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The effects of feed splitting and heat integration in classical arrangements on cost minimization in separation of ternary mixture

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ABSTRACT

Multi-component separation by distillation is known as a conventional method in chemical processes. In this study the effects of feed splitting on three classical arrangements (with and without heat integration) were investigated in order to reduce the total annual cost (TAC). Ternery mixture separation (propane, butane and pentane) by distillation was selected as a case study. An optimization problem was defined based on the effective parameters affecting the total annual cost. Optimum values for decision variables were calculated by applying the genetic algorithm. Calculation results showed that the heat integration procedure in the feed splitting method reduced the TAC significantly. It was also indicated that the prefractionator arrangement with heat integration resulted in the greatest decrease in the total annual cost.

1. Introduction

In recent years, significant attention has been focused on saving energy in chemical industries. This can be attributed to the increase in energy cost and environmental issues. The energy recovery procedures can save large amounts of operating costs in chemical processes [1,2]. Distillation columns are used for separation as a basic part in many chemical industries. Since distillation consumes significant amount of heat, many activities have been focused on saving energy in distillation columns. From a technical and economical point of view, high energy consumption is one of the important weaknesses of distillation columns. High level of energy consumption leads to increase in operating costs. Process integration has been known as a proper method for reducing the energy consumption and has attracted lots of interest in chemical processes. Heat integration is used in order to design integrated distillation configurations with energy savings in condensers and reboilers of the compound distillation columns. The required duty in the towers can be supplied by the cold/hot streams available from the other parts in the plant [3]. Many techniques have been implemented in chemical industry to save energy such as thermal coupling, pinch method, and feed splitting [2,4–7]. There are three classical arrangements for separation of ternary mixtures; direct split, indirect split and prefractionation [8,9]. Integrated prefractionator arrangement gives the highest energy saving compared to the other schemes. The separation process in multi-effect distillation was accomplished in two columns operating at low and high pressure. Appropriate arrangements decreased operating costs in different processes [8,10]. Distillation works based on the difference in boiling points of the components. Preheating the feed has been known as a common procedure for saving energy in industrial distillation towers. Heating whole or a portion of the feed with one of the column streams was introduced as an appropriate way for energy saving in distillation columns. Soave and Feliu [7] showed that feed splitting and preheating of the feed by the bottom stream can result in a considerable energy saving in a binary mixture (benzene and propane). Three different arrangements were considered among them was the feed splitting [7]. Feed splitting and preheating (58% of the feed) resulted in decrease in rebolier duty while condenser duty remained almost unchanged. The main objective of this work is to propose an optimum scheme for ternary distillation systems considering all effective variables. The effects of feed splitting in three classical arrangements are investigated. Total annual cost is defined as the objective function to be minimized applying genetics algorithm (GA).

Genetic algorithm is an attractive technique used to solve optimization problems in chemical processes. Optimal design of coupled systems for separation of multicomponent mixture was achieved by GA [11,12].

In the present study the modified HYSIM inside-out Methods were used by HYSYS® simulator instead of the shortcut methods used in previous investigations to increase the accuracy. As it was indicated in [13] shortcut method has higher errors because of its simple assumptions.

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Table 1
Feed data.

Feed rate	300 mol/s
Feed composition	Propane 0.15,butane 0.70,pentane 0.15
Feed pressure	100 kPa

2. Case study

As said the effects of feed splitting on three classical separation schemes is discussed focusing on economical aspects. The optimization was carried out for following arrangements:

- Direct feed splitting arrangement.
- Indirect feed splitting arrangement.
- Prefractionator feed splitting arrangement.

Distillation columns were designed for separation of three components (propane, butane, and pentane) and purity of the products was fixed at 99.5%. Table 1 provides the feed data used in different arrangements.

2.1. Direct and indirect feed splitting arrangement

Fig. 1a and b, shows the column arrangements for direct and indirect split. In both arrangements the feed stream is preheated before entering the first column.

In the feed splitting scheme, the feed stream of each column is divided into two parts. In the direct feed splitting arrangement, the propane is regarded as a distillate product of the first column and the bottom product of this column which contains butane and pentane enters the second column. In the second column, butane and pentane are separated as a distillate and bottom product, respectively. In the indirect feed splitting arrangement pentane is separated as a bottom product in the first column and propane and butane which are top product of the first column are introduced to the second column. Propane and butane are separated as a top and bottom products in the second column, respectively (Fig. 2a and b).

2.2. Prefractionator feed splitting arrangement

Fig. 3a and b illustrates the prefractionator arrangement and the prefractionator feed splitting arrangement, respectively. In the prefractionator feed splitting the feed stream is divided into two parts. A portion of it is preheated and enters the lower section of the first column. The rest enters the column without any treatment. In the first column a partial separation occurs meaning that all components exist in the top and bottom products. The final separation is achieved in the second column. The second column has three products. Top product of the column contains propane, bottom product contains pentane and a side product contains butane.

It should be noted that all of the abovesaid arrangements can be used in two states; with and without heat integration.

2.3. Defining the optimization problem

For synthesis of these processes two kinds of data are needed. The data related to the design of columns and the data related to the design of heat exchangers. In the case of the columns the design variables can be defined as below:

1. Number of trays.
2. Columns operating pressure.
3. Feed vapor fraction.
4. Feed tray.

Table 2
Equipment and utility costs.

Equipment cost	Cost function [14]
Distillation column	C_P (Cost of the vessel) + C_T (Cost of the trays)
Heat exchanger	Cp1
Pump	Cp2
Utility cost	
LP-Steam ($/ton)	13
MP-Steam ($/ton)	16
HP-Steam ($/ton)	20
Cooling water ($/ton)	0.082

5. Pressure.

Operating pressure of the column was selected as one of the decision variables. A fixed pressure drop for each actual tray was considered. Column operating pressure was searched for by Genetics Algorithm and each tray pressure was calculated assuming the fixed pressure drop per tray.

In addition to the above variables which are similar among all arrangements, the following variables are also considered:

1. Column arrangements (direct or indirect).
2. Side stream tray in the prefractionator arrangement (without feed splitting and with feed splitting).
3. Feed splitting fraction in the direct and indirect arrangement and the prefractionator arrangement.

As it was said before, the objective function to be minimized is TAC. TAC is defined as:

TAC = Operating cost + (Capital cost × Payback factor).

Capital cost is calculated with the payback period of 5 years and using the cost data in [14]. It should be noted that 2011 cost index (585.7) was applied in the economic analysis. A clear definition of all elements of the objective function can be presented as below:

Capital cost = Direct costs + Indirect costs + other outlays, [14]

Equipment costs (Table 2) are an element of the direct costs and other direct and indirect costs are a portion of it. Table 3 illustrates the definition of the optimization problem and its elements. All equality constraints are checked by simulator.

2.4. Genetic algorithm

Fig. 4 presents implemented architecture between the user, optimization algorithm, MATLAB, and HYSYS®. As can be seen the optimization algorithm navigates the simulator in the MATLAB software interface. In this regard, selection of the simulator setting should be done automatically by the optimizer through the optimization operation because it is not possible to enter the simulator interface when the algorithm is controlling the simulation [15].

Table 3
Definition of the optimization problem.

Optimization problem			
Objective function:		Total annual cost	
Decision variables:			
		Lower bond	Upper bond
Tray number	x1	15	60
Pressure (bar)	x2	1	15
Feed tray	x3	0.1x1	0.9x1
Side stream tray	x4	0.1x1	0.9x1
Constraints:			
Min temp approach (°C):		5	50
Distillate concentration (%)	99.5		