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CONTINUOUS TIME IDENTIFICATION AND DECENTRALIZED PID CONTROLLER OF AN AEROTHERMIC PROCESS

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Abstract- The interactions between input/output in multivariable processes represent a major challenge in the design of decentralized controllers. In this paper, a simple method for the design of decentralized PID controller is proposed. It consists to combine the conventional PID controller with the static decoupler approach. For each single loop, the individual controller is independently designed by applying the internal model control (IMC) tuning rules. To demonstrate the effectiveness of the proposed method, the PID controller with and without decoupling is implemented on an aerothermic process. It is a pilot scale heating and ventilation system equipped with a heater grid and a centrifugal blower, fully connected through the Humusoft MF624 data acquisition system for real time control. The outcome of the experimental results is that the main

control objectives, such as set-point tracking and interactions rejection are well achieved. The experimental results have shown that the proposed method provides a significant improvement compared to conventional PID controller.

Index terms: Continuous-time identification, aerothermic process, decentralized PID controller, static decoupling, TITO control systems.

I. INTRODUCTION

The heating and ventilation system plays an important role in many industrial sectors including chemical, mineral, drying and distillation processes, as well as pharmaceutical and agro alimentary production units. It is argued that the temperature control is no more a challenging control problem in most of these applications. Nevertheless, some practical issues in many temperature control applications stimulate new developments and further investigations [1-5].

For education and training purposes, many aerothermic processes are available. They highlight most heating and ventilation problems, and they are widely referenced in the process control literature. Different prototypes of these processes have been used to check new control strategies and many results were reported in the single variable control cases [6-10].

As most industrials multivariable processes, the aerothermic processes are generally subject to significant interactions between its main variables. However, they were not explicitly considered in most reported control. Worth to mention herein that the basic factory control system delivered with most of aerothermic processes is restricted to the classical analog PID controller without taking into account of interactions between its main parameters [11].

In this paper, we highlight further aspects of multi-loops PID controller which consist to associate this conventional controller with the partial static decoupler approach in order to eliminate the interactions between the main aerothermic process parameters. In this synthesis, a multivariable transfer function is identified using the numeric Direct Continuous-Time Identification (DCTI) approach [12]. This technique has attracted an increasing attention of several researchers in the last few years [13-18]. It provides a robust and accurate method for the identification of dynamical systems under the influence of perturbations. Among the advantages of the DCTI methods, we mention its ability to deal with multi-input multi-output identification in a straightforward manner from process experimental data and the ease of use due to the small number of parameters which have to be chosen by the user.

The paper content is organized as follows: Section II introduces the description of the aerothermic process and underlines the interaction between its main variables. Section III discusses the multivariable continuous-time identification, which represents the first step in the design of the controllers. The decentralized PID controller is introduced in section IV. Its parameters are calculated by using the IMC tuning rules. In this section, we recall the main steps of static decoupler. Section V reports the experimental control results of the aerothermic process under set-point change of the ventilator speed in order to show its impact on the air temperature when the PID controller, with and without static decoupler, is applied. Robustness of the decentralized PID controller is also discussed and a final conclusion is given.

II. AEROTHERMIC PROCESS DESCRIPTION

The considered pilot scale aerothermic process [11], is shown as a schematic diagram in figure 1 and depicted in a three dimensional view in figure 2. It has the basic characteristics of a large process, with a tube through which atmospheric air is drawn by a centrifugal blower, and is heated as it passes over a heater grid before being released into the atmosphere.

