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Tracking and Disturbance Rejection in the 13C Cryogenic Separation Column

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Abstract: The separation of carbon isotopes represents a major research area due to the numerous uses of the least abundant carbon isotope, ^{13}C. One of the methods used for separating these isotopes is the cryogenic distillation, in large counter- current columns. Such industrial plants represent a difficult problem in terms of automatic control, since they are characterized by nonlinearities, delay times and extremely severe control input constraints. The paper presents a simplified nonlinear model of the isotope separation process as well as the control strategy for tracking and disturbance rejection. The tracking problem is solved based on a multi-loop design with a modified feedback linearization technique as an inner loop controller and an outer robust controller. The disturbance rejection solution consists of a new feed-forward compensator, derived from the classical approach used in feedback linearization techniques. The resulting control strategy achieves robust stability and robust performance for a certain amount of model uncertainties.

Keywords: cryogenic isotope separation column, robust nonlinear controller, nonlinear model, disturbance rejection

1. INTRODUCTION

Carbon isotopes and separation methods represent an important field of interest due to their wide utilities in medicine, industry, geology, chemistry. The least abundant carbon isotope, ^{13}C, has the most uses, however increasing its natural concentration of approximately 1.1% represents a challenging problem, due to the minor differences that exist between the ^{13}C and the ^{12}C isotopes. The separation method implemented at the National Institute for Research and Development of Isotopic and Molecular Technologies Cluj-Napoca (NIRDIMT) consists of the cryogenic carbon monoxide distillation.

Very few information, both theoretical and practical, regarding the construction and the principle of operation of cryogenic distillation plants for isotopes separation are known today. Additionally, there is even less information available regarding the modeling and control of the separation process. However, for a large scale ^{13}C production, it is of outmost importance the efficient control of the carbon monoxide distillation process. As far as the separation process model is concerned, there exist several models that could be used, such as those based on mass, component and energy balance equations (Radoi, 1999; Gligan, et al., 2006), on the nonlinear wave theory (Gligan, et al., 2006) or the Cohen equations (Gligan, et al., 2006; Cohen, 1951). These models are, nevertheless, translations from a classical distillation process, and they can generally be used to determine in each moment and column-coordinate the concentration of the useful isotope, thus describing and modeling the isotope concentration distribution as a function of time and as a function of the column dimension (Gligan, et al., 2006).

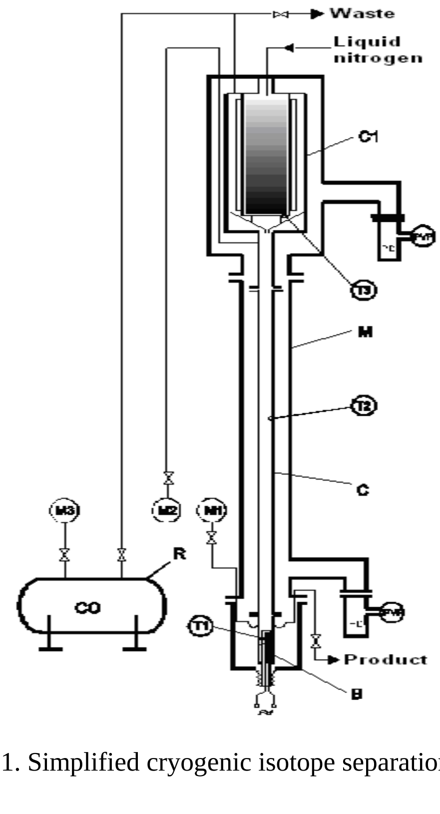

Fig. 1. Simplified cryogenic isotope separation column

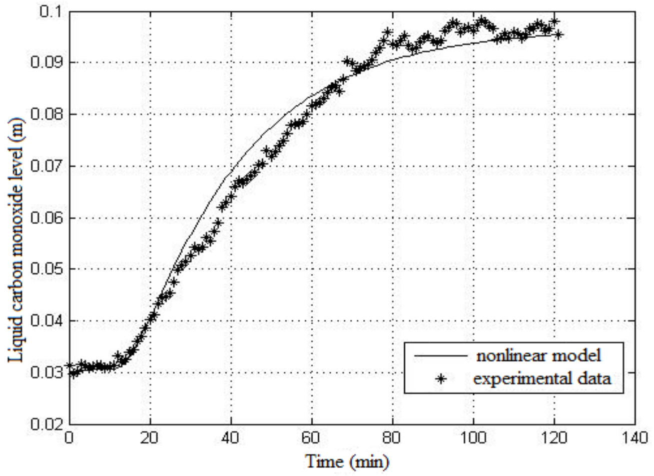

Fig. 2. Liquid carbon monoxide level evolution due to a step change in the feed flow (nonlinear model validation)

However, they represent a rather poor choice for control purposes, since they fail to model the actual control signals and controlled outputs, mainly due to the fact that the control/controlled signals in the case of the cryogenic carbon monoxide distillation column differ consistently from those of a classical distillation column. For an efficient cryogenic column operation it is necessary to derive first of all an adequate model and then design a control strategy capable of ensuring the main control requirement, namely keeping the isotope separation coefficient constant. This requirement can be satisfied by maintaining the column parameters (pressures, levels) at some prescribed set points.

The paper is organized as follows. In Section 2, the carbon isotopes separation column, built at NIRDIMT is presented, as well as the control problems associated. Section 3 describes the simplified nonlinear model and different simulations compared to experimental data. The control strategy designed is presented in Section 4. The nonlinear closed loop simulations are presented, with emphasis on the robust stability and disturbance rejection despite model uncertainties. Some concluding remarks are formulated in the final section of the paper.

2. THE ^{13}C CRYOGENIC SEPARATION COLUMN

The column developed at NIRDIMT uses the principle of cryogenic distillation to separate the carbon isotopes from a mixture of pure carbon monoxide, based on the vapor pressure difference that exists between the ^{12}C carbon monoxide (P_1) and the ^{13}C carbon monoxide (P_2). The parameter that dictates the separation rate is the separation coefficient, which at a temperature of about -192$^{\circ}C$ is (Axente, et al, 1994):

$$\frac{P_1^o}{P_2^o} = \alpha \approx 1.007 \qquad (1)$$

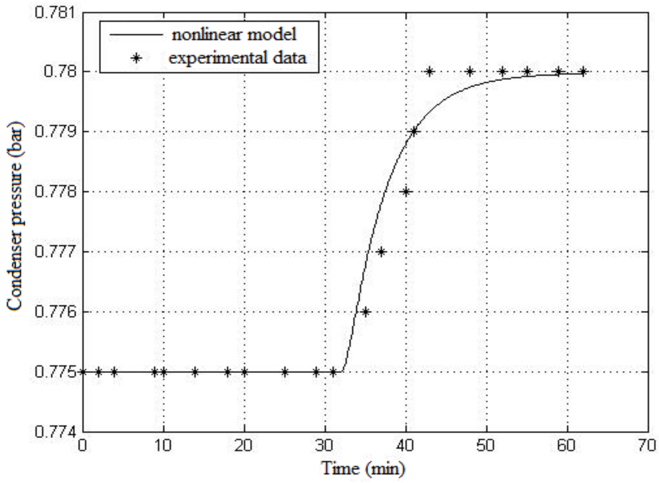

Fig. 3. Condenser pressure evolution due to a step change in the feed flow (nonlinear model validation)

The schematic representation of the column (C) is given in figure 1. The carbon monoxide is fed at a constant flow rate as a gas through the feeding system, from a pure carbon monoxide tank (CO). Due to the very-low operating temperatures, the efficient thermal isolation vacuum jacket (M) is ensured by the vacuum pumps (PVP).

