DECOUPLING IN DISTILLATION

Sanda Florentina Frâncu

Department of Control Engineering and Computers
Petroleum&Gas University of Ploieşti, România
Email: sfrancu@upg-ploiesti.ro

Abstract: *Due to the dynamic characteristics of the distillation process, the control design by process decoupling is suited especially for two point composition case. The proposed decoupling method is a theoretical-experimental procedure that can be applied as a rule to two inputs - two outputs processes. The purpose of the paper is to present a simple and robust decoupling procedure, and to emphasize the advantages of distillation process control by decoupling technique. The designed decoupler has a standard general structure, which can be implemented in 4x4 distinct variants, corresponding to the dynamic characteristics of process direct and crossed channels. It has six tuning parameters: two time constants, two deadtimes and two gains, which can be experimentally tuned in order to obtain better decoupling performance. The decoupler is tested on two binary distillation columns, and the simulation results show that the proposed decoupling method is a useful tool for composition decoupling. The applied technique can also gain recognition in other areas of chemical process control, especially when relative gain array elements are relatively small and larger than one.*

Keywords: *two point composition control, decoupled multivariable process, dynamic simulations.*

1. INTRODUCTION

A two-product distillation column separating relatively ideal binary mixtures is a common example of a multivariable system, extensively studied in distillation literature. The study of interactions between the control loops associated to the distillation column emphasized the importance of composition control loops behavior, the interactions between inventory control loops having less importance [Skogestad, 1992, Shinskey, 1996]. In order to obtain almost no interactions between composition control loops one may use partial or complete decoupling [Waller, 1974, Waller et al., 2003]. The composition control loop pairing is made in order to obtain as week as possible interactions. Luyben [1970] designed two decouplers physically realizable, starting from a linear model of the binary distillation column. His paper on distillation decoupling has been paid considerable attention at the time, Niederlinski [1971] showing that advantages can be obtained of interaction in order to attenuate disturbances. Toijala and Fagervik [1972] demonstrated the generality of some of Luyben's results, Luyben and Vinante [1972] have experimented the proposed decouplers.

Later research [Skogestad and Morari, 1988] showed that the use of decouplers is not recommended for control configurations which have large RGA elements compared to one. If RGA elements are large, the response is very sensitive to decoupler design errors, e.g. input-output gains. The decoupler is based on a linear model of the distillation column, model that works out at the steady-state operating point about which to linearize. Consequently, the decouplers should never be used for high-purity distillation columns using LV configuration (with the largest RGA elements), whereas there are recommended in the case of double ratio configuration where RGA values are always small [Skogestad et al., 1990, Waller, 1990].

Due to distillation column dynamics, the decoupling of composition control loops is suited when the column works in two-point control mode. The usual control system of a distillation column controls the composition at only one end of the column or on some suitable tray. The other composition varies with changes in operating conditions. The product with controlled composition is chosen based on a certain criterion (process dynamics, economics etc.). Frequently, both compositions are important (which is the case of propylene-propane distillation column). The changes in product compositions can disturb subsequent process units and lead to costly off-specification problems. The solutions for rejecting the effect of these disturbances are also expensive (the use of columns with many more trays than required for normal operation in order to obtain a good enough product even under the most adverse conditions, run columns at higher reflux ratios, the use of large feed tanks to attenuate feed disturbances). The paper will present a practical design procedure to decouple the composition control loops.

2. DECOUPLING PROBLEM

Most of composition decoupling methods (one-point control or two-point control) cannot be used as general method for decoupling multivariable processes with two inputs - two outputs. The proposed practical method for composition decoupling addresses the general two inputs - two outputs multivariable processes, the resulted decoupler having a standard structure, that can be realized in 4×4 distinct forms, depending on process direct and crossed input-output process channels features. In order to synthesize the controller of a multivariable system it must be known a model of the process either in input-output or input-state-output form. Modeling and identification tasks are usually time consuming and require specific knowledge of control theory, good practical experience in operating the process, even direct experiments on the process (in order to get the process response at different test input signals).

In industrial practice, the binary distillation column represents a multivariable system, having crossed interactions that cannot be neglected and can cause difficulties in control. The binary distillation column is a multivariable system with five manipulated variables $u = \left(L, V, D, B, Q_c\right)^T$ and five control variables (outputs) $y = \left(x_D, x_B, M_D, M_B, p\right)^T$, where:

- L reflux flow [kmol/h];
- V boilup flow [kmol/h];
- D distillate product flowrate [kmol/h];
- B bottom product flowrate [kmol/h];
- Q_C cooling agent flowrate [kmol/h];
- x_D liquid composition in distillate product [mole fraction];
- x_B liquid composition in bottom product [mole fraction];
- M_D liquid holdup in reflux vessel [kmol];
- M_B liquid holdup in the bottom of the column [kmol];
- p column pressure [bar].

The decoupling of composition control loops will be made to a partial control system, meaning that pressure and level control loops will be closed. In that way, the control configuration is established by closing inventory control loops. Following this closing, there are two available manipulated variables for composition control. The process to be controlled becomes two inputs - two outputs multivariable process. As shown in introduction, the use of decouplers should never be used when the model has large RGA elements compared to one (the interactions between control loops must be not so strong).

