BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LX No. 3B/2008	87 - 96	Seria Tehnică

Researches Regarding the Control of a Gas Separation Unit

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Abstract

This paper tries to present some researches regarding the control structures from a distillation unit. To be more precise, a gas separation unit with three fractionation columns is analyzed. The columns are simulated and the best configuration is chosen for each column based on commands sensitivity, disturbances sensitivity and also based on the values from the steady-state relative gain array. The simulation of the columns is made using PRO/II® environment, which is a rigorous simulator for steady-state process simulation.

Key words: *fractionation columns, process control, control structures, simulation*.

Introduction

Distillation units are an important part of most chemical processing plants.

The distillation unit studied in this paper takes part of a catalytic cracking complex and has as purpose gas fractionation and obtainment of pure components or components mixtures which must satisfy certain quality conditions. The simplified scheme of the gas separation unit is presented in fig. 1.

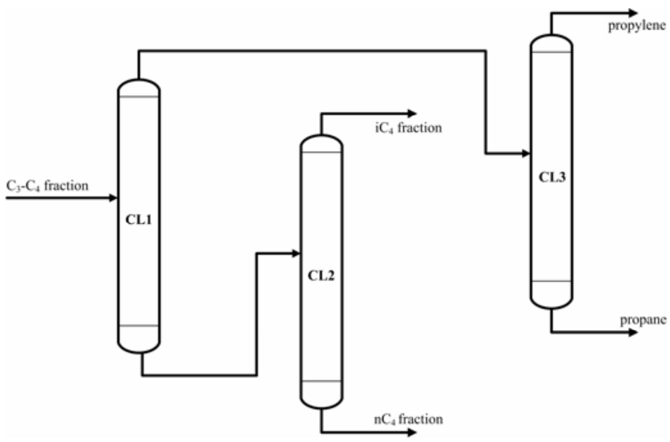

Fig. 1. Gas separation system

The feed for the first column (as well as for the entire distillation unit) is the $C_3 - C_4$ fraction. From this column, the top product, consisting specially of propane and propylene, is condensed and sent to a drying column (not represented here) and then to $C_3 - C_3^{'}$ separation column (CL3). The bottom product of the CL1 column represents the feed of the butane-butene separation column (CL2).

The depropanizer (CL1), which has 30 real trays, with 20 as the feed tray, makes the split between C_3 and C_4 hydrocarbons.

The $C_4 - C_4^{'}$ separation column (CL2) has 100 real trays, with the feed tray 35, 43 or 51, depending on feed composition. The column feed contains: propane, iso-butane, iso and 1-butene, n-butane, cis- and trans-butene. The top product consists mostly of iso-butane, iso and 1-butene. The bottom product contains n-butane, cis- and trans-butene.

The $C_3 - C_3^{'}$ separation column (CL3) has 90 real trays, with the feed tray 15, 19 or 23, depending on feed composition. The overhead product is propylene and the bottom product is propane.

In order to control the distillation unit a control structure for each column has to be chosen.

The selection of an appropriate control configuration (structure) is the most important decision when designing control systems.

For a typical distillation column there are available five control agents, namely: the flowrate of the reboiler thermal agent Q_r, reflux flowrate L, distillate flowrate D, bottom product flowrate B and the flowrate of the condenser cooling agent Q_c. Results from here that there can be controlled with these five variables: distillate composition x_D, bottom product composition x_B, column pressure P, reflux drum level H_{rd} and column bottom level H_B.

Such columns can be seen, from control point of view, as a 5×5 system. Associated controller would modify five inputs to control the five outputs. In practice, few columns use a 5×5 controller. Instead a decentralized system with single-loop controllers is used. This kind of system is much easier to understand and retune, is more failure tolerant and is less sensitive to plant operation [6].

It is presumed that for stabilizing the column the inventory control loops are closed. What remains is a 2×2 composition control problem, with the remaining control agents determining the control configuration or structure.

