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THE EFFECT OF PRESSURE ON DYNAMICS AND CONTROL OF SIDESTREAM DISTILLATION COLUMNS

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ABSTRACT

Distillation column control is widely explored by literature due to its complexity and importance in chemical and petrochemical industries. In this process, pressure represents one of the most important variables to be controlled, however, pressure effect on the dynamics and control of distillation columns has not been carefully studied. Furthermore, most researches on distillation column control is limited to columns with two withdrawals (top and bottom), but in many cases, distillation columns have sidestreams once their application can provide significant reduction in operating and capital costs. This paper investigates the effect of pressure on the dynamics of an industrial sidestream distillation column and compares the performance of its current pressure control configuration with two other configurations. The results showed that the pressure control currently used in the studied column is not the most effective and other control configurations have a better performance.

Keywords

Effect of pressure, dynamics and control, sidestream distillation columns.

1. INTRODUCTION

Sidestream column is designed to replace two or more conventional columns that separate multicomponent mixtures or binary mixtures when different purity levels are desired. In sidestream columns, the component with intermediate volatility is removed through a sidestream, reducing investment, operation costs and especially energy consumption.

Sidestreams rarely provide a final product because of their limited purity. Therefore, sidestream columns are suitable for prefractionators (where the sidestream feeds another column for further separation) and to generate recycle streams where there is no restrict composition requirement [Glinos and Malone, 1985b]. Sidestream is commonly carried out in vapor phase when it is below feed stage and in liquid phase when it is above feed stage. Most works on this topic are concerned with defining design methods [Glinos 1985b and Malone, Malone and Nikolaides 1987 and Gutiérrez-Antonio Jiménez-Gutiérrez, 2007].

Although sidestream columns provide savings by reducing capital and operating costs, they pose challenging control problems. According to Buckley et al. (1985), even the simplest sidestream column is generally more difficult to control than conventional columns with only two product streams. Tyreus and Luyben (1975) say the use of sidestream columns in binary distillation was not common in the past because, with inexpensive fuel, it was more practical and economical to use an inefficient processing scheme to obtain two different products than to take on the control difficulties of simultaneous control of three compositions. However, in the current economic scenario, applying efficient control systems to minimize energy consumption without loss of quality has become essential. In contrast, sidestream columns

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control has not been a very explored subject. This fact and the widespread use of sidestream columns in the chemical and petrochemical industry encouraged the development of this article.

Pressure is perhaps the most important control variable in a distillation column [Kister 1990]. Pressure affects condensation, temperatures of vaporization, volatilities and almost all the process that occurs in the column. According to Kister (1990), unsatisfactory pressure control often indicates a poor column control. However, there are few studies about how pressure affects the dynamic behavior of distillation columns and their control system. Pressure variations make column control more difficult, so that most control systems consider that distillation columns operate at a constant pressure. According to Skogestad (1997a), the assumption of constant pressure is often justified because pressure is tightly controlled, but overall, pressure dynamics and their effect on the column behavior are not well understood.

According to Liu and Jobson (1999), pressure has a very complex influence on distillation process. In their work, the authors provided a clear and quantitative picture of pressure influence on the throughput of an existing distillation column. Their results showed that the pressure influence on the diameter required for the distillation column is strongly dependent on pressure itself. In other words, for different separation systems (easy or difficult separations, binary or multicomponent mixtures), a pressure variation has a similar effect on the diameter of the column. Despite the importance of understanding these effects for the retrofit and grass-roots design of distillation columns, no discussion was made on pressure control and its effect on the dynamic behavior of distillation columns.

Regarding the control of sidestream distillation columns, Glinos and Malone (1985a) investigated the characteristics of control of sidestream columns in steady state and discussed qualitatively various control strategies. RGA analysis were done to compare different control schemes and to evaluate their performance in terms of steady state. To gain a further degree of freedom in composition control, Doukas and Luyben (1978) presented the idea of changing the sidestream location. Tyreus and Luyben (1975) tested an efficient control scheme in which the sidestream composition was also controlled by manipulating its location. Papastathopoulou and Luyben (1991) presented the study of the dynamics and the analysis of various control configurations for a large industrial column that separates a binary mixture of propylene and propane in three products. Bettoni et al. (2000) developed an advanced control of a sidestream column that removes benzene from a reformed gasoline stream. Fieg (2002) described a concept for composition control of all product streams of a distillation column with a liquid sidestream. In his work, all products' compositions were determined by online gas chromatographs and are characterized by high dead time.