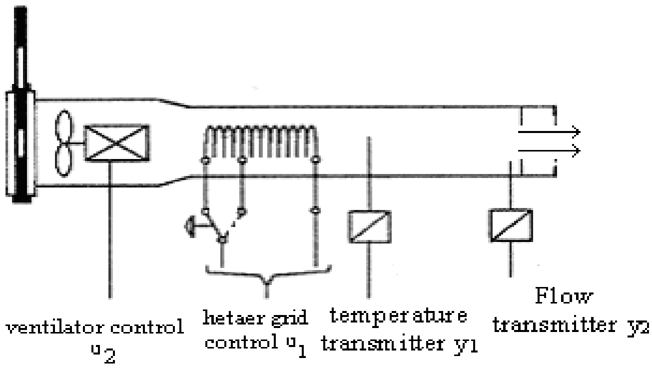

Figure 1. Schematic illustration of aerothermic process

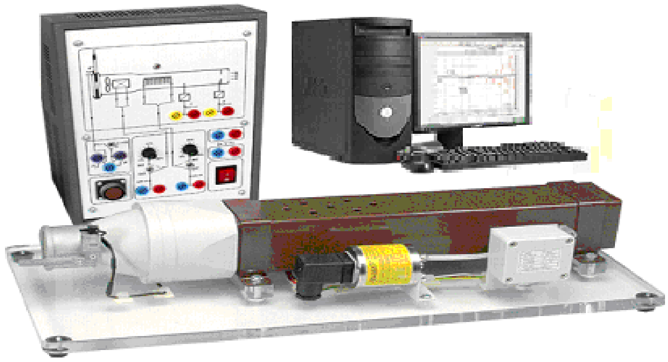

Figure 2. Three-dimensional view of aerothermic process

The command objective for the aerothermic process is to regulate the flow and the air temperature respectively by the PI and PID controllers with and without decoupling the interaction parameters. The temperature control is achieved by varying the electrical power supplied to the heater grid. There is an energized electric resistance inside the tube, and due to the Joule effect, heat is released by the resistance and transmitted, by convection, to the circulating air, resulting in heated air [6]. The air flow is adjusted by varying the speed of the ventilator.

This process can be characterized as a non-linear system. The physical principle which governs the behavior of the aerothermic process is the balance of heat energy. Hence, when the air temperature and the flow inside the process are assumed to be uniform, a linear system model can be obtained. This kind of aerothermic process is being used by many researchers to check their new control strategies [6-10].

As shown in the schematic of the aerothermic process, the system inputs, (u_1, u_2), are respectively the power electronic circuit feeding the heating resistance and the ventilator speed. The outputs, (y_1, y_2), are respectively the flow and air temperature. The input-output signals are expressed by a voltage, between *0* and *10* V, issued from the transducers and conditioning electronics. Figure 3 shows a Two-Input Two-Output (TITO) block diagram of the aerothermic process.

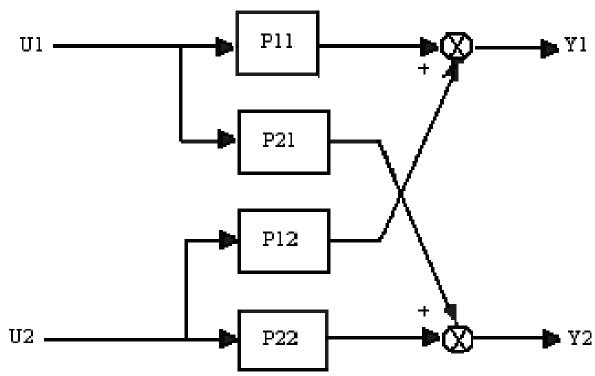

Figure 3: TITO Block diagram

The fundamental relationship between inputs and outputs signal are expressed as:

$$\begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix} = \begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \end{pmatrix} \quad (1)$$

where the P_{11}, P_{12}, P_{21} and P_{22} are the continuous process transfer functions which will be identified in the section III. P_{12} and P_{21} are called the process interaction.

To examine the possibility of interaction between the temperature and air flow, two experiments were carried out. In each case, the two process inputs were held constant and allowed to settle. If one of them undergoes a step change, the behavior of the other output will be observed to see if this change had any effect on it. Figure 4 shows the results from both experiments.