The standard configurations introduced by Shinskey [4], include the flowrates L, D, B, V and their ratios. Using these control agents has the advantage that the structures are easy to implement and understand by operators. Usual combinations with L and D are used for top of the column, and the combinations with V and B are used for column bottom. The most implemented structures are the LV, DV, LB types and the ratio structures SV/B, DV/B, SV etc. [3, 5].

The LV structure (fig. 2) uses for composition control the reflux flowrate and respectively the reboiler vapor flowrate. This configuration is almost independent regarding the level control and is most suitable for one-point control. The LB and DV structures (fig. 3 and fig. 4) are called material balance structures because a product flowrate (B respectively D) is used as command in order to control one of the compositions, the other composition being controlled using an internal flowrate (L respectively V). The SV/B structure (fig. 5) is applicable to a relatively large class of columns. It presents the advantage of a fast dynamic response of the bottom composition control loop and a pretty small bigger than 1 relative gain array value.

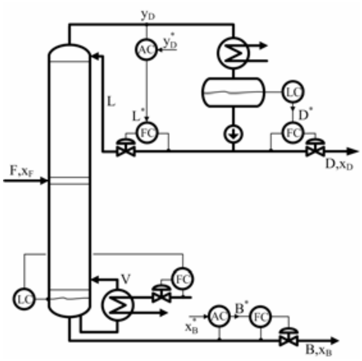

Fig. 2. *LV* structure

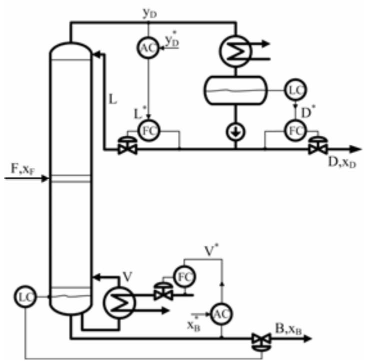

Fig. 3. *LB* structure

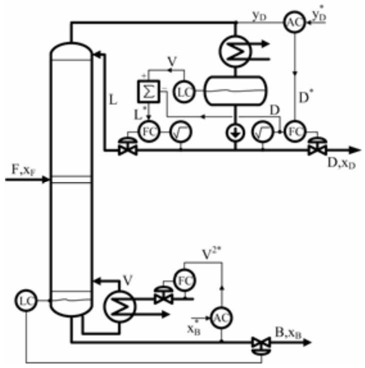

Fig. 4. *DV* structure

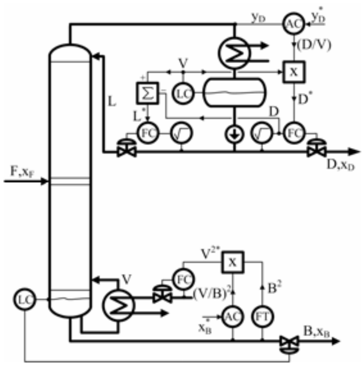

Fig. 5. *SV* / *B* structure

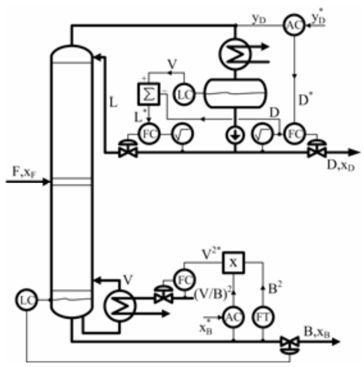

Fig. 6. *DV* / *B* structure

The DV/B structure (fig. 6) uses for bottom composition control the ratio V/B in a way similarly with the one from SV/B configuration, and for overhead composition control uses directly the command D.

PRO/II® Simulation Environment

The PRO/II® environment is a product which integrates powerful routines and properties databases, computing methods and mathematical models to treat with high accuracy, in steady state, the problem of material and energy balances for large categories of chemical industry processes. Using the graphical interface PROVISION® it offers an interactive environment for building and simulating systems from the simplest ones to high complexity systems [1].