The column operates with two zones: the stripping zone, from the feeding point to the top of the column and the enriching (rectifying) zone, in its lower part (Gligan, et al., 2006). Since the “elementary separation ratio” (α) (Axente, et al., 1994) is very close to unity, in order to raise the (^{13}C) isotope concentration, the boiler (B) in the bottom-side of the column and the condenser (C1) in the top-side ensure a permanent counter-current of the liquid-gaseous phases of the carbon monoxide.

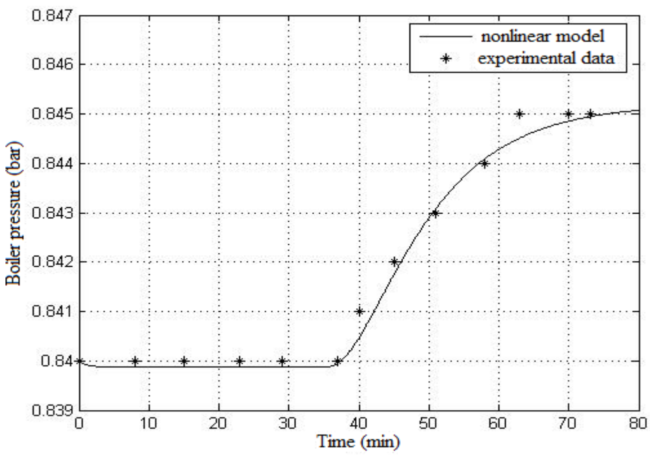

Fig. 4. Boiler pressure evolution due to a step change in the feed flow (nonlinear model validation)

The (^{13}C) isotope accumulates in liquid phase and will be extracted as end product at the bottom of the column, while the (^{12}C) component accumulates in vapor phase and will be extracted as waste at the top of the column.

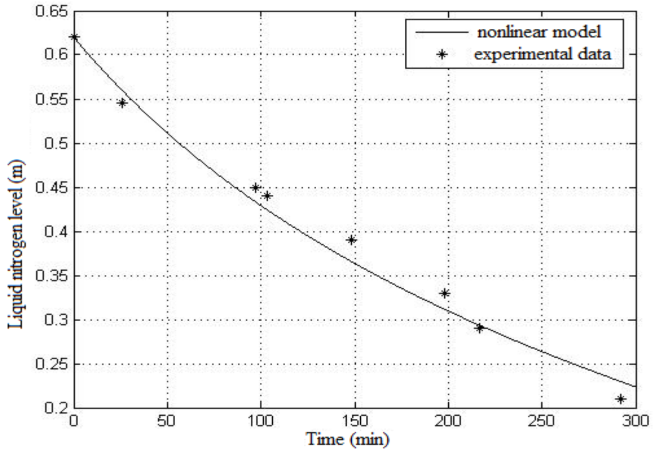

Fig. 5. Liquid nitrogen level evolution (nonlinear model validation)

The carbon monoxide cryogenic distillation process is a highly complex, nonlinear, multivariable process described by large time constants and with delay times that overcomplicate the control solutions. The control strategy is to maintain the column operation parameters constant, which ensure a constant separation rate. By keeping the required parameters at some prescribed reference points, the separation coefficient is kept constant, and thus the ^{13}C isotope concentration can be increased up to a desired value.

The main parameters of the separation process that need to be overseen are:

The liquid nitrogen level in the condenser needs to be kept at the prescribed value. The drop of the liquid nitrogen level below a critical value would lead to the impossibility of efficiently condensing the vapor upstream and thus would compromise the entire separation process.

The electrical power supplied to the boiler. Large variations in amplitude or over a wide period of time would affect the separation by modifying the upward gaseous stream. Moreover, excessive boiling power compared to lower condenser efficiency can lead to the column flooding (Festila, et al., 2008; Pop, et al., 2008).

The feeding stream flow and the waste stream flow. Large variations between the two flows imply a slight increase or decrease of the column pressure, but more importantly a rapid increase/decrease of the liquid carbon monoxide at the boiler.

The column pressure. Given some values for the electrical power, nitrogen level, feeding stream flow,

waste stream flow, the boiler and condenser pressures need to be kept at a constant value. Large variations of the column pressures imply variations of the separation coefficient (Pop, et al., 2010).

The liquid carbon monoxide at the boiler. The level must be kept constant since it interferes in the separation process. Variations of the liquid carbon monoxide quantity retained at the boiler implies variations in the boiler hold up and thus variations in the efficiency of the liquid- gas contact in the column with a direct impact upon the separation process.

3. NONLINEAR MODEL OF THE 13C ISOTOPE SEPARATION COLUMN

The nonlinear model proposed in this paper consists of a four-state system of differential equations that model the evolution of the top (x_1) and bottom (x_2) column pressures, the liquid nitrogen level (x_3) and the liquid carbon monoxide level (x_4), as controlled signals. The control inputs are the electrical power (P_{el}) supplied to the boiler, the liquid nitrogen stream flow (q_N) in the condenser, the feed flow (A) and the waste flow (E), while the disturbances are the vacuum pressure (p_{vac}) and the product flow (P).

