ADVANCED INDUSTRIAL CONTROL USING FUZZY LOGIC OF TUNNEL KILN BRICK PRODUCTION

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Abstract: A case study of two-level and set point-oriented controls in complex industrial heating plants has been carried out. Task-oriented controls occur at command and supervision level in conjunction with human process operator, while set-point controls occur at regulation level of energy conversion and heating process. Fuzzy logic control is involved on the second control level on the basis of products quality control. The control system has been implemented in factory for clay-brick productions "KIK" in Kumanovo. A suitable and intelligent automation can save energy and therefore costs. *Copyright © 2005 IFAC*

Keywords: Complex systems; thermal processes, two-level fuzzy logic supervisory control, set-point control, clay-bricks kiln production,

1. INTRODUCTION

Processes and plant constructions of thermal systems and industrial furnaces, kilns and ovens in particular, have been subject to both scientific and technological research for long time (Rhine and Thucker 1991). Due to the process complexity of energy conversion and transfer into thermal systems, however, their control and supervision have recently become topics of extensive research. These thermal processes have been summarized and operationally characterized as: operating regimes of low-load and start-up, medium-load and full-load as well as start-up and shut-down; multi-input-multi-output (MIMO) convex, control or steady-state (SS), input-output (I/O) characteristics at operating points; slow and non-linear overall dynamics, but locally linearizable; low-frequency bandwidth; time-delay and non-minimum phase phenomena; problematic sensor allocation distribution in order to extract and provide on-line real-time all relevant information on operating the thermodynamics; main controlled (output) variables are temperatures and main controlling (manipulating) variables are energy and mass (fuel/gases) supply/release.

The overall control task is to drive the process to the desired thermodynamic equilibria and to regulate the temperature profile through the plant. In industrial operating environment, technical control specifications involve goal and task description of aims and procedures of supervision functions and recommended set-ups of regulatory and other control functions along with certain terms of preconditions, constraints, interactions, limitations, etc. From the general systems theoretical standpoint, it is the thermal systems where it became apparent that controlled processes in the real-world plants constitute a non-separable, unique interplay of the three fundamental natural quantities: energy, mass and information. Moreover, thermal plants exhibit essentially interacting MIMO (McAvoy, 1984) and generic complex processes.

From control point of view, in thermal systems the essential impact occurs due to time delay