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The Quality Control of the Multi-Component Fractionation Processes

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Abstract

The fractionation processes are the most important processes in Romanian refineries. Usually, these processes are divided in two categories: the binary fractionation processes and the multi-component fractionation processes. The first category has two industrial applications: the ethane - ethylene splitter and the propane – propylene splitter. For these fractionation processes are used many composition control structures. For the second category there are not available the same composition control structures. In this paper the multi-component fractionation processes and the objectives of the specific composition control structures of these processes are studied. Based on this study, the authors had elaborated a specific composition control structure for the butane – butane fractionation process.

Key words: *multi-component process, fractionation column, composition, control*

Introduction

The quality control system has a major importance for industrial fractionation processes. The fractionation processes are divided into two categories: the binary fractionation processes and the multi-component fractionation processes. For the first category, there are developed many quality control systems [2, 3].

For the multi-component fractionation processes there are some quality control system [3, 4].
In these conditions, the authors have studied and developed a quality control system destined to butane-butene fractionation process.

The Structure of the Multi-Component Fractionation Process

The most common multi-component fractionating process is characterized by one feed stream, one distillated product and one bottom product, figure 1-a. The feed stream, distillated and bottom products contain the same components but in various concentrations. Usually, the column pressure is maintained at constant value and in this condition the process is characterized by the disturbance vector $\boldsymbol{P}^T = [F, \boldsymbol{X_F}]$, the output vector $\boldsymbol{Y}^T = [\boldsymbol{X}_D, \boldsymbol{X}_B]$ and the manipulated variables vector $\boldsymbol{U}^T = [u_1, u_2]$, figure 1,b.

For the fractionation process modeling the PRO/II program or UNISIM program can be used [5, 6].

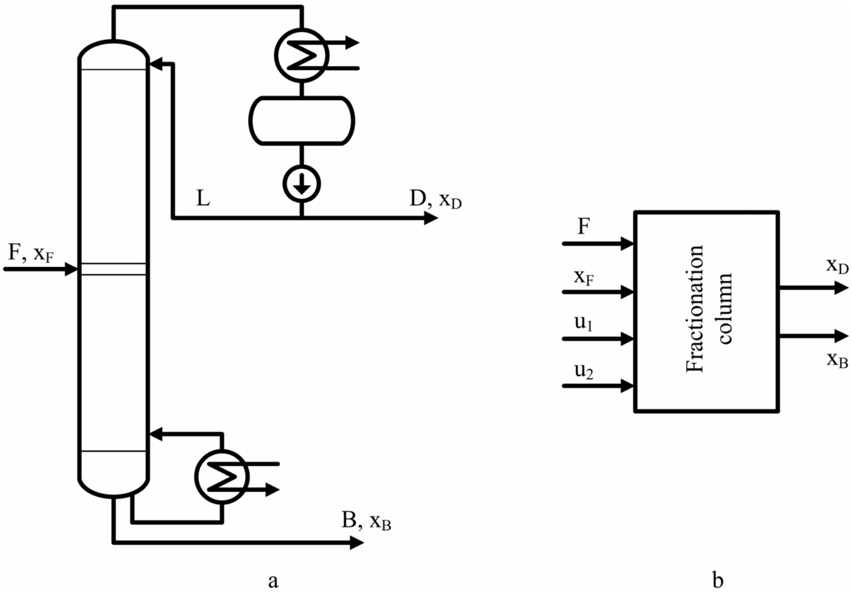

Fig. 1. The multi-component fractionation column:
a) the fractionation process; b) input-output structure of the fractionation process.

The studied process is the butane – butane fractionation process. The multi-component system is characterized by the chemical components presented in table 1.

Table 1. The chemical components
of the butane – butane fractionators process

No.	Component	Chemical formula
1	Propane	C_3
2	iso-butane	iC_4
3	iso+1 butene	$(i+1)C_4'$
4	normal butane	nC_4
5	cis 2 butene	$cis\text{-}2\text{-}C_4'$
6	trans 2 butene	$trans\text{-}2\text{-}C_4'$

The Objectives and the Specifications of the Multi-Component Fractionation Process

The objectives of the fractionation process are: the products quality, the yield and the financial benefit. These three quality components must be simultaneous assumed and must be implemented into a complex control system [3].

