Fuzzy Supervisory Control of Air Flow and Temperature in Industrial Tunnel Furnaces

S. A. Manesis
University of Patras
Electrical & Computer Engineering Dept.
Patras 26500, Greece
stam.manesis@ee.upatras.gr

P. M. Michael
University of Patras
Electrical & Computer Engineering Dept.
Patras 26500, Greece
irouli81@yahoo.gr

Abstract

In tunnel-type industrial furnaces there are various subsystems concerning either the temperature regulation or the air flow and pressure. These subsystems are usually controlled by conventional techniques and controllers offering simply an acceptable operation of the whole system. This paper presents design and implementation of a fuzzy control scheme for supervising coordination of the individual subsystems in order to achieve the desired conditions and improve the overall operation of the industrial furnace. The proposed control structure can be easily applied to the process environment and the implementation may be realized directly on a programmable logic controller.

1. Introduction

Tunnel-type continuous furnaces are used in brick and tile production plants to fire the products at high temperatures of more than 1000 degrees C. A main characteristic of these furnaces are their large dimensions with tunnel length usually greater than 100 m and tunnel cross section about 15 m^2, divided in a number of thermal processing zones. The products travel through the tunnel, typically with a piecewise constant flow, and get subjected to this successive thermal processing. A brief review of the fundamental principles and applications of thermal systems control is given in [1], where the heat exchanging procedure is mainly treated.

High reliability of furnace systems is a crucial factor in achieving high product yield. A good mathematical model of the system is required in order to implement a better control scheme. The model will have to include continuous and discrete dynamics, but may also be infinite dimensional, depending on whether the temperature and aerodynamic states are modeled as distributed or lumped parameter systems. A furnace system for semiconductor manufacturing has been modeled in [2], based on physical considerations, experimental data and an electrical equivalent network. The modeling and control of distributed thermal systems is investigated in [3] where model-based control design techniques are applied. A dynamic model of reheating furnace based on fuzzy system and genetic algorithm is proposed in [4]. A basic goal in all research efforts concerning the control of tunnel-type furnace systems is the mathematical modeling of them as has been done in other classical types of furnaces [5, 6, 7]. The obtained models can be used efficiently for the analysis as well as for the synthesis of the control strategy of these furnace thermal systems.

Along a tunnel-type furnace there are several subsystems in operational interrelation which are responsible for the dominant thermal and aerodynamic states inside the furnace. According to a standard practice, in brick and tile manufacturing we use a series of single loop controllers in order to control these different subsystems. The control task is today performed with conventional or specially designed PID controllers that provide acceptable operation of the plant [8]. The PID controllers however cannot ensure that there is not deviation from the desirable operating points. This means that there are still significant open control problems; one such problem is the difference in temperature between the top and the bottom of the tunnel, despite the action of the air-recycling and side-burners subsystems. Furthermore, current operation is far from an optimal one from the energy consumption point of view. There are significant thermal losses and the fuel consumption can be substantially reduced. Multi-loop controllers have also been used in other types of industrial furnaces as is the multi-loop temperature control scheme for a television glass furnace described in [9]. It is difficult, time-consuming and expensive to coordinate a great number of single-loop controllers required for many subsystems while in parallel achieving precise control is not always possible. A control tool has been proposed by ControlSoft Inc., the MANTRA 47 [10], which can be used instead of single loop controllers in glass manufacturing furnaces. One control loop refers to the combustion procedure performed in industrial burners that use either fuel oil or natural gas. A passive and active control scheme of NOx in industrial burners is proposed in [11]. The goal of this control loop is to achieve good mixing of fuel and air in order to obtain the desired titrimetric concentrations imposed by environmental conditions.

