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# DECENTRALIZED PI-D CONTROLLER APPLIED TO AN AEROTHERMIC PROCESS

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***Abstract- The aerothermic process is a pilot scale heating and ventilation system. It is equipped with a heater grid and a centrifugal blower, fully connected through the Humusoft MF624 data acquisition system for real time control. The interaction between its main variables is considered as challenging for mono-variable controllers. An abrupt change in the ventilator speed might cause an undesirable disturbance in the air temperature representing a factor that must be managed to conserve energy. To annul the effect of this interaction, this paper presents an experimental comparison between three forms of the PID controller: the conventional PID controller, the PI-D controller and its decentralized version. A multi-variable continuous state space model is obtained from on-line experimental data. The outcome of the experimental results is that the main control***

***objectives, such as set-point tracking and interactions rejection, are well achieved for the temperature and the air flow simultaneously.***

**Index terms*:* Decentralized PI-D Controller, PI controller, Derivative kick, Aerothermic Process, TITO control systems, static decoupler.**

## I. INTRODUCTION

Although many advanced control approaches have been introduced over the last 50 years, a large majority industrial control systems are still of the PID type. This success is due to effectiveness, operational simplicity and easy implementation of these controllers. However, this controller is not without disadvantage. Indeed, when there is an abrupt change in the set-point, the derivative term might become very large and thus provide a “derivative kick” to the control variable which might damage the actuators. This is also the case in the multi-variable processes where the interactions usually exist among the loops. An abrupt change in the set-point of one loop will be a large load disturbance to the other loops. To remove this disadvantage, several researchers were focused to restructure the PID controller so that the derivative term has moved into the feedback path and does not directly operate on reference changes [1-6]. Others researchers were interested in improving its tuning parameters in order to meet the industry expectations.

This case of problem occurs also in aerothermic processes. Indeed, an abrupt change in the air flow affects considerably the air temperature behaviour which represents a factor that must be managed for saving the energy [7]. It is argued that the temperature control is no more a challenging control problem in most applications. Nevertheless, some practical issues in many temperature control applications stimulate new developments and further investigations [7-14].

Besides the PID controller restructuration, decoupling the multi-variable 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 suddenly changed, it will not have a significant effect on the other controlled variables.

In [7], the aerothermic process is decoupled into two loops that were controlled separately by the conventional and the decentralized PID controller. The experimental results were very significant. In the present paper, the new formulation of a PID controller, named PI-D controller, is used not only to eliminate the “derivative kick” as mentioned in [4-5], but also to ensure the desired level of the temperature and the air flow of the aerothermic process by reducing the interaction effect between these two parameters.

Different prototypes of the considered process have been used to check new control strategies and many results were reported in the single variable control cases [7,15-18]. Worth to mention herein that the basic factory control system delivered with the process is restricted to classical analogue PID control [19]. The objectives of decentralized PI-D controller which are about reaching reference set-points for the temperature and the air flow, subject to effects of the interaction perturbations. These goals are achieved by manoeuvring the heating resistance and the ventilator speed of the aerothermic process.

In the synthesis of the decentralized PI-D controller, a multivariable transfer function is identified using the numeric Direct Continuous-Time Identification (DCTI) approach [7,20-21]. This technique has attracted an increasing attention of several researchers in the last few years [22-26]. 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 is organised as follows. Section II introduces the description of the aerothermic process and underlines the interaction between the main process variables. Section III discusses the multivariable direct continuous-time identification of the aerothermic process, which represent the first step in the design of the controller. Section IV presents the design of the decentralized PI-D controller. 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 operation under the interaction perturbation. Robustness of the Decentralized PI-D controller compared to the conventional ones is also discussed and a final conclusion is given.

## II. AEROTHERMIC PROCESS DESCRIPTION

The considered pilot scale aerothermic process [19], 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.

