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Dynamic simulation, numerical control and analysis of a novel bottom flashing scheme in batch distillation

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ABSTRACT

In this communication, the concept of bottom flashing under the mechanical heat pump system is introduced in the batch distillation columns. Proposing an operating strategy at transient state, a numerical control mechanism is formulated to simultaneously adjust the following variables aiming to ensure the optimal use of internal heat source: flow rate of reboiler liquid subjected to bottom flashing, operating pressure of throttling valve, compression ratio for pressure adjustment in the isentropic compressor and external heat input to the reboiler. The potential of this novel energy efficient batch distillation is numerically quantified in terms of the two performance indexes, namely energy savings and cost. Finally, a binary system is dynamically simulated to demonstrate the proposed configuration.

1. Introduction

There is no doubt that global warming is strongly associated with the combustion of fossil fuels, the rate of which gets intensified, particularly from 1980s onward (Zhao et al., 2013). The challenges in reducing the world's dependence on fossil fuels and the greenhouse gas concentration in the atmosphere have led to the introduction of a couple of new elements in the energy vector (Fasahati et al., 2015). In parallel, there is a strong voice in support of improving the energetic potential of the existing and matured process technologies through thermal integration route. In this light, distillation column that shares 60–70% of the total energy consumption in chemical industries (Diez et al., 2009) has emerged as a potential candidate for enhancing its energy efficiency, which is typically around 10% (Jana, 2010).

There are several variants of the heat integrated scheme reported for continuous flow distillation columns seeking higher energy efficiency and better profitability. Most widely available configurations include direct vapor recompression column (VRC) (e.g., Fonyo et al., 1995; Jana and Mane, 2011), distillation with bottom flashing (e.g., Fonyo et al., 1995; Diez et al., 2009), internal heat integrated distillation column (HIDiC) (e.g., Naito et al., 2000; Harwardt and Marquardt, 2012; Felbab et al., 2013) and dividing wall column (DWC) (e.g., Kolbe and Wenzel, 2004; Kiss and Rewagad, 2011).

As far as batch processing in distillation column is concerned, so far the feasibility of heat pump assisted VRC system (Babu and Jana, 2013) and a column with a concentric reboiler (Maiti et al., 2011, 2013) is explored in recent past. The same research group is currently involved in devising the batch HIDiC configuration (Jana, 2015a). However, there is a limited progress made on batch distillation with bottom flashing and divided wall. Based on our knowledge, there is a single article (Jana, 2015b) available that reports the development of bottom flashing for a batch rectifier mainly to perform the closed-loop control study. In this short note, a multivariable numerical control for the flashing loop is proposed, showing its detailed computation for the transient batch distillation in open-loop fashion.

This research work aims at introducing a novel energy efficient batch distillation with bottom flashing (BDBF) under the framework of mechanical heat pump system. This configuration targets to ensure the optimal use of an internal energy source generated by the proposed thermal arrangement. Accordingly, the BDBF scheme is attempted to operate at the close, if not same, dynamical response with its conventional analogous and this equality condition is considered here as a prerequisite for a fair comparison between them. With this objective, an operating strategy is formulated for the proposed scheme with introducing a numerical control policy to minimize the external energy use. To numerically quantify the promising potential of the transient BDBF column, two performance indexes, namely energy efficiency and total annual cost

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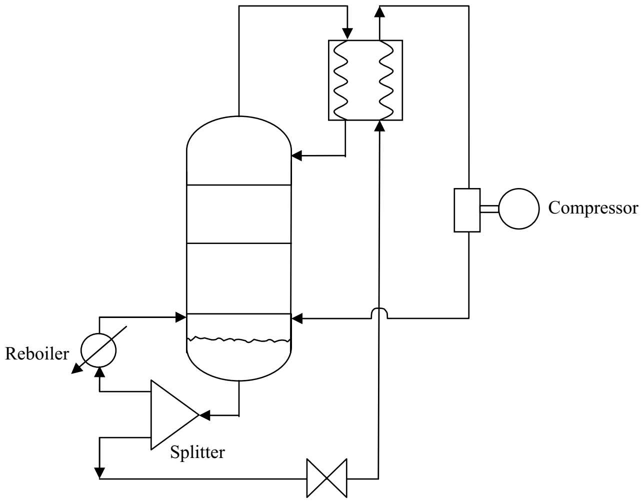

Fig. 1. Schematic of the proposed BDBF configuration.

(TAC) are used. Finally, a binary system is dynamically simulated to illustrate the proposed thermal coupling.