In most of the cases, controlling multivariable processes with monovariable controllers is a difficult task due to mutual interactions between monovariable control loops. In a centralized approach, the use of multivariable controller makes possible the partial or even total elimination (in theoretical case) of these interactions with a disturbing effect for control performance. Usually, a multivariable controller with *n* inputs and *n* outputs consists of a block of *n* monovariable controllers (PID type, IMC type etc.) and a decoupler for the process itself (Fig.1). The controller with such a structure is named decoupling controller, while the serial connection between the decoupler and process forms the so called pseudoprocess (decoupled process), that is characterized only by direct input-output channels. The main advantage of this structure is that the tuning problem of the multivariable controller is reduced to tuning independent monovariable controllers associated to each control loop [Friman and Waller, 1997, Wang et al., 1997, 2000, Ho et al., 1996, Cîrtoaje et al., 2002, 2003a, 2003b].

Most of decoupling methods considers that the multivariable process model is known, being determined at previous phases, namely the modeling and identification ones. In the case of binary distillation column, the resulted model is nonlinear. In order to use the proposed decoupling method the distillation column model will be linearized near an operating point. Obviously, the modeling errors will affect the decoupling performance and consequently the performance of the entire control system. For high purity distillation column or columns with large RGA numbers this can never be avoided.

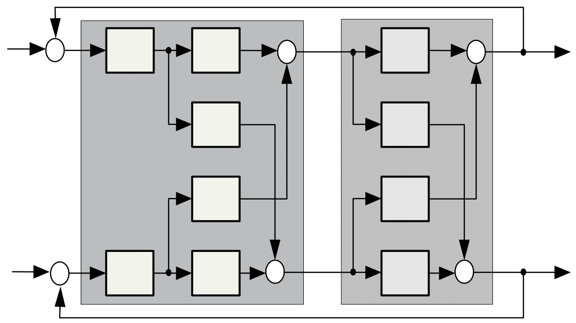

Fig. 1. Multivariable control system with decoupling controller.

Even in the case of an ideal model of the process the resulted decoupled process can have direct channels with worse dynamics than the process. The decoupler may introduce undesired lags on direct input-output channels. The dynamic features of the pseudoprocess are determined by the type and intensity of crossed interactions of the process and by the decoupling method. For strong crossed interactions, even if the direct process channels have monotonic and finite step response, the direct pseudoprocess channels can be non-monotonic (non-minimum phase or with large overshoot) or even become unstable. There are well known the difficulties in controlling non-minimum phase processes (e.g. the practical case of controlling the level at the bottom of distillation columns which has an inverse response to a step increase of boiling agent in reboiler). In such cases, even if the pseudoprocess is completely decoupled, the monovariable controllers design becomes a very difficult task, and the control performance compared to the direct process channels process dynamics remains unsatisfactory [Cîrtoaje et al., 2003a, 2003b, Frâncu and al., 2002, Frâncu and Popescu, 2003].

The relation between the transfer matrix of the process denoted by $H(s)$, of the decoupler transfer matrix $D(s)$ and the pseudoprocess transfer matrix $G(s)$ can be written:

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} = \begin{bmatrix} G_{11} & 0 \\ 0 & G_{22} \end{bmatrix} \tag{1}$$

From decoupling equations

$$\begin{cases} H_{11}D_{12} + H_{12}D_{22} = 0 \\ H_{21}D_{11} + H_{22}D_{21} = 0 \end{cases}, \tag{2}$$

there are obtained the transfer functions of the pseudoprocess as follows:

$$\begin{cases} G_{11} = \dfrac{H_0 D_{11}}{H_{11}} \\ G_{22} = \dfrac{H_0 D_{22}}{H_{22}} \end{cases}, \tag{3}$$

where

$$H_0 = 1 - \frac{H_{12}H_{21}}{H_{11}H_{22}} \tag{4}$$

is the decoupling factor of the process. For the complete decoupled process (with

$H_{12} = H_{21} = 0$), the decoupling factor is equal to 1, while from complete coupled the decoupling factor is 0.

The decoupling equations provide two relations, while the number of unknown decoupler transfer functions is four. This lead to a free choice of two decoupler transfer functions, usually the diagonal ones, D_{11} and D_{22}. The other two transfer functions of the decoupler become:

$$\begin{cases} D_{12} = \dfrac{-H_{12}D_{22}}{H_{11}} \\ D_{21} = \dfrac{-H_{21}D_{11}}{H_{22}} \end{cases}. \tag{5}$$

If it is chosen $D_{11} = D_{22} = 1$, the non-diagonal decoupler transfer functions may result improper. In this case the diagonal transfer functions D_{11} and D_{22} are chosen as lag filters of the necessary rank, with time constants that have small values related to the dominant time constants of the process.

Another variant of decoupler design is to impose that the pseudoprocess dynamic performance on direct channels to be exactly the process dynamic performance on direct channels: $G_{11} = H_{11}$, $G_{22} = H_{22}$. This variant is recommended if the process has good dynamic performance. The resulted decoupler can be also improper, so that it is recommended a serial connection with lag filters of necessary rank, with time constant appreciatively 10 times smaller than the dominant constant time of the process.