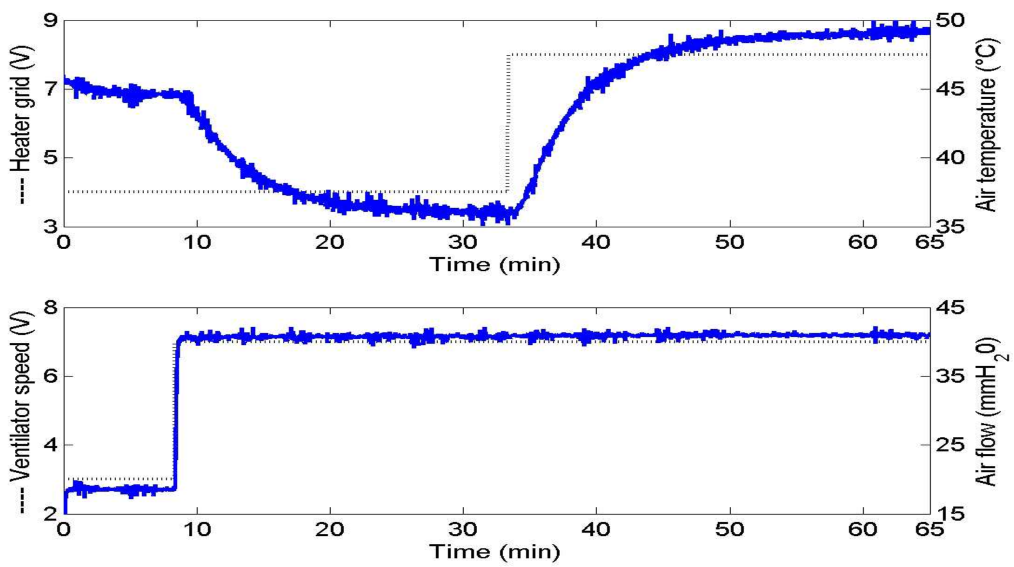

Figure 4. Interactions between the main variables of the aerothermic process

In the first half plot of this figure, the electric voltage supplied to the heater grid is held constant (at *4V*) and the ventilator speed undergoes a step change from *30%* to *70%* of its full range. The air temperature varied considerably from *4V* (*45°C*) to *2V* (*35°C*). The second half plot shows the results when the ventilator speed is held constant and the electric voltage of the heater grid undergoes a step change, from *40%* to *80%* of full range. As can be seen, the air temperature is varied accordingly but the air flow is remained unaffected.
These results show that the air temperature behavior depends also of the operating conditions of the air flow. Hence, the change in air temperature behavior is provided by two effects: a direct effect, by the heater grid and indirect effect via the ventilator speed. Our main aim is then to eliminate the indirect effect.
Equation 2 summarizes this relationship in continuous-time transfer function form.

$$\begin{pmatrix} Y_1(s) \\ Y_2(s) \end{pmatrix} = \begin{pmatrix} P_{11}(s) & P_{12}(s) \\ 0 & P_{22}(s) \end{pmatrix} \begin{pmatrix} U_1(s) \\ U_2(s) \end{pmatrix} \quad (2)$$

Therefore, the figure 3 takes the following new representation:

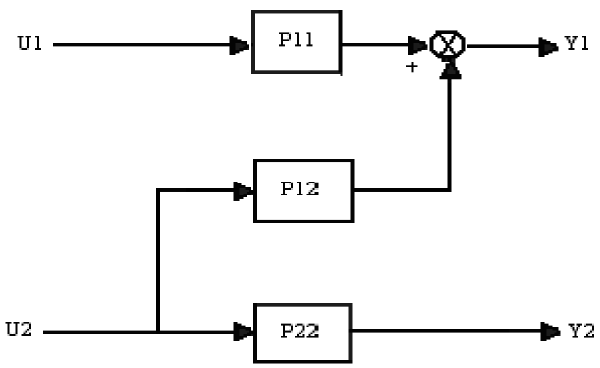

Figure 5: Partial interaction TITO Block diagram

III. CONTINUOUS-TIME IDENTIFICATION

System identification is an experimental approach to determine the transfer function or equivalent mathematical description for the dynamic of an industrial process component by using a suitable input signal. This approach represents the first step in the design of a controller.
From a conceptual standpoint, the modeling of most mathematical models of industrial processes is formulated in terms of continuous-time (CT) differential equations using the

physicochemical laws. Nonetheless, in the past, the majority of system identification schemes have been based on discrete-time (DT) models. Their corresponding CT models are obtained indirectly from the existing DT models.

In fact, the development of CT model identification techniques originated in the last century [19]. However, it has attracted an increasing attention of several researchers in the recent years [13-16]. This interest is due to the ability of these approaches to provide consistent results even for an imperfect noise structure which is the case in most practical applications [16]. The early contributions on continuous-time identification can be found in [17-18].