The authors consider that the quality specifications of the fractionation products may be classified into four classes:

a) hard specifications defined by fixed distillate composition and fixed bottom composition. In this case, the fractionation column will have only one operation point. This case is very rare.
b) upper hard - down soft specifications, defined by fixed distillate composition and a variable bottom composition domain. This case is used when the distillate composition is more important than the bottom composition.

c) upper soft – down hard specification, defined by fixed bottom composition and a variable distillate composition. In opposite to the upper soft specification, the down soft specification is applicable when the bottom product composition is more important than the distillate product composition.
d) upper soft – down soft specification, characterized by the variable distillate and bottom composition domain.

In the case of the multi-component fractionation, the specifications of product compositions are not formulated in terms of each chemical component concentration. Usually, the upper and down soft specifications are formulated in terms consisting in the maximization of the most important chemical component or the minimization of the impurity in the product.

A technical and economic problem consists in the measurement of the streams compositions (feed, distillate and bottom). The transducer used for the composition measurement is a process chromatograph. The financial effort to implement the composition transducers for each stream is substantial and for this reason the control systems based on process chromatographs are very rarely used.

Modeling of the Multi-Component Fractionation Process

For modeling the multi-component fractionation process, the authors used the UNISIM simulation program [6]. The Component List used into UNISIM program has the chemical components defined in table 1. The thermodynamic model selected from the Fluid Package section is the Peng-Robinson model, because between the chemical components there are no interactions. The UNISIM modeling specifications of the butane – butene fractionation process are presented in table 2.

Table 2. The UNISIM fractionation model specifications

Variable / value	
UNISIM model	**Mathematical model**
Stage 35	Feed
Ovhd Vapour Outlet	Distillate product flow rate
Bottoms Liquid Outlet	Bottom product flow rate
Reboiler Energy Stream	Reboiler steam flow rate
Stages	75
Condenser Pressure	980 kPa
Reboiler Pressure	1020 kPa
Optional Condenser Temperature Estimate	40 °C
Reflux Ratio	6
Distillate Rate	84.37 kmol/h
Btms Prod Rate	64.85 kmol/h

An aspect of the UNISIM modeling of the butane – butane fractionation process is illustrated in figure 2. The UNISIM model developed by the authors has been used in the simulation of the butane – butane column. For this simulation of the fractionation process industrial data for eight operating days has been used. The comparative results for the n-butane chemical component are presented in figure 3. The numerical results have validated the UNISIM model and this model will be used to simulate the process or the control system for the butane – butane fractionation process.

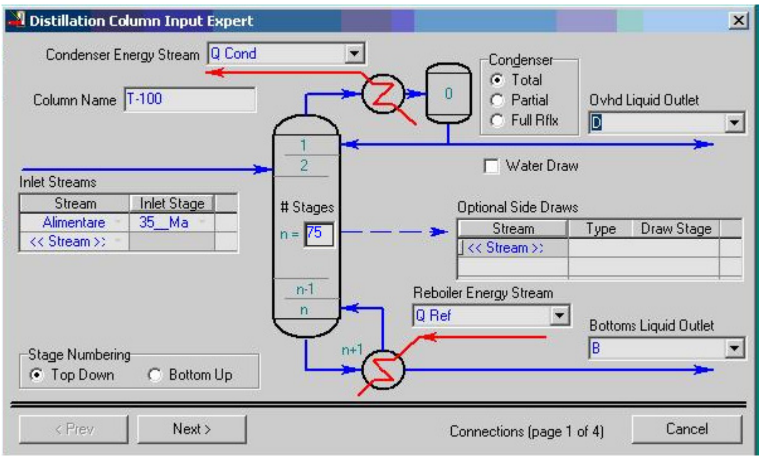

Fig. 2. The UNISIM modeling of the butane – butane fractionation process.