3. PROPOSED DECOUPLING METHOD

The decoupling method can be applied to two inputs - two outputs multivariable processes, with all input-output channels of proportional type with finite step response. It is a general method that can be applied to distillation decoupling. In order to design the decoupler each input-output channel of the process must be characterized by three parameters, which are determined experimentally: the proportional gain $(K_p)_{ij}$, deadtime $(\tau_p)_{ij}$ and transient time $(T_t)_{ij}$:

$$\text{Process}: \begin{bmatrix} (K_{p11}, \tau_{p11}, T_{pt11}) & (K_{p12}\ \tau_{p12}, T_{pt12}) \\ (K_{p21}, \tau_{p21}, T_{pt21}) & (K_{p22}, \tau_{p22}, T_{pt22}) \end{bmatrix}.$$

The decoupler has the following structure:

$$D = \begin{bmatrix} \dfrac{e^{-\tau_{11}s}}{T_{11}s+1} & \dfrac{k_{12}e^{-\tau_{12}s}}{T_{12}s+1} \\ \dfrac{k_{21}e^{-\tau_{21}s}}{T_{21}s+1} & \dfrac{e^{-\tau_{22}s}}{T_{22}s+1} \end{bmatrix}, \tag{6}$$

where

$$k_{12} = -K_{p12} / K_{p11},\ k_{21} = -K_{p21} / K_{p22} \tag{7}$$

For a process without deadtime or with equal deadtime allover the input-output channels, the decoupler will be a system without deadtime. The no deadtime decoupler has the following features:

1) the proportional gain of direct channels are equal to 1;

2) two input-output channels are pure proportional type (zero order) , the other two being first order lag elements.

These features simplify the decoupler structure and lead to a decoupled process with faster dynamics.

The decoupling problem is solved based on the idea of compensating the effects of two parallel opposite input-output channels, with almost the same proportional gains, deadtimes and transient times (Fig.2).

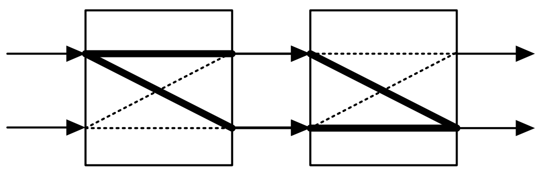

Fig. 2. The compensation of two opposite- parallel channels effects.

From the second feature of the decoupler and relations (considering the decoupler transient time being four times the decoupler time constant and the transient time of the serial connection being the sum of decoupler and process transient times)

$$\begin{aligned} 4T_{11} + T_{pt21} &= 4T_{21} + T_{pt22} \\ 4T_{22} + T_{pt12} &= 4T_{12} + T_{pt11} \end{aligned}, \tag{8}$$

which express the compensation of transient time on parallel-opposite channels, the time constants of the decoupler will be computed, according to process dynamics, as follows:

$T_{pt22} \le T_{pt21} \Rightarrow T_{11} = 0$, $T_{21} = (T_{pt21} - T_{pt22})/4$;

$T_{pt22} \ge T_{pt21} \Rightarrow T_{21} = 0$, $T_{11} = (T_{pt22} - T_{pt21})/4$;

$T_{pt11} \le T_{pt12} \Rightarrow T_{22} = 0$, $T_{12} = (T_{pt12} - T_{pt11})/4$;

$T_{pt11} \ge T_{pt12} \Rightarrow T_{12} = 0$, $T_{22} = (T_{pt11} - T_{pt12})/4$.

From these implications result mainly four variants of decoupler:

A. direct input-output channels are faster than the crossed ones, the case of A-type decoupler:

$$D_A = \begin{bmatrix} 1 & \dfrac{k_{12}}{T_{12}s+1} \\ \dfrac{k_{21}}{T_{21}s+1} & 1 \end{bmatrix}; \tag{9}$$

B. direct input-output channels are slower than the crossed ones, the case of B-type decoupler:

$$D_B = \begin{bmatrix} \dfrac{1}{T_{11}s+1} & k_{12} \\ k_{21} & \dfrac{1}{T_{22}s+1} \end{bmatrix}; \tag{10}$$

C. the direct input-output channel 1-1 is faster than the crossed channel 2-1, while the direct input-output channel 2-2 is slower than the crossed channel 1-2, the case of C-type decoupler:

$$D_C = \begin{bmatrix} \dfrac{1}{T_{11}s+1} & \dfrac{k_{12}}{T_{12}s+1} \\ k_{21} & 1 \end{bmatrix}; \tag{11}$$

D. the direct input-output channel 1-1 is slower than the crossed channel 2-1, while the direct input-output channel 2-2 is faster than the crossed channel 1-2, the case of D-type decoupler:

$$D_D = \begin{bmatrix} 1 & k_{12} \\ \dfrac{k_{21}}{T_{21}s+1} & \dfrac{1}{T_{22}s+1} \end{bmatrix}. \tag{12}$$