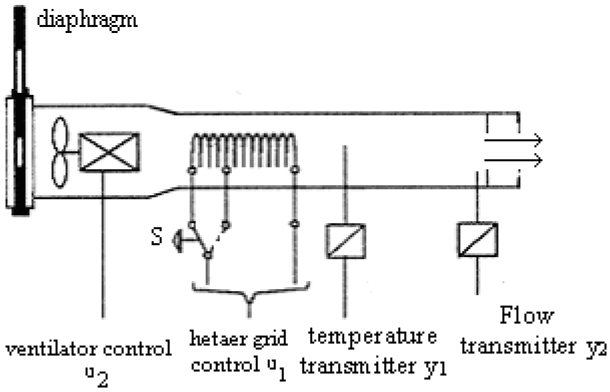


Figure 1. Schematic illustration of aerothermic process

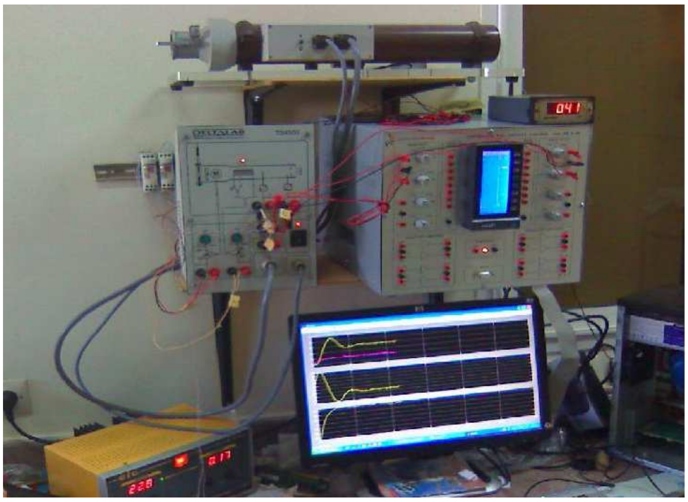

Figure 2. Three-dimensional view of aerothermic process and analog PID

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 [17]. 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 behaviour of the aerothermic process is the balance of heat energy. Hence, when the air temperature and the air 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 [7,15-18].

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 temperature and the air flow. The input-output signals are expressed by a voltage, between *0* and *10* V, issued from the transducers and conditioning electronics.

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 behaviour of the other output will be observed to see if this change had any effect on it. Figure 3 shows the results from both experiments.

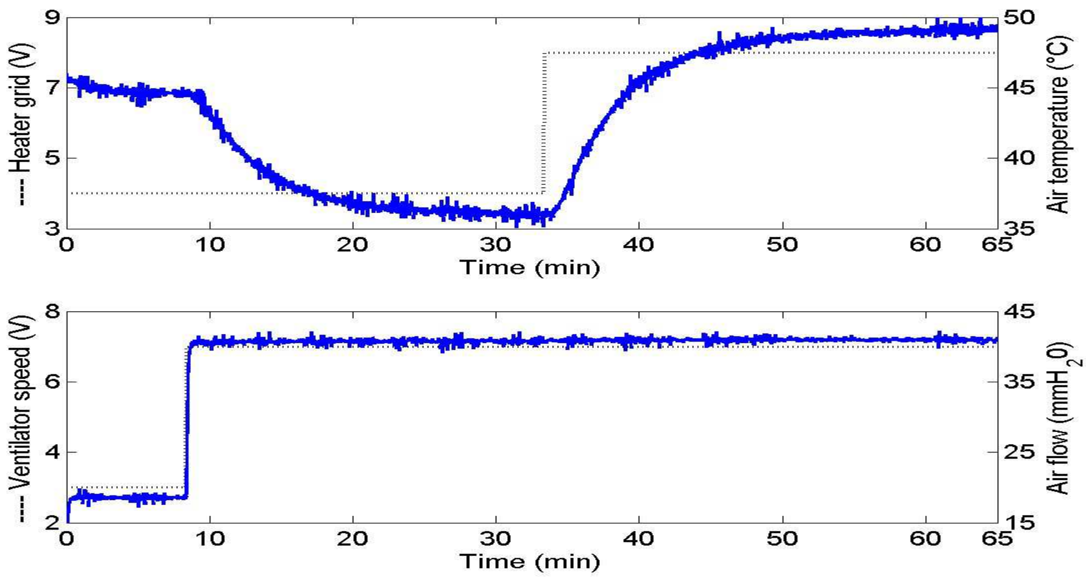


Figure 3. Interactions between the main variables of the aerothermic process

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 behaviour depends also of the operating conditions of the air flow. Hence, the change in air temperature behaviour 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.