From the large number of processes modeled in PRO/II® here are presented only a few [2]: gas processing (deethanizer, cascade refrigeration, compressor train, gas dehydration etc.); refining processes (crude oil distillation, gas fractionation, naphtha stabilizer, sour water stripping etc.); petrochemical processes (ethylene fractionation, C_3 and aromatics separation etc.); extractive and azeotropic distillation, phenol fractionation; pharmaceutical industry processes.

The resources of the PRO/II® environment can be categorized as follows: “operational” mathematical models (hydraulic systems, distillation, heat exchangers, reactors, auxiliary devices – decanters, centrifuges, filters etc.); auxiliary mathematical models (mono and multivariable feedback/feedforward control structures, optimization etc.); physical and chemical properties databases (pure components and mixtures, data validation and regression etc.); the graphical interface with capabilities to import primary data and export the results; high interactivity; open system characteristic, which allows adding complementary modules.

Simulation stages of a process include:

- choosing a measurement system;
- process definition: placing process devices (distillation columns, pumps, compressors etc.) and input, output and intermediary streams;
- components definition (choosing components from a database);
- selection of thermodynamic methods;
- parameter definition (flowrate, composition, temperature, pressure) for existing streams;
- customizing the mathematical models of some elements;
- run the simulation.

The PRO/II® environment is a complex, rigorous simulator for processes from chemical and petrochemical industry. It includes: mathematical models for a large variety of processes and devices, methods and algorithms for simulation, physical properties of the components.

Results

Determining the optimal control structure for a fractionation column needs a study which has to present the column response to changes in control agents and disturbances. This sensitivity analysis can be made through dynamic and steady state process simulation. Although the dynamic response provides more information than the steady state one, the latter is sometimes enough to estimate the column response to commands and disturbances action.

A quantitative criterion can be also formulated to reflect this sensitivity. Thus, the sensitivity or steady state gain is defined as

$$S = \frac{\Delta y_j}{\Delta u_i},\ j = \overline{1,n}, \tag{1}$$

for $u_d = \text{constant}$ $(d \neq i)$; $i, d = \overline{1,m}$, where: Δy is the output variation; Δu - the input (command or disturbance) variation; n - number of outputs; m - number of inputs.

In the next part will be analyzed the (steady state) behavior of the three columns from the gas separation system, for different control structures (the ones presented in the Introduction section), to changes in available commands and disturbances. The sensitivity analysis to commands and disturbances was made by modifying the commands for every control structure and the disturbances (F and x_F) and recording the outputs evolutions in each of these cases.

The results obtained for the **propylene-propane separation column** are presented next.

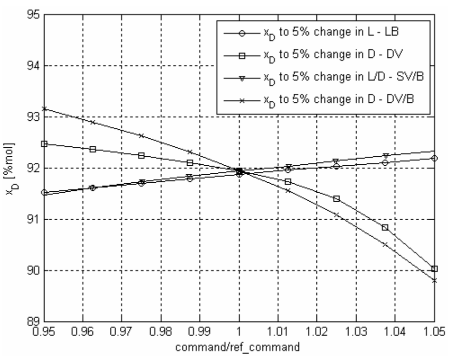

Fig. 7. x_D evol. to changes in the 1st command

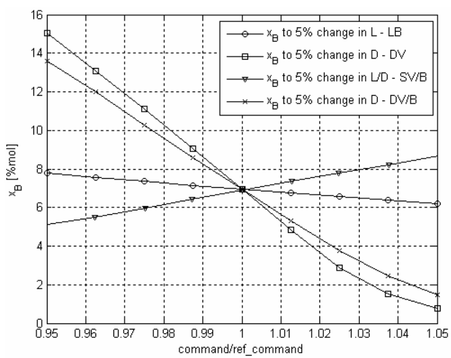

Fig. 8. x_B evol. to changes in the 1st command

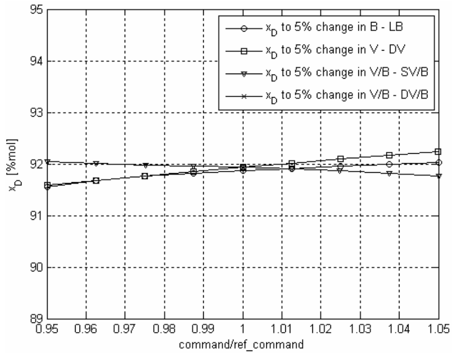

Fig. 9. x_D evol. to changes in the 2nd comman.