Another decoupler feature can be written as:

$$\begin{aligned} \tau_{11} + \tau_{p21} &= \tau_{21} + \tau_{p22} \\ \tau_{22} + \tau_{p12} &= \tau_{12} + \tau_{p11} \end{aligned}, \tag{13}$$

Using (13), the deadtimes are computed with:

$\tau_{p22} \le \tau_{p21} \quad \Rightarrow \quad \tau_{11} = 0$, $\tau_{21} = \tau_{p21} - \tau_{p22}$;

$\tau_{p22} \ge \tau_{p21} \quad \Rightarrow \quad \tau_{21} = 0$, $\tau_{11} = \tau_{p22} - \tau_{p21}$;

$\tau_{p11} \le \tau_{p12} \quad \Rightarrow \quad \tau_{22} = 0$, $\tau_{12} = \tau_{p12} - \tau_{p11}$;

$\tau_{p11} \ge \tau_{p12} \quad \Rightarrow \quad \tau_{12} = 0$, $\tau_{22} = \tau_{p11} - \tau_{p12}$.

From these implications result four variants of decoupler:

$$\text{a.} \begin{cases} \tau_{p11} < \tau_{p12} \\ \tau_{p22} < \tau_{p21} \end{cases} \Rightarrow \begin{cases} \tau_{12} = \tau_{p12} - \tau_{p11} \\ \tau_{11} = \tau_{22} = 0 \\ \tau_{21} = \tau_{p21} - \tau_{p22} \end{cases};$$

$$\text{b.} \begin{cases} \tau_{p11} > \tau_{p12} \\ \tau_{p22} > \tau_{p21} \end{cases} \Rightarrow \begin{cases} \tau_{11} = \tau_{p22} - \tau_{p21} \\ \tau_{12} = \tau_{21} = 0 \\ \tau_{22} = \tau_{p11} - \tau_{p12} \end{cases};$$

$$\text{c.} \begin{cases} \tau_{p11} < \tau_{p12} \\ \tau_{p22} > \tau_{p21} \end{cases} \Rightarrow \begin{cases} \tau_{11} = \tau_{p22} - \tau_{p21} \\ \tau_{21} = \tau_{22} = 0 \\ \tau_{12} = \tau_{p12} - \tau_{p11} \end{cases};$$

$$\text{d.} \begin{cases} \tau_{p11} > \tau_{p12} \\ \tau_{p22} < \tau_{p21} \end{cases} \Rightarrow \begin{cases} \tau_{21} = \tau_{p21} - \tau_{p22} \\ \tau_{11} = \tau_{12} = 0 \\ \tau_{22} = \tau_{p11} - \tau_{p12} \end{cases}.$$

In any case, the decoupler is characterized by 6 parameters: two proportional gains, two time-constants and two deadtimes.

It can be stated that the proposed method is an experimental decoupling method for two inputs - two outputs processes, based on a standard structure decoupler that can be implemented in 16 distinct variants, according to the dynamics of direct and crossed channels process features.

The decoupler has 6 tuning parameters: two proportional gains, two deadtimes and two transient times. The decoupler structure leads to a faster dynamic quasi-decoupled process. Two channels have proportional gain equal to 1 and two channels have time constant equal to zero. The initial values of the decoupler are determined by 3×4 process parameters, each of the *4* input-output process channels being characterized by three parameters: proportional gain, deadtime and transient time (the difference between the whole transient time of step response and the deadtime). The simulation results demonstrated the practical character of the proposed decoupling method, the decoupling procedure being tested on many multivariable processes, as the one introduced by Menani and Koivo in 1996 [Cîrtoaje, Frâncu şi Băieşu, 2003]. Next, the effectiveness of the proposed method in the case of binary distillation column will be emphasized.

4. CASE STUDIES

In the following, the proposed decoupling method will be applied for two binary distillation columns: propylene-propane distillation column (PPDC) and butane-butylene distillation column (BBDC) from hydrocarbon distillation plant, within catalytic-cracking unit.

PPDC. For propylene-propane column, which will be referred as PPDC, the control configuration is already established taking into account steady state and dynamic criteria. The best control configuration from steady state RGA and dynamic simulation behavior is SV/B configuration [Frâncu et al., 2002]. It is a double ratio configuration with the following manipulated variable – controlled variable pairing:

- reflux ratio L/D – x_D composition in distillate product;
- ratio V/B – x_B composition in bottom product.