The main objectives to applying the Decentralized P-ID controller are to searching for desired levels of the temperature and the air flow by reducing completely or partially the interactions effect.

## III. MATHEMATICAL MODELS

The 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 most controller.

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 4. 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).

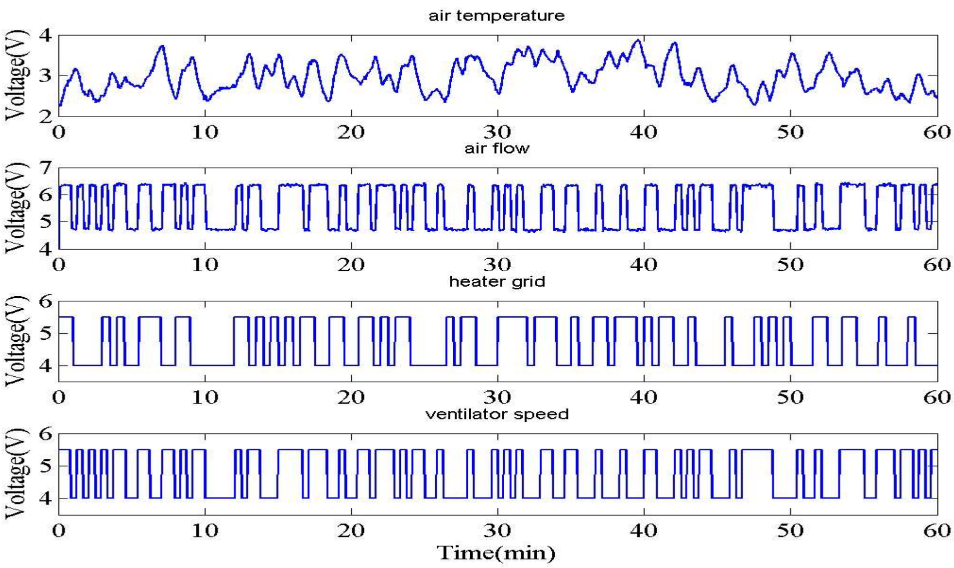


Figure 4: Data set for direct continuous-time identification

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). Its transfer function is given by the following equation:

$$G(s) = \frac{Ke^{-\theta s}}{\tau s + 1} \qquad (1)$$

where $K$ represents the steady-state gain, $\tau$ is the time constant, and $\theta$ is the time delay of the system.

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

$$\begin{pmatrix} Y_1(s) \\ Y_2(s) \end{pmatrix} = \begin{pmatrix} \frac{0.7891}{34.0716s+1}e^{-7s} & \frac{-0.4616}{30.9789s+1}e^{-7s} \\ 0 & \frac{1.0888}{1.4302s+1}e^{-s} \end{pmatrix} \begin{pmatrix} U_1(s) \\ U_2(s) \end{pmatrix} \qquad (2)$$

This equation can be shown as a schematic diagram in figure 5

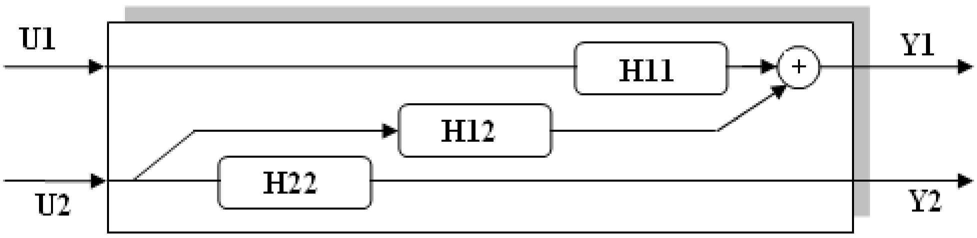


Figure 5: Schematic illustration of a partial interaction

where

$$H_{11}(s) = \frac{0.7891}{34.0716s+1}e^{-7s}$$

$$H_{22}(s) = \frac{1.0888}{1.4302s+1}e^{-s}$$

$$H_{12}(s) = \frac{-0.4616}{30.9789s+1}e^{-7s}$$

represent respectively the continuous process transfer functions of first loop, the continuous process transfer functions of the second loop and the continuous transfer function of the process interaction.