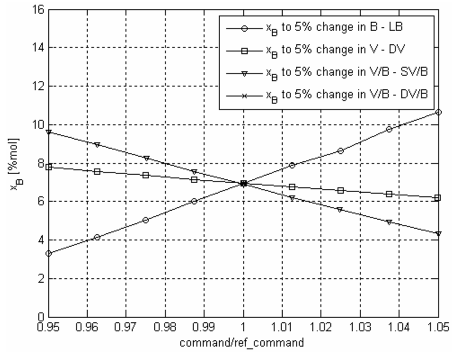

Fig. 10. x_B evol. to changes in the 2nd command

Table 1. Outputs sensitivities to commands

Commands	x_D	x_B	Structure
L	0.088	-0.2093	LB
B	0.06267	0.98	
L	15.487 1.2133	0.2311 22.133	LV
V	-1.1332 -15.825	-22.538 -0.2044	
D	-0.1883 -0.7302	-1.8975	DV
V	0.08667	-0.2067	
S (L/D)	0.114	0.4731	SV/B
V/B	-0.03731	-0.7036	
D	-0.4477	-1.6137	DV/B
V/B	0.08662	-0.2065	

In fig. 7 – fig. 10 are presented the evolutions of the two compositions (x_D and x_B) to changes in the two commands of each control structure. The numeric values of the sensitivities to commands are presented in table 1.

Next, the sensitivity to disturbances in the case of $C_3 - C_3^{'}$ column is presented.

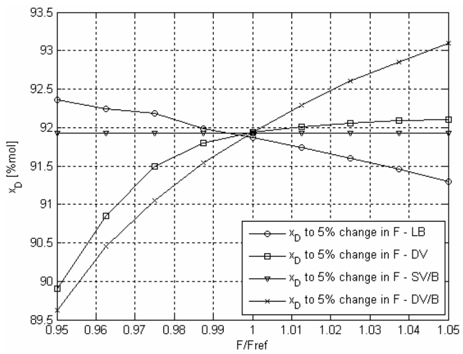

Fig. 11. x_D evolution to changes in F

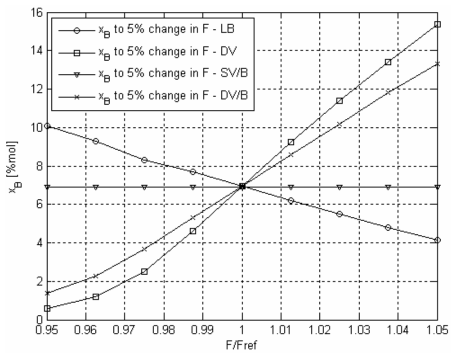

Fig. 12. x_B evolution to changes in F

In the fig. 11, fig. 12 are presented the evolutions of the two compositions (x_D and x_B) to changes in the disturbance F for each control structure. The numeric values of the sensitivities to both disturbances are presented in table 2.

Table 2. Outputs sensitivities to disturbances

Disturbance / Structure	F		x_F	
LB	-0.1585	-0.8849	0.4910	2.2328
LV	0.0933	1.8549	0.3694	1.7575
DV	0.7591 0.07165	2.2123	0.4821	2.0657
SV/B	0	0	0.4851	2.0552
DV/B	0.5202	1.7818	0.4836	2.0672
	x_D	x_B	x_D	x_B

The **butane-butene separation column** has more than two components and for simulation (and simplicity) purposes it was treated like a pseudo-binary column. Thus, it was considered that there are two products separating, one at the top, a pseudo-light product (consisting of propane, iso-butane and i+1-butene), and one at the bottom, a pseudo-heavy product (consisting of n-butane, cis- and trans-butene). For simplicity, the compositions of these two products were denoted also by x_D and x_B. The results obtained for this column are presented next.