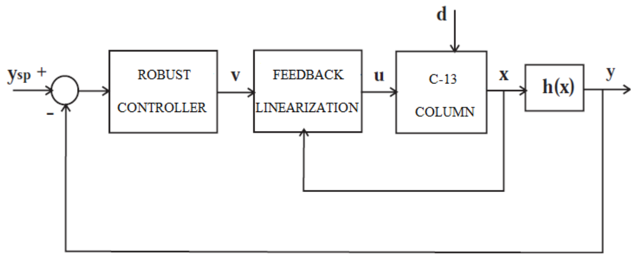

Fig. 6. Nonlinear closed loop control scheme

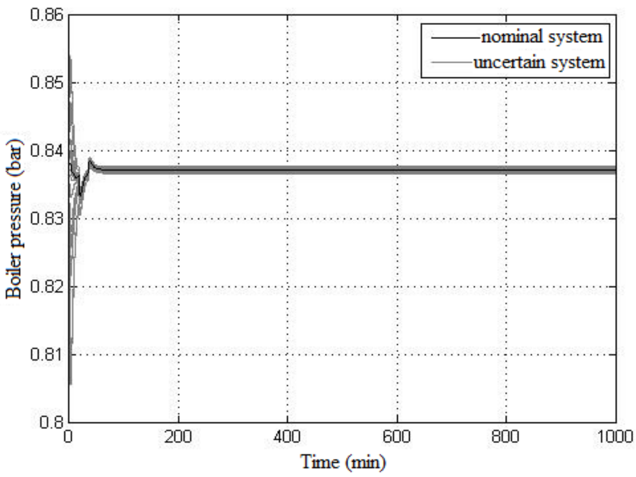

Fig. 7. Closed loop boiler pressure evolution

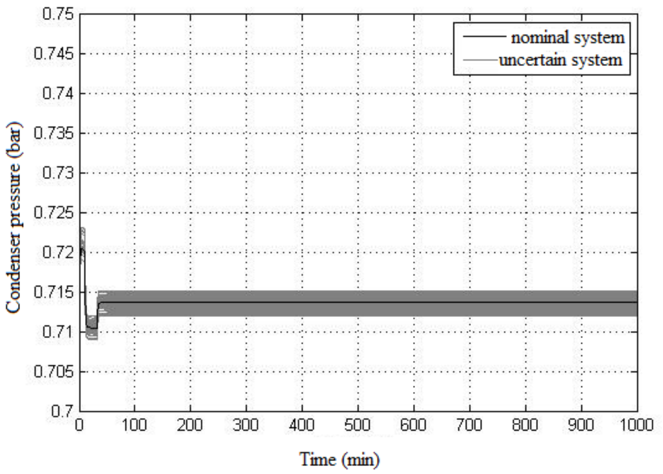

Fig. 8. Closed loop condenser pressure evolution

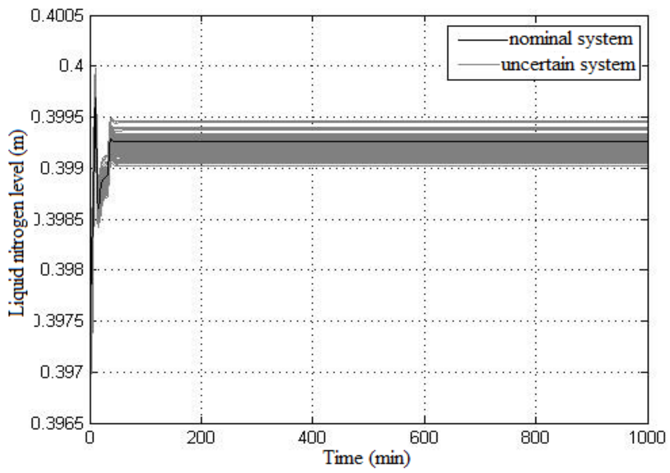

Fig. 9. Closed loop liquid nitrogen level evolution

The nonlinear model was developed using the experimental data measured at NIRDIMT and it is described by the following set on nonlinear equations:

$$\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{pmatrix} = \begin{pmatrix} -\frac{1}{T_s}x_1^4 + k_{11}x_3^{-\frac{1}{2}} \\ -\frac{1}{T_j}x_2^2 - k_{22}x_3^2 \\ -\frac{1}{T_N}x_3^2 - k_{13}e^{-x_1} \\ \frac{1}{T}x_4 + k_{14}x_3 \end{pmatrix} + g_1A + g_2E + g_3q_N + g_4P_{el}^{\frac{1}{2}} +$$

$$+p_1(x)p_{vac} + p_2(x)P \qquad (2)$$

with $g_1 = \begin{pmatrix} k_{21}\\ k_{32}\\ 0\\ k_{24}\end{pmatrix}$, $g_2 = \begin{pmatrix} -k_{31}\\ -k_{42}\\ 0\\ -k_{34}\end{pmatrix}$, $g_3 = \begin{pmatrix} 0\\ 0\\ k_{23}\\ 0\end{pmatrix}$,

$g_4 = \begin{pmatrix} 0\\ k_{12}\\ 0\\ -k_{44}x_4\end{pmatrix}$, $p_1 = \begin{pmatrix} k_{41}\\ k_{52}\\ -k_{33}\\ -k_{64}\end{pmatrix}$ and $p_2 = \begin{pmatrix} 0\\ 0\\ 0\\ -k_{54}\end{pmatrix}$.

We denote by T_s, T_j, T_N and T the time constants of the condenser pressure, boiler pressure, liquid nitrogen level and liquid carbon monoxide equations and by $k_{11}, k_{22}, k_{13}, k_{14}, k_{21}, k_{32}, k_{24}, k_{31}, k_{42}, k_{34}, k_{23}, k_{12}, k_{44}$ $k_{41}, k_{52}, k_{33}, k_{64}, k_{54}$ the corresponding coefficients. The control inputs- for a convenient representation- are chosen as:

$$u = [u_1 \quad u_2 \quad u_3 \quad u_4] = \left[E \quad A \quad q_N \quad P_{el}^{\frac{1}{2}}\right].$$

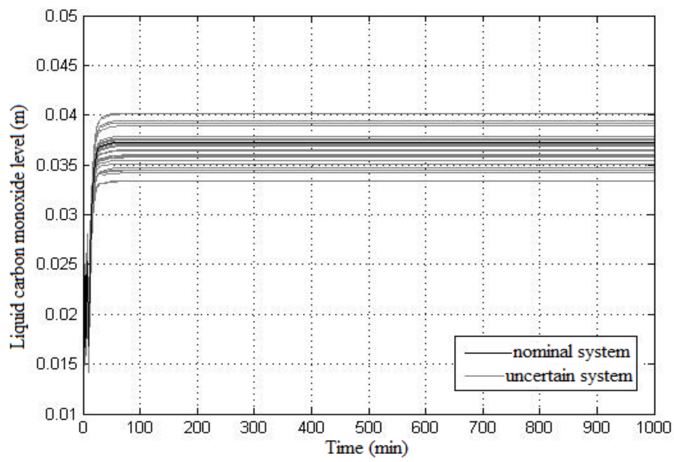

Fig. 10.Closed loop liquid carbon monoxide level evolution

The nonlinear model in (2) was developed based on previous modeling approaches (Dulf, et al., 2008; Festila, et al., 2007), and on evaporation theory, for the liquid nitrogen evolution. Estimation of the polynomial orders was done using Matlab, Basic Fitting, according to experimental data. Identification of parameters has been done using various steady state values and solving corresponding systems of equations using Matlab Optimization Toolbox.

Examples of the validation simulations for the nonlinear model against experimental data are given in figures 2, 3 and 4, considering a step change in the feed flow.

The results show a good agreement between the nonlinear model behavior and the experimental data collected through a dedicated monitoring system installed on the plant (Dulf, et al., 2007). Figure 5 presents the evolution of the liquid nitrogen level in the condenser considering no input to the condenser, meaning the liquid nitrogen flow considered is null. The liquid nitrogen level evolution is validated based on experimental data (Pop, et al., 2010).

