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# Evaluation of various heat pump assisted direct, indirect, Petlyuk and side stripper sequences for three-product separations

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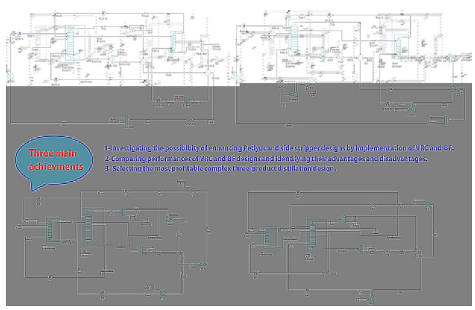
## HIGHLIGHTS

- Novel arrangements are developed for complex three-product distillation systems based on VRC and BF.
- A comparative study between VRC and BF on reduction of energy and costs of the systems is performed.
- BF outperforms VRC when applied on Petlyuk and direct designs.
- Using BF and VRC on Petlyuk systems, payback period of 1.14 and 1.25 years can be obtained respectively.

## GRAPHICAL ABSTRACT

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## ABSTRACT

In this paper, various configurations of vapor recompression and bottom flashing systems were developed. The systems were developed based on direct sequence, indirect sequence, Petlyuk and side stripper designs. This research was performed with three main aims. First aim was to investigate possibility of enhancing energy and economic performance of complex three-product distillation systems via implementation of vapor recompression and bottom flashing. Second aim was to shed light on differences in potentials of vapor recompression and bottom flashing systems in energy and costs savings of three-product distillation schemes. Third aim was to name the best configuration of three-product separation schemes from economic and energy points of view. Twelve configurations were designed. Energy and costs requirements of each configuration were evaluated and compared to each other. Based on the presented results, implementation of vapor recompression and bottom flashing systems can lead to better economic performance of complex three-product distillation systems. In case study presented in this work, application of vapor recompression and bottom flashing enhanced performance of direct sequence, indirect sequence, Petlyuk and side stripper designs. Equivalent work requirements of base direct sequence separation system was 5.59 MW. Based on the obtained results, considering energy requirements, Side stripper and Petlyuk arrangements are the best options for separation of the three-product system with equivalent work savings of 27.6 and 23.5%, respectively. Considering equivalent mechanical work of the systems, the highest savings was obtained in Side stripper with VRC heat pump (71.3% saving). It is shown that the most economically attractive configuration is Petlyuk with bottom flashing with total annual costs (TAC) saving of 43.4% (compared to 9.58 mUSD/year TAC of the base case), while the best performances of vapor recompression systems were obtained on Petlyuk and side stripper designs with TAC savings of 37.4 and 31.0%, respectively.



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## 1. Introduction

Distillation is the most commonly utilized technology for separation of chemicals (King, 2013). However, it is a very energy intensive system and numerous studies focused on energy and costs savings in distillation systems (Li et al., 2016; Osuolale and Zhang, 2016; Shahandeh et al., 2014). Various types of heat pumps have been used for improving energy performance of distillation systems (Felbab et al., 2013; Fonyo and Benkő, 1996; Kazemi et al., 2018b, 2017b; King, 2013). Among these, distillation with vapor recompression (VRC) and distillation with bottom flashing (BF) have been the topic of several studies (Díez et al., 2009; Fu and Gundersen, 2013; Gao et al., 2015). In comparison to internally heat integrated distillation columns (i-HIDiC), VRC and BF systems are simpler and in many cases, more economical. Simplified process flow diagrams of these systems are shown in Fig. 1. In these systems, reduction of energy requirements is achieved through heat transfer from top to the bottom product of the column. The vapor top product totally or partially liquefies through this heat loss and the required reflux stream is produced. Also, the bottom product, totally or partially vaporizes by gaining heat to provide the required boil up for the column. Transferring heat from top to bottom product can be achieved by increasing temperature and dew point temperature of the top product (using a compressor) and/or reducing temperature and dew point temperature of bottom product (using a valve). Utilizing the same concepts, in another study, novel coconfigurations of distillation were proposed that do not require any sources of hot utilities (Kazemi et al. (2018a).