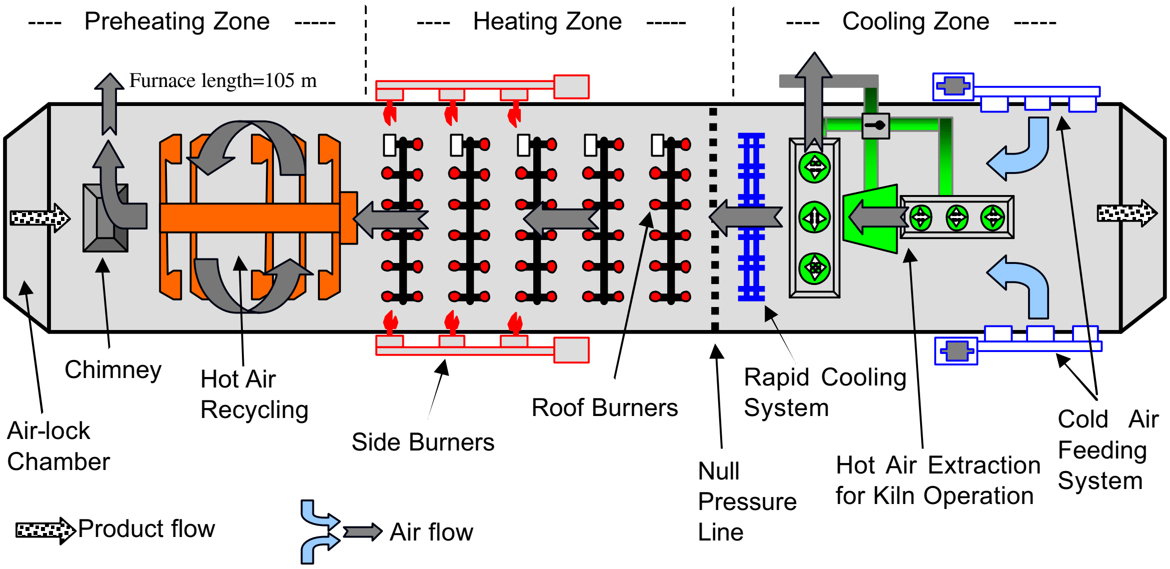

Figure 1. Schematic overview of a tunnel-type furnace for brick and tile production.

Any control scheme in continuous industrial furnaces is based on an extended measurement system including many temperature and pressure sensors. The proper function of a heating control system requires good knowledge of the heat transfer processes inside the furnace. The measurement system and its capabilities in computer modeling for the analyses of continuous reheating furnaces are presented in [12].

This paper introduces a fuzzy supervisory control scheme in order to coordinate local controllers and to evaluate whether they satisfy prespecified performance criteria. A two-level hierarchical structure has been applied concerning the primary system variables and the process behavior respectively. Furthermore, two supervisory configurations have been tested one for parameters adjustment and another for outputs addition in order to estimate the impact of the high level control strategy.

2. The tunnel furnace for brick and tile production

A tunnel-type industrial furnace consists of several subsystems in operational interrelation and is divided usually in three zones, the pre-heating zone, the heating zone and the cooling zone as shown in Figure 1. Two basic subsystems are responsible for the thermal and aerodynamic states created inside the furnace. The system's heart is the heating zone consisting of a matrix-set of burners. A typical number is eighty burner flames or more located on the roof of the furnace. In order to achieve isothermal distribution of heat from top to bottom, there are also side burners at each side of the furnace for rapid actions and temperature corrections. In some cases, the fuel used in these two burner-groups is different and the corresponding combustion control presents additional difficulties.

In some production processes, the products have to be dehydrated before entering the furnace. In such cases a parallel passive kiln operates with hot air from furnace. Hence, another subsystem is that of hot air extraction from the furnace and specifically from the cooling zone. The hot air flow is regulated in various points of the furnace either by on/off tampers or by analog position tampers performing mixing with environment air in order to keep hot air flow and temperature constant. Immediately after the heating zone, there is a small subsystem performing a rapid reduction of the temperature. Another subsystem with multiple air fans feeds cool air from the environment at the end of the tunnel. To keep the tunnel temperature constant from top to bottom, in addition to the side burners, there is also a subsystem for recycling hot air before the heating zone. Finally, a chimney at the beginning of the tunnel forces exhaust emissions to the environment affecting so the overall aerodynamic state inside the furnace.