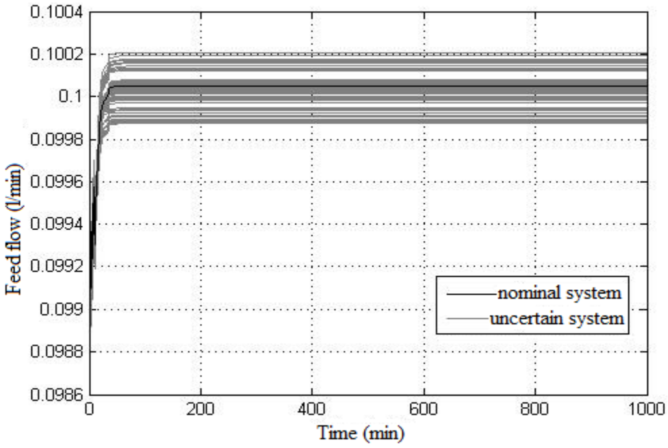

Fig. 11. Closed loop column feed flow evolution

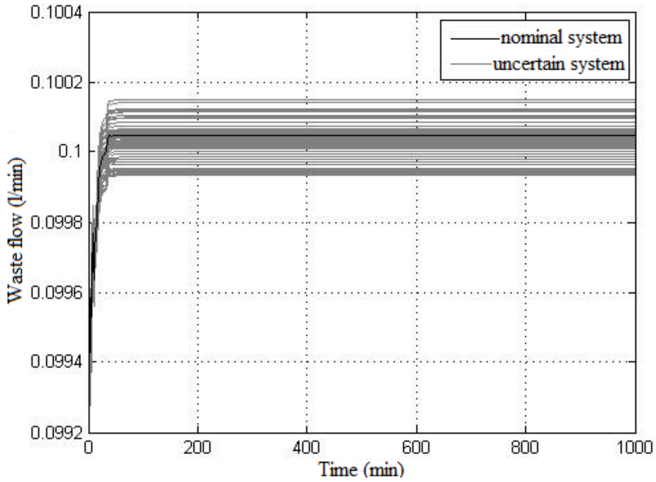

Fig. 12. Closed loop column waste flow evolution

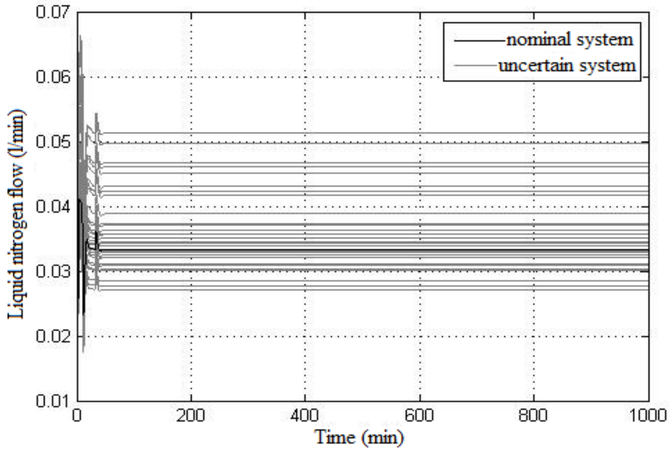

Fig. 13.Closed loop liquid nitrogen flow evolution

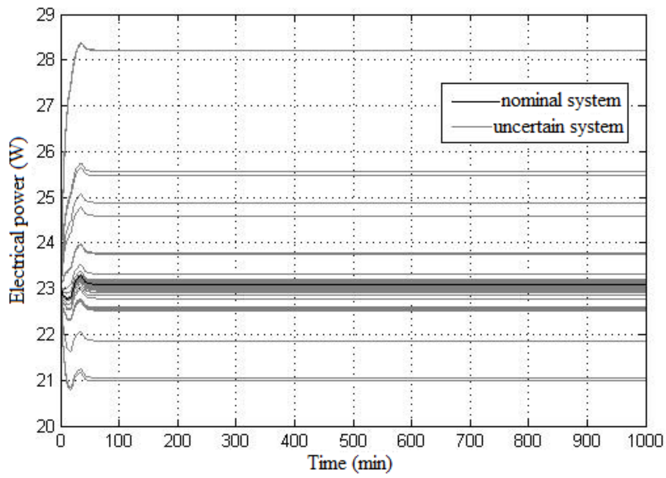

Fig. 14.Closed loop electrical power evolution

4. TRACKING AND DISTURBANCE REJECTION SOLUTION

The control strategy implemented consists of an inner loop feedback linearization technique and an outer loop linear robust controller. The inner loop is designed in such way that it yields the nonlinear system in (2) into a linear one. Then for the linear system obtained a robust controller is designed. Combined with this robust controller a feed-forward strategy is implemented in order to reject the two disturbances.

The output of the nonlinear system given in (2) can be chosen as $y(x) = \lambda(x) = [x_1(x) \quad x_2(x) \quad x_3(x) \quad x_4(x)]$. Given such choice for the controlled outputs, the sum of the relative degrees of each function $\lambda_i(x)$ is $r_1 + r_2 + r_3 + r_4 = 4$, equal to the number of states. The decoupling matrix of the system in (2) is:

$$M = \begin{bmatrix} k_{21} & -k_{31} & 0 & 0 \\ k_{32} & -k_{42} & 0 & k_{12} \\ 0 & 0 & k_{23} & 0 \\ k_{24} & -k_{34} & 0 & -k_{44}x_4 \end{bmatrix} \qquad (3)$$

In a classical approach, feedback linearization leads to a linearized state space system, $\dot{x}_f = A_f x_f + B_f w$, with w a linear control, obtained using a linear control law given by, $u = \alpha_f(x) + \beta_f(x)w$ and a state transformation given by $x_f = \Phi_f(x)$.

The control law for the nonlinear system in (2) would be given by :

$$\alpha_f(x) = -M^{-1}(x)[L_f^{r_1}\lambda_1(x).......L_f^{r_4}\lambda_4(x)]^T \qquad (4)$$

$$\beta_f(x) = M^{-1}(x) \qquad (5)$$

A new feedback linearization approach that ensures robust stability of the nonlinear closed loop system (Guillard, et al., 2000), is based on a linearized system around an equilibrium point, chosen for the nonlinear system in (2) as:

$$x_0 = [0.715 \quad 0.84 \quad 0.4 \quad 0.037]^T \qquad (6)$$

computed for an electrical power of 23.1W, a nitrogen flow of 0.033l/min, a feed flow and waste flow of 0.1 l/min, under nominal operating conditions and without disturbances acting on the column.