The negative gain in the interactive transfer function, $H_{12}(s)$, implies that the air temperature behaves in the opposite way. In fact, the interaction effect tends to reduce the air temperature when the air 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 6. From this figure, it may be observed that there is a relatively good agreement between the measured and the simulated model output. The identified model has been validated using the remaining experimental data which were not used to build it.

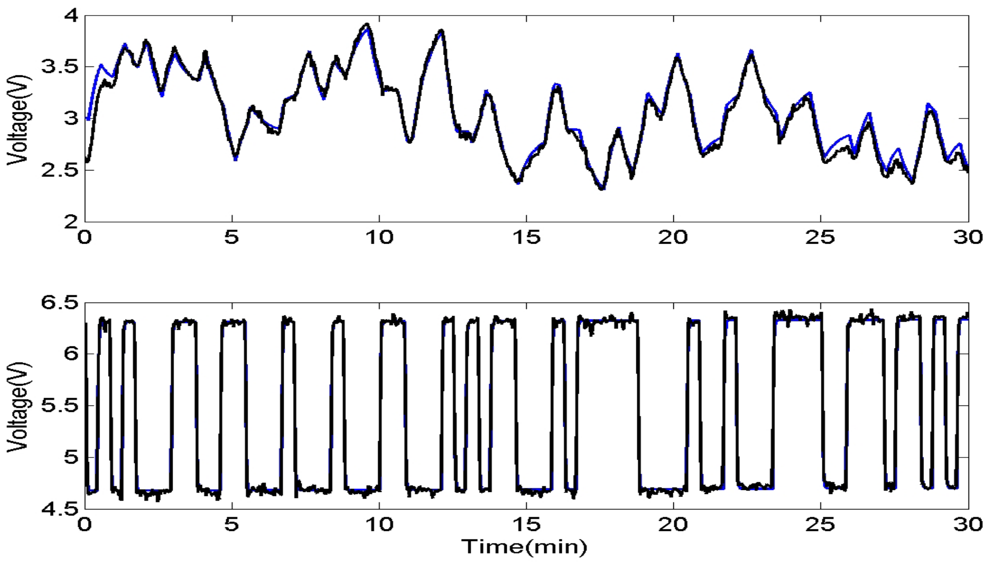


Figure 6: Cross-validation results (black: measured output; blue: simulated output)

## IV. DECENTRALIZED PI-D CONTROLLER

In the multi-variable processes where the interactions usually exist among the loops, a sudden change in the set-point of one loop will be a large load disturbance to the other loops. Hence, when these processes are controlled by the conventional PID controller without taking into account of these interactions, the derivative term can become very large and thus provide a “derivative kick” on the variable control. In the aerothermic process case, an abrupt change in the air flow affects considerably the air temperature behaviour. Therefore, the interaction caused by the second loop needs to be eliminated. To do it, the aerothermic process must be decoupled into separate loops.

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 modelling errors compared to the complete decoupling [27]. 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. This partial decoupling is represented by the Figure 7.

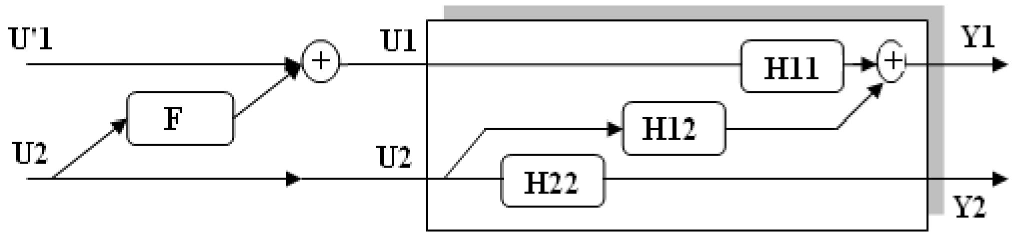


Figure 7: Decoupled system

where *F* represent the ideal decoupler.