The sidestream column used as a case study in some of those papers separates binary mixtures (Tyreus and Luyben, 1975; Papasthopoulou and Luyben, 1991). Other papers deal with sidestream columns that separate multicomponent mixtures (Doukas and Luyben, 1978; Bettoni et al, 2000; Glinos and Malone, 1985a; Fieg, 2002). Among them, Tyreus and Luyben (1975), Papastathopoulou and Luyben (1991) Bettoni et al. (2000) and Fieg (2002) were the ones that studied the process dynamics in order to select the best control strategy, but none of them undertook the study of pressure control for sidestream columns.

2. PROBLEM DEFINITION

The studied column is part of an isobutane and hexene recovery area; isobutane and hexene come from a polymerization reactor. The column recovers, as top product, ethylene and isobutane solvent not consumed in the reactor and removes hexene not reacted through a sidestream. The column t is an unconventional column because it has three feed streams and four withdrawals. Two feed flows are in liquid phase and one feed flow is in vapor phase. Two withdrawals correspond to the sidestream and bottom stream. The other two withdrawals come from the column overhead stream, which is partially condensed and sent to a reflux drum, giving rise to distillate in vapor phase and distillate in liquid phase. Part of liquid distillate provides the reflux flow of the column and the other part, combined with vapor distillate, is connected to another column, which separates ethylene from isobutane. Fourteen components are considered in the simulation; however, the most representative components are isobutane, hexene and ethylene.

A column with one sidestream presents three degrees of freedom. However, the column was simulated using the reboiled absorption model from Aspen Plus, where the degree of freedom is reduced to the unit due to the condenser absence. Figure 1 shows a schematic flowsheet of the sidestream column and Table 1 contains the properties (designed and simulated) of some streams numbered in Figure 1. Table 2 contains the compositions of the global streams for the major components. The stationary simulation was validated by comparing simulated data with design data (provided by the plant).

Figure 1 also shows the control structure used in the plant (Configuration 1) and Table 3 contains the controlled and manipulated variables. The temperature is measured on tray 23 because this tray presents the largest change in temperature (Figure 2). Since the bottom flowrate is too low, bottom level is controlled by manipulating the reboiled heat duty. The pressure control valve is after the reflux drum, in the vapor distillate stream. The reflux drum level is controlled

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by manipulating the liquid distillate flowrate. The reflux ratio is fixed as a ratio of reflux flowrate and liquid feed flowrate.

Sidestream flowrate should be maintained in dozens of kg/h, but it is varying from 0 to 1000 kg/h (Figure 3), resulting in a specification problems at the bottom stream (loss of hexene) and at the sidestream (loss of isobutane). However, this behavior could not be observed in steady state simulations for a variation in vapor feed flowrate (Figure 4). Analyzing the global process, it was observed an oscillation in the vapor flow rate of the feed stream, resulting in pressure variation through the column. Changing the pressure, temperature profiles vary, forcing the temperature control system to open and close the sidestream control valve, causing a fluctuation in the outflow. It is important to note that this effect was not observed in steady state simulations, because the pressure in each tray of the column is kept constant. Thus, transient simulations were essential to evaluate the effect of pressure on the process behavior.

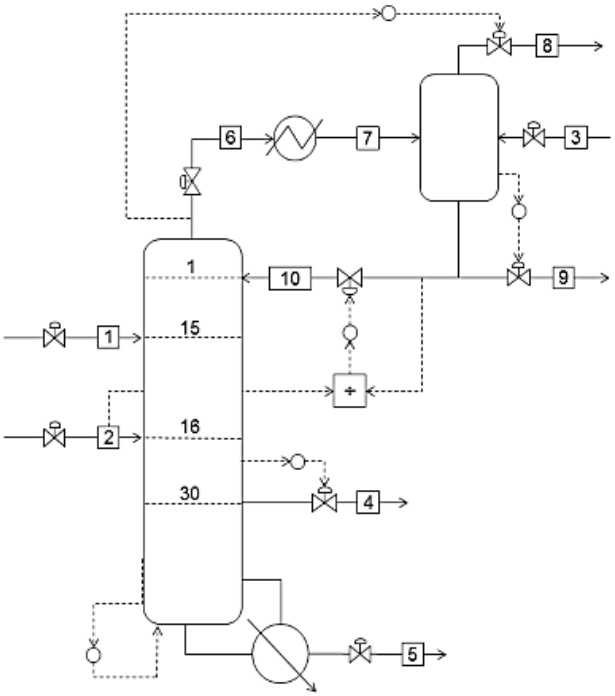

Fig 1: Sidestream column of isobutane and hexene recovery.