As mentioned before, decoupling composition loops is effective only if the crossed interactions are not so strong. The SV/B configuration proved to have the best decoupling features. However, the PPDC presents crossed interactions, as it can be seen from the associated linearized model:

$$\begin{bmatrix} (0.9, 7\,\text{min}, 120\,\text{min}) & (-0.76, 8\,\text{min}, 400\,\text{min}) \\ (0.2, 9\,\text{min}, 300\,\text{min}) & (-0.83, 7\,\text{min}, 400\,\text{min}) \end{bmatrix}.$$

Applying the decoupling procedure to the linearized model, the resulting decoupler is C-a type, the direct input-output channel 2-2 being slower than the crossed channel 1-2:

$$T_{pt11} < T_{pt12} \Rightarrow \begin{cases} T_{12} = 45\,\text{min} \\ T_{11} = 25\,\text{min} \end{cases}, \tag{14}$$

$$T_{pt22} > T_{pt21} \Rightarrow \begin{cases} T_{21} = 0 \\ T_{22} = 0 \end{cases}, \tag{15}$$

$$\begin{cases} \tau_{p11} < \tau_{p12} \\ \tau_{p22} < \tau_{p21} \end{cases} \Rightarrow \begin{cases} \tau_{11} = \tau_{22} = 0 \\ \tau_{12} = \tau_{p12} - \tau_{p11} = 1\,\text{min} \\ \tau_{21} = \tau_{p21} - \tau_{p22} = 2\,\text{min} \end{cases}, \tag{16}$$

$$D_{C-a} = \begin{bmatrix} \dfrac{1}{T_{11}s+1} & \dfrac{k_{12}e^{-\tau_{12}s}}{T_{12}s+1} \\ k_{21}e^{-\tau_{21}s} & 1 \end{bmatrix}. \tag{17}$$

In (17), the steady-state decoupling coefficients for composition loops are computed using the following relations:

$$\begin{cases} k_{12} = -K_{p12} / K_{p11} = 0.76/0.9 \\ k_{21} = -K_{p21} / K_{p22} = 0.2/0.83 \end{cases}, \tag{18}$$

The decoupled process has the transfer matrix:

$$G(s) = H(s)D(s) = \begin{bmatrix} \dfrac{K_{pm1}e^{-T_{d1}s}}{(T_{2m1}s+1)^2} & \cong 0 \\ \cong 0 & \dfrac{K_{pm2}e^{-T_{d2}s}}{(T_{2m2}s+1)^2} \end{bmatrix},$$

where

$$\begin{cases} K_{pm1} = K_{p11} - \dfrac{K_{p12}K_{p21}}{K_{p22}} \cong 0.72 \\ K_{pm2} = K_{p22} - \dfrac{K_{p12}K_{p21}}{K_{p11}} \cong -0.66 \end{cases}. \tag{19}$$

The distillation column in SV/B configuration presents the following coupling coefficient CC :

$$CC = \frac{K_{p12}K_{p21}}{K_{p11}K_{p22}} \cdot 100 = 20.34\%. \tag{20}$$

Using the decoupler, in a serial connection with PPDC, the decoupled process has the new coupling coefficient CC' :

$$CC' = \frac{K_{pm12}K_{pm21}}{K_{pm1}K_{pm2}} \cdot 100 = 1.03\%. \tag{21}$$

It is noticeable that the decoupling features of pseudoprocess are 20 times better than the ones of PPDC. For PPDC simulation, in SV/B configuration, open-loop mode with C-a type decoupler, it was used the model from Fig.3. The decoupler from Fig.3 with the parameters computed from (14), (15), (16) and (18) improved the decoupling features on crossed input-output channels $L/D - x_B$ and $V/B - x_D$, as it can be seen from Fig.4 and Fig.5 [Frâncu and Popescu, 2003].

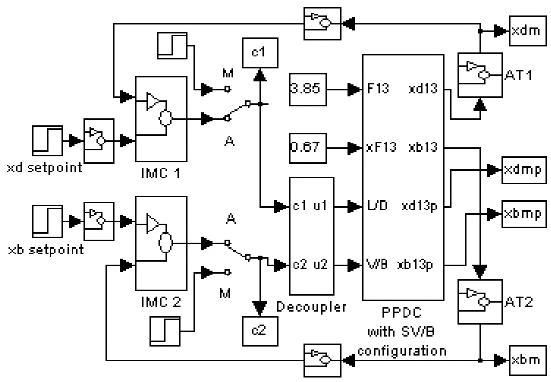

Fig. 3. PPDC. The Simulink model of the serial connection decoupler-distillation column.

Analyzing the simulation results it can be stated that the x_D output is more sensitive to changes in V/B input than the other output to L/D input changes. As it can be seen from Fig.5 the best value for time constant T_{12} is 50 min, the composition x_D having an evolution very close to the ideal one situated above and under the horizontal line. A good response is achieved even in steady state decoupling, a better one result using $T_{11} = 50\,\text{min}$ (Fig.4). The new decoupled process is sensitive to large changes of inputs, but gives good results to medium and small changes in operating conditions.

The most valuable product from economics criterion is propylene (the setpoint for x_D being 0.90 mole fr.). The rigid constraint is imposed by contract, while the constraint for the bottom product is flexible (the setpoint for x_B being 0.01…0.05 mole fr.). From economical point of view, a purer bottom product means energy loss due to the growth of operating effort, while from process point of view loss means more propylene in bottom product. A compromise between the two approaches will bring the optimum x_B .

The decoupling quality can be validated and adjusted by tuning the decoupler parameters, mainly of the two time constants (which are less precise at a first evaluation than the other parameters). The best value for T_{12} is greater than the theoretical one that works as an initial value in tuning the decoupler. If the decoupler gains are precise (the case of perfect steady-state decoupling), and the time constants are conveniently chosen, then the step responses of crossed channels are very close to the ideal ones.