For identifying a continuous-time model from discrete sampled data, there exist two main approaches. The first, namely the indirect approach, it consists to estimate from the sampled data, an initial DT model and then convert it into a CT model using a standard algorithm for discrete to continuous-time conversion. The second, namely the direct approach, which formulates the identification of the CT model directly based on samples of the measured CT signal. The main computational tools of this approach are based on the Refined Instrumental Variable method for Continuous-time Systems (RIVC) and its Simplified version (SRIVC) that are discussed in detail by [20].

In order to generate estimation and validation data for system identification, an experiment is performed. Data set used for the parameter identification step is build up with Pseudo Random Binary Sequence (PRBS) signals which are applied simultaneously to the two manipulated variables of aerothermic process. This data set and their correspondent outputs are displayed in figure 6. The sampling interval is $T_s=1$ second. The signals collected, via the *Humusoft MF624* data acquisition module, are yield in the interval (*0V, 10V*).

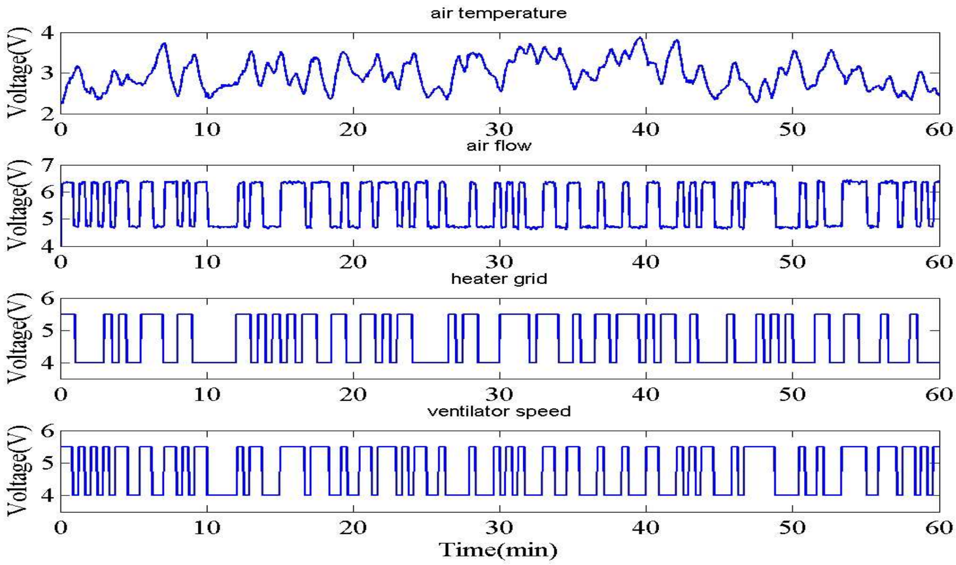

Figure 6: Data set for direct continuous-time identification

Based on the outcome analyses of section II, two loops will be considered in the aerothermic process identification. The first loop will be represented by Two-Inputs (u_1, u_2) and Single-Output (y_1), TISO. The second loop will be represented by a Single-Input (u_2) and a Single-Output (y_2), SISO. After the application of the DCTI approach on first half experimental sampled data of identification (i.e.: 30 minutes), the identified models of the aerothermic process suggests that the dynamic relationship between the measured inputs and the measured outputs for the two loops are linear and first-order plus dead time (FOPDT). The dead time is equal to 7 seconds for the first loop and is equal to 1 second for the second one. In general, the transfer function of FOPDT system is given by:

$$G(s) \quad = \quad \frac{Ke^{-Ds}}{Ts+1} \tag{3}$$

where *K* is the steady state gain, *D* is the dead time, and *T* is the time constant.

The identified transfer functions of the aerothermic process are given by the following system equation:

$$\begin{pmatrix} Y_1(s) \\ Y_2(s) \end{pmatrix} = \begin{pmatrix} \frac{0.7891}{34.0716s+1}e^{-7s} & \frac{-0.4616}{30.9789s+1}e^{-7s} \\ 0 & \frac{1.0888}{1.4302s+1}e^{-s} \end{pmatrix} \begin{pmatrix} U_1(s) \\ U_2(s) \end{pmatrix} \tag{4}$$

The negative gain in the interactive transfer function implies that the air temperature behaves in the opposite way. In fact, the interaction effect tends to reduce the air temperature when the flow increases.