3. Synthesis of the supervisory control strategy

Most industrial furnaces are controlled using classical control algorithms such as ON-OFF or PID controllers. The popularity of PID control can be attributed to both its good performance over a wide range of operating conditions and to its functional simplicity. A common problem with PID controllers used for control of highly nonlinear processes is that the set of controller parameters produces satisfactory performance only when the process is within a small operational window. Outside this window, other parameters or set points are necessary, and these adjustments may be done automatically by a high level strategy. The new control systems require looking for new and better control algorithms. Neural networks and fuzzy systems are being used more often now due to development of microprocessors. A supervisory system is a system that evaluates whether local controllers satisfy prespecified performance criteria, diagnoses causes for deviation from the performance criteria, plans actions, and executes the planned actions. For high level control and supervisory control several simple controllers can be combined in a priority hierarchy. The applied control system with supervisory fuzzy controller consists of two hierarchical levels as shown in figure 2. The process control strategy

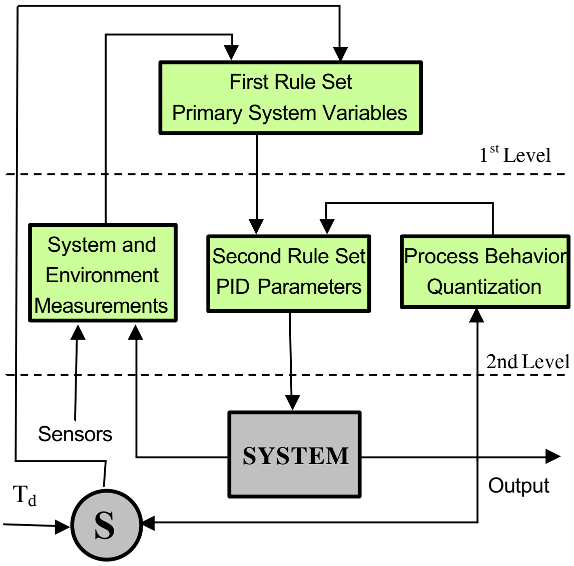

Figure 2. Hierarchical fuzzy supervisory structure.

is expressed linguistically as a set of imprecise conditional statements which form a set of decision rules. A fuzzy expert controller typically takes the form of a set of IF-AND-THEN rules whose antecedents and consequences are membership functions. The membership functions of the fuzzy sets used to formulate the linguistic terms can be defined in many ways and their choice depends on each practical situation. In this approach, the classical triangular membership functions, from negative big to positive big, have been used. In the first level, all the heuristic rules of an expert operator or that derived from simulation tests, are included and refer to the primary system variables including the air flow rate to kiln, the temperature in various points along the furnace and the corresponding set points. The evaluation of these (first set) decision rules leads to fuzzy control actions which must farther determined. This is done in the second level where the rules contain IF conditions which refer to the process behavior. The overshoot, damping and period variables characterize the system transient response and are calculated before the adjustment of the controller parameters.

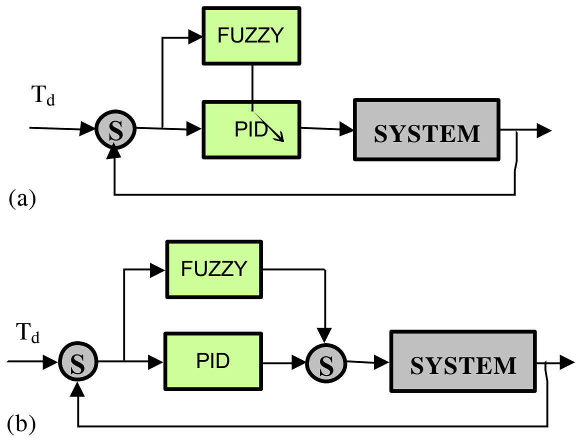

Figure 3. Fuzzy controller configurations.

Fuzzy controllers may be integrated with other controllers in various configurations. Two basic configurations of the furnace supervisory control, shown in Figure 3, were tested. Fuzzy in Figure 3 refers to the high level furnace control strategy while PID stands for a conventional control scheme which in furnace case consists of various independent or coupled PID loops. In configuration (a), the supervisory strategy is used for adjustments of the parameters of the PID control loops. Normally, conventional PID controllers are capable of controlling the process when the operation is steady and close to normal conditions. However, if sudden changes occur or if the process enters abnormal situations, then the configuration (b) is useful to bring the process back to normal operation as fast as possible.

4. Furnace performance results and discussion

Typical goals of a supervisory controller are safe operation, highest product quality, and most economic operation. All three goals are usually impossible to achieve simultaneously, so they must be prioritized. The temperature along the whole length of the tunnel must follow a predefined curve depending on the kind of the process. For example, in furnaces for conventional .