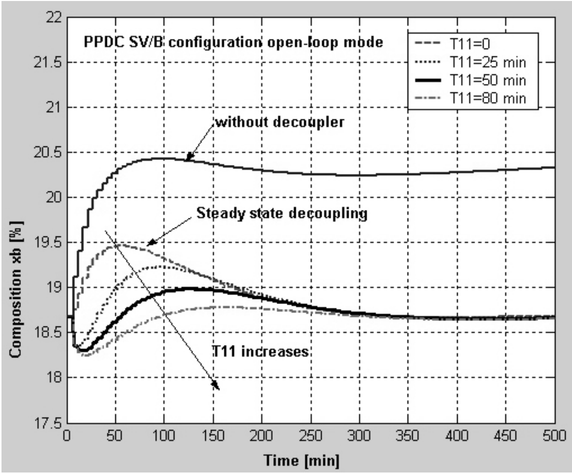

Fig. 4. PPDC. The composition evolution x_B to a step increase of L/D input with 5%, with and without decoupler, SV/B open-loop mode.

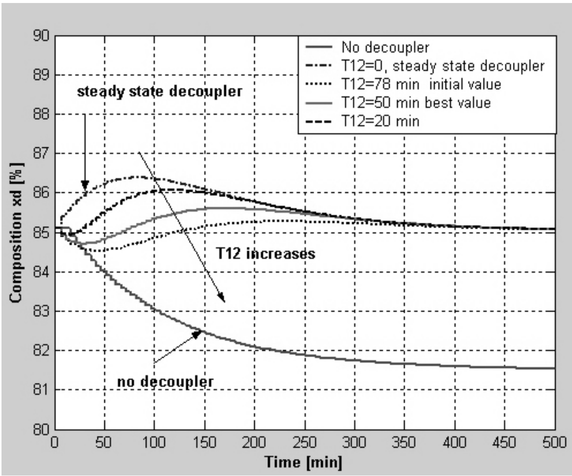

Fig. 5. PPDC. The composition evolution x_D to a step increase of V/B input with 5%, with and without decoupler, SV/B open-loop mode.

We cannot achieve perfect decoupling using this practical method, but the results are very close to the ideal ones, the system performance being improved by conveniently adjusting the decoupler tuning parameters. The simulation results prove the effectiveness of the proposed decoupling method in the case of PPDC. The method was used knowing that SV/B configuration has RGA elements relatively small and larger than one.

BBDC. For butane-butylene distillation column (BBDC), the best control configuration is also SV/B, from steady state and dynamic criteria. The BBDC has crossed interactions as in the linearized model associated with SV/B configuration:

$$\begin{bmatrix} (1.2, 7\,\text{min}, 240\,\text{min}) & (-1.3, 8\,\text{min}, 320\,\text{min}) \\ (0.75, 9\,\text{min}, 400\,\text{min}) & (-2.5, 7\,\text{min}, 400\,\text{min}) \end{bmatrix}$$

Using the proposed decoupling procedure in the case of the linearized model we get an A-a type decoupler, the direct input output channels being faster than the crossed ones:

$$T_{pt11} < T_{pt12} \Rightarrow \begin{cases} T_{11} = 0 \\ T_{12} = 20\text{ min} \end{cases}, \quad (22)$$

$$T_{pt22} = T_{pt21} \Rightarrow \begin{cases} T_{22} = 0 \\ T_{22} = 0 \end{cases}, \quad (23)$$

$$\begin{cases} \tau_{p11} < \tau_{p12} \\ \tau_{p22} < \tau_{p21} \end{cases} \Rightarrow \begin{cases} \tau_{11} = \tau_{22} = 0 \\ \tau_{12} = \tau_{p12} - \tau_{p11} = 1\text{ min} \\ \tau_{21} = \tau_{p21} - \tau_{p22} = 2\text{ min} \end{cases}, \quad (24)$$

$$D_{A-a} = \begin{bmatrix} 1 & \dfrac{k_{12} e^{-\tau_{12} s}}{T_{12} s + 1} \\ k_{21} e^{-\tau_{21} s} & 1 \end{bmatrix}. \quad (25)$$

In (25), the decoupling gains are computed with:

$$\begin{aligned} k_{12} &= -K_{p12} / K_{p11} = 1.3/1.2 \\ k_{21} &= -K_{p21} / K_{p22} = 0.75/2.5 \end{aligned}. \quad (26)$$

The decoupled process has the direct input-output channels gains:

$$\begin{cases} K_{pm1} = K_{p11} - \dfrac{K_{p12} K_{p21}}{K_{p22}} \cong 0.81 \\ K_{pm2} = K_{p22} - \dfrac{K_{p12} K_{p21}}{K_{p11}} \cong -1.68 \end{cases}. \quad (27)$$

The BBDC has the coupling coefficient CC :

$$CC = \frac{K_{p12} K_{p21}}{K_{p11} K_{p22}} \cdot 100 = 32.5\%. \quad (28)$$

The pseudoprocess formed by the serial connection between the decoupler and BBDC has the coupling coefficient CC' :

$$CC' = \frac{K_{pm12} K_{pm21}}{K_{pm1} K_{pm2}} \cdot 100 = 0.007\%. \quad (29)$$

The decoupling features of the pseudoprocess are considerably improved compared to process features.

