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A hybrid technology combining heat pump and thermally coupled distillation sequence for retrofit and debottlenecking

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ABSTRACT

Increasing the capacity of an existing distillation process has been a major focus of the chemical process industry. On the other hand, entrainment flooding can occur as a result, which can create a bottleneck in the distillation process. This paper reports the results of a techno-economic feasibility study to debottleneck the distillation column using a proposed hybrid process combining a heat pump and thermally coupled distillation sequence. Fractional utilization of the area was used to identify flooding problems in the column as well as how much area is available for vapor flow on an existing stage. A heat pump aided thermally coupled distillation sequence (HPTCDS) was designed and optimized using a response surface methodology. Two cases were examined to test the proposed sequence. The results showed that the proposed sequence can achieve significant energy savings and remove the bottleneck problem.

1. Introduction

In an existing distillation process with a fixed feed composition, there will be a maximum feed flow rate that can be separated to meet certain fixed product specifications [1]. An increase in production capacity can cause bottleneck problems, which is caused by some of the installed equipment not being able to accommodate higher flows than those associated with this maximum feed flow rate. A retrofit design aims to identify and remove these bottlenecks. The product needs can be accomplished by building new units or by debottlenecking existing capacity [2]. In the time required to fund, permit, design, build, and startup a new plant, the undulations of production can render the project unprofitable. Existing facility debottlenecking is an attractive method for increasing the production with minimal risk.

A retrofit project in a distillation process generally covers a wide range of modifications and uses an existing process, ranging from simple modification or replacement of column internals to large modifications of the column configuration [3], partial enlargement of the shell diameter and height, and a modification of the auxiliary equipment. In any case, the key to a successful retrofit lies in exploiting the existing hardware by maximizing the use of existing equipment while, at the same time, minimizing the need for new hardware to minimize the capital cost. The re-arrangement of existing columns to complex column arrangements, such as the Petlyuk column and prefractionator arrangement has been proposed for retrofitting [4]. Similarly, the addition of a new column, such as a post-fractionator or prefractionator, can also provide a process debottlenecking option [5].

Many studies have examined the relative advantages of a dividing wall column (DWC) including the huge potential for reduced consumption of utilities. These studies showed that DWC systems can achieve energy savings of up to 30% over conventional direct and indirect distillation sequences [6]. DWC can also be used to conduct azeotropic [7], extractive [8], and reactive distillation [9] without any major changes to the types of internals used. Furthermore, dividing wall columns have shown potential in retrofit from conventional 2-column system [10] and side stream column [11]. They reported that a dividing wall column can be used to save energy and other costs. On the other hand, this can have practical difficulties [4]. Furthermore, the lengthy payback period a DWC makes it unattractive when the plant lifetime is not long. Instead, the thermally-coupled distillation sequence (TCDS) has attracted considerable attention in retrofit projects because of the lower energy requirements compared to existing conventional column sequences, as well as the easy design and small modification [12].

A heat pump, which allows the heat of condensation released at the condenser to be used for evaporation in the reboiler, is used

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mainly to conserve energy when the temperature difference between the overhead and bottom of the column is small and the heat load is high [13]. A heat pump on the top of the column does not alter the vapor and liquid traffic inside the column. Nevertheless, a side heat pump can reduce the vapor and liquid traffic on the trays above it and increase the vapor and liquid traffic below it, which will increase the area utilization below the side heat pump. Heat pumps can also be used in grass-roots or retrofitting designs because they are easy to introduce and plant operation is normally simpler than heat integration [14]. Recently, it was utilized to improve energy efficiency of dividing wall column [15]. In this paper, in addition to being used to reduce the operating cost, a heat pump was used to remove the bottleneck by combining with TCDS to produce a hybrid technology. A hydraulic performance indicator and fractional utilization of the area (FUA) was used to identify a bottleneck in a distillation column when the capacity was increased. The design and optimization procedures using the response surface methodology (RSM) were used to retrofit the conventional distillation sequences to a heat pump aided thermally coupled distillation sequence (HPTCDS) with particular emphasis on the utilization of existing hardware with minimal investment cost and construction effort. Two mixtures were used to evaluate the proposed sequence, which combines a heat pump and TCDS. The proposed sequence was shown to require less energy than conventional distillation sequences, and remove the bottleneck problem effectively.