To evaluate the quality of the estimated transfer function models, a cross-validation procedure has been applied to the remaining experimental data were not used to build the model. Cross-validation result is plotted in Figures 7. From this figure, it may be observed that there is a relatively good agreement between the measured and the simulated model output.

To confirm this validation, a numeric test is also applied to evaluate the models quality. It consists to use the coefficient of determination, given in equation 5, in order to determine the strength of the linear association between the simulated and measured output.

$$CD = 1 - \frac{\mathrm{var}(y - \hat{y})}{\mathrm{var}(y)} \tag{5}$$

Table 1 summarizes the results of the coefficient of determination for DCTI approaches.

Table1: Coefficient of Determination

	Coefficient of Determination
TISO	0.9914
SISO	0.9920

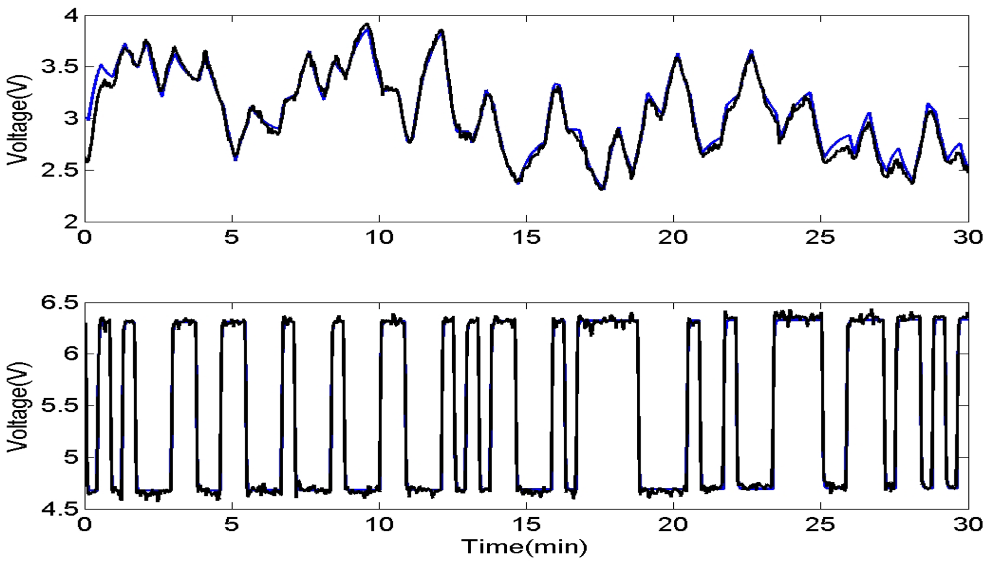

Figure 7: Cross-validation results (black: measured output; blue: simulated output)

As shown in both figure 7 and table 1, it appears a good similarity between the true system output and the identified one. Furthermore, the identified process has no modes associated with eigenvalues in the unstable region.

IV. DECENTRALIZED PID CONTROLLER

a. Decoupling control systems

As shown in section III, changes in second loop might cause an undesirable disturbance in first loop and hence cause y_1 to vary from its desired value. Therefore, the interaction caused by the second loop needs to be completely or partially eliminated. To do it, the aerothermic process must be decoupled into separate loops.

There exist two ways to see if a system can be decoupled. The first One is with mathematical models and the other is a more intuitive educated guessing method. The mathematical methods include the relative gain array (RGA) method, the Niederlinski Index (NI) and singular value decomposition (SVD) [21]. In this paper the SVD method is used to discuss the determination of whether the TITO control scheme can be decoupled to SISO ones. It starts with the steady state gain matrix of the process as shown in the following equation.

$$P = \begin{pmatrix} P_{11}(0) & P_{12}(0) \\ 0 & P_{22}(0) \end{pmatrix} \quad (6)$$

Using P, the calculation of the eigenvalues can be calculated by hand from the following equations [22]:

$$\beta_1 = s_1{}^2 = \frac{b + d + \sqrt{(b-d)^2 + 4c^2}}{2} \quad (7)$$

$$\beta_2 = s_2{}^2 = \frac{bd - c^2}{s_2{}^2} \quad (8)$$

where $b = P_{11}^2(0) + P_{12}^2(0)$; $c = P_{12}^2(0)\ P_{22}^2(0)$ and $d = P_{22}^2(0)$. s_1 and s_2 are the positive square roots of the respective eigenvalues. The condition number (CN) is defined as the ratio of the larger s_i to the smaller s_j:

$$\begin{cases} CN = \dfrac{s_1}{s_2} & if\ \ s_1 > s_2 \\ CN = \dfrac{s_2}{s_1} & if\ \ s_2 > s_1 \end{cases} \quad (9)$$

The greater the *CN* value, the harder it is for the system in question to be decoupled. A rule of thumb is that when $CN \geq 50$ the system is nearly singular and decoupling is not feasible [23].