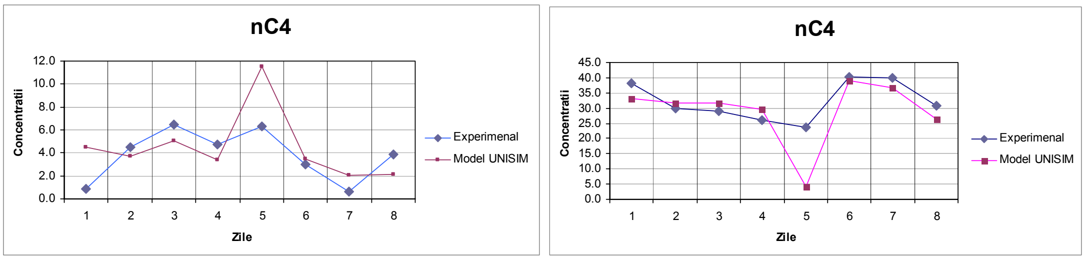

Fig. 3. The n-butane concentration: a) in distillate product; b) in bottom product.

The Composition Control System

The authors propose the following steps to elaborate the composition control system structure:

1. The process modeling
2. The simulation and the adaptation of the fractionation model
3. The design of the control system structure
4. The control algorithm
5. The simulation of the control system
6. The implementation of the proposed control system.

The first two steps have been studied in previous paragraphs.

The design of the control system structure

The design of the control system structure has two steps. First step is the analysis of the existing control system for the butane - butene fractionation column. The control system contains five mono-variable control systems: one pressure control system, two level control systems and two flow control systems, on manual, in order to control the distillate and bottom quality, figure 4. The column does not have process chromatograph for measure or control the products quality.

The role of the second step is to analyze the quality specifications. For the butane - butene fractionation process the quality specifications are included in the upper soft – down soft category, table 3. In these conditions, the first option to design the control system structure is an optimal quality control system. However, the complexity of the optimal quality control system and the absence of the process chromatograph lead to the development of other control system structure.

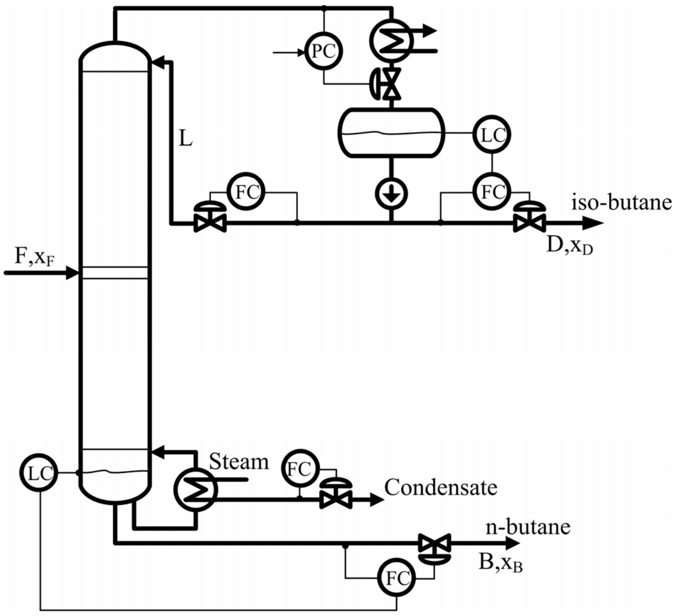

Fig. 4. The existing control system structure of the butane-butene fractionation column.

Table 3. The quality specifications for the distillate and bottom products [mole %]

Component	**Distillate product**		**Bottom product**	
	Industrial	**Hypothetic**	**Industrial**	**Hypothetic**
C_3	max 1	$x_{Dl} = 90.8$	max 0.2	$x_{Bl} = 2.2$
iC_4	min 86.8		max 1	
$(i+1)C_4'$	min 3		max 1	
nC_4	max 8.7	$x_{Dh} = 9.2$	min 39.3	$x_{Bh} = 97.8$
cis-2-C_4'	max 0.2		min 0.5	
trans-2-C_4'	max 0.3		min 58	

In this case, the authors have decided to elaborate a quality control system based on feed-forward control. The proposed control structure is presented in figure 5. The pseudo-binary components hypothesis has been used. The light pseudo-component is composed of propane, iso-butane and iso-butene. The heavy pseudo-component contains normal butane, cis and trans 2 butene.