To eliminate the interaction between U2 and Y1, after some simple mathematical manipulations, the expression for the ideal decoupler is given by the following expression [7]:

$$F(s) = \frac{-H_{12}(s)}{H_{11}(s)} \qquad (3)$$

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 3 becomes:

$$F = -\frac{H_{12}(0)}{H_{11}(0)} = 0.5850$$

In this paper, the decentralized PI-D controller is considered to reject the interaction effect between the temperature and the air flow. Its transfer function in the Laplace domain is given by the following equation [4]:

$$U(s) = K_c\left(1 + \frac{1}{\tau_i s} + \frac{w_d \tau_d s}{1 + \alpha \tau_d s}\right)E(s) + \frac{K_c \tau_d s}{1 + \alpha \tau_d s}(w_d - 1)Y(s) \qquad (4)$$

where *U(s)* is the manipulated variable, *Y(s)* is the output variable and *E(s)* the error signal. Parameters *Kc*, $\tau_i$, and $\tau_d$ represent proportional gain, integral gain and derivative gain respectively. $w_d$ is the parameter who can prevent the “derivative kick”, which happens when a step set-point change enters.

With $w_d$ =1, the equation 4 represents the conventional PID controller given by the following equation:

$$U(s) = K_c(1 + \frac{1}{\tau_i s} + \frac{\tau_d s}{1 + \alpha\tau_d s})E(s) \qquad (5)$$

But with $w_d$ =0, the equation 4 is transformed to a PI-D controller given by the following equation:

$$U(s) = K_c(1 + \frac{1}{\tau_i s})E(s) - \frac{K_c\tau_d s}{1 + \alpha\tau_d s}Y(s) \qquad (6)$$

As shown by the equation 6, the derivative action does not directly operate on reference changes. But, it is entirely applied to the process output; which represents the newness of the traditional PID controller restructuring.

To calculate the PI and PI-D parameters, the Internal Model Control (IMC) tuning rules is adopted [4]. 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 PI-D controller parameters are given by the table 1:

Table 1: IMC tuning rule

| controller | Tuning parameters | | | |
|---|---|---|---|---|
| | $Kc$ | $\tau_i$ | $\tau_d$ | $\lambda$ |
| PI | $\frac{2\tau+\theta}{2K\lambda}$ | $\tau+\frac{\theta}{2}$ | - | $\geq 1.7L$ |
| PI-D | $\frac{2\tau+\theta}{2K(\lambda+\theta)}$ | $\tau+\frac{\theta}{2}$ | $\frac{\tau\theta}{2\tau+\theta}$ | $\geq 0.25L$ |

where $K$ represents the steady-state gain, $\tau$ is the time constant, and $\theta$ is the time delay of the system.

## V. EXPERIMENTAL RESULTS

The Decentralized PI-D controller described in the previous section was first tested in simulation using the multi-variable model obtained from continuous-time identification. This investigation was done especially to evaluate the computational complexity of the controller and to find the controller tuning parameters before its implementation in the real aerothermic process.

To illustrate the effectiveness of the decentralized PI-D controller, real-time experiments of with and without partial static decoupler have been performed on the aerothermic process. The robustness of Decentralized PI-D is evaluated by changing the set-point of the ventilator speed at time 200 second and 400 second. Referring to table 1, the parameters of the Decentralized PI-D and PI controllers for respectively the first and the second loop are given in the following table:

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

| controller | Tuning parameters | | | |
|---|---|---|---|---|
| | *Kc* | $\tau_i$ | $\tau_d$ | $\lambda$ |
| PI | *1.0428* | *1.9302* | - | *2* |
| PI-D | *1.0804* | *37.5716* | *3.1740* | *2* |

The implementation of the Decentralized PI-D controller, in real time, uses the Humusoft MF624 Data Acquisition Card of *14*-bit Analog to Digital (A/D) conversion module, plugged into ISA port. The signals are transmitted between the PC and the Aerothermic Process via a *37*-way cable and connector block.