A similar model with the one presented in Fig.3. was used to simulate the BBDC in SV/B configuration with A-a type decoupler.

The A-a type decoupler with the parameters from (22), (23), (24) and (26) improved the decoupling features on crossed channels $L/D - x_B$ and $V/B - x_D$, as it can be seen in Fig.6 and Fig.7.

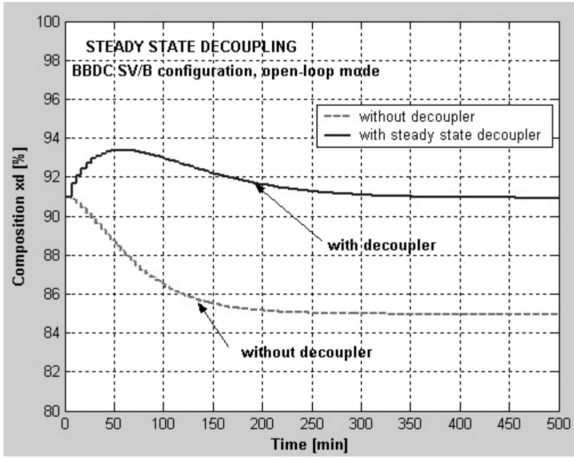

Fig. 6. Composition x_D to a 5% step increase of V/B, SV/B open-loop mode, steady-state decoupling.

Analyzing Fig.6 and Fig.7 it can be observed the effect of decoupler introduction on crossed input-output channels. The considerable improvement of decoupling features on these channels will lead to a simpler tuning of the multivariable control system. A multivariable control system without decoupler uses a complicated tuning procedure. Thus, in order to properly tune such a system, process must be first identified in open loop mode (also considering crossed interactions). The results are pre-tuning parameters of the multivariable controller (PID, IMC etc.). The next stage is the so-called tuning, when the process identification is made with the other loop closed, the results being the final tuning parameters. In the case of a quasi-decoupled process, tuning the multivariable control systems becomes tuning two separate SISO control systems.

Fig.6 and Fig.7 presents the evolution of x_D and x_B composition to changes of the manipulated variables of the crossed channels V/B and L/D. The simulations were done without decoupler or with steady-state decoupler ($T_{12} = 0$).

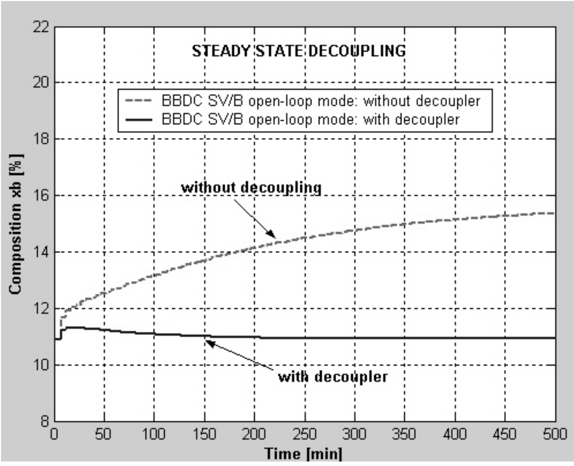

Fig. 7. Composition x_B to a 5% step increase of L/D, SV/B open-loop mode, steady-state decoupling.

Assuring steady-state decoupling is the first step in tuning the decoupler, and it is noticeable that the decoupler parameters computed with (27) accomplish this target. The composition loops are not decoupled in dynamic regime.

As mentioned before, the dynamic decoupling is not perfect. In Fig.8 it is presented the tuning of decoupler in order to obtain a better response. For as good as possible dynamics decoupling, the time constant T_{12} is tuned. This mainly affects the crossed channel V/B - x_D. It can be seen that for $T_{12} = 55$ min we get the best response for both x_D composition. The system response using steady-state decoupler is represented with continuous line in Fig.8.

5. CONCLUSIONS

In conclusion it can be stated that the simulation results demonstrate the practical character of the proposed method. The decoupling effectiveness can be validated and adjusted by tuning the decoupler parameters, mainly of the two time constants (which are less precise at a first evaluation than the other parameters).

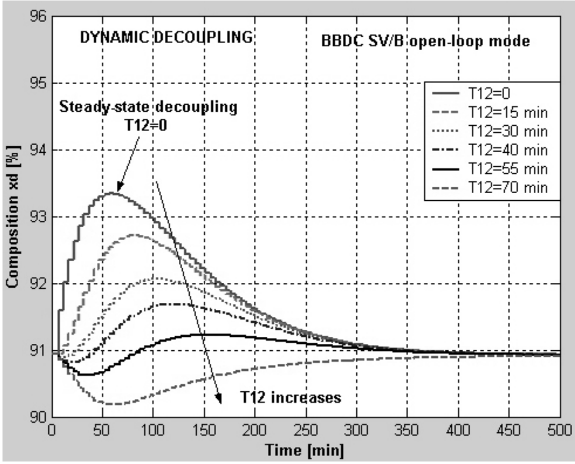

Fig. 8. Tuning decoupler time constant T_{12} to a 5% step increase of V/B.

