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Hierarchical Control of a Depropanizer Column

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Abstract

The paper presents the design of a hierarchical control system for a depropanizer column. The hierarchical system has two levels: conventional control level and optimal control level. At the second level, a two-dimensional objective function is proposed. The optimization problem solving, which involved determining the optimal variables which maximize the objective function, was done in MATLAB®. The hierarchical control system with two levels was simulated in SIMULINK®, and the results confirmed that the application of the optimal variables determined at the second hierarchical level leads to an improvement in separation, which is the main objective of the depropanizer column.

Key words: *hierarchical control, optimization, distillation column, simulation*

Introduction

Distillation columns are very high energy consumers. A continuous focus was made in the development of control structures and column designs that optimize the energy consumption. If the designs methods generated the reactive distillation columns [2, 3, 6] or wall divided columns [5, 11, 16], the proposed control structures use the optimal consumption with nonlinear techniques that proved to be more suited for the distillation process. The Model Predictive Control (MPC) was a one of the most used technology in industrial field. Recent studies on MPC focus on faster MPC algorithm with simpler structure more suitable for industry [8, 15]. Another direction is represented by artificial intelligence used in distillation control with fuzzy control, neuro-fuzzy control and genetic algorithms [1, 9, 12]. All the mentioned optimization problems usually generate memory use problems when configured on programmable logic controllers (PLCs) or distributed control systems (DCSs). Less powerful PLCs and DCSs are still omnipresent in process plants due to robustness, industry-proven reliability, and long-term support.

The proposed method in this paper is simple and robust and can be implemented on DCSs or PLCs. The paper presents a hierarchical control for a depropanizer column and covers all the issues from designing the optimal control to the simulated results. The results are interpreted and the proposed structure is analyzed.

Depropanizer Column

A depropanizer column can be part of a gas processing unit from a catalytic cracking complex in a refinery, having as purpose the separation of C_3-C_4 fraction. The overhead product of the column represents the feed of a propylene-propane separation column (COL 2) and the bottom product is the feed for a butylene-butane separation column (COL 3).

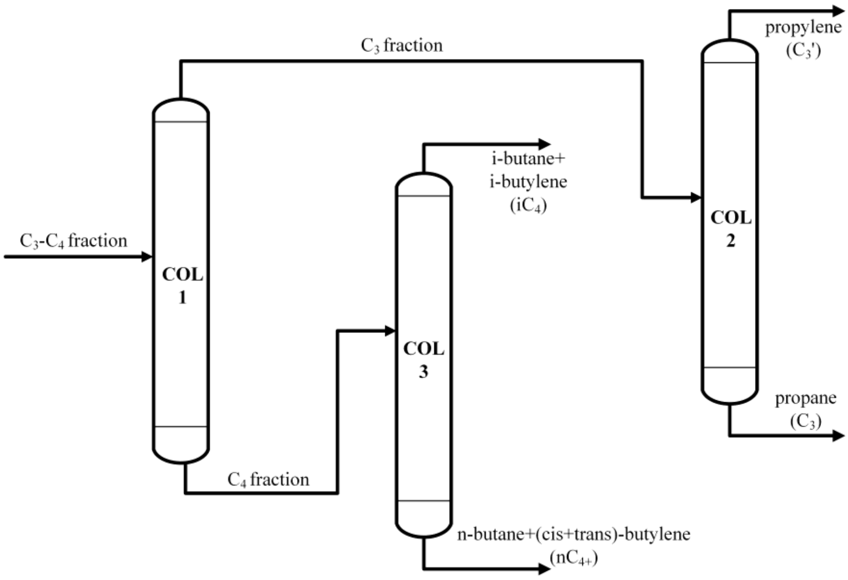

Fig. 1. Gas processing unit.