1.1. Increasing daily production

Distillation column retrofitting is performed more often than the installation of new equipment because distillation is an energy-intensive process requiring considerable capital investment [16]. In the retrofit design to increase the throughput of distillation processes, existing internals are normally replaced with high capacity or high efficiency internals. The process can also be revamped by improving the utilization of existing equipment and making relatively minor modifications, including adjusting the operating conditions and adding equipment [1]. In this paper, the purpose of a retrofit project is to increase the throughput without producing a bottleneck problem with the following assumptions:

a. The capacity must increase by 10% over the existing one.
b. The existing columns are already operating with the highest performance internals.
c. All columns are fully utilized.
d. The recovery of all products is kept constant.
e. The FUA_{max} of all columns is 1.
f. The remaining years: 8 years

With a target production capacity of up to 10%, the new base was simulated using the old process configuration, where all columns were used to obtain the products. Unfortunately, the results showed that it is impossible to use the existing column sequence because all columns are bottlenecked when the throughput is increased. Therefore, the HPTCDS was utilized to determine the requirements of the product in terms of productivity, recovery and purity.

1.2. A hydraulic performance – fractional utilization of area

The performance indicator for the hydraulic condition of an existing distillation was used. This indicator is related to the area needed for vapor flow if flooding is to be avoided [17]. The indicator allows one to identify bottlenecks, and evaluate the modifications proposed to overcome these bottlenecks. Knowing the extent to which the area available for vapor flow on each stage is utilized when a column is operating at its maximum throughput is very important. This knowledge is essential for determining at which stages the vapor and liquid traffic should be reduced, and which stages can accommodate the increased flows. For a given feed flow rate and at each stage, the column diameter that would be needed if the flows on that stage represent the maximum flows that could be tolerated can be calculated. For example, the vapor velocity could be assumed to correspond to 85% of the flooding velocity. The minimum diameter required for satisfactory hydraulic performance can then be compared with the diameter of the existing column to determine if, and to what extent, the flows to that stage can be increased. Knowing the extent to which the area available for vapor flow is utilized is useful because the area required is proportional to the feed flow rate, i.e. throughput. Therefore, the following new indicator of the hydraulic performance of an existing distillation column, the FUA, is utilized:

$$\mathrm{FUA} = \frac{\text{Area required on stage } i \text{ for vapor flow}}{\text{Area available on stage } i \text{ for vapor flow}} \tag{1}$$

where the area required for vapor flow is calculated for a given approach to the flooding conditions (e.g. when the vapor velocity is 85% of the flooding velocity). A more detailed description of the FUA can be found elsewhere [1].

2. Design and optimization of hybrid technology

2.1. Design

Fig. 1a shows the possibility of re-arranging two existing columns into an HPTCDS. In addition, instead of supplying heat to the reboiler, a heat pump can be used to provide side heating (Fig. 1b) to reduce the traffic in the stripping section, which brings more opportunity to increase the capacity. Furthermore, supplying heat to the side reboiler can reduce the temperature difference between the heat pump and side reboiler location, which allows a decrease in heat pump duty. To highlight the optimal use of the existing columns, this study assumes no change in the diameter or the total number of stages of each column. Debottlenecking the existing distillation sequence begins with the development of preliminary designs for complex systems and minimizes the operating cost through the optimization procedures. The HPTCDS was designed using a thermal link in the vapor phase in a conventional indirect sequence, which eliminates the condenser in the conventional scheme and adds a heat pump, which utilizes the heat in the condenser. Modification for the retrofit involves a change in the draw trays for the vapor and liquid streams. More pipe work is also needed for the thermal link and re-assignment of the eliminated condenser to the main column.

2.2. Optimization

The RSM is a general technique for an empirical study of the relationships between the measured responses and independent input variables [18]. A response surface is normally a polynomial, whose coefficients are extracted by a simple least-square fit to the experimental data. The RSM is quite powerful because, in addition to modeling, it can also optimize the conditions of a process [19]. Normally, a low-order polynomial is used in some regions of the independent variables [20]. A simple first-order model can be used as an approximating function if the response is modeled well by a linear function of the independent variables. On the other hand, a polynomial of higher degree, such as a second-order model, must be used if there is curvature in the system. According to the