Table 1. Stream properties

Stream	Mass Flow (kg/h)		Temperature (C)		Pressure (kg/cm^2)		Vapor Fraction	
	Designed	Simulated	Designed	Simulated	Designed	Simulated	Designed	Simulated
1	723,0	723,0	37,70	37,70	10,95	10,90	1,0	1,0
4	23,6	23,6	160,30	157,10	10,81	10,85	1,0	1,0
5	26,4	26,4	175,00	175,50	10,88	10,90	0,0	0,0
8	740,7	744,5	37,78	35,10	10,48	10,45	1,0	1,0
9	3318,4	3314,5	37,78	38,10	10,48	10,45	0,0	0,0

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Table 2. Stream compositions

Stream	1	2	3	4	5	8	9
$x_{ethylene}$	0,21	0,02	0,0	0,0	0,0	0,20	0,03
$x_{isobutane}$	0,74	0,92	0,96	0,0	0,0	0,75	0,93
x_{hexene}	0,0	0,01	0,0	0,95	0,56	0,0	0,0

Aiming the evaluation of pressure effect on column dynamics, two new control configurations were elaborated, defined as Configuration 2 and Configuration 3 (Figure 5). These differ from Configuration 1 only by pressure control. In Configuration 2, pressure is controlled by a valve located in the column overhead stream. The controller action is direct, that is, if column pressure increases, the control valve opens, increasing top flowrate. In Configuration 3, pressure is controlled by manipulating the condenser coolant flowrate. The controller action is also direct. The controllers' parameters were those suggested by Aspen Dynamics.

Table 3. Controlled and manipulated variables

Controlled Variable	Manipulated Variable
Base Level	Reboiler Heat Duty
Tray 23 Temperature	Sidestream Flowrate
Reflux Drum Level	Liquid Distillate Flowrate
Reflux Ratio	Feed Flowrate/Reflux Flowrate
Top Pressure	Vapor Distillate Flowrate

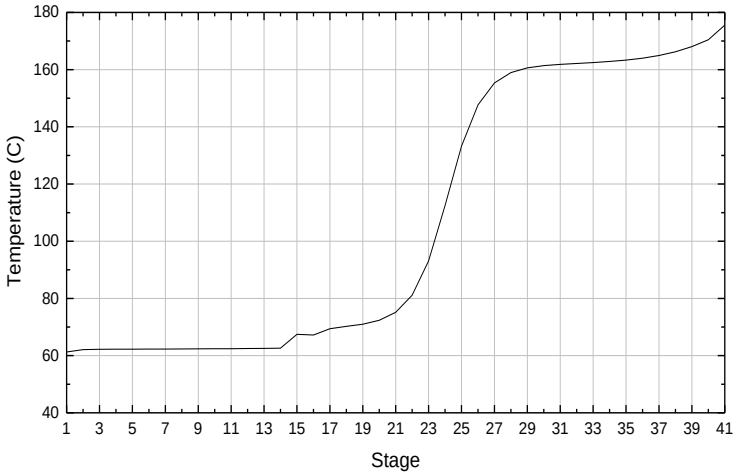

Fig 2: Temperature Profile

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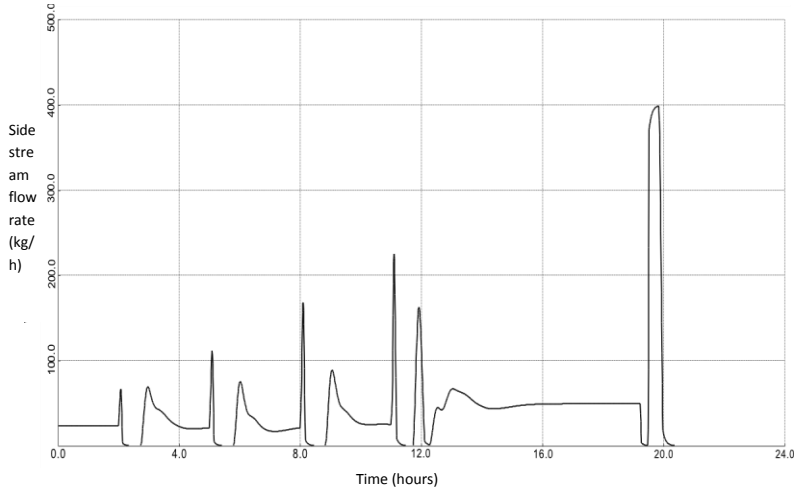

Fig 3: Dynamic behavior of sidestream flowrate.

