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NEW HEAT-INTEGRATED DISTILLATION CONFIGURATIONS FOR PETLYUK ARRANGEMENTS

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The Petlyuk arrangement has been proved to require the minimum energy consumption for multicomponent distillation that is an advantage for saving both energy and capital costs. On the other hand, the Petlyuk arrangement contains a maximum number of thermal couplings that is a disadvantage for the operability due to the harsh pressure constraints in terms of vapour transfers. This paper presents the synthesis of new distillation configuration with a reduced number of thermal couplings than the Petlyuk arrangement. Starting from the same separation sequence for the Petlyuk arrangement, a strategy taking advantage of simultaneous thermal coupling and heat integration achieves new distillation configuration for any *n*-component mixture. Compared to the Petlyuk arrangement, the new distillation configuration has the same number of columns, as well as the same number of column sections with only one condenser and one reboiler, while it has reduced the number of vapour transfers between columns. As a consequence, it has the potential to have the similar minimum energy consumption and capital investment, but improved operability than the Petlyuk arrangement. A simple procedure is formulated which generates the new distillation configuration systematically. It is shown that the new distillation configurations produce distinct thermodynamically equivalent structures due to the inherent different mass and heat transfers than the original Petlyuk arrangements. The new distillation configurations provide new alternatives when looking for the optimal distillation system with respect to both steady-state and dynamic performance.

Keywords: Petlyuk arrangement; new distillation configuration; thermal coupling; heat integration; operability.

INTRODUCTION

It has been proved that the Petlyuk arrangement requires the minimum energy consumption compared with other possible thermally coupled configurations (Fidkowski and Krolikowski, 1987; Triantafyllou and Smith, 1992; Fidkowski and Agrawal, 2001; Halvorsen and Skogestad, 2003a, b). Moreover, it uses the same number of $n-1$ columns as in a conventional distillation scheme but only one condenser and one reboiler for any *n*-component distillation (Petlyuk *et al*., 1965). These distinct features make it attractive in saving on both energy and capital costs and account for most of the subsequent studies on fully thermally coupled configurations (i.e., Petlyuk arrangements) (Fidkowski and Krolikowski, 1986, 1987; Glinos and Malone, 1988; Carlberg and Westerberg, 1989b; Triantafyllou and Smith, 1992; Wolff and Skogestad, 1995; Christiansen *et al*., 1997; Halvorsen and Skogestad, 1997, 2003a, b, 2004; Agrawal, 1996, 1999, 2000a; Agrawal and Fidkowski, 1998; Mutalib and Smith, 1998; Hernandez and Jimenez, 1999; Amminudin *et al*., 2001; Serra *et al*., 2001; Kim, 2002; Adrian *et al*., 2004; Wendel and Röhm, 2004). On the other hand, as illustrated (Rong and Turunen, 2006), in the Petlyuk arrangement, all the communications between the columns are two-way thermally linked streams. These two-way communications are created by thermal couplings. The thermal couplings are introduced by eliminating the condensers and reboilers associated with submixtures of binary or more components. It is known that the separation sequence of the Petlyuk arrangement contains all of the feasible subgroups of a multicomponent mixture (i.e., $n(n+1)/2$ subgroups). This results in the fact that the Petlyuk arrangement contains a maximum number of thermal couplings compared to other possible thermally coupled configurations. In this sense, it is often called the fully thermally coupled configuration (Triantafyllou and Smith, 1992; Agrawal, 1999, 2000a).

It is known that a thermal coupling is composed of a vapour stream and a liquid one transferring in opposite directions between two columns. In order to avoid the use of expensive compressors, the pressure at the location withdrawing the vapour flow is expected to be a little

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higher than that at the location receiving the vapour flow between the thermally linked columns (Carlberg and Westerberg, 1989a). This pressure difference is needed for each of the thermal couplings in any thermally coupled configuration. As to the Petlyuk arrangement, not only it contains the maximum number of thermal couplings, but also the number of thermal couplings increases rapidly with the increase of the number of components in the feed mixture. For example, in the Petlyuk arrangement for an *n*-component mixture ($n \geq 4$) [see figure 2 in Rong and Turunen (2006)], the first column with feed is linked by two thermal couplings, the last column with n products is linked by $n-1$ thermal couplings. While a column between the first and the last one [let us say m ($m = 2$, $n-2$)] is linked to its two-side neighbour columns by $2m + 1$ thermal couplings. As a consequence, there exist harsh pressure constraints between the columns in the Petlyuk arrangement in terms of both system's design and operation. On the one hand, at the thermally linked locations between the different columns, in order to minimize exergy losses, there need to be small pressure driving forces to facilitate the vapour transfers. At the same time, inside a column along different sections, one needs to carefully design the pressure drops in order to meet the requirements of the pressure driving forces. On the other hand, the harsh pressure constraints could cause the system to be sensitive to pressure disturbances, which would incur difficulties in the system's control. Therefore, thermally coupled configurations with a reduced number of thermal couplings are considered to be advantageous in terms of the system's controllability and operability (Agrawal, 2000b).