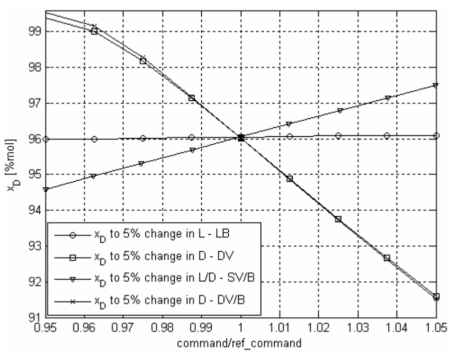

Fig. 13. x_D evol. to changes in the 1st command

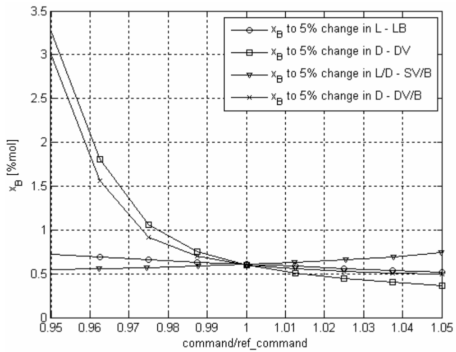

Fig. 14. x_B evol. to changes in the 1st command

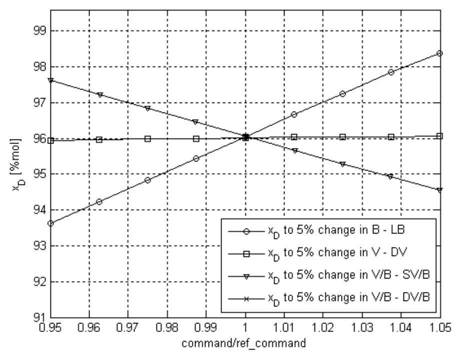

Fig. 15. x_D evol. to changes in the 1st command

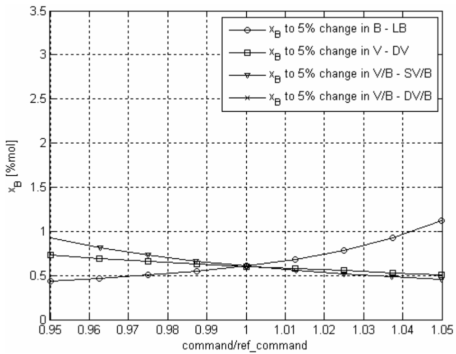

Fig. 16. x_B evol. to changes in the 1st command

In fig. 13 – fig. 16 are presented the evolutions of the two compositions (x_D and x_B) to changes in the two commands of each control structure. The numeric values of the sensitivities to commands are presented in table 3.

Table 3. Outputs sensitivities to commands

Commands	x_D	x_B	Structure
L	0.01333	-0.02667	LB
B	0.6365	0.09074	
L	6.1418 0.08534	0.1493 11.312	LV
V	-0.07823 -6.7158	-12.593 -0.1547	
D	-1.0409	-0.8921 -0.08316	DV
V	0.016	-0.02933	
S (L/D)	0.3867	0.02533	SV/B
V/B	-0.408	-0.06267	
D	-1.0702	-0.8174 -0.04265	DV/B
V/B	0.01467	-0.02933	