According to [10], for the C_3-C_4 separation column (COL 1) was determined the *LV* control structure (fig. 2). This implies that the top composition is controlled using the reflux flowrate *L* and the bottom composition is controlled using the boilup flowrate *V*. The other parameters that are supposed to be controlled are: column top pressure with the cooling agent from the condenser, reflux drum level with distillate flowrate, and column bottom level with bottom product flowrate.

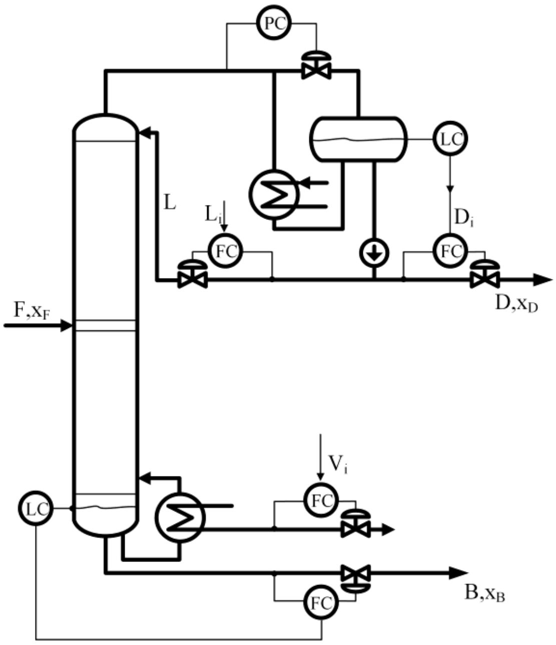

Fig. 2. LV control structure.

The column was analyzed by simulation in SIMULINK®, using a nonlinear mathematical model [13, 14], the initial data for simulation being presented in table 1. Although is a multicomponent column, for its simulation it was considered a pseudo-binary one with two products: a pseudo-light product consisting of propylene and propane (*C_3* fraction) and a pseudo-heavy product composed of i-butane, i-butylene, n-butane, (cis- and trans)-butylene (*C_4* fraction).

Table 1. Synthetic data for simulation of COL1.

Parameter	**Value**
NT	31
NF	17
F [kmole/min]	8.63
xF [mole fr.]	0.4975
qF	1
L [kmole/min]	12.15
V [kmole/min]	16.44
M0_i [kmole]	1
M0_1 [kmole]	37.8
M0_NT [kmole]	85.4
α	1.873

The meanings of the parameters from table 1 are:
- *NT* – number of theoretical stages;
- *NF* – location of feed stage;
- *F* – feed flowrate;
- *xF* – feed composition;
- *qF* – feed liquid fraction;
- *L* – reflux flowrate;
- *V* – boilup flowrate;
- *M0_i* - nominal stage holdups;
- *M0_1* - nominal reboiler holdup;
- *M0_NT* – nominal condenser holdup;
- α – relative volatility.

Optimal Control System Design and Simulation Results

Because the separation at the C_3-C_4 distillation column has to be very high the control system from figure 3 is proposed. This control system is a hierarchical one with two levels: conventional control level (represented by the *LV* control structure) and optimal control level.

At the optimal control level is implemented a two-dimensional objective function which signifies a (theoretical) profit obtained from the expected sale of the products from the final columns (COL 2 and COL 3 which separate the C_3 and C_4 fractions), minus expenses associated with utilities (in this case, steam) from the C_3-C_4 separation column. This objective function has the following form:

$$\begin{aligned} F_{ob}(L,V) = (price_{propylene} \cdot x_{D\_propylene} + price_{propane} \cdot x_{D\_propane}) \cdot D \cdot MM_D + \\ + (price_{iC_4} \cdot x_{B\_iC_4} + price_{nC_4} \cdot x_{B\_nC_4}) \cdot B \cdot MM_B - price_{steam} \cdot r \cdot V \end{aligned} \quad (1)$$

The constraints of the objective function are of simple margins type for variables *L* and *V*.