We cannot achieve perfect decoupling using this method, but the results are very close to the ideal ones, the system performance being improved by conveniently adjusting the decoupler tuning parameters. In the case of binary distillation columns, the simulation results show that the proposed decoupling method is a useful tool for composition decoupling, whereas RGA elements for different configurations are relatively small and larger than one. The new decoupled process is sensitive to large condition changes but performs well and even very well to medium and small condition changes. Decoupling multivariable systems can have advantages such as an easier operating of a decoupled system than of an interacting one. The main advantage of decoupling in two point control is that it offers the possibility of tuning and treating the multivariable system as two single composition loops.

REFERENCES

[1] Cîrtoaje, V., Frâncu, S., Guțu, A. Valențe noi ale reglării cu model intern. In: Buletinul UPG Ploieşti, Sesiunea de comunicări ştiințifice „35 de ani de activitate a Universității Petrol-Gaze la Ploieşti", 2002.

[2] Cîrtoaje, V., Frâncu, S., Băieşu, A. A practical control method for multivariable systems. In SINTES 11 Proceedings: The International Symposium on System Theory, Automation, Mechatronic Systems, XIth, Vol.I, Romania, Craiova, 2003a.

[3] Cîrtoaje, V., Guțu, A., Frâncu, S. A practical decoupling method for linear multivariable systems. In: Proceedings of International Symposium on Process Control, SPC 2003, Buletinul UPG Ploieşti, Vol.LV, Seria Tehnică, 2003b.

[4] Frâncu, S., Cîrtoaje, V., Marinoiu, V. Hierarchical Control of Hydrocarbon Distillation Process. Structure, Functions and Control. In: Periodica Politehnica, Transactions on AUTOMATIC CONTROL AND COMPUTER SCIENCE, 47(61), no.1, 1-6, 2002.

[5] Frâncu, S., Popescu, M. (2003). On the internal model control applied to propylene separation process. In: Proceedings of International Symposium on Process Control, SPC 2003, Buletinul UPG Ploieşti, Vol.LV, Seria Tehnică, 2003.

[6] Friman, M., Waller, K.V., A Two-Channel Relay for Autotuning. In: Ind. Eng. Chem. Res., 36(7), p.2662-2671, 1997.

[7] Häggblom, K.E., Waller, K.V., Transformation and Consistency Relations of Distillation Control Structures. In: AIChE Journal, 34(10), p.1634-1648, 1988.

[8] Ho, W.K., Lee, T.H., Gan, O.P. Tuning of multiloop PID controllers based on gain and phase margin specifications. In: Proc. IFAC 13th Triennial World Congress, San Francisco, Vol. M, 1996.

[9] Luyben, W.L., Distillation Decoupling. In: AIChE Journal, 16, p.198-203, 1970.

[10] Luyben, W.L., Vinante, C.D., Experimental Studies of Distillation Decoupling. In: Kem. Teollisuus, 29, 499-511, 1972.

[11] Luyben, W. L., Practical distillation control, Ed. Van Nostrand Reinhold, New York, 1992.

[12] Luyben, L.M., Luyben, L.W., Essentials of Process Control, Ed. McGraw-Hill, New York, 1997.

[13] Niederlinski, A., Two-Variable Distillation Control: Decouple or Not Decouple. In: AIChE Journal, 17, p.1261, 1971.

[14] Shinskey, G.F., Process Control Systems (fourth edition), Ed. McGraw-Hill, New York, 1996.

[15] Skogestad, S., Morari, M., Understanding the Dynamic Behaviour of Distillation Columns. In: Ind. Eng. Chem. Res., 27, p.1848-1862, 1988.

[16] Skogestad, S., Lundström, P.,Jacobsen, E.W., Selecting the Best Distillation Control Structure. In: AIChE Jornal, 36,5, p.753-764, 1990.

[17] Skogestad, S. (1992), Dynamics and Control of Distillation Columns - A Critical Survey, (plenary conference). In: Preprints IFAC-symposium DYCORD'92, Maryland, Apr. 27-29, 1992, p.1-25. Reprinted în Modeling, Identification and Control, 18(2), p.485-490, 1997.

[18] Toijala [Waller], K., Fagervik, K., A Digital Simulation Study of Two-Point Feedback Control of Distillation Collumns. In: Kem. Teollisuus, 29, p.5-12, 1972.

[19] Waller, K. V., Decoupling in Distillation. In: AIChE Journal, 20, p.592-594, 1974.

[20] Waller, K.V., Distillation: Control Structures. In: Systems&Control Encyclopedia, Suppl. Vol. 1, p.174-181,1990.

[21] Waller, M. Waller, J.B., Waller, K.V., Decoupling Revisited. In: Ind. Eng. Chem. Res., 42, p.4575-4577, 2003.

[22] Wang, Q.G., Huang, B., Guo, X. Auto-tuning of decoupling controllers from step test. In: ISA Transactions, Vol. 39, 1997.