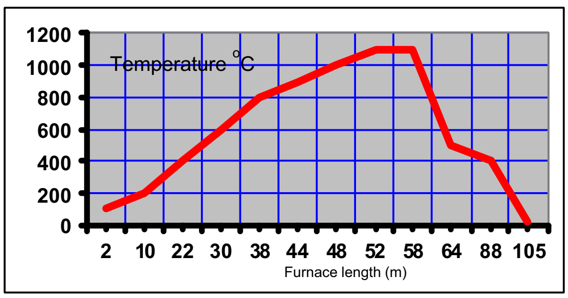

Figure 4. Furnace temperature pattern.

ceramic products, the temperature pattern must follow the one depicted in Figure 4. As mentioned above there is a forced inlet of air at the end of the furnace (which results in high pressure at one end of the tunnel) while there is a forced outlet at the beginning of the furnace (which results in low pressure at the other end). This difference in pressure results in a net flow of air from one end to the other. In addition to controlling the temperature of the furnace, one has also to regulate and control the stability of this aerodynamic state. Between high and low pressure there is an imaginable line which presents null pressure. This line must lie in a constant location between the heating and cooling zone. A possible shifting of null-pressure line in the heating zone means that cool air enters the heating zone which is forbidden. On the other hand, a possible shifting in the cooling zone implies that exhaust emissions will enter the kiln, which is also undesirable. To keep the null-pressure line constant, there must be a continuous control of the cool air inlet flow. The chimney flow is treated as a disturbance, since it varies independently to keep exhausts temperature at a low level for saving energy.

The desirable temperature pattern succeeded mainly by the matrix-set of roof burners, shown in Figure 5, is strongly affected by the convenient or no operation of the overall air flow system. From the above description it is

Figure 5. Overview of the roof burners.

obvious that the supervisory control system has to perform continuous control of various physical variables such as temperature, air flow and titrimetric combustion, and discrete control (ON/OFF) of various tampers, burners, fans and doors. The most basic of the PID control loops is the one concerning the combustion of the roof burners shown in Figure 5. The controller regulates the operation of burners based on the measurement of air flow inlet and temperature, and on the titrimetric analysis data. A preliminary parametric study was made to investigate the impact of flame-vortex interactions and fuel/air mixture inhomogeneity on combustion instability. The dependency of combustion instability on fuel mean velocity is strong and suggests that the dominant mechanism causing combustion instability is hydrodynamics and its interaction with flame.

The proposed fuzzy supervisory control scheme has been tested with experimental data obtained from a 250 ton/24 hour brick furnace in Greece. The fuzzy logic part of the controller and the corresponding rule base were implemented in a S7-300 PLC using the FuzzyControl++ S7 ® software package by Siemens. Figure 6 shows typical temperature variations at the top and the bottom of the tunnel furnace without the action of the supervisory controller. The temperature deviation

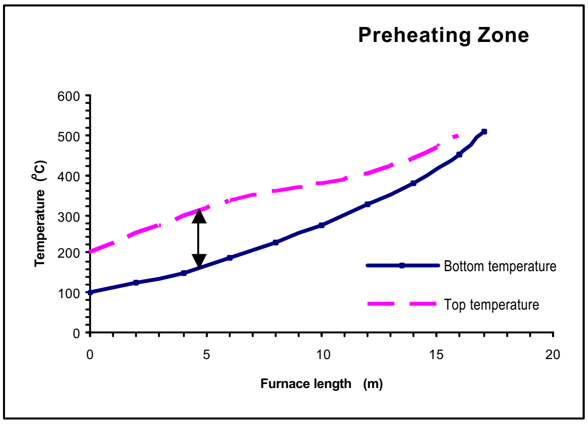

Figure 6. Temperature variation along the tunnel furnace at the top and the bottom without supervisory control.

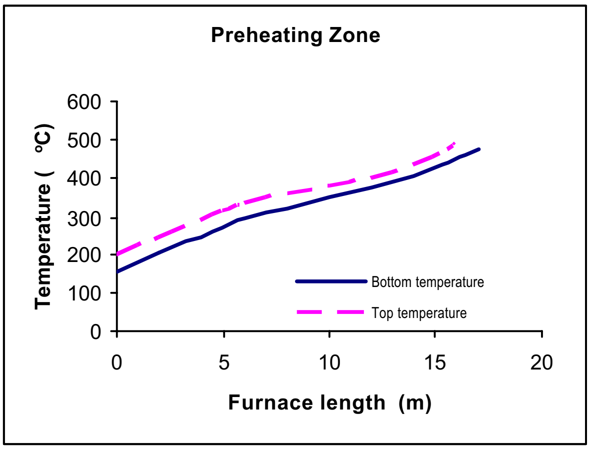

Figure 7. Temperature difference of Figure 6 after the action of the fuzzy supervisory controller.

must be null in the optimum case and if possible without the aid of the air recycling and side-burners subsystems. Since something like this it seems impossible today, new and better control algorithms are required. Figure 7 shows the reduction of the temperature difference between the top and the bottom of the tunnel obtained after the action of the fuzzy supervisory controller.