The meanings of the notations used in equation (1) are:
- $price_{propylene}$ - selling price of propylene from the top of the COL 2 column [lei/t];
- $price_{propane}$ - selling price of propane from the bottom of the COL 2 column [lei/t];
- $price_{iC4}$ - selling price of i-butane – i-butylene mixture the top of the COL 3 column [lei/t];
- $price_{nC4}$ - selling price of n-butane – (cis + trans)-butylene mixture separated at the bottom of the COL3 column [lei/t];
- $price_{steam}$ - price of steam [lei/t];
- $x_{D\_propylene}$ - concentration of propylene in the propylene-propane mixture separated at the top of COL 1 column;

- $x_{D\_propane}$ - concentration of propane in the propylene-propane mixture separated at the top of COL 1 column;
- x_{B_iC4} - concentration of i-butane – i-butylene mixture in the C_4 fraction from the bottom of COL 1 column;
- x_{B_nC4} - concentration of n-butane – (cis + trans)-butylene mixture in the C_4 fraction from the bottom of COL 1 column;
- MM_D - molar mass of propylene-propane mixture [kg/kmole];
- MM_B - molar mass of C_4 fraction [kg/kmole];
- D - COL 1 distillate flowrate, $D = V – L$ [kmole/min];
- B - COL 1 bottom product flowrate, $B = F – D = F + L – V$ [kmole/min];
- r - ratio between the latent heat of vaporization of the mixture from the bottom of the COL 1 column and the latent heat of condensation of the steam [kg/kmole].

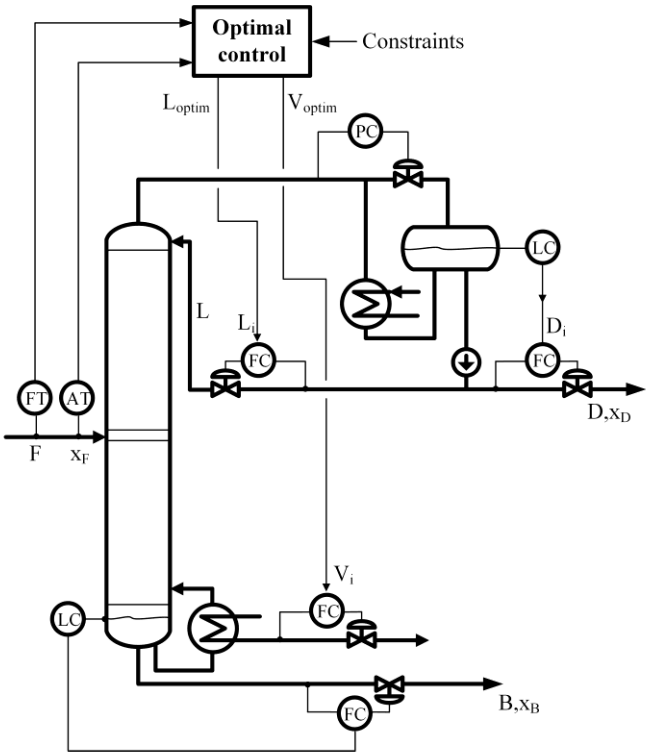

Fig. 3. Structure of the hierarchical control system for COL 1.

The optimization problem solving, which involved determining the optimal references for L and V which maximize the objective function, was done in MATLAB® and comprises the following steps:

- building a MATLAB function with the process model;
- development of a MATLAB function with the calculation of the objective function;
- writing a script for the optimization problem solving.