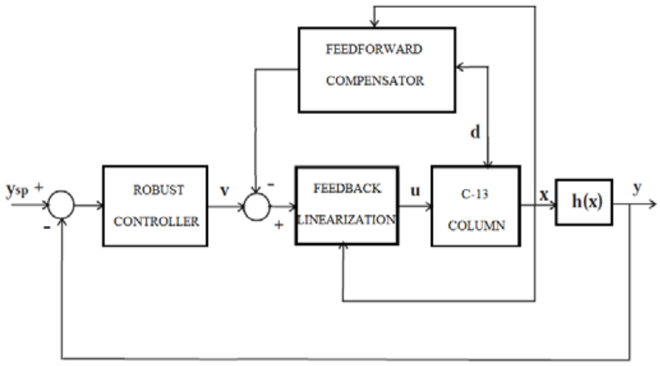

Fig. 15. Closed loop control scheme including the feed-forward compensator

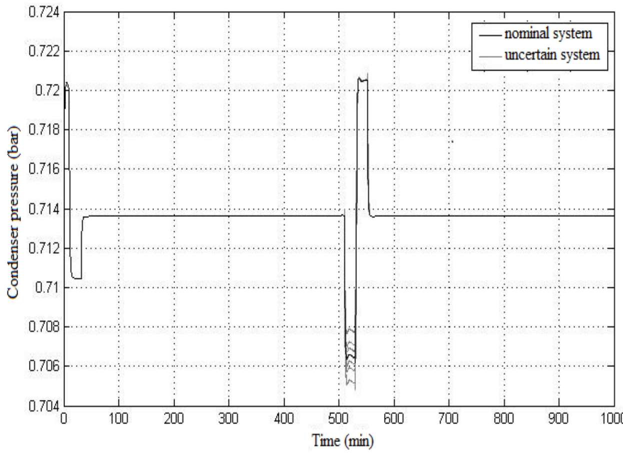

Fig. 16. Closed loop condenser pressure evolution considering a vacuum pressure disturbance

Previous experiments on the column show that an optimum isotope transfer rate occurs under this circumstances. The constraints imposed for the design of a nonlinear robust controller refer mainly to the possible input range: an electrical power between $(19 \div 30)$ W, a liquid nitrogen flow to the condenser of $(0 \div 0.08)$ l/min, and feed and waste flows of $(0 \div 0.35)$ l/min. The constraints mentioned are imposed by the functional and constructive aspects of the pilot plant, in order to avoid the column flooding (Pop, et al., 2008).

The linearized system is obtained in a similar manner as with the classical approach. The linearizing control law has the form:

$$u = \alpha_r(x) + \beta_r(x)v \tag{7}$$

with v a linear control and a state transformation given by the mathematical equation, $x_r = \Phi_r(x)$, which in this case is $x_r = \Phi_r(x) = [x_1 \quad x_2 \quad x_3 \quad x_4]^T$. The computation steps to determine the linearized system are as follows (Franco, et al., 2006; Guillard, et al., 2000): $\alpha_r(x) = \alpha_f(x) + \beta_f(x)LT^{-1}\Phi_f(x)$, $\beta_r(x) = \beta_f(x)R^{-1}$, with $R = M^{-1}(x_0)$, $L = -M(x_0)\partial_x \alpha_f(x_0)$, $T = \partial_x \Phi_f(x_0)$ and $\Phi_r(x) = T^{-1}\Phi_f(x)$.

The matrices to perform feedback linearization are:

$$L = \begin{bmatrix} -0.981211 & 0 & -0.227379 & 0 \\ 0 & -0.984876 & -0.0638814 & 0 \\ 0.000489 & 0 & -0.0042027 & 0 \\ 0 & 0 & 0.0192 & -0.205906 \end{bmatrix} \tag{8}$$

$$R = \begin{bmatrix} -15.521 & 0.614503 & 0 & 21.811 \\ -15.407 & 0.202432 & 0 & 7.185 \\ 0 & 0 & 25.084 & 0 \\ -3.094 & 11.200 & 0 & -2.167 \end{bmatrix} \tag{9}$$

$$T = I_{4\times 4} \tag{10}$$

The linearized system is (Pop, et al., 2010):

$$\dot{x}_r = A_r x_r + B_r v \tag{11}$$

$$B_r = g(x_0) = \begin{pmatrix} k_{21} & -k_{31} & 0 & 0 \\ k_{32} & -k_{42} & 0 & k_{12} \\ 0 & 0 & k_{23} & 0 \\ k_{24} & -k_{34} & 0 & -k_{44}x_{40} \end{pmatrix} \tag{12}$$

$$A_r = \begin{pmatrix} \frac{-4x_{10}^3}{T_s} & 0 & -\frac{k_{11}}{2x_{30}^{\frac{3}{2}}} & 0 \\ 0 & \frac{-2x_{20}}{T_j} & -2k_{22}x_{30} & 0 \\ k_{13}e^{-x_1} & 0 & -\frac{2x_{30}}{T_N} & 0 \\ 0 & 0 & k_{14} & \frac{1}{T} \end{pmatrix} \tag{13}$$

The linear H_∞ controller is designed using the McFarlane-Glover method (McFarlane, et al., 1989; Skogestad, et al., 2007) with loop-shaping that ensures the robust stabilization problem of uncertain linear plants, given by a normalized left co-prime factorization.

The choice of the weighting matrix corresponds to the performance criteria that need to be met. Despite robust stability, achieved by using a robust H_∞ controller, all process outputs need to be maintained at their setpoint values as mentioned in Section 2 above. To keep the outputs at the prescribed setpoints, the steady state errors have to be reduced. The choice of the integrators in the weighting matrix *W* above ensure the minimization of the output signals steady state errors. To keep the controller as simple as possible, only a pre-weighting matrix is used (Skogestad, et al., 2007). The resulting robust controller provides for a robustness of 36%, corresponding to a value of gamma of $\gamma = 2.71$.

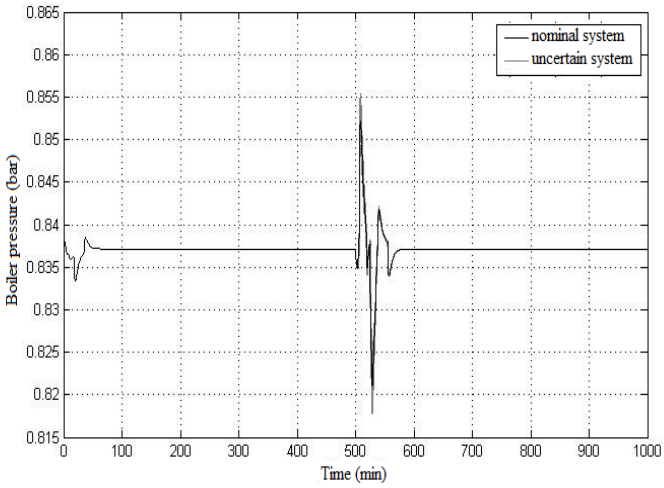

Fig. 17. Closed loop boiler pressure evolution considering a vacuum pressure disturbance