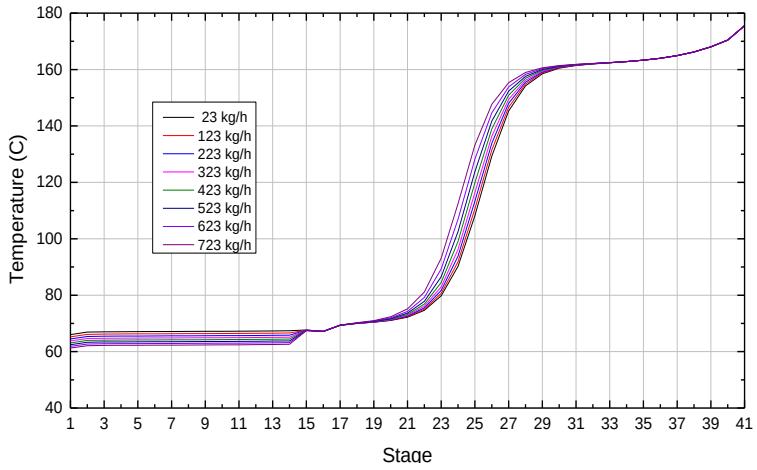

Fig 4: Temperature profiles for several vapor feed flowrate.

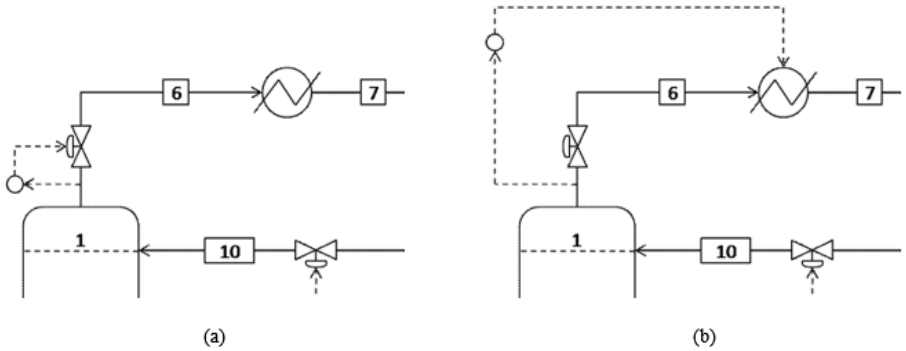

Fig 5: Pressure control structures of the sidestream column: Configurations 2 (a) and 3 (b)

3. DYNAMIC SIMULATIONS

The dynamic mathematical model for distillation columns is constituted by differential and algebraic equations. Differential equations are derived from mass and energy balances and were solved by implicit Euler method, which is Aspen Dynamics standard method. Algebraic equations are obtained from equilibrium and hydraulics relations. Liquid

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holdup was calculated by Francis equation. Thermodynamic properties of both liquid and vapor phases were calculated by Peng-Robinson model due to the column operation pressure value (moderate) and due to the mixture to be separated is a mixture of hydrocarbons. The specifications are bottoms flowrate and sidestream flowrate. The three studied control configurations showed good performance when disturbances were applied in liquid feed flowrate. Thus, each configuration performance was evaluated taking into account only disturbances in vapor feed flowrate.
Vapor feed flow (stream 1) ranged from 0 to 600 kg/h by 100 kg/h. After 600 kg/h, the process was also simulated with vapor feed designed flowrate (723 kg/h). Both studies were done every two hours in ascending and descending order, in a total of 34 hours of simulation for each varied flowrate. One flowrate was changed at a time while all the other variables were held constant for each simulation. Initially, the effect of the applied disturbance was observed for open-loop pressure. Results for isobutane and hexene compositions in the sidestream and in the liquid distillate were observed. Sidestream flowrate, vapor distillate flowrate, temperature profile, base and reflux drum levels and pressure of stage 1 (top of the column), stage 23 and stage 41 were also observed. In the simulation with open-loop pressure, for all monitored variables, vapor feed flowrate disturbances had more influence than liquid feed flowrate disturbances.