In our case, $P = \begin{pmatrix} 0.7891 & -0.4616 \\ 0 & 1.0888 \end{pmatrix}$ and *CN = 1.7957*. Then the aerothermic processes can be quite decoupled into separate SISO systems.

Generally, there exist two decoupling approaches: the complete decoupling and the partial decoupling. In the complete decoupling, all decouplers are used. While in the partial decoupling; only some decouplers are used and the remainder decouplers are set equal to zero. Among the advantageous of the partial decoupling, we note its tendency to be less sensitive to modeling errors compared to the complete decoupling [22]. The partial decoupling is an attractive approach for control problems where one of the controlled variables is more important than the other or where one of the process interactions is absent. In the aerothermic process case, the partial decoupling is considered in order to eliminate the interactions caused by the second loop on the first one. Figure 8 shows this partial decoupling.

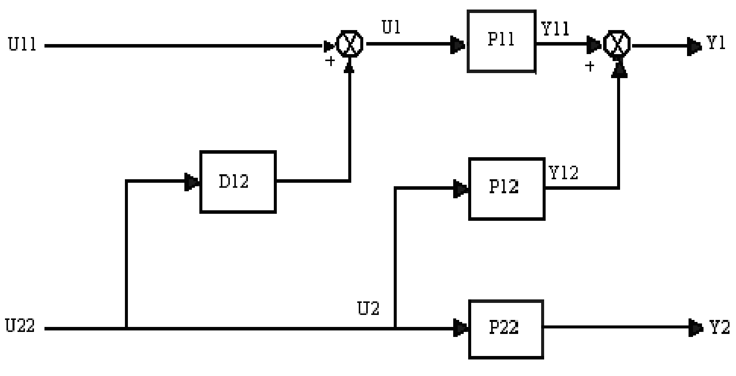

Figure 8: Decoupled system

From figure 8 we have the following equation:

$$Y_1 \quad = \quad P_{11}U_{11} + (P_{11}D_{12} + P_{12})U_2 \qquad (10)$$

To eliminate the interaction between U_2 and Y_1, the right half of the equation 10 must satisfy the following condition:

$$(P_{11}D_{12} + P_{12})U_2 \quad = \quad 0 \qquad (11)$$

To satisfy equation (11) it follows that

$$P_{11}D_{12} + P_{12} \quad = \quad 0 \qquad (12)$$

Solving for D_{12} gives an expression for the ideal decoupler,

$$D_{12}(s) \quad = \quad -\frac{P_{12}(s)}{P_{11}(s)} \qquad (13)$$

b. multivariable decentralized PID controller

In principle, decoupling control can provide two important points. In the first one, the control loop interactions will be eliminated. Consequently, the stability of the closed-loops system will be determined only by the stability characteristics of the individual feedback control loops. In the second one, if the set-point of a controlled variable is changed, it will not have an effect on the other controlled variables.

Several control approaches such as neural networks, model predictive control can resolve the multivariable control problems with or without severe interactions. However, these controls are used primarily on a higher level. In the lower level, improving the performance and robustness of a system can be made by the improvements in the separate proportional-differential-integral (PID) loops [24]. In this paper, the improvement is obtained by using the partial static decoupling where the design is based on the steady state process interactions. The design equations for the decoupler can be adjusted by setting (s = 0), i.e. the process transfer functions are simply replaced by their corresponding steady state gains. Hence, the expression for the ideal decoupler given by the equation 12 becomes:

$$D_{12} = -\frac{P_{12}(0)}{P_{11}(0)} = 0.5850 \tag{14}$$

Figure 9 shows the partial decoupling control system for the aerothermic process.

