Modeling and Control of Industrial Tunnel-type Furnaces for Brick and Tile Production

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***Abstract* – The dynamic behavior of an industrial tunnel-type furnace is of the fundamental importance for the quality of the processed products. The knowledge of the furnace dynamics can make the control of the system easier as well as it can eliminate certain operational problems. The various subsystems existent in a tunnel-type furnace are usually controlled by conventional techniques and independent controllers offering simply an acceptable operation of the whole system. This paper approaches the overall furnace system by considering both mathematical modeling and fuzzy logic based techniques. It proposes a control scheme for model-based coordination of the individual subsystems which are controlled locally by fuzzy controllers combined with conventional ones. The proposed control structure can be easily applied to the process environment and the implementation may be realized directly on a programmable logic controller.**

Index Terms – Industrial Furnaces, System Modeling, Control, Simulation, Fuzzy logic

I. INTRODUCTION

System modeling and control is an important issue in industrial engineering applications and particularly in complicated thermal processes. Conventional approaches to system modeling need many assumed conditions and rely heavily on mathematical tools, such as differential equations, transfer function and so on, which emphasize the precision and exact description of each quantity involved. The use of these mathematical tools is suitable and well-applied only in simple or well-defined systems. However, when the system is complicated, these conventional approaches become less effective [1].

Fuzzy logic based techniques have become a suitable alternative and have been successfully employed in various areas where conventional methods fail to provide satisfactory results. Although they can be used in system modeling as well as in control, it seems that their use in control is more feasible, attractive and widely accepted.

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 [2], 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. The first step in the design of a model-based controller is the development of a thermal model which accurately captures the actual physical behavior of the system to be controlled. This high-fidelity thermal model is based on the application of the dynamic heat transfer equations to the system. The model may contain physical variables whose values are not known in advance (e.g. heat transfer coefficients) and are identified from experimental data. A comparison of the model response with the actual system output provides a measure of model accuracy.

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 [1]. 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 [4, 5, 6]. 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 PID controllers that provide an acceptable operation of the plant [7]. 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 [8]. 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 [9], 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 [10]. The goal of this control loop is to achieve good mixing of fuel and air in order to obtain the desired stoichiometric concentrations imposed by environmental conditions.

In this paper, the proposed approach for modeling and control of industrial tunnel-type furnaces combines conventional mathematical modeling with fuzzy logic based techniques. This combination of both technologies gives in some cases better results [1]. Particularly, 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.