In recent years, some studies focused on development of new configurations of these systems. In a previous paper (Long and Lee, 2013), separation of a mixture mainly consisting of isobutane and normal butane was studied. In this study, a commercial process simulator was used as a tool. Some schemes were proposed based on the idea of self-heat recuperation. It was shown that the proposed system can lead to 74.43% and 83.48% reduction of condenser and reboiler energy, respectively (Long and Lee, 2013). In another study (Waheed et al., 2014) enhanced vapor recompression heat pump models were developed for reduction of heat losses and the size of heat pump. In this study, the models were applied on a system for separation of ethane from a hydrocarbon mixture. Similarly, in this study, a commercial simulator was used as a tool and 6 models of vapor recompression were investigated and economic performance of each model was evaluated. It was concluded that by utilizing one of the suggested models, payback period of 1.42 years can be obtained (Waheed et al., 2014). In a similar study (Kazemi et al., 2016), a commercial process simulator was utilized for evaluating performance of various vapor recompression systems. In this study, the best configurations were selected based on their energy and economic performances (Kazemi et al., 2016). Furthermore, in another study (Kumar et al., 2013), various vapor recompression (VRC) arrangements with intermediate reboilers were investigated on catalyzed ethyl *tert*-butyl ether column (Kumar et al., 2013). Utilizing a similar concept on VRC systems can be found in other recent studies (Asprion et al., 2011; Jana and Mane, 2011). Also, a variable speed VRC reactive batch rectifier was proposed in a related previous study (Johri et al., 2011). It was shown that application of this system can result in 65.85% energy saving and payback period of 4 years (Johri et al., 2011).

Many studies focused on development of applications of VRC to new processes. For instance, VRC concepts were utilized in post combustion carbon capture process (Jeong et al., 2015; Karimi et al., 2011), sour water stripping process (Kazemi et al., 2017a) and a wastewater treatment system (Liang et al., 2013).

Separation of isobutane and normal butane was studied in another research (Díez et al., 2009). For this separation, performances of vapor recompression VRC, bottom flashing BF and absorption heat pump systems were evaluated. Similar to the other related studies, a commercial process simulator was utilized. A comparative study was carried out to identify the most economic system and it was concluded that for the investigated case, the BF arrangement showed more economic potential compared to VRC (Díez et al., 2009). In this field, performance of a partial bottom flashing system in reduction of energy requirements of separation of zirconium tetrachloride and hafnium tetrachloride was studied in another research (Minh et al., 2015). A commercial process simulator was used and it was concluded that by using the proposed bottom flashing system, 70.1% reduction in energy requirements of the separation systems can be achieved (Minh et al., 2015).

Various arrangements can be used for separation of three-product mixtures (Khalili-Garakani et al., 2016). Direct sequence,

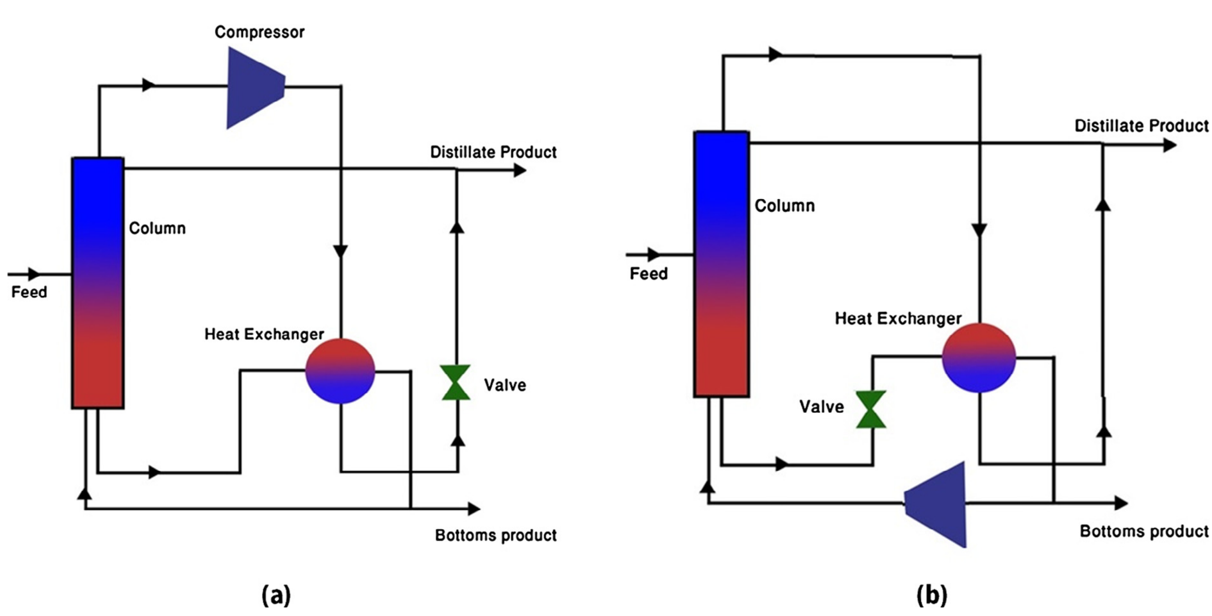


**Fig. 1.** Simplified process flow diagrams of (a) vapor recompression VRC (Kazemi et al., 2017a) and (b) bottoms flashing BF.