3.1 Configuration 1

As shown in Figures 6b, 7b e 8b, before the complete closure of the vapor feed control valve, the main monitored variables tended to come into steady state after some oscillation. However, after the valve closure (14h), the column top pressure (and hence pressure of entire column) became impossible to control. Pressure continues to decrease and stability is achieved only by opening the vapor feed control valve (when pressure begins to increase).
When vapor feed flowrate is null (14h), pressure gets "out of control" tending to stabilize at a much lower value than the set point. When vapor feed flowrate is no longer zero (around 16h), pressure increases sharply, causing the control valve opening of the vapor distillate flowrate.
According to Figure 7b, when vapor feed flowrate goes to zero (14h), isobutane composition in the sidestream increases sharply, causing a temperature rise in tray 23 and then, by the action of control system, the sidestream flowrate also increases sharply (Figure 8b), increasing the isobutane composition in this stream.

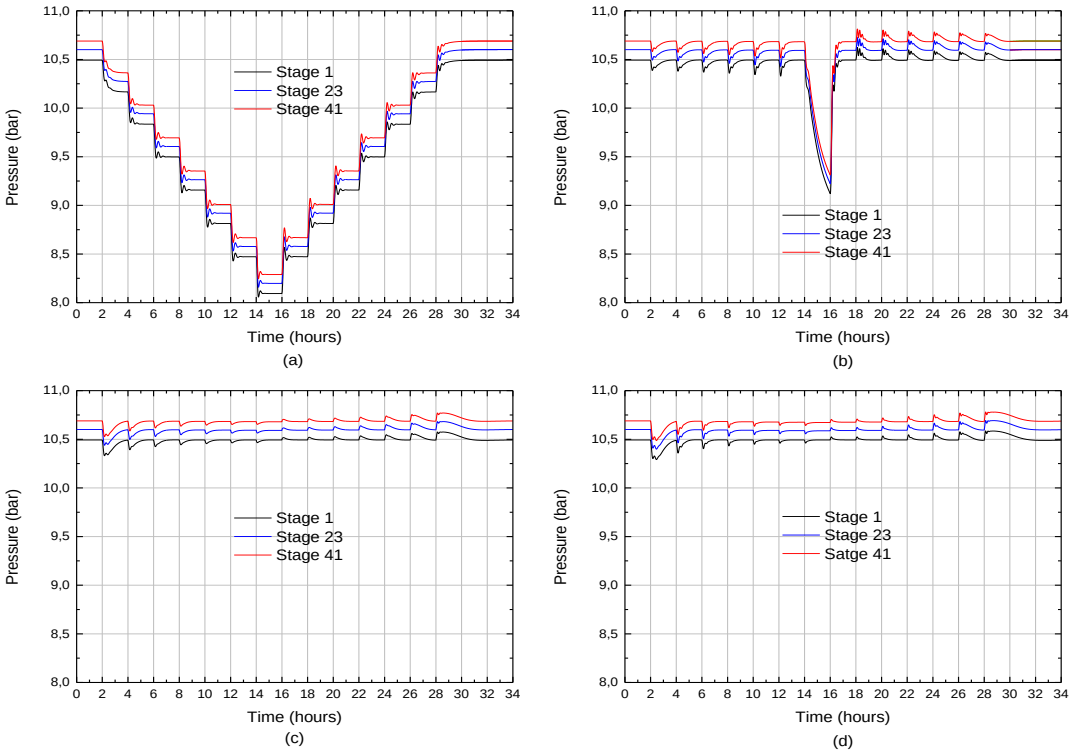

Fig 6: Dynamic response of the column pressure for changing in vapor feed flowrate – Open-loop pressure (a), Configuration 1 (b), Configuration 2 (c), Configuration 3 (d).

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3.2 Configurations 2 and 3

Addition of a control valve in the column overhead stream and the manipulation of condenser coolant prevent abrupt pressure drop at the top of the column (Figures 6c and 6d). Those actions also reduce the amplitude of variation of the sidestream flowrate (Figures 8c and 8d), and consequently reduce the amount of isobutane in the sidestream (Figures 7c and 7d).

Pressure control of Configuration 2 does not solve the problem of vapor distillate flowrate. According to Figure 6c, column pressure is stabilized, but as shown in Figure 9c, the liquid distillate flowrate is still proportional to the vapor feed flowrate. On the other hand, Configuration 3 also stabilizes the column pressure, but greatly reduces the flowrate oscillation of vapor distillate (Figure 9d).

In Configurations 1 and 2, the condenser coolant flowrate is kept constant while the condenser outlet temperature is free. Thus, when top flowrate decreases, the condenser outlet temperature decreases. However, temperature fluctuation is very low (less than 2 °C). In Configuration 3, the condenser coolant flowrate is manipulated so that when column pressure decreases, condenser coolant flowrate also decreases. When condenser coolant flowrate reaches very low values, the condenser outlet temperature increases significantly and modifies VLE, inducing the inverse behavior of vapor distillate flowrate.

