

$$COP = \frac{\sum VS_i}{S} \tag{1}$$

where VS_i is the vapor flow from evaporator i and S is the total live steam used in the system.

For a list of nomenclature used in this work, see Nomenclature section.

2. Mathematical modeling

The system selected for investigation is a septuple effect evaporator system operating in a kraft pulp and paper mill used for the concentration of black liquor.

The mathematical model developed for the evaporation system is shown in Fig. 1. The liquor flow is a counter current. Live steam is fed into the first and second effects. The liquor and condensate flows are subject to flash, resulting in additional vapor generation. The program was developed in the MAPLE® platform.

The answers of the obtained mathematical model were: all temperatures and operating pressures of effects and flash units, flow rates, compositions of the liquor flows, as well as all temperatures, vapor flows and condensate flow rates. For the resolution of the system, it is necessary to know seven variables which in this case are the last evaporator temperature, the flow rate, the composition and supply temperature, the ratio of live steam feeds, and the live steam temperature of evaporators 1 and 2.

2.1. Generic mathematical model for an evaporator

The overall mass balance for the ith evaporator is mathematically represented by Equation (2):

$$LE_i - LS_i - VS_i = 0 \tag{2}$$

Considering that the vapor does not drag a stream of solid particles, the mass balance for the solid component can be represented by Equation (3):

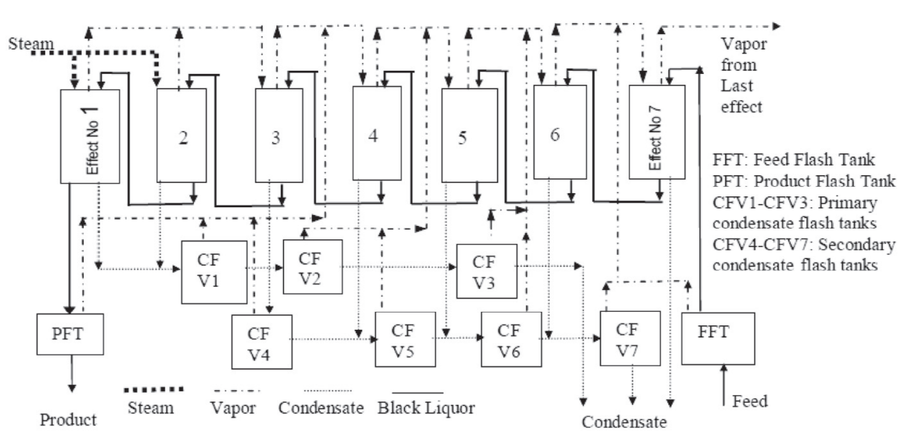
$$XE_i LE_i - XS_i LS_i = 0 \tag{3}$$

The energy balance is represented by Equation (4):

$$LE_i hLE_i - LS_i hLS_i - VS_i HVS_i + Q^t = 0 \tag{4}$$

where Q^t is the heat received by heat transfer, represented by the following equation:

$$Q^t = A_i U_i \Delta T \tag{5}$$



Source: Adapted from Bhargava et al. (2008)

Fig. 1. Schematic diagram of multiple effect evaporation system. Source: Adapted from Bhargava et al. [6]