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Distribution of juice heater surface for optimum performance of evaporation process in raw sugar manufacturing

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ABSTRACT

The evaporation process in raw sugar manufacturing turns diluted juice into granulated sugar. It consists of three main components: juice heater, multiple-effect evaporator, and crystallizer. Previous studies are concerned mostly with multiple-effect evaporator with the assumption that sugar juice entering the evaporator is at the saturation temperature. In fact, juice temperature must be raised to the saturation temperature in juice heater using vapor bled from the evaporator. This study investigates a model of the evaporation process with the objective of determining the distribution of juice heater surface that results in the optimum performance. The model takes into account mass and energy balances in the three components of the evaporation process. If the total juice heater surface is fixed, it is shown that there is a unique distribution of juice heater surface when vapor is bled from the first and second effects of the multiple-effect evaporator. However, if vapor is bled from the first, second, and third effects, many surface distributions are possible, and one of which is the optimum distribution that maximizes either the amount of granulated sugar produced from the process or the ratio of the amount of water evaporated from the process to the amount of high-pressure steam required for the process. Increasing the total juice heater surface increases both performance parameters. Results for two specific systems using different quadruple-effect evaporators are shown to demonstrate the application of the proposed model.

1. Introduction

The ideal raw sugar manufacturing process may be considered as consisting of two processes: the juice extraction process and the evaporation process. The first process extracts juice from sugar cane using either diffuser or milling machinery. Since a substantial amount of water is required in this process, the output from the process is diluted juice. The second process evaporates water from the diluted juice and produces granulated sugar as the final product. Main components of this process are juice heater, multiple-effect evaporator, and crystallizer. The juice heater increases the diluted juice temperature to the boiling point. The multiple-effect evaporator removes a substantial amount of water from saturated diluted juice, and produces concentrated juice (Chantasiriwan, 2016). The crystallizer removes the remaining amount of water from the concentrated juice, and produces granulated sugar as the final product of the process.

All three components of the evaporation process require steam for either juice heating or water evaporation. Most sugar factories use bagasse, which is the by-product of the juice extraction process, as the main fuel for boilers to produce high-pressure steam, which is then used to run steam turbines. Although steam extracted or exhausted from turbines at an absolute pressure of approximately 200 kPa may be used in all three components, it is more energy efficient to use the steam for only the multiple-effect evaporator, and to use vapor bled from the evaporator for the juice heater and the crystallizer. A typical design of multiple-effect evaporator uses vapor bleeding from the first effect for the crystallizer, and vapor bleeding from the first two effects for the juice heater, which leads to specification of larger surfaces of the first two effects compared with the other effects. Pinch analysis has suggested that improved energy efficiency can be achieved by using vapor bled from the third effect (Higa et al., 2009). However, using vapor bled from the third effect requires a special arrangement for removing condensate and incondensable gases because the third-effect pressure is sub-atmospheric. Moreover, there may be questions about using third-effect vapor bleeding in an existing installation with a small third-effect surface without adversely affecting the subsequent effect that requires vapor from the third effect.

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In this paper, a mathematical model of the evaporation process is presented. A survey of the relevant literature indicates the lack of such a model. Previous studies are mostly concerned with only multiple-effect evaporator because of its large consumption of thermal energy (Higa et al., 2009; Cortes et al., 2010) despite the fact that juice heater is an indispensable component of an evaporation process in raw sugar manufacturing. The model of the evaporation process takes into account interaction between the three components through mass and energy balances. The model is capable of assessing the improved performance of the evaporation process that results from increasing the total juice heater surface. The performance parameters are the rate of raw sugar production and the steam economy, which is defined as the ratio of the water content of the diluted sugar juice to the amount of steam input to the process. To demonstrate the use of this model, two cases of evaporation process that are installed with quadruple-effect evaporators are considered. The evaporator in the first case, which is intended for vapor bleeding from the first effect, has a large surface for the first effect, and smaller equal surfaces for the other three effects. The evaporator in the second case, which is intended for vapor bleeding from the first and second effects, has large surfaces for the first and second effects, and smaller equal surfaces for the other two effects.

2. Mathematical model

The schematic representation of the evaporation process is shown in Fig. 1. The juice heater is of the indirect type consisting of 4 heat exchangers (HC, H1, H2, and H3). It receives diluted juice at a flow rate of $m_{f,in}$ from the juice extraction process. After passing through H3, H2, and H1, the juice temperature increases from $T_{h,3}$ to $T_{h,0}$. The juice is assumed to be saturated, and its pressure is above the atmospheric pressure. Dissolved gases in the juice are got rid of by passing it through the flash tank (FC). Finally, the juice is passed through HC to increase its temperature to the boiling point using exhaust steam from the turbine as the heating medium. Although there has been suggestion of the elimination of HC (Peacock and Love, 2003), it is still indispensable in most sugar factories due to the fact that using part of the heating surface of the first effect of the evaporator to heat the juice up to the boiling point is generally considered inefficient. This argument, however, is based on the assumption that installation cost depends on only heating surface area. It should be noted that a practical optimum takes into account other costs in addition to installation cost due to heating surface.