The controller has two set points: the concentration of the light pseudo-component in distillate (x_{Dl}) and the concentration of the light pseudo-component in bottom product (x_{Bl}).

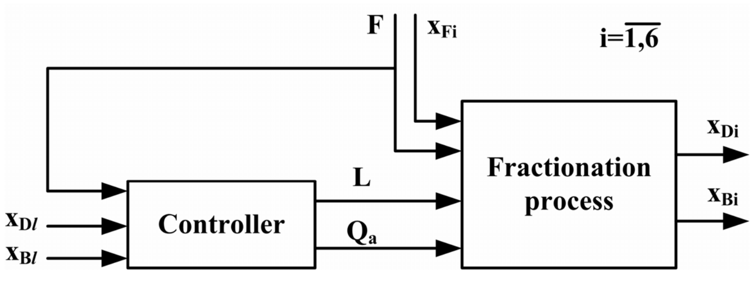

Fig. 5. The feed forward control system structure.

The control algorithm

The control algorithm is based on Fenske-Gilliland-Underwood model [1, 3]. The authors have adapted this mathematical model in order to be used in quality control. The proposed control algorithm has the following relations:

$$B = F\frac{x_D^i - x_F}{x_D^i - x_B^i}; \text{ [kmol/h]} \tag{1}$$

$$N_{min} = \frac{ln\left(\frac{x_D^i}{1-x_D^i} * \frac{1-x_B^i}{x_B^i}\right)}{ln\,\alpha}; \tag{2}$$

$$\theta = \frac{\alpha}{x_F(\alpha - 1) + 1}; \tag{3}$$

$$R_{min} = \frac{\alpha x_D^i}{\alpha - \theta} + \frac{1 - x_D^i}{1 - \theta} - 1; \tag{4}$$

$$A = \left(1 - 1.333 * \frac{N - N_{min}}{N + 1}\right)^{1.7587}; \tag{5}$$

$$R = \frac{A + R_{min}}{1 - A}; \tag{6}$$

$$L = R(F - B); \text{ [kmol/h]} \tag{7}$$

$$Q_a = r\,(L + F - B). \text{ [t/h]} \tag{8}$$

The variables of the control algorithm have the following meanings:

α - the relative volatility of the light pseudo-component;
θ - the Underwood parameter;
R_{min} – the minimal reflux ratio;
N – the theoretical equilibrium stages of the column;
N_{min} – the minimal equilibrium stages;
R – reflux ratio;
A – Eduljee parameter;
L – reflux flow rate;
i – control system set point marker;
Q_a – steam flow rate;
r – the ratio between the pseudo-component vaporization heat and the condensed steam heat [t/kmol].

The simulation of the control system

Using the control algorithm, the quality control system was simulated. The numerical results are comparable with the industrial data. The analysis led to the following conclusions:

a) Using the quality control system has been obtained a good concordance between the distillate concentrations from the simulation and the industrial concentrations, figure 6-a. With this observation we will validate the control algorithm and the quality control structure.

b) For the external light and heavy components a good correlation could not be obtained.
c) For the bottom concentrations, the results were good for the iso-butene, n-butane and for the external components, figure 6-b. These results confirm the control algorithm and the quality control structure.
d) The non-concordance between the concentration of some components is caused by the industrial data errors and the errors caused by the control algorithm adaptation.