As mentioned above, typical goals for a supervisory controller are safe operation, highest product quality and most economic operation. All three goals are usually impossible to achieve simultaneously. Hence, they must be prioritized and presumably safety gets the highest priority. The proposed hierarchical supervisory control scheme is the most suitable to assign priorities to the various control objectives. In this work, we have considered only the air flow and temperature control as the primary goal of the supervisory scheme. Of course, the product quality depends strongly on the actual temperature curve, but the quality goal in general is a complicated criterion.

5. Conclusions

Control problems in the furnace-based process industry are dominated by non-linear and time-varying behavior, many inner loops and much interaction between the control loops. The introduction of a single multiple-input multiple-output controller is not useful because of the rather high design effort and the low transparency of its complex structure. A more suitable hierarchical fuzzy-logic-based supervisory control scheme has been described in this paper. In the upper level of the hierarchy the supervisory controller classifies the actual system situation and in the lower level performs the specific control mode selection.

References

[1] M. Sen, "A Review of the Principles and Applications of Thermal Control", Journal of the Mexican Society of Mechanical Engineering, vol.1, No.4, pp. 115-131, 2004.

[2] J. Wang and C.J. Spanos, "Real-Time Furnace Modeling and Diagnostics", IEEE Transactions on Semiconductor Manufacturing, vol.15, No.4, November 2002.

[3] A.E. Naeini, J.L. Ebert, D. Roover, R. L. Kosut, M. Dettori, L. Porter and S. Ghosal, "Modeling and Control of Distributed Thermal Systems", IEEE Transactions on Control Systems Technology, vol.11, No.5, September 2003.

[4] B. Zhang, L. Xu, J. Wang and H. Shao, "Dynamic Model of Reheating Furnace Based on Fuzzy System and Genetic Algorithm", Proceedings of the American Control Conference 2002, vol.5, pp.3823-3828, May 2002.

[5] S. Pal and A.K. Lahiri, "Mathematical Model of COREX Melter Gasifier: Part II, Dynamic Model", Metallurgical and Materials Transactions B, Vol.34B, pp.115-121, September 2001.

[6] D.Lj. Debelikovic, I. Buzurovic, M.V. Rancic and S.D. Sarbon, "Mathematical Model of the Pulverising Plant as a Mass Accumulator with Associated Dynamics of Both Impeller and Coal Drying Process", Scientific Journal Facta Universitatis Mechanical engineering, vol.1, No.6, pp.653-664, 1999.

[7] Q. He, S.J. Qin and A.J. Torpac, "Computationally Efficient Modeling of Wafer Temperatures in an LPCVD Furnace", Journal on Advanced Process Control and Automation, vol.5044, pp.97-108, 2003.

[8] S. Martineau, K.J. Burnham, O.C.L. Haas, G. Andrews and A. Heeley, "Four-term bilinear PID controller applied to an industrial furnace", Control Engineering Practice, 12, pp.457-464, 2004.

[9] U.C. Moon and K.Y. Lee, "Multi-Loop Control of Temperature for TV Glass Furnace", Proceedings of the 39th IEEE Conference on Decision and Control, Sydney, December 2000.

[10] "Temperature Maintenance and Fuel Flow in Glass Furnace using MANTRA 47", ControlSoft Publications No. AN303, rev. 06-05-02, www.controlsoftinc.com

[11] O. Delabroy, E. Haile, F. Lacas, S. Candel, A. Pollard, A. Sobiesiak and H.A. Becker, "Passive and active control of NOx in industrial burners", The Experimental Thermal and Fluid Science Journal, 16, pp.64-75, 1998.

[12] M. Honner, Z. Vesely and M. Svantner, "Temperature and heat transfer measurement in continuous reheating furnaces", Scandinavian Journal of Metallurgy vol.32, pp.225-232, Denmark, 2003.