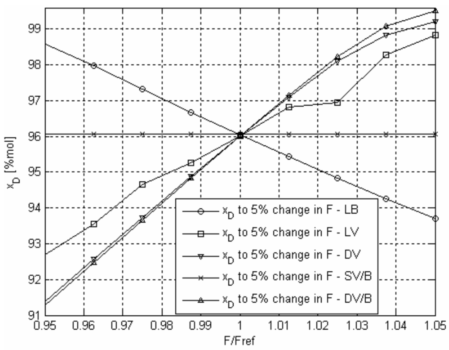

Fig. 17. x_D evolution to changes in F

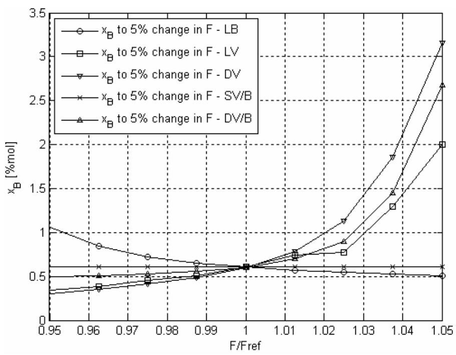

Fig. 18. x_B evolution to changes in F

Table 4. Outputs sensitivities to disturbances

Structure \ Disturbance	F		x_F	
LB	-0.78	-0.08791	1.2859	0.1429 1.4459
LV	0.9815	0.09164 0.7864	0.9249	0.1645
DV	1.2515	0.1228 1.014	1.2891	0.09207 1.0809
SV/B	0	0	1.27	0.09207 1.0766
DV/B	1.3139	0.08525 1.138	1.2891	0.08951 1.0851
	x_D	x_B	x_D	x_B

In the fig. 17, fig. 18 are presented the evolutions of the two compositions (x_D and x_B) to changes in the disturbance F for each control structure. The numeric values of the sensitivities to both disturbances are presented in table 4.

Choosing the Best Control Structures

The sensitivity analysis and the RGA associated with the studied separation columns show how the compositions are influenced to changes of the commands and the disturbances.

Thus, after analyzing the $C_3 - C_3^{'}$ separation column the following remarks can be drawn:

- the internal flowrates L şi V have a small influence on the compositions in cases when the control structure has as command one of these flowrates. In the case of LV structure both flowrates have big influence on the compositions;
- changes of external flowrates D and B are felt pretty strong in the compositions evolution (structures LB, DV, DV/B);
- the structures which contains flowrate D are highly coupled;
- in case of ratio structures (SV/B and DV/B) both commands have an important influence on compositions;
- the SV/B structure rejects the effects of the disturbance F.

Taking into account these remarks, the values of the commands and disturbances sensitivities, and the relative gain array values given in table 5, it can be stated that the SV/B control structure is the right choice for the propylene-propane separation column.

Analyzes of the butane-butene separation column has led to the following remarks:

- pseudo-light product compositions variation, both on top and bottom, is pretty small when the internal flowrates are changing (in cases when the control structure has as command one of these flowrates) and quite significant in case of LV structure;
- changes of external flowrates D and B produce important variations in the compositions evolution (structures LB, DV, DV/B);
- as in the case of $C_3 - C_3^{'}$ separation column the effect of feed flowrate disturbance is compensated in the case of SV/B structure.

Having as criteria the selection of the commands with the greater sensitivity, the disturbance sensitivity, but also the relative gain array values from table 5, it can be observed that the DV/B structure is suitable for $C_4 - C_4^{'}$ separation column.

Table 5 presents the relative gain array values for the analyzed control structures associated to the $C_3 - C_3^{'}$ and $C_4 - C_4^{'}$ separation columns.

Table 5. RGA values

Λ / Col.	Λ_{LD}	Λ_{LV}	Λ_{DV}	$\Lambda_{SV/B}$	$\Lambda_{DV/B}$
CL2	0.0610	34.3262	0.9407	1.4640	0.9741
CL3	0.1997	38.0637	0.8046	1.0529	0.9818

The $C_3 - C_4$ column is not a terminal one (as in the case of the other two) and the selection of the control structure is based on different criteria.

Thus, for the CL1 column the LV control structure is chosen, a modified version with the bottom composition control being done through a temperature control system which operates on vapor flowrate (fig 19).

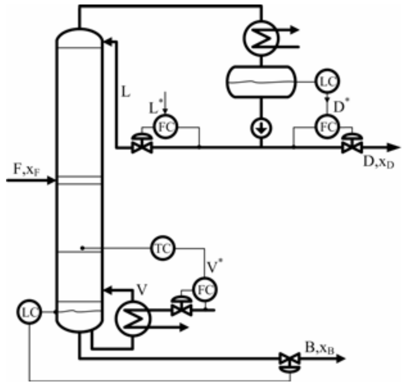

Fig. 19. LV structure – temperature control version

In table 6 is presented the evolution of the 20th tray temperature (significant tray) to vapor flowrate modification.

Table 6. Evolution of the 20th tray temperature to a ±5% change in V .

V[kmol/h]	1444.95	1463.96	1482.98	1501.99	1521	1540.01	1559.02	1578.04	1597.05
T_{20} [°C]	81	84.5	88.6	93.1	96.1	96.5	96.8	97	97.3

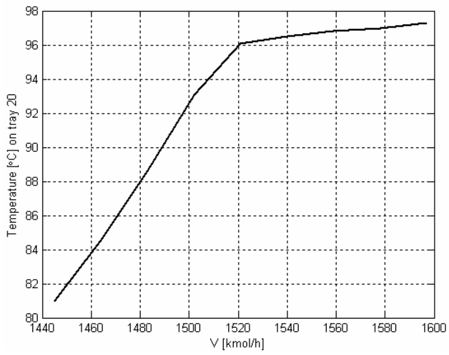

Fig. 20. Evolution of the 20th tray temperature to a ±5% change in V

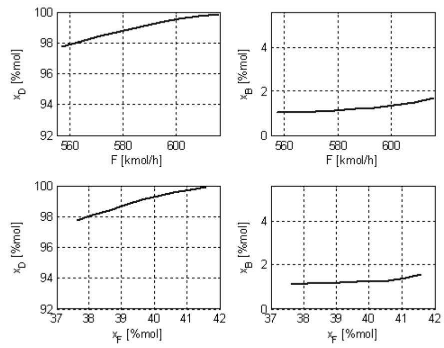

Fig. 21. x_D and x_B evolution to disturbances changes (LV structure)

It can be seen that the column operating domain has two sections, the column having different sensitivity on those sections. On the first section the sensitivity is good, while on the second section the column is less sensitive.

The ratio of the two sensitivities shows that the column is more than 10 times sensitive on the first section in comparison with the second. On large vapor loads the sensitivity diminishes and the temperature control and the composition control is questionable.

Another criterion which can impose the LV structure is the disturbance sensitivity showed in fig. 21.

Conclusions

The paper's primary goal was to present the analyses on the gas separation unit from a catalytic cracking plant. This unit consists of three columns: $C_3 - C_4$ fraction separation column, butane-butene separation column and propylene-propane separation column. For each of these columns the sensitivity to commands and disturbances was analyzed, for different control structures associated to every column. This analysis was made by simulation using the PRO/II® simulation environment, which is a powerful and rigorous simulator. Also, the steady state relative gain array was computed for the control structures associated to columns which separates $C_3 - C_3^{'}$ and $C_4 - C_4^{'}$ fractions. The analyses had as result the selection of control configurations for each of the three columns from the separation unit. Thus, for the propylene-propane separation column the SV / B structure was chosen, for the butane-butene separation column the DV / B structure was chosen and for the $C_3 - C_4$ separation column was chosen the LV structure, a modified version with the bottom composition control being done through a temperature control system which operates on vapor flowrate.

The analysis which it was done was a steady state analysis. This is not always enough to comprise process behavior. Future work should include a dynamic analysis as well.

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Cercetări privind conducerea unei instalaţii de fracţionare a gazelor

Rezumat

Prezenta lucrare prezintă câteva rezultate ale unor cercetări privind structurile de reglare pentru coloanele dintr-o instalaţie de fracţionare. Mai precis, este analizată o instalaţie cu trei coloane de fracţionare. Coloanele sunt simulate şi este aleasă cea mai bună configuraţie de reglare pe baza sensibilităţii la comenzi, la perturbaţii şi de asemenea pe baza valorile matricei amplificărilor relative în regim staţionar. Simularea celor trei coloane a fost realizată în mediul de simulare PRO/II®, care este un simulator riguros pentru simularea proceselor în regim staţionar.