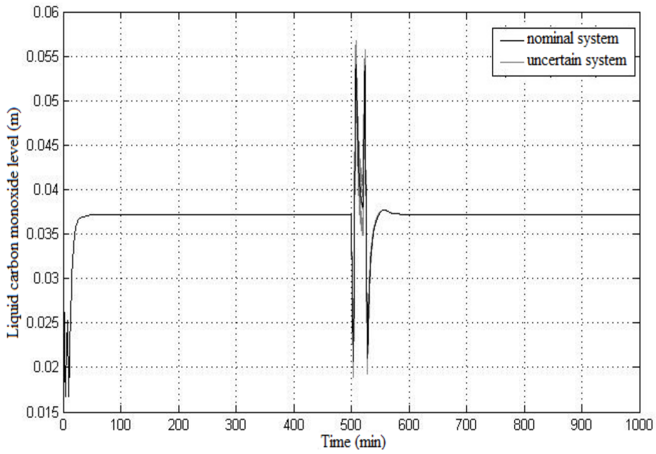

Fig. 18. Closed loop liquid carbon monoxide level evolution considering a vacuum pressure disturbance

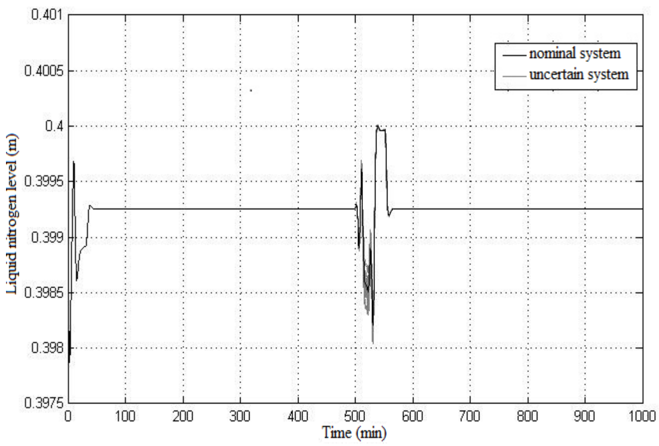

Fig. 19. Closed loop liquid nitrogen level evolution considering a vacuum pressure disturbance

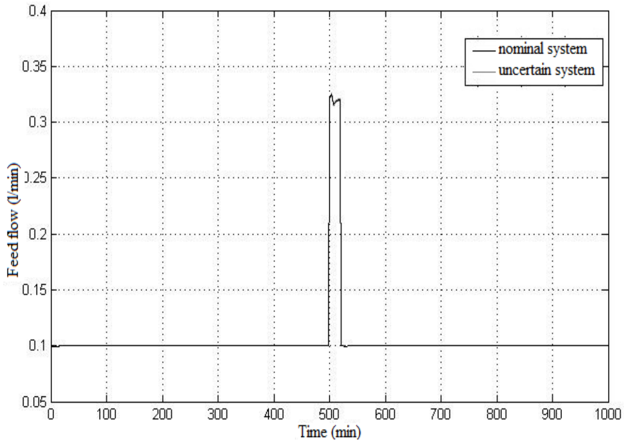

Fig. 20. Closed loop feed flow evolution considering a vacuum pressure disturbance

The loop-shaping $P_s(s) = W(s)P(s)$, with $P(s)$ the matrix transfer function of the linear system given in (10), is done with the weighting matrix, W:

$$W = \text{diag}\left(\frac{50}{s}, \frac{10}{s}, \frac{8}{s}, \frac{40}{s}\right) \quad (14)$$

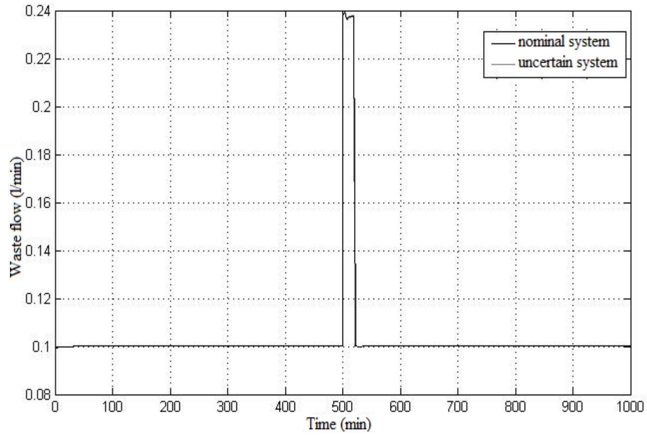

Fig. 21. Closed loop waste flow evolution considering a vacuum pressure disturbance

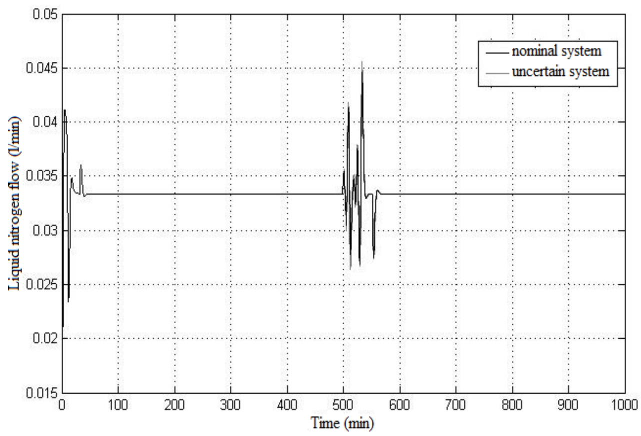

Fig. 22. Closed loop liquid nitrogen flow evolution considering a vacuum pressure disturbance

The nonlinear closed loop control scheme is given in figure 6. Simulations of the closed loop scheme were performed considering also time delays in the nonlinear model, such as 35 min for output x_1 when input A is applied and 18 min for input E; 32 min for output x_2 corresponding to input A and 10 min for input E; 4 min for output x_4, if input A is applied and 8 min for input E. The simulations of the closed loop nonlinear system under nominal parameter values are given in Figures 7-14, as well as the simulations considering the uncertain family of nonlinear closed loop system.