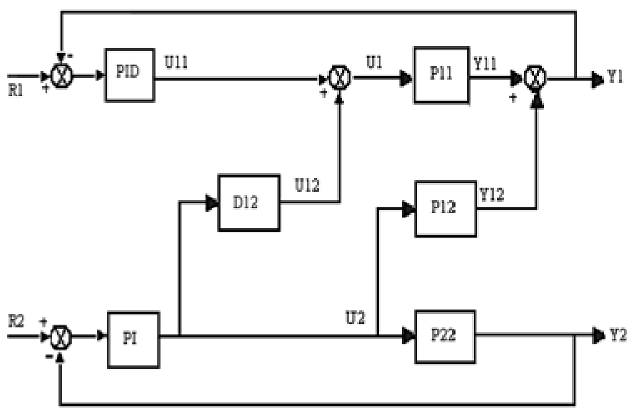

Figure 9: A partial decoupling control system

The PI controller is used to regulate the air flow since this loop has generally very fast dynamics and its measurement is inherently noisy; while, the air temperature is regulated by the PID controller. Once a partial decoupler is obtained, the PI and the PID controllers are designed separately for the two loops. Hence, as shown in figure 9, three controllers are used: two conventional feedback controllers, PID and PI, plus one decoupler, D_{12}. The input-signal to D_{12} decoupler, which is designed to compensate the undesirable process interactions, is the output signal from the feedback PI controller.

The continuous PID controller transfer function can be written as

$$u(t) \quad = \quad K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \qquad (15)$$

where *u(t)* is the manipulated variable, *e(t)* the error signal, K_p, T_i, and T_d represent proportional gain, integral gain and derivative gain respectively.

In the Laplace domain, this control equation can be written as:

$$U(s) \quad = \quad (K_p + \frac{K_i}{s} + K_d s)E(s) \qquad (16)$$

To calculate the PI and PID parameters, the Internal Model Control (IMC) tuning rules is adopted [25]. It is used most frequently in industrial processes because of its many advantages, including simplicity, robust performance, and its analytical form which is easier to implement in real time.

The PID controller parameters are given as follows:

$$\begin{aligned} K_p &= \frac{2T + D}{2K(D+\beta)} \\ K_i &= \frac{1}{K(D+\beta)} \\ K_d &= \frac{TD}{2K(D+\beta)} \end{aligned} \qquad (17)$$

where *K* represents the steady-state gain, *T* is the time constant, and *D* is the time delay of the system. β should satisfy $\beta > 0.2T$ and $\beta > 0.25L$ [26].

V. EXPERIMENTAL RESULTS

To illustrate the effectiveness of the proposed method, real-time experiments of the Decentralized PID controller with and without partial static decoupler have been performed on the aerothermic process. The robustness of Decentralized PID is evaluated by changing the set-point of the ventilator speed. Referring to equation 17, the parameters of the Decentralized PID and PI controllers for respectively the first and the second loop are given in the following table:

Table 2: parameters of the PID and PI controllers using IMC tuning rules

	proportional	differential	integral	β
First loop	1.9812	6.2881	0.0527	17.0350
Second loop	1.3633	0.7063	0	0.3003

Figure 10 and 11 present the results of multi-loop PI/PID controllers with and without static decoupler using IMC tuning rules. It is apparent from these figures that the proposed decentralized controllers provide a good performance. Their robustness and their effectiveness are confirmed by the elimination of the interaction effect on the air temperature variable compared to the controller without decoupler. It is obvious that the proposed controller affords a good robust performance consistently. We noted that there is no change in the behavior of the second loop parameters controlled by the PI with and without static decoupler. This can be justified by the fact that this loop is not infected by the first one represented by the air temperature and the heater grid. Which confirms quite the interaction test result obtained in section II.