II. 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 Fig. 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.

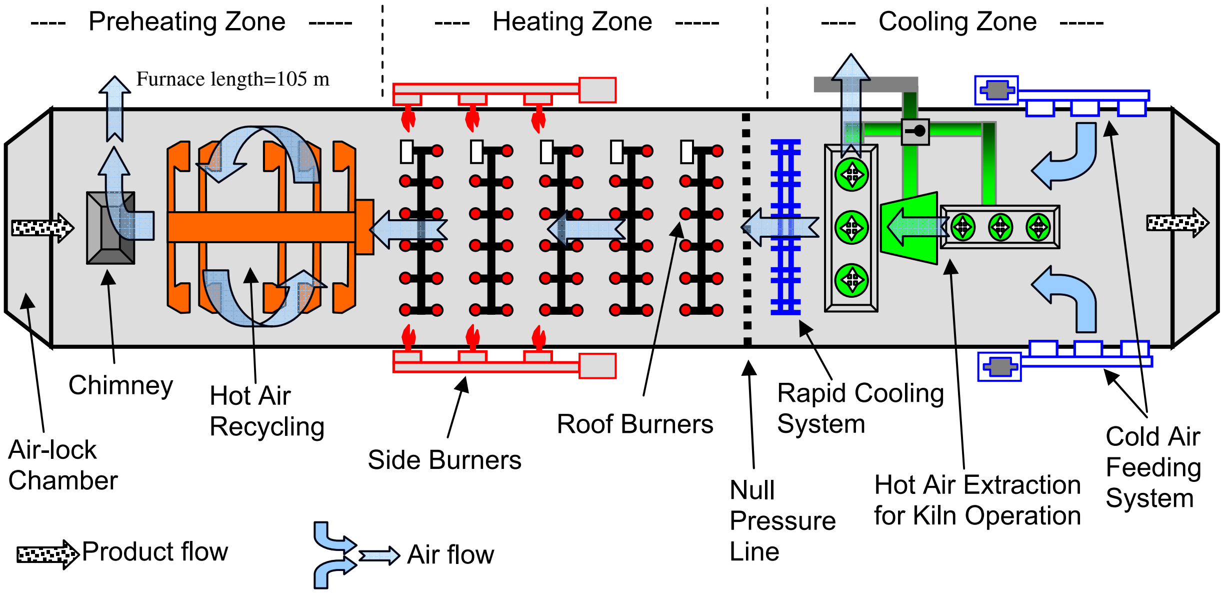

Fig. 1. Schematic overview of a tunnel-type furnace for brick and tile production.

III. PHYSICAL MODEL OF THERMAL PROCESS

The tunnel-type industrial furnace is a very complex object for modeling and control, because multiple exchange of energy occurs in it due to the nature of process that leads to complex mathematical models describing its dynamics. In the past, tunnel-type industrial furnaces were often built with a central heating zone and thermal insulation that minimized heat loss through furnace walls. The result of such a design was to create an almost static system within the furnace from the aerodynamic point of view. A typical brick production process would involve placing a car of bricks inside the furnace, raising the temperature slowly to process temperature, holding for a specified time and then quickly cooling the furnace. While such processes are still common today, increasing demands for better temperature uniformity and greater yield are driving furnace makers to address complications related to the dynamics of the heating and cooling processes [3]. Today, furnace makers introduce forced multi-input multi-output air flow in order to achieve the desired temperature distribution across the furnace and to exploit as much as possible the heat losses in secondary zones.

The thermal efficiency of a fuel-fired furnace is usually expressed by the ratio of heat transfer to the load to the energy input in the fuel. There are three basic and interdependent mechanisms of heat transfer, the thermal radiation, convection and conduction. The steady-state energy balance is given by

$$\dot{Q}_G + \dot{Q}_{pa} = \dot{Q}_g + \dot{Q}_L + \dot{Q}_l \tag{1}$$

where $\dot{Q}_G$ is the energy input supplied by the fuel, $\dot{Q}_{pa}$ is the rate of energy supply in preheated combustion air, $\dot{Q}_g$ is the heat content of the flue products, $\dot{Q}_L$ is the rate of heat transfer to the load and $\dot{Q}_l$ expresses any kind of energy losses. The energy input supplied by the fuel is given by

$$\dot{Q}_G = \dot{V}_G C_V \tag{2}$$

where $\dot{V}_G$ is the volumetric flow rate of fuel and C_V is the calorific value. The rate of energy supply in preheated combustion air is given by

$$\dot{Q}_{pa} = \dot{V}_G R_s (1+X) \rho_a E_{th,a} \tag{3}$$

where R_s is the stoichiometric air/fuel volume ratio, X is the percentage excess air level, ρ_a is the density of air at the reference temperature and pressure and $E_{th,a}$ is the specific enthalpy of the preheated air. Assuming complete combustion, the heat content of the flue products at temperature T_g is given by

$$\dot{Q}_g = \dot{V}_g \left(P_s + R_s X \right) \rho_g E_{th,g} \left(T_g \right) \tag{4}$$

where P_s is the combustion product/fuel volume ratio, ρ_g is the density of the combustion products and $E_{th,g}$ is the specific enthalpy of the combustion products as a function of temperature. Finally, assuming a process load throughput of $\dot{b}_L$, the rate of heat transfer to the load is given by

$$\dot{Q}_L = \dot{b}_L \left[E_{th}(T_o) - E_{th}(T_i) \right] \tag{5}$$

where $E_{th}(T_o)$ and $E_{th}(T_i)$ are the specific enthalpies of the load at the outlet and inlet temperature respectively.