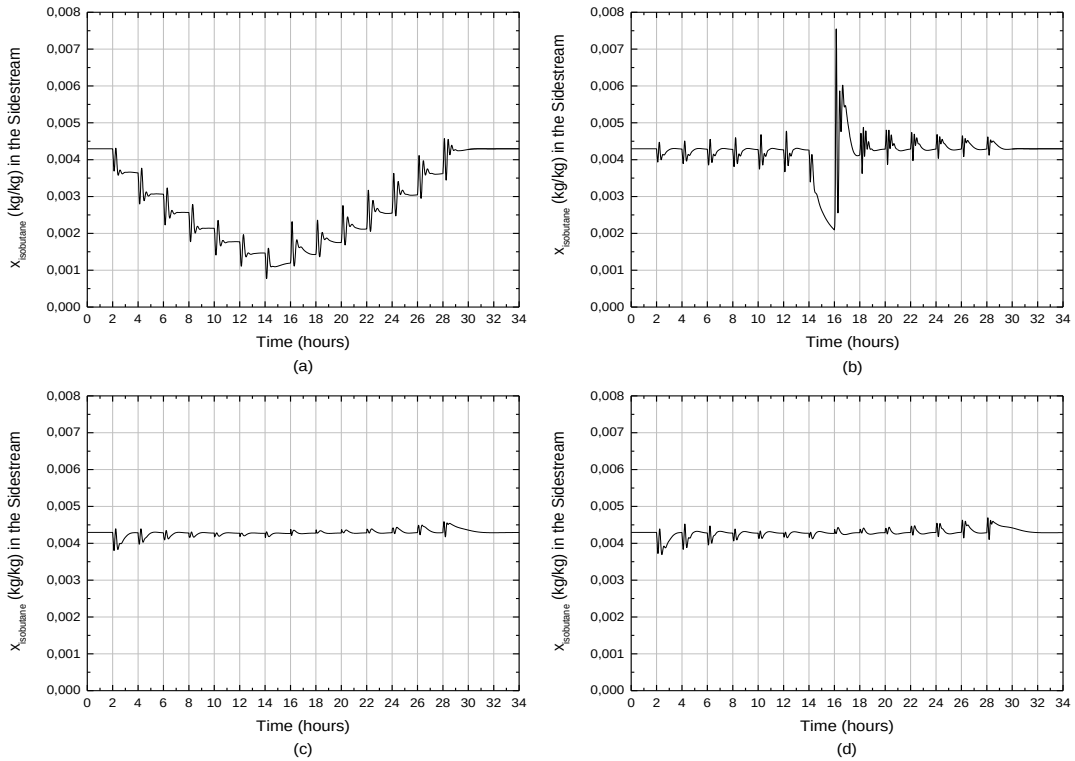

Fig 7: Dynamic response of $x_{isobutane}$ in the sidestream for changing in vapor feed flowrate - Open-loop pressure (a), Configuration 1 (b), Configuration 2 (c), Configuration 3 (d).