Because the variables of the objective function are L and V, the function with the process model has the form $[x_D, x_B] = f(L, V)$. In order to write this function, the relations of Douglas-Jaferey-McAvoy model [7] were used. This mathematical model, applicable to binary columns, is based on an approximation relation of analytical solution of Smoker [4]. He deduced a general calculation relation of the number of stages, considering constant the relative volatility and molar flows in the two sections of a column. Douglas, Jafarey and McAvoy have established the following approximation of analytical solution of Smoker

$$S = \left(\frac{\alpha_m}{\sqrt{1 + 1/(Rx_F)}} \right)^N , \qquad (2)$$

where the separation factor S is

$$S = \frac{x_D / x_B}{(1 - x_D)/(1 - x_B)} . \qquad (3)$$

Starting from relation

$$\frac{D}{F} = \frac{x_F - x_B}{x_D - x_B} , \qquad (4)$$

x_B is extracted and replaced in relation (3), thus obtaining the second order equation with x_D as variable:

$$\frac{D}{F}(S-1)x_D^2 - \left[\left(\frac{D}{F} + x_F \right)(S-1) + 1 \right] x_D + Sx_F = 0 . \qquad (5)$$

Using x_D obtained by solving equation (5), x_B is obtained from relation (4):

$$x_B = \frac{(D/F)x_D - x_F}{D/F - 1} . \qquad (6)$$

In relation (2), the reflux ratio R is written depending of the objective function variables (L and V): $R = \frac{L}{D} = \frac{L}{V - L}$. Also, ratio $\frac{D}{F}$ is written $\frac{V - L}{F}$.

In this way, the function which contains the process model will have as outputs x_D and x_B, and as inputs L and V. This function implements relations (2)-(6).

The MATLAB function which calculates the objective function (1) contains the following elements:

- the function with the process model: *[xd, xb] = model (l, v)*;
- relations for calculate $x_{D\_propylene}$, $x_{D\_propane}$, x_{B_iC4} and x_{B_nC4};
- relations with values for variables $price_{propylene}$, $price_{propane}$, $price_{iC4}$, $price_{nC4}$, $price_{steam}$, F, MM_D, MM_B and r;
- expression of the objective function described by relation (1).

Calculation relations for $x_{D\_propylene}$ and $x_{D\_propane}$ are percentage representations of propylene and propane concentrations in composition of the light product from the top of the column (x_D), and x_{B_iC4} and x_{B_nC4} are percentage representations of i-butane – i-butylene and n-butane – (cis + trans)-butylene concentrations in composition of the heavy product from the bottom of the column ($1 - x_B$).

Regarding the optimization problem solving, this was done by using *fmincon* function from the optimization toolbox of MATLAB®. This function determines the solution of a constrained multidimensional optimization problem, starting from an initial estimate of the solution.

Figure 4 illustrates a 3D representation of the objective function on the domain imposed by constraints.

The maximization of the objective function had as result the pair [*L_optim V_optim*] = [13.2 17.5] [kmole/min] which ensure a very good separation with x_D = 0.9934 mole fr. and x_B = 0.0057 mole fr., the recorded profit being of thousands of lei/h. It should be reiterated that this is a "theoretical" profit in the sense that there have been taken into account only expenses with steam, in a refinery being also other expenses associated with operation of a distillation column.