The dominant mode of heat transfer from the flame and combustion products inside furnace is the non-luminous gaseous radiation. In fossil-fuel fired combustion processes, carbon dioxide and water vapor are the most important emitters of gaseous radiation. Carbon monoxide and methane also absorb and emit radiation, but they are usually absent or exist at very low concentrations. Thermal radiation transfer can occur from surfaces and gases within a tunnel-type furnace. All surfaces within industrial furnaces, emit, reflect and absorb radiation from their surroundings and thereby participate in the overall exchange of radiant energy to a load. For modeling a tunnel-type industrial furnace, we consider that all furnace surfaces are grey Lambert surfaces where emissivity is assumed to be independent of both wavelength and direction of radiation. For a grey Lambert surface the emissivity (ε) is equal to absorptivity (α) and $\varepsilon = 1 - \boldsymbol{\rho}$, where $\boldsymbol{\rho}$ is the reflectivity coefficient. The energy transfer between two grey Lambert surfaces A_1 and A_2 of emissivities ε_1 and ε_2 respectively is given by

$$\dot{Q}_{1\rightarrow 2} = \left(E_{b,1} - E_{b,2} \right) / \left[\frac{1}{A_1 \varepsilon_1} + \frac{1}{A_2} \left(\frac{1}{\varepsilon_2} - 1 \right) \right] \tag{6}$$

where E_b is the emissive energy of surface.

The gaseous atmosphere in any fuel-fired furnace participates in the overall interchange of radiation. A parallel beam of radiation passing through an absorbing grey gas is attenuated in proportion to its intensity and the distance traversed through the gas. The radiant emission from a volume V of gas at temperature T_g and with attenuation coefficient K is given by $\dot{Q} = 4\sigma K V T_g^4$ where σ is the Boltzman constant. When a beam of radiation is incident upon a particle, scattering occurs by diffraction, refraction and reflection. However, because the diameter of soot particles in gaseous and liquid fuel flames is usually quite small, scattering of radiation by soot may be considered negligible compared with emission and radiation. On the other hand, methods of calculating scatter and for predicting the scattering coefficient are dependent on the particle distribution/concentration and this information is difficult to obtain.

IV. 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 Fig. 2. The process control strategy 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 derived from model-based 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.

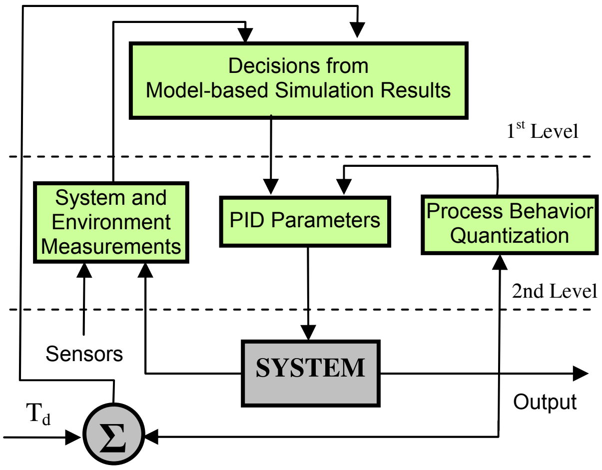

Fig. 2. Hierarchical fuzzy supervisory structure.