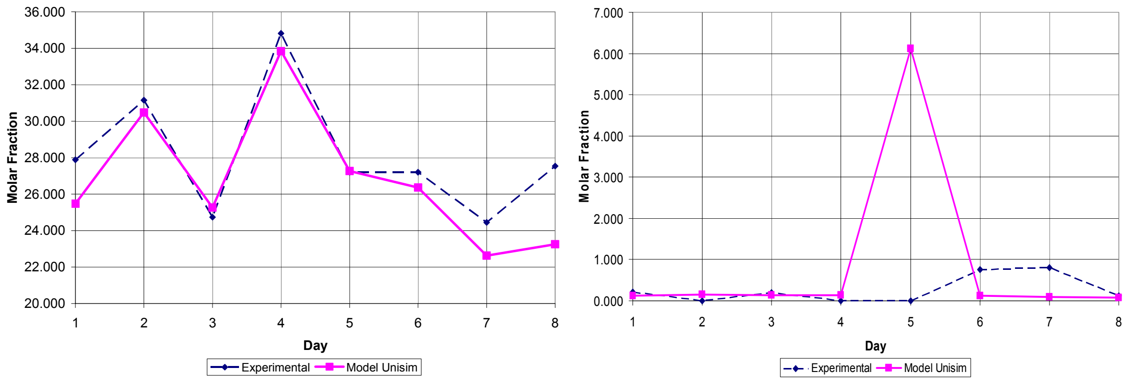

Fig. 6. The iso-butene concentration comparison between the results obtained using the control system and the industrial data: a) distillate product; b) bottom product.

The implementation of the proposed control system

Based on the industrial control structure and the proposed quality control structure, the authors have elaborated an industrial quality control structure, figure 7. The quality controller has as input the feed flow rate and computes the set points of the reflux and steam flow control systems.

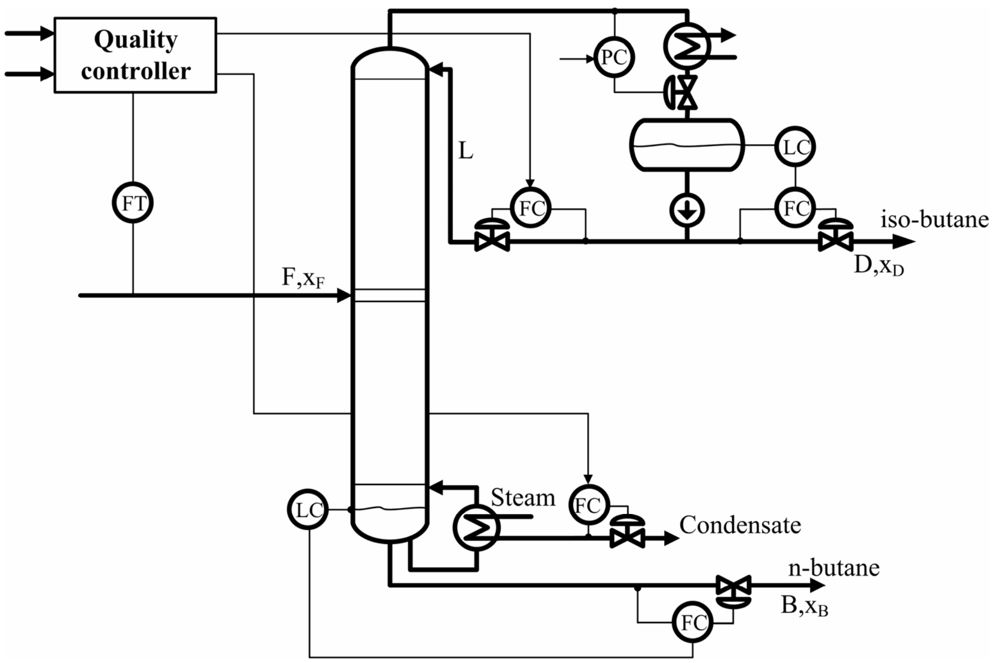

Fig. 7. The industrial quality control structure.

Conclusions

In this paper has been studied a multi-component fractionation process. The objectives and the quality control specifications have been defined for this process. The quality control system for the butane-butene fractionation process has been investigated. The quality control structure and the control algorithm have been elaborated. The proposed quality control system has been validated by the comparison of the industrial products concentrations and the concentrations obtained by numerical simulation of the quality control system.

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Reglarea calității produselor pentru procesele de fracționare multicomponent

Rezumat

Procesele de fracționare sunt unele dintre cele mai importante procese din rafinăriile româneşti. În general, aceste procese sunt împărțite în două categorii: procese de fracționare binară şi procese de fracționare multicomponent. Pentru procesele din a doua categorie nu sunt disponibile aceleaşi structuri de reglare ca pentru procesele de fracționare din prima categorie. Autorii au studiat unele procese de fracționare multicomponent şi obiectivele asociate structurilor de reglare a compozițiilor pentru aceste procese. Pe baza acestui studiu, a fost elaborată o structură de reglare a calității produselor separate, specifică pentru procesul de separare butan-butene.