In order to reduce the number of thermal couplings in the thermally coupled configurations, Agrawal (2000b) presented a strategy to convert a two-way thermal coupling to a one-way liquid-only transfer. The main purpose of Agrawal's work was to avoid intercolumn vapour transfers by converting two-way communications into one-way communications. However, along with the conversion, a number of additional column sections as well as additional heat exchangers were added to the modified configurations. For example, for the Petlyuk arrangement for a four-component mixture, one extreme modified scheme without any intercolumn vapour transfers was composed of four columns, 24 sections and eight heat exchangers, instead of three columns, 12 sections and two heat exchangers in the original configuration. This considerably increased the capital investment of the distillation system (Agrawal, 2000b). Moreover, these additional column sections brought complexity and design difficulty to the distillation system.

A strategy that can keep the same number of columns as well as the same number of column sections and heat exchangers, but simultaneously can reduce the number of thermal couplings of the original Petlyuk arrangement is desired. Such a strategy would produce new distillation configuration that would not only have the similar minimum energy consumption and capital costs, but also improved operability compared to the original Petlyuk arrangement. Notice that, essentially, except for the condenser for the most volatile component and the reboiler for the least volatile component, all the other heat exchangers were eliminated by thermal couplings in the Petlyuk arrangement. Therefore, if we want to keep the same number of columns as well as the same number of column sections and heat exchangers, but simultaneously to achieve a reduced number of thermal couplings, we need a new strategy other than only the thermal coupling technique to eliminate all of the other heat exchangers. In a recent work (Rong *et al.*, 2003), it was found that thermal coupling and heat integration could be simultaneously used to eliminate the heat exchangers in conventional simple column configurations. Therein, the thermal couplings were first used to eliminate the condensers and reboilers associated with the submixtures of binary or more components, from which the partially coupled configurations (PC) were generated. Then, among some of the PC configurations, for the remaining heat exchangers, heat integrations were performed between condenser(s) associated with a heavier middle component and reboiler(s) associated with a lighter middle component. This resulted in the heat-integrated partially coupled configurations (HIPC) (Rong *et al.*, 2003). Therein, the heat integration has also been used to reduce the number of columns by combination of two-section columns. This resulted in the fact that the number of columns in a heat-integrated thermally coupled system can be lower than that of original thermally coupled systems (e.g., less than $n-1$ columns). However, the heat integrations did not affect the thermal couplings in the original partially coupled configurations. In other words, the HITC configurations and the corresponding original PC configurations have the same thermal couplings. Nevertheless, it was shown that the impact of heat integration was two-fold: First, it can further eliminate the heat exchangers in the original thermally coupled configurations. Second, it can combine two-section columns to reduce the number of columns.

Without question, wherever feasible, thermal coupling and heat integration can be simultaneously used to achieve new distillation configurations which would have distinct features than those obtained by using either thermal coupling or heat integration alone. Therefore, simultaneous thermal coupling and heat integration can be regarded as a general strategy to deal with heat exchangers during the synthesis of distillation systems whenever possible. In this article, we take advantage of simultaneous thermal coupling and heat integration as a new strategy to achieve new distillation configuration from the Petlyuk arrangement. The thermal couplings are used to eliminate the condensers and reboilers associated with the submixtures involving the two extreme volatility components, while the heat integrations are used to eliminate the condensers and reboilers associated with the submixtures composed of only intermediate volatility components. It will be shown that, except for the elimination of heat exchangers and the combination of two-section columns, heat integration can further reduce the number of thermal couplings of the original Petlyuk arrangement. This triple effect of heat integration will result in the fact that the new distillation configuration has the same number of columns as well as the same number of column sections and heat exchangers, but a reduced number of thermal couplings than the original Petlyuk arrangement.

In the following, we first briefly analyse the heat exchangers information in the fully sloppy separation sequence for an *n*-component mixture. Then, the strategy of simultaneous thermal coupling and heat integration to eliminate