Most heating plant models are based on either the zone method for radiation analysis or the computational fluid dynamics models referred to in [11]. Because of the large length (105 m) of the industrial furnace for brick and tile production, it is more convenient to consider the multi-dimensional zones model shown in Fig.3. In multi-dimensional zone models, both longitudinal and cross-sectional or radial variation in temperature and heat flux are considered. According to zone method, the furnace radiating enclosure is divided into isothermal volume and surface zones. A total energy balance is written over each zone in terms of the radiation arriving at it from all the zones in enclosure. Thus the radiant energy balance including radiation arriving at surface i is

$$\dot{Q}_i = \sum_{j=1}^{n} \overline{S_j S_i} E_{bj} + \sum_{j=1}^{l} \overline{G_j S_i} E_{gj} - A_i \varepsilon_i E_{bi} \qquad (7)$$

where $\dot{Q}_i$ is the energy flow to zone i, $\overline{SS}$ and $\overline{GS}$ are the exchange factors known as surface-surface and gas-surface directed flux areas respectively, E_g is the black body emissive power of a gas, n is the number of surface zones and l is the number of volume zones. The geometry and input data for each volume and surface zone can be varied to match the specified design and operating conditions of the furnace. For a long-furnace model with fuel and air input to the specified zones shown in Fig.3, the flow of combustion products between zones is resolved into forward and reverse flow components $\dot{m}^+$ and $\dot{m}^-$ respectively. The energy balance is then given by

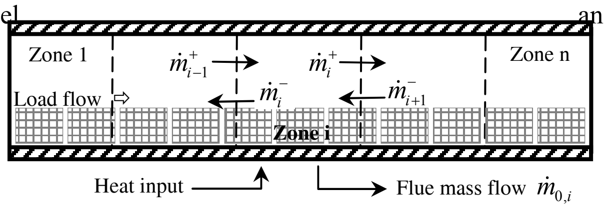

Fig. 3. A long-furnace model with recirculation between zones.

$$\dot{Q}_{G,i} + \dot{Q}_{pa,i} + \dot{Q}_{th,i} - \dot{Q}_{co,i} - \dot{Q}_{ra,i} = 0 \qquad (8)$$

where $\dot{Q}_{G,i}$ is given by (2), $\dot{Q}_{pa,i}$ is the heat input in the combustion air given by (3). $\dot{Q}_{co,i}$ and $\dot{Q}_{ra,i}$ are the convective and radiative heat transfer from the combustion products to the surrounding surfaces in zone i. $\dot{Q}_{th,i}$ is the flow of enthalpy to zone i in the combustion products and is given by

$$\begin{aligned}\dot{Q}_{th,i} &= \dot{m}^+_{i-1} E_{th,g}\left(T_{g,i-1}\right) + \dot{m}^-_{i+1} E_{th,g}\left(T_{g,i+1}\right) - \\ &- \left[\dot{m}^-_i + \dot{m}^+_i + \dot{m}_{0,1}\right] E_{th,g}\left(T_{g,i}\right)\end{aligned} \qquad (9)$$

The above model is capable of simulating the effects of recirculation between zones (described in section II) provided the forward and reverse flow components are specified. The solution of each volume zone energy balance equation is dependent on the combustion product temperatures in the neighboring zones. The equations for all volume zones must therefore be solved simultaneously in the 1st level of the supervisory structure in order to derive the temperature $T_{g,i}$.

Fuzzy controllers may be integrated with other controllers in various configurations. Two basic configurations of the furnace supervisory control, shown in Fig. 4, were tested. Fuzzy in Fig. 4 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.

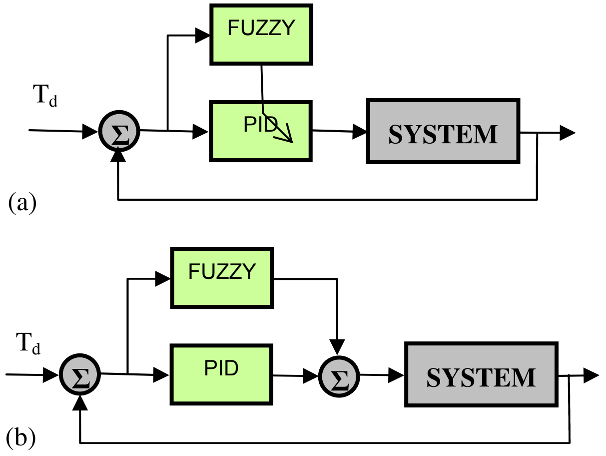

Fig. 4. Fuzzy controller configurations.