The quadruple-effect evaporator requires a supply of high-pressure steam. The thermal energy released by the condensation of the steam causes the evaporation of water in sugar juice at a lower pressure p_1 in the first effect (E1), resulting in vapor and more concentrated sugar juice. The vapor leaving all effects (E1, E2, and E3) except the last effect (E4) is used to evaporate water in sugar juice in the succeeding effect. The arrangement in Fig. 1 makes use of full condensate flash recovery in order to improve the efficiency of the evaporator. A flash tank is placed after each effect except the last one. The first flash tank (F1) receives condensate from the first effect at pressure p_0 to produce vapor and condensate at pressure p_1. Each of the other two flash tanks (F2 and F3) receives condensate from the preceding effect and the preceding flash tank at pressure p_i to produce vapor and condensate at pressure p_{i+1}.

Vapor is bled from all effects of the evaporator except the last one. Vapor bled from the first, second, and third effects is used to increase juice temperature in H1, H2, and H3, respectively. Additional vapor bled from the first effect is used to evaporate the remaining water in the concentrated juice leaving the evaporator in the crystallizer (C). The output of the crystallizer is granulated sugar.

The mathematical model of the evaporation process consists of 3 sub-models for the juice heater, the quadruple-effect evaporator, and the crystallizer. The evaporator sub-model is a modification of

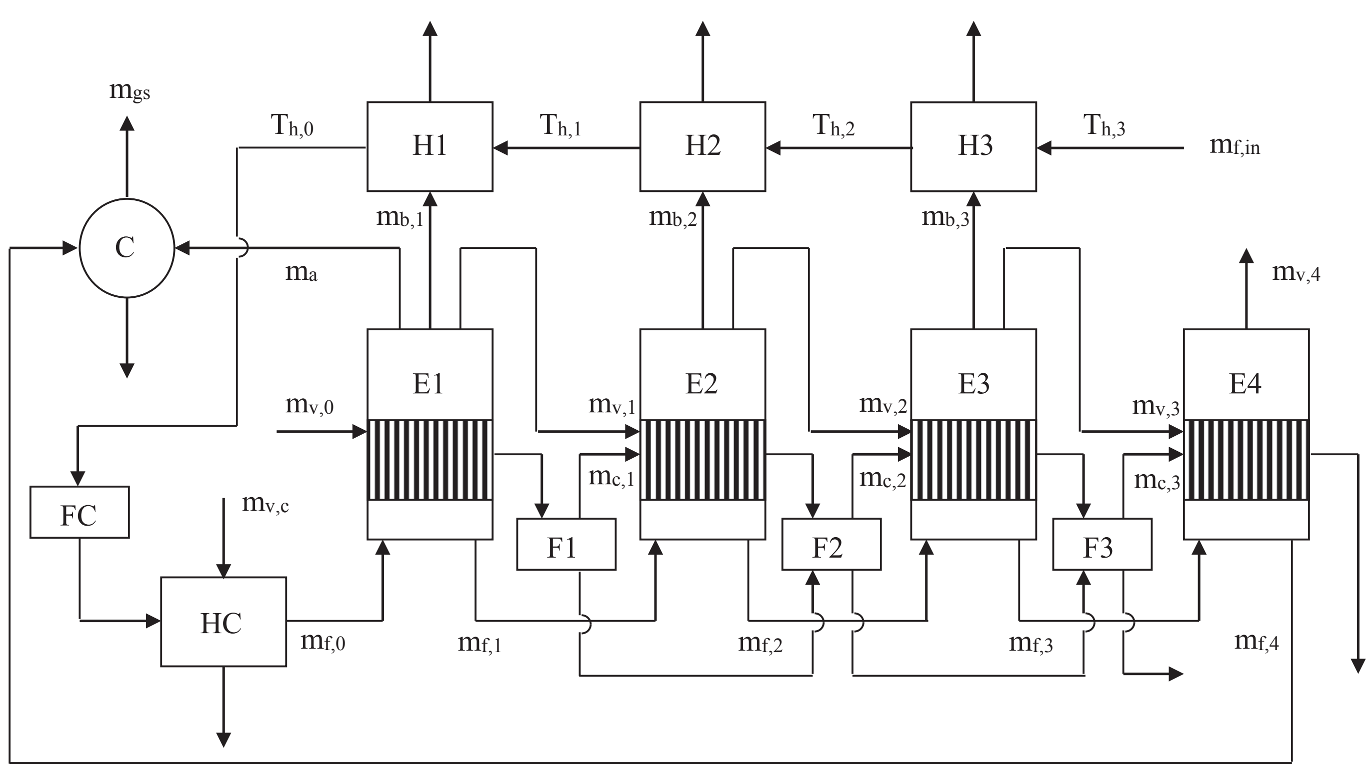

Fig. 1. Schematic representation of evaporation process.