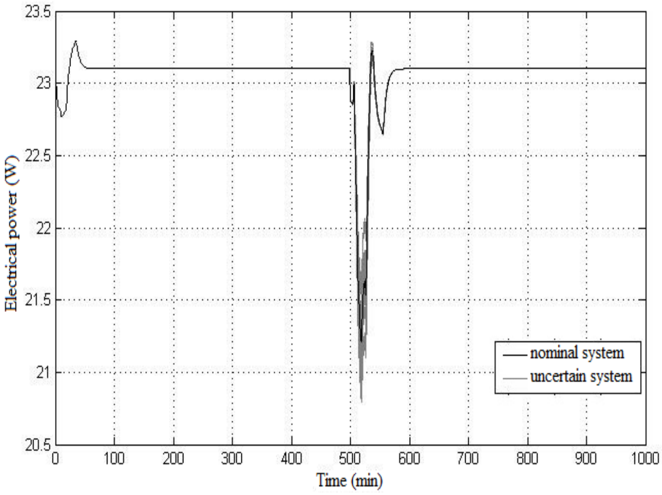

Fig. 23. Closed loop electrical power evolution considering a vacuum pressure disturbance

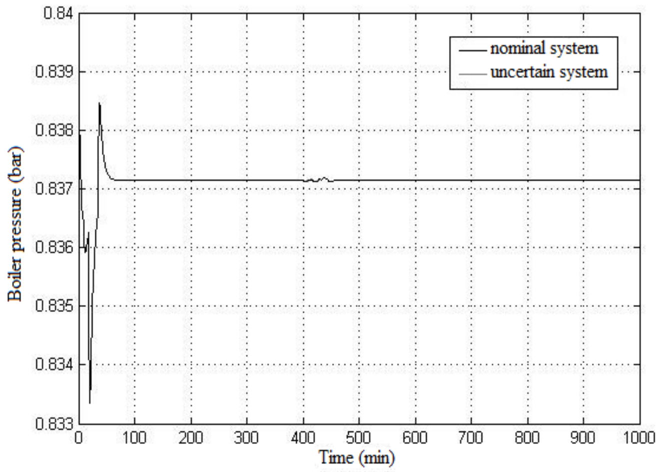

Fig. 24. Closed loop boiler pressure evolution considering a product flow disturbance

The results, presented as Matlab, Simulink simulations, show that with all the considered parameter variations the closed loop system controlled by the McFarlane-Glover regulator associated with the feedback linearization, behaves as desired, since the performance of the entire family of nonlinear systems tested (simulations presented as grey "-"lines) remain close to the nominal values (simulations presented as black "-" lines), prescribed as the desired operating conditions of the column.

The robust performance of the nonlinear uncertain system is maintained for $T_s, T_j, k_{11}, k_{12}, k_{24}, k_{34}, k_{44}$ ranging between $\pm 5\%$, $k_{13}, k_{23}, k_{31}, k_{21}, k_{32}, k_{42}, k_{22}, T_N$ ranging between $\pm 20\%$, k_{14}, T between $\pm 7\%$ and k_{41}, k_{52}, k_{33}, k_{54}, k_{64} between $\pm 25\%$.

A degradation of the robustness occurs, mainly because of the overlooking of the delay times when designing the controller.

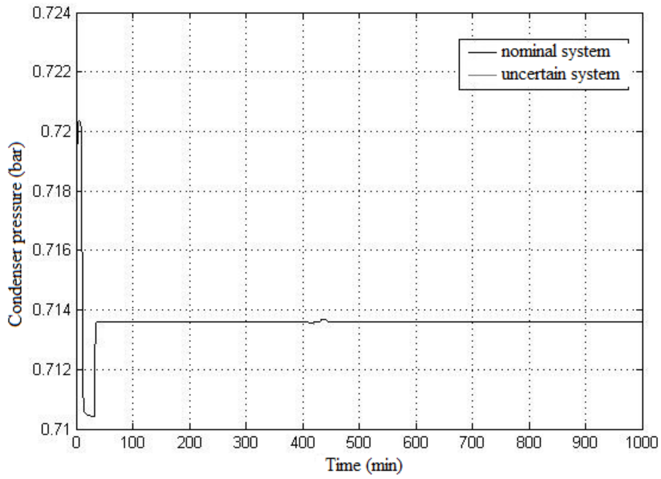

Fig. 25. Closed loop condenser pressure evolution considering a product flow disturbance

The two disturbances acting on the process are the product flow (carbon monoxide enriched in the ^{13}C isotope) and the vacuum pressure. If a product variation has minor consequences upon the isotope separation process, variation of the vacuum pressure- especially a drop of the vacuum- will have disastrous effects upon the process, by modifying the column temperature and implicitly the isotope separation coefficient. Both disturbances are measurable, a fact that simplifies greatly the problem of rejection. Most feed-forward strategies designed for nonlinear systems are based on classical feedback linearization theory (Daoutidis, et al., 1989). To maintain the advantages of the feedback linearization theory described in this paper and proposed by (Franco, et al., 2006), a special type of feed-forward compensator needs to be designed. The paper presents a simple technique to design this disturbance compensator in order to ensure the mathematical background for the feedback linearization method as proposed by (Franco, et al., 2006). First, the relative degrees of the disturbances to each output are:

$$r_{x_1} = 1 \quad r_{x_2} = 1 \quad r_{x_3} = 1 \quad r_{x_4} = 1 \qquad (15)$$

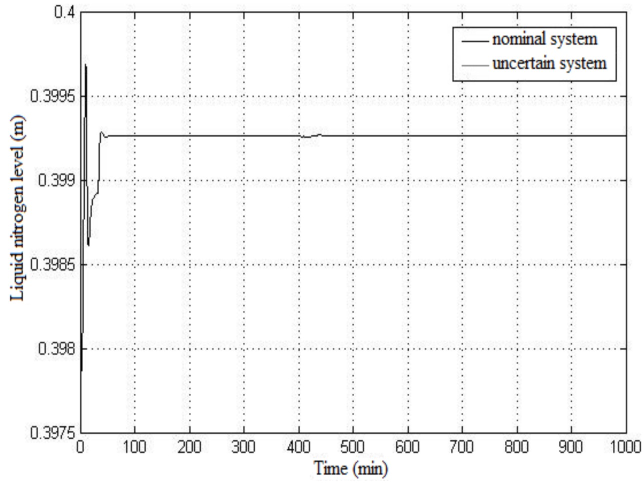

Fig. 26. Closed loop liquid nitrogen level evolution considering a product flow disturbance

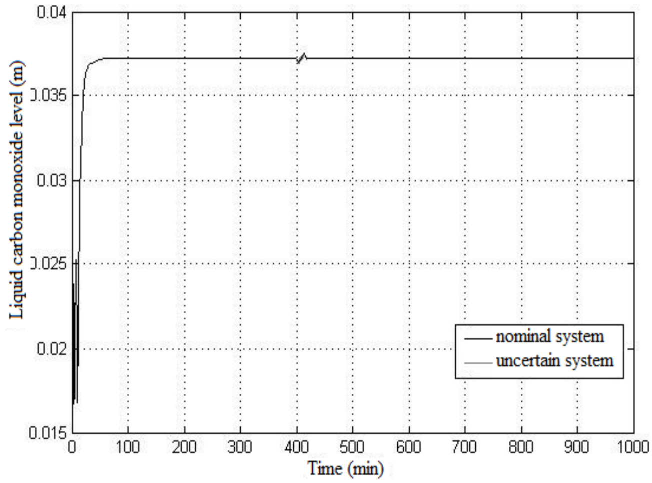

Fig. 27. Closed loop liquid carbon monoxide level evolution considering a product flow disturbance