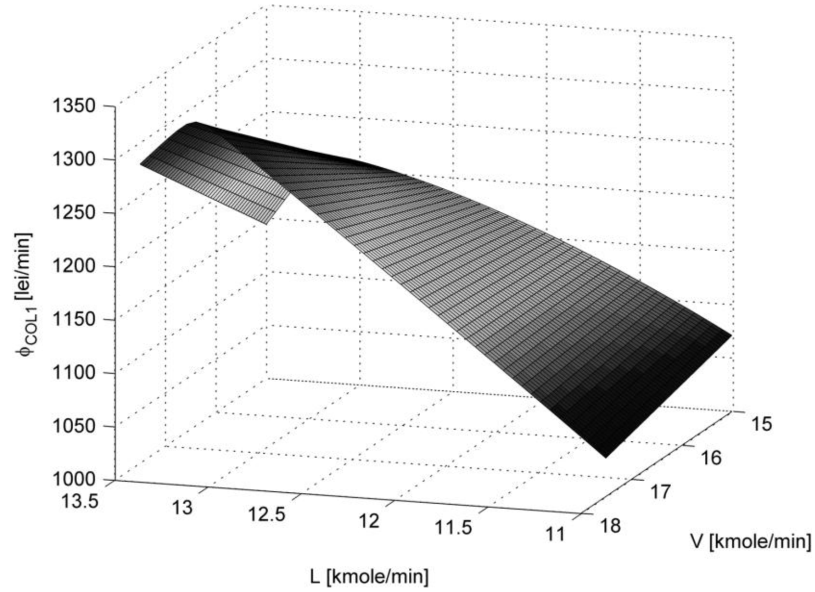

Fig. 4. The objective function representation.

The hierarchical control system from figure 3 was simulated in SIMULINK®, the associated model being presented in figure 5. This model consists of the two levels of the control system, namely conventional automation and optimal control.

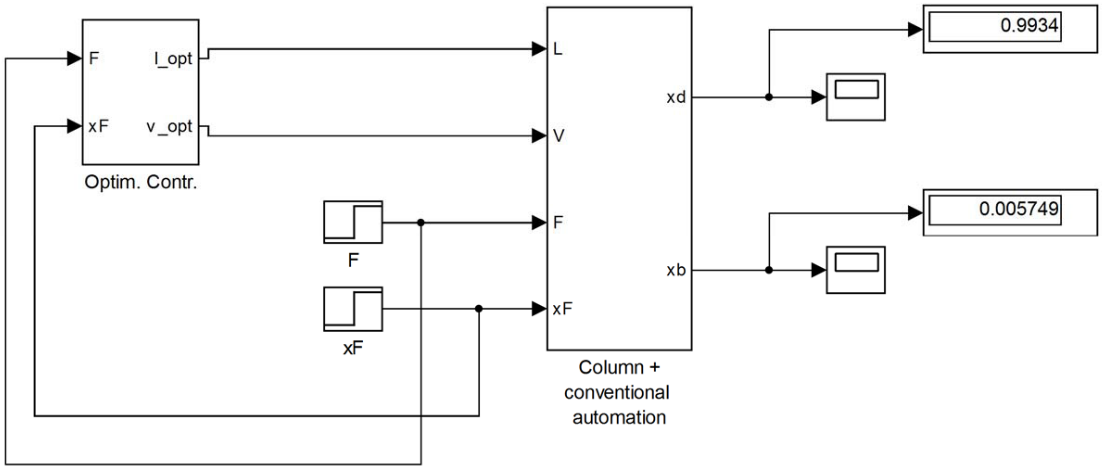

Fig. 5. SIMULINK model associated with the hierarchical control system for COL 1.

The optimal controller outputs are the optimal values of the references for the reflux flowrate control system, and the boilup flowrate control system respectively (figure 6). The combination of the effects of the two references leads to the time evolutions of the concentrations shown in figure 7.

From figure 7 it can be observed that the application of the optimal references for *L* and *V* leads to an improvement in separation, thus assuring a top product with very little heavy components and a bottom product with very little light components.