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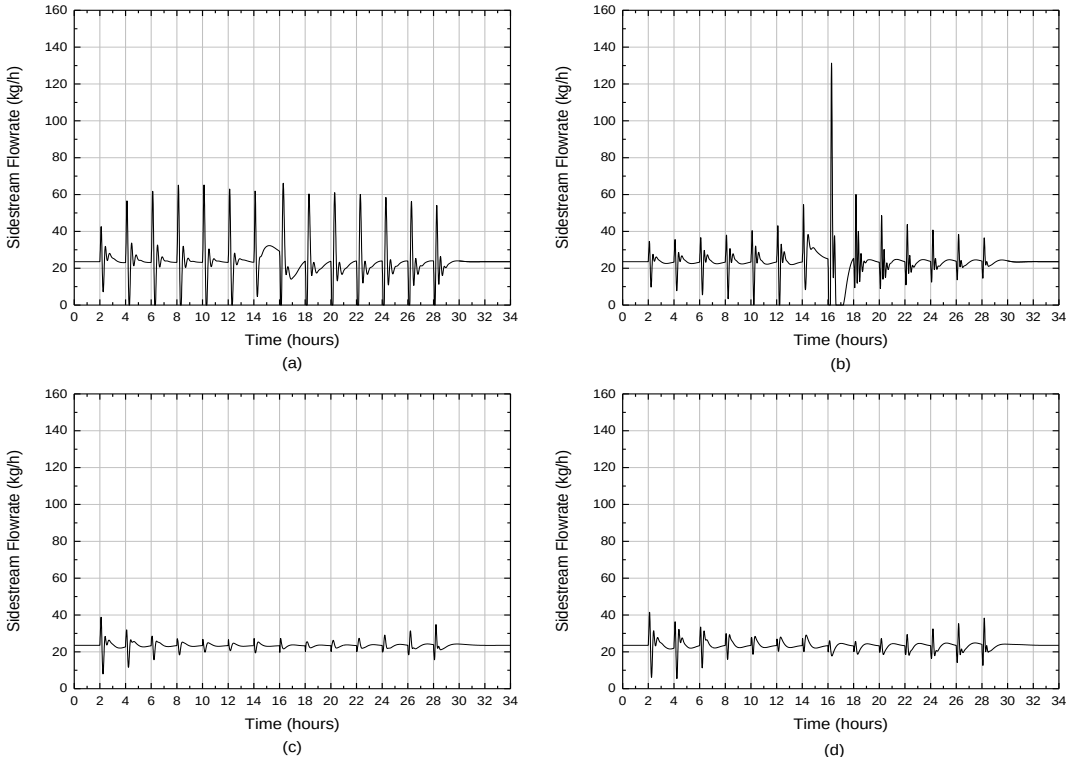

Fig 8: Dynamic response of the sidestream flowrate (stream 4) for changing in vapor feed flowrate - Open-loop pressure (a), Configuration 1 (b), Configuration 2 (c), Configuration 3 (d).

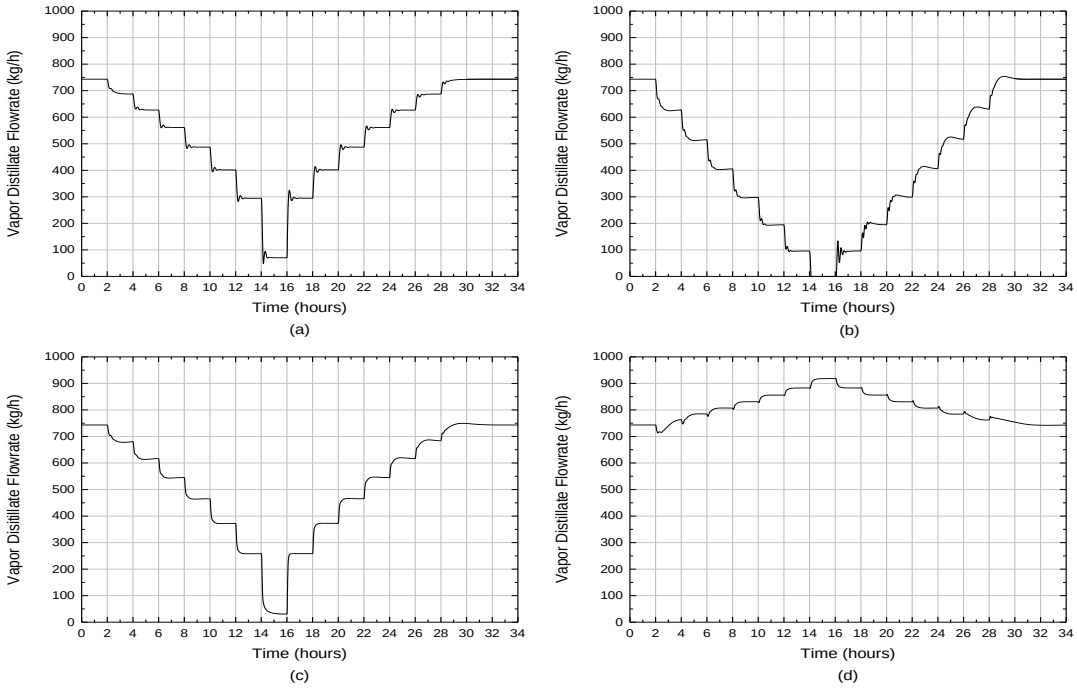

Fig 9: Dynamic response of the vapor distillate flowrate (stream 8) for changing in vapor feed flowrate - Open-loop pressure (a), Configuration 1 (b), Configuration 2 (c), Configuration 3 (d).