Under this conditions, taking into account that the relative degrees of the disturbances to the outputs are equal to those of the inputs, decoupling and disturbance rejection are both possible using a modified feed-forward structure as:

$$u = \alpha_r(x) + \beta_r(x)v - \gamma_r(x)d \qquad (16)$$

with $\alpha_r(x)$ and $\beta_r(x)$ having the same form as given before and $\gamma_r(x) = M^{-1}(x)D(x_0)$ representing the feed-forward structure, with:

$$D(x) = \begin{bmatrix} k_{41} & 0 & 0 & 0 \\ k_{52} & 0 & 0 & 0 \\ -k_{33} & 0 & 0 & 0 \\ -k_{64} & -k_{54} & 0 & 0 \end{bmatrix} \qquad (17)$$

the matrix being extended in order to facilitate the mathematical approach. As a consequence, vector d, above, is extended to include the supplementary disturbances, d_1 and d_2:

$$d = [p_{vac} \quad P \quad d_1 \quad d_2]^T \qquad (18)$$

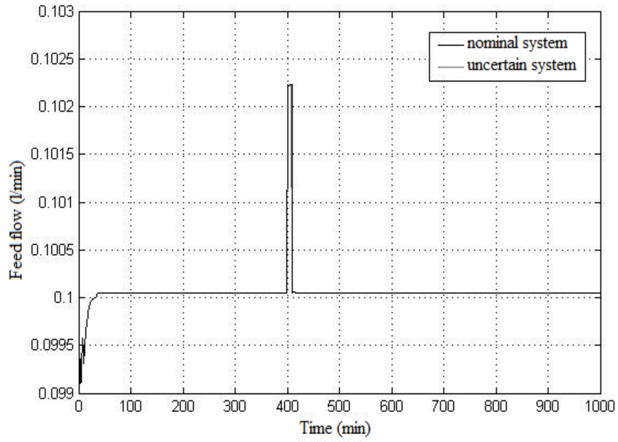

Fig. 28. Closed loop feed flow evolution considering a product flow disturbance

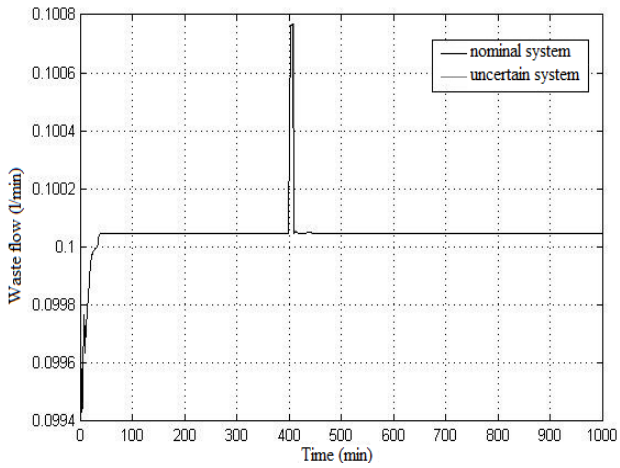

Fig. 29. Closed loop waste flow evolution considering a product flow disturbance

The control scheme given in figure 6 is modified to include the disturbance rejection strategy, as given in figure 15. Nonlinear closed loop simulations – considering the delay times and a disturbance in the vacuum pressure are presented in figures 16-19. The vacuum pressure increases from nomial value of $2.5 \cdot 10^{-5}$ up to $1.4 \cdot 10^{-3}$, at 500 min of column operation, acting for 20 min. A larger action of the disturbance cannot be counteracted by the controller, under the input constraints presented previously.

The simulations show the nominal case, as well as uncertainty situations regarding the disturbance parameters: a variation of $\pm 20\%$ for k_{41}, k_{52}, k_{33}, and a variation of $\pm 10\%$ for k_{64}. The results presented prove the performance of the feed forward structure designed , however the effort to reduce the effect of the disturbance is considerably high, as seen in figures 20-23. As far as the product outflow is concerned, the disturbing effect is much smaller as compared to the first disturbance presented. Figures 24-31 present the outputs and the inputs of the process, considering the product flow necessary for isotopic analysis.

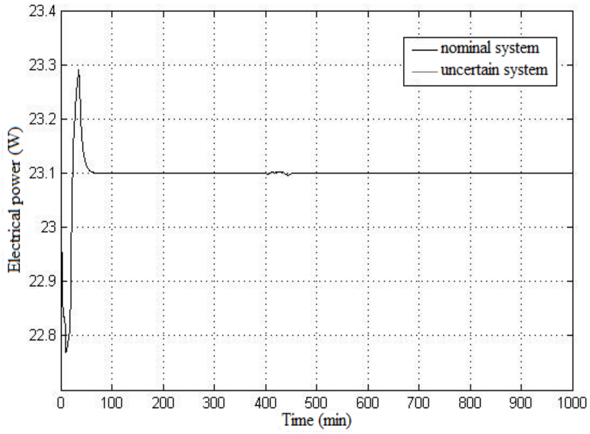

Fig. 30. Closed loop electrical power evolution considering a product flow disturbance

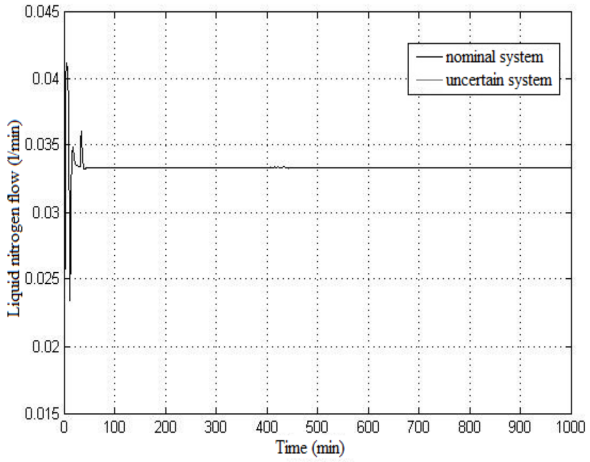

Fig. 31. Closed loop liquid nitrogen flow evolution considering a product flow disturbance

Since the quantity of product necessary to carry on isotopic analysis is small, the simulations present an hypothetical situation in which product collection starts at 400 min of column operation and aquisition lasts for 10 minutes. Simulations show the nominal case, as well as a $\pm 20\%$ deviation for k_{54} parameter, weighting the disturbance in the nonlinear model in (2).

5. CONCLUSIONS

The robust controller designed and the feedback linearization method used, ensure the robust stability of the nonlinear system, despite parameter uncertainties. Also, the robust performance for the parameter uncertainties mentioned is maintained. Additionally, the proposed feed-forward design proves to be successful in disturbance rejection. However, for greater parameter variations than considered the system no longer possesses the robust performance property.

The constraints imposed on the control signals do not allow for the output specifications to be met considering the controller designed and the simplifications done when designing it. The overlooking of the delay times in the process when designing the control strategy proves to be the main source for robustness degradation. Better results should be obtained using also a delay time compensator combined with the feedback linearization strategy.

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