In this experimental study, 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 conventional PID controller, the conventional PI-D controller and its decentralized version. Once a partial decoupler is obtained, the PI and the two versions of PI-D controllers are designed separately for the two loops.

Three experiences are then envisaged in order to challenge the performances of the decentralized PI-D controller. In the first experience, the air temperature is controlled by the conventional PID controller. In the second and the third one, the air temperature is controlled respectively by the conventional PI-D controller and its decentralized version. The figure 8 represents the aerothermic process controlled by the decentralized PI-D and PI techniques. ($Y_1$,$Y_2$) represent the measured outputs or controlled variables, ($U_1$,$U_2$) represent the manipulated inputs and ($R_1$,$R_2$) represent the set-points. As shown in this figure, three controllers are used: the PI-D controller, conventional PI controller and the decoupler, *F*. noting that the input-signal to the decoupler, which is designed to compensate the undesirable process interactions, is the output signal from the feedback conventional PI controller.

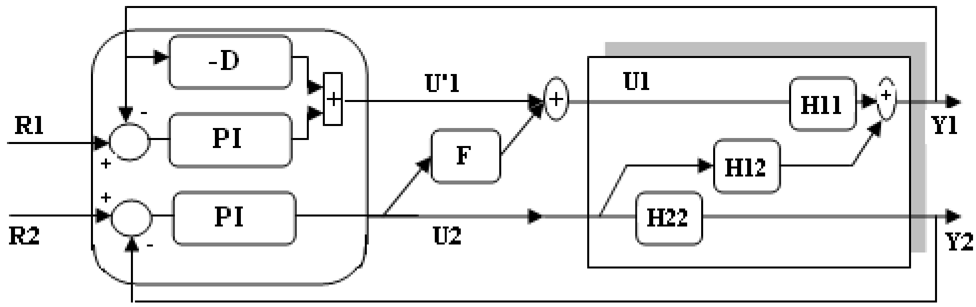


Figure 8. Block diagram of PI-D and PI applications

Figure 9 and 10 present the results of multi-loop PI-D/PI controllers with and without static decoupler using IMC tuning rules. It is apparent from these figures that the decentralized PI-D controller provides a good performance compared to the conventional PI-D and PID controller. Its robustness and its effectiveness are confirmed by the elimination of the interaction effect on the air temperature variable compared to the controllers without decoupler. It is obvious that the decentralized PI-D controller affords a good robust performance consistently. We noted that there is no change in the behaviour of the second loop parameters controlled by the PI controller. 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.