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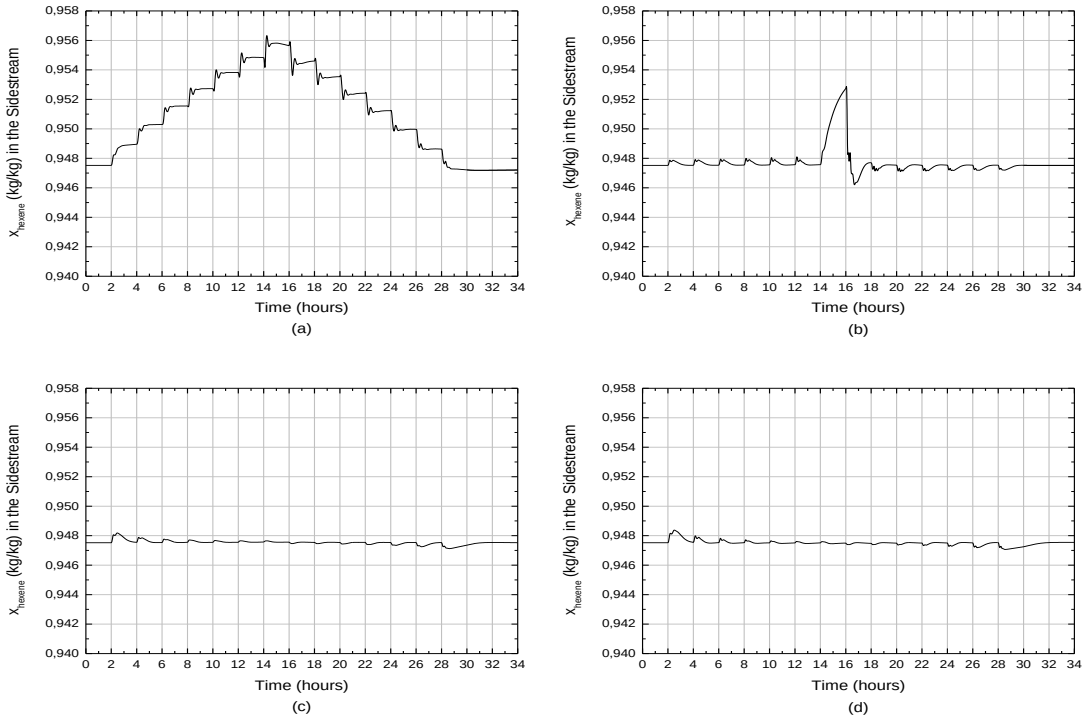

Fig 10: Dynamic response of x_{hexene} in the sidestream for variations in vapor feed flowrate - Open-loop pressure (a), Configuration 1 (b), Configuration 2 (c), Configuration 3 (d).

Hexene and isobutane compositions are in open loop and their responses are consequences of other controlled variables (pressure and temperature). Compositions are then indirectly controlled or controlled by inference, that is, if pressure and temperature are controlled, compositions are also controlled. Configurations 2 and 3 maintain hexene and isobutane compositions in the sidestream close to the desired values (Figures 11c, 11d, 10c, and 10d), obtained in steady state simulations.

4. CONCLUSIONS

Three pressure control configurations of a multicomponent sidestream distillation column were evaluated. The dynamic behavior of the column and the performance of the control system were evaluated for disturbance in the vapor feed flowrate, which is directly related to the column pressure. In Configurations 1, 2 and 3, the pressure is controlled by manipulating the column overhead flowrate, vapor distillate flowrate and condenser coolant flowrate, respectively. Results showed that Configurations 2 and 3 present a better performance compared to Configuration 1 for pressure control and, consequently, for all the other monitored variables. In Configuration 1, the column remains stable only up to the point at which vapor feed flowrate is not null. Configuration 2 controls column pressure, temperature and composition with the same performance of Configuration 3, but does not eliminate the variation of vapor distillate flowrate, representing disturbances to the next column of the unit. In terms of applicability, Configuration 2 adopts a simple method. However, varying the condenser feed flowrate may require a relatively large control valve, as well as an increased heat exchange area. But in this case, the column overhead flowrate is relatively low (5.3 t/h). The main disadvantage of Configuration 3 is that the condenser coolant flowrate can be high, which requires a very large control valve. Besides this problem, changes in coolant flowrate imply variations of flow, which can result in increased fouling. Despite these restrictions, Configuration 3 has the best control performance and causes the least disturbance to the next column of the unit. Eliminating the oscillation of vapor feed flowrate would be the definitive solution to the pressure problem of the studied column.

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