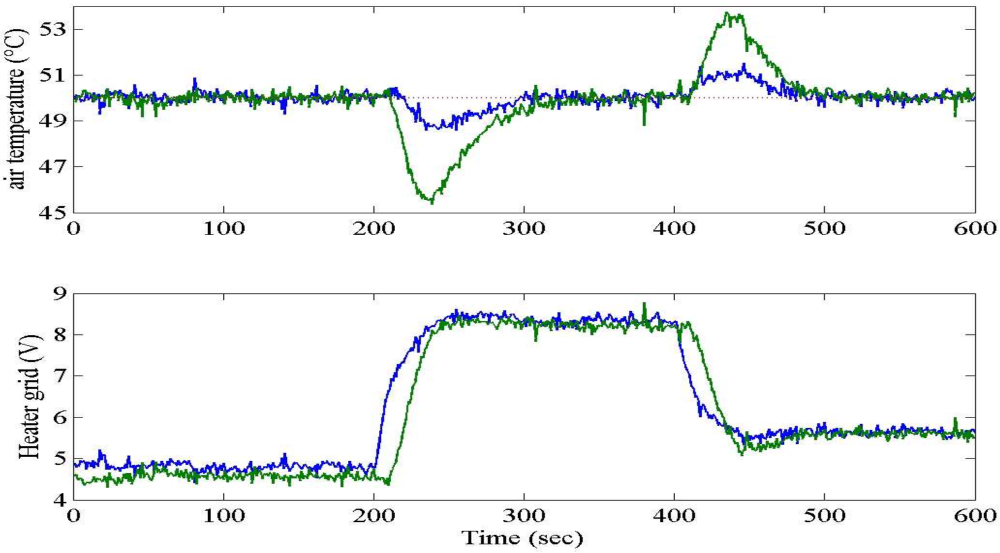

Figure 10: Top figure: closed-loop air temperature response; bottom figure: Closed-loop heater grid control response. (Blue: Decentralized PID controller, Green: conventional PID controller, Red: set-point signal).

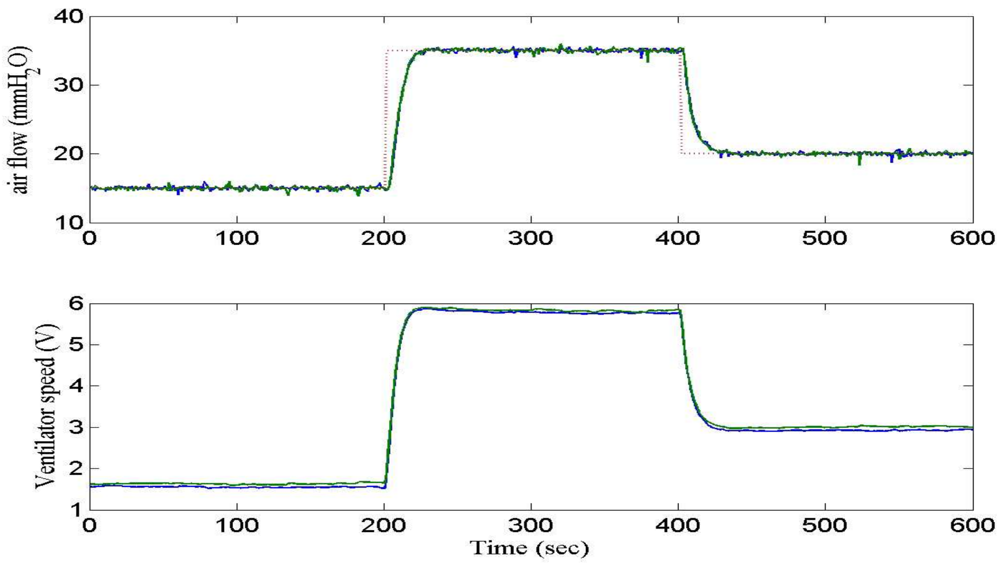

Figure 10: Top figure: closed-loop air flow response; bottom figure: Closed-loop ventilator speed control response. (Blue: Decentralized PI controller, Green: conventional PI controller, Red: set-point signal).

VI. CONCLUSIONS

In this paper, the aerothermic process has been successfully modeled by Direct Continuous-Time Identification (DCTI) approach. The strong interaction effect caused by the ventilator speed on the air temperature was reduced considerably by using a partial static decoupler. A Decentralized Proportional-Integrate-Derivative controller is implemented to this process. The comparison between the decentralized PID controller, with and without interaction, is analyzed. From this study, it can be clearly seen that the proposed control method is better than the conventional ones.

In conclusion, the use of decentralized controller obtained from the partial static decoupler demonstrates robust performance for tracking set point change and rejecting the interaction effect of the second loop on the first one. It constitutes a worth extension of the multi-loop control methods and an alternative to the basic classical control for these kind of processes used for both engineering education and research training.

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