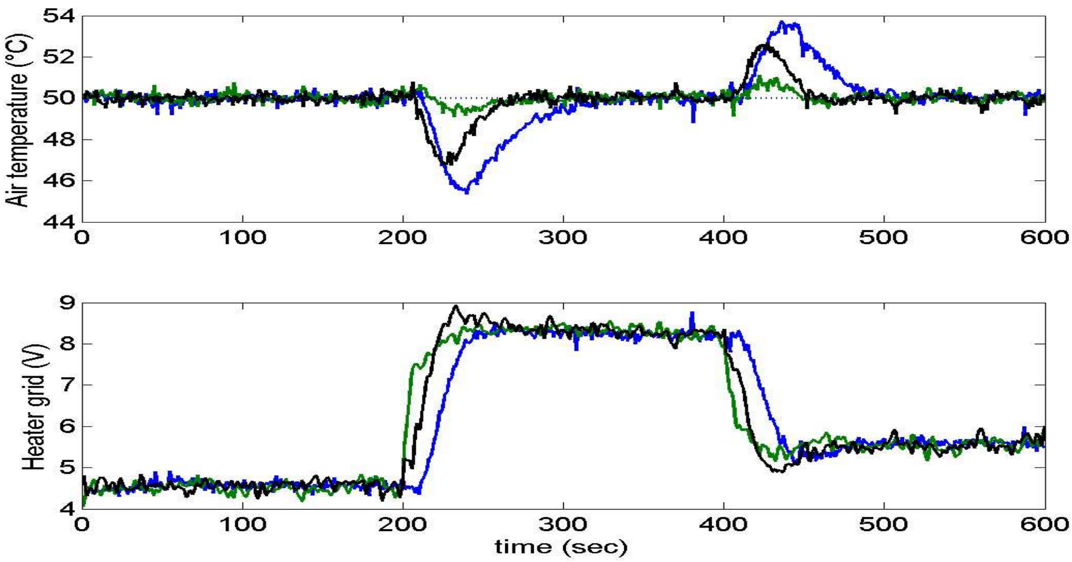


Figure 9: Top figure: closed-loop air temperature response; bottom figure: Closed-loop heater grid control response. (green: Decentralized PI-D controller, black: conventional PI-D controller, blue: conventional PID controller).

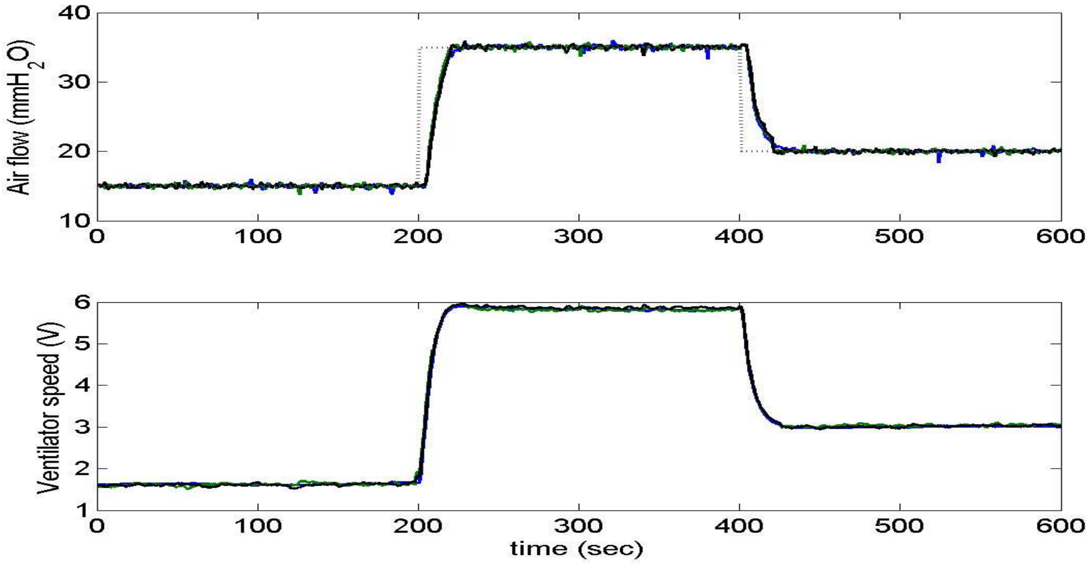


Figure 10: Top figure: closed-loop air flow response; bottom figure: Closed-loop ventilator speed control response.

## VI. CONCLUSIONS

In this paper, the PI and the decentralized PI-D controllers are implemented to an aerothermic process. The strong interaction effect caused by the ventilator speed on the air temperature was reduced considerably by combing a PI-D controller with a partial static decoupler. The comparison between the conventional PI-D, PID and decentralized PI-D controllers is analyzed. From this study, it can be clearly seen that the decentralized PI-D controller method is better than the conventional ones.

Usually, the PI-D controller is used to eliminate the “derivative kick”. This experimental study shows that this controller, improved by the static decoupler, can be used also to eliminate the interaction effect between the main parameters of an aerothermic process. It demonstrates robust performance for tracking set point change and rejecting the interaction effect. The decentralized PI-D controller 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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