2. Batch distillation with bottom flashing (BDBF): the proposed configuration

In a conventional batch distillation (CBD), the fresh feed is charged in the reboiler (or still pot), above which, a tray tower is vertically mounted. The batch processing additionally requires an overhead condenser during startup (total reflux) and production (partial reflux) phases. It is a well-known fact that during the fractionation, heat is traditionally supplied to the reboiler operated at highest temperature level and the same is simply thrown away from the top condenser, which is run at lowest temperature. Obviously, the degradation of energy is associated with the temperature difference existed between these two heat exchangers. This, in turn, leads to a low thermodynamic efficiency, making the distillation a highly irreversible operation. In fact, this separation unit typically consumes many times the theoretical minimum energy requirement.

Aiming to enhance the energy efficiency of a conventional distillation column operated in batch mode by increasing its degree of reversibility (i.e., by reducing its entropy production), a novel heat integrated configuration is introduced here under the framework of mechanical heat pump system. As shown in Fig. 1, the proposed batch distillation with bottom flashing (BDBF) develops a thermal arrangement that is pretty compatible with an existing CBD. This heat integration arrangement basically couples the top vapor (heat source) with the reboiler content or bottom liquid (heat sink) in the overhead condenser, yielding a vapor stream in the bottom flashing loop to come up with the boil-up vapor after a necessary pressure adjustment.

As stated before, in a conventional batch distillation, the bottom liquid remains hotter than the overhead vapor. If it is so, then there arises a question: how to make the proposed thermal arrangement feasible when the heat sink is hotter than the heat source? Yes, it is feasible; the answer is in adiabatic flashing of bottom liquid, which leads to lower the temperature of that liquid by the use of a pressure reducing throttling valve. Actually, the pressure of bottom stream has to be reduced to such a level that its saturation temperature falls below the temperature of overhead vapor with a certain driving force. As shown in Fig. 1, this should happen prior to employ the bottom liquid as a cooling medium in the overhead condenser, which doubles as the reboiler.

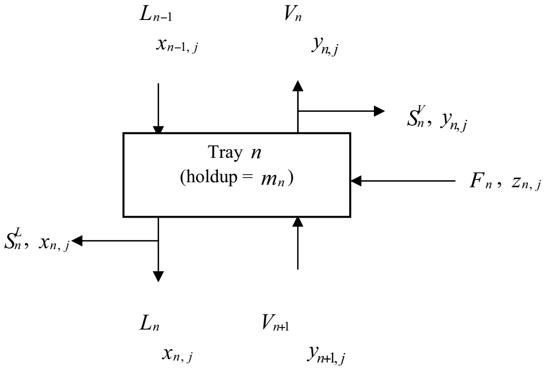

Fig. 2. A typical *n*th tray.

It is worth noticing that the proposed bottom flashing arrangement typically performs two major operations: (i) it recovers the latent heat of top vapor in the overhead condenser at the exchange of vaporizing the flashed liquid, thereby avoiding the consumption of an external cooling medium, and (ii) installing an isentropic compressor at the end of bottom flashing loop, the vapor produced in the condenser (i.e., cold vapor) is subsequently compressed back to column bottom pressure before its entry at the bottommost tray as boil-up vapor, thereby further avoiding the use of an external thermal utility in the still pot. At this point, however, it should be noted that an additional amount of heat added by this proposed thermal arrangement may not be adequate to make up the difference between reboiler and condenser duties. In such an event, the supply of auxiliary heat from an external source to the reboiler is needed.

3. Process modeling

As demonstrated in Fig. 1, a thermal arrangement proposed under bottom flashing mechanism can suitably be fitted with the CBD. For the resulting batch distillation with bottom flashing (BDBF) scheme, therefore, we separately present the modeling equations of these two units, namely the tray tower and the heat integration arrangement.

3.1. Tray tower

At first, the mathematical model of a tray column is developed based on the following assumptions: perfect mixing and equilibrium on each tray, inefficient tray, fast energy dynamics, existence of liquid phase nonideality and negligible vapor holdup. For a typical *n*th tray shown in Fig. 2, we have the following equations:

Total mole balance

$$\dot{m}_n = L_{n-1} + V_{n+1} + F_n - (L_n + S^L_n) - (V_n + S^V_n) \tag{1}$$

Component mole balance

$$\begin{aligned}\dot{m}_n \dot{x}_{n,j} = {} & L_{n-1}x_{n-1,j} + V_{n+1}y_{n+1,j} + F_n z_{n,j} - (L_n + S^L_n)x_{n,j} \\ & - (V_n + S^V_n)y_{n,j}\end{aligned} \tag{2}$$

Energy balance

$$\dot{m}_n \dot{H}^L_n = L_{n-1}H^L_{n-1} + V_{n+1}H^V_{n+1} + F_n H^F_n - (L_n + S^L_n)H^L_n - (V_n + S^V_n)H^V_n \tag{3}$$

Equilibrium

$$y_{n,j} = k_{n,j}x_{n,j} = \gamma_{n,j}\frac{P^0_{n,j}}{P_t}x_{n,j} \tag{4}$$