V. 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 ceramic products, the temperature pattern must follow the one depicted in Fig. 5. 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.

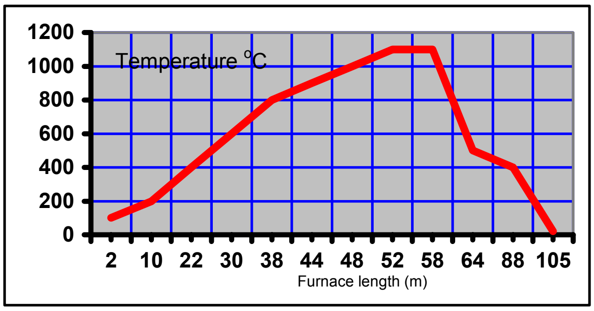

Fig. 5. Furnace temperature pattern.

The desirable temperature pattern succeeded mainly by the matrix-set of roof burners, shown in Fig. 6, is strongly affected by the convenient or no operation of the overall air flow system. From the above description it is obvious that the supervisory control system has to perform continuous control of various physical variables such as temperature, air flow and stoichiometric 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 Fig. 6. The controller regulates the operation of burners based on the measurement of air flow inlet and temperature, and on the stoichiometric 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.

Fig. 6. Overview of the roof burners.

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 7 shows typical temperature variations at the top and the bottom of the tunnel furnace without the action of the supervisory controller. The temperature deviation 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 8 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.

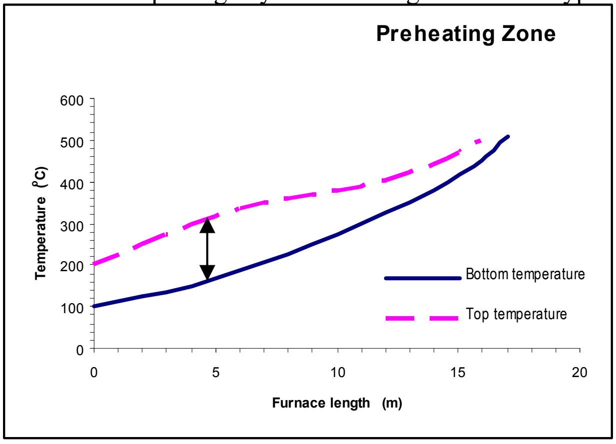

Fig. 7. Temperature variation along the tunnel furnace at the top and the bottom without supervisory control.

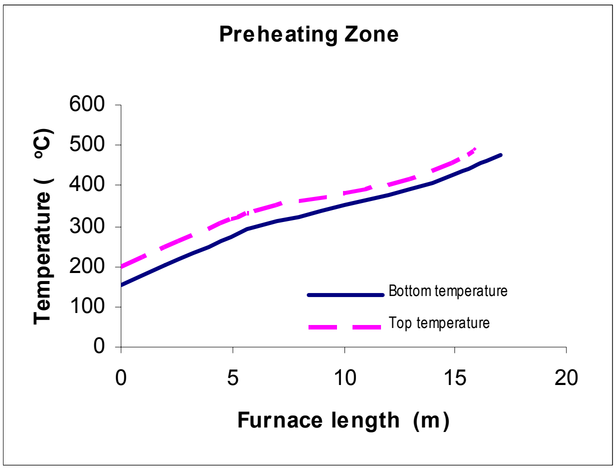

Fig. 8. Temperature difference of Fig. 6 after the action of the fuzzy supervisory controller.

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.

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 based on the mathematical model of the process and in the lower level performs the specific control mode selection.

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