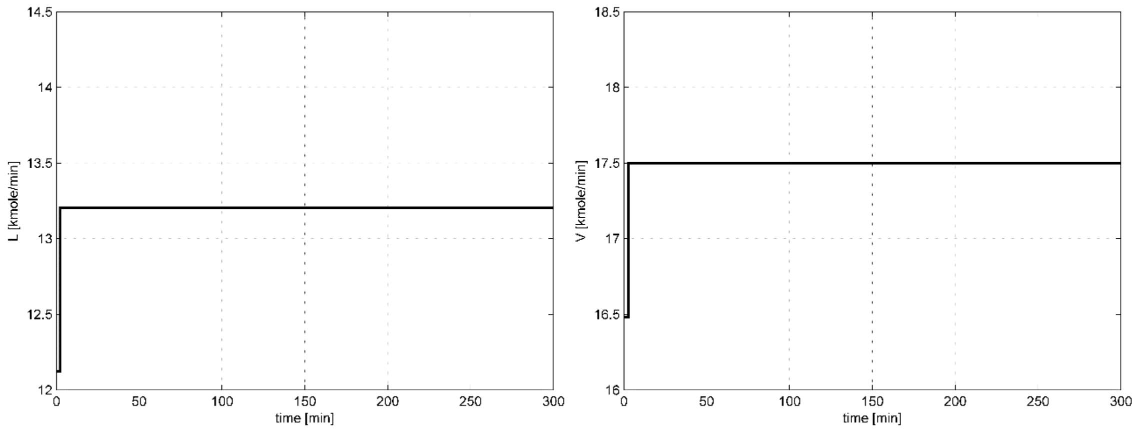

Fig. 6. Changes in references L_i and V_i.

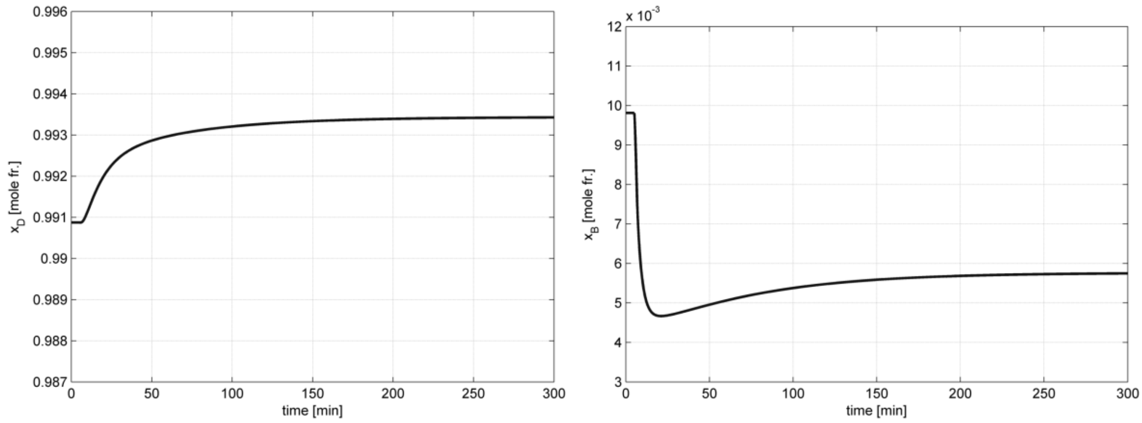

Fig. 7. Time evolution of x_D and x_B to changes in references L_i and V_i.

Conclusions

The paper presents a hierarchical control system for a depropanizer column with LV - configuration. The hierarchical control system has two levels: a basic control level and an optimal one. The optimal control level maximizes a "theoretical" profit for operating the depropanizer column. The objective function has two variables (namely the reflux L and boilup V flowrates).The off line results of objective function maximization can be stored in a lookup table and memorized at PLC or DCS level. The optimal pair [L, V] assures a purer top product (with very little heavy components) and a bottom product with very little light components. The simulation results show an improvement of process separation along with reduction of energy consumption.

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Reglarea ierarhică a unei coloane de depropanizare

Rezumat

Lucrarea prezintă proiectarea unui sistem ierarhic de conducere pentru o coloană de depropanizare. Sistemul ierarhic are două niveluri: nivelul reglării convenționale și nivelul reglării optimale. La nivelul 2 este propusă o funcție obiectiv de două variabile. Rezolvarea problemei de optimizare, care a constat în determinarea variabilelor optime care maximizează funcția obiectiv, a fost realizată în MATLAB®. Sistemul ierarhic cu două niveluri a fost simulat în SIMULINK®, rezultatele simulării confirmând faptul că aplicarea comenzilor optime de la nivelul ierarhic 2 conduce la o îmbunătățire a separării, care este obiectivul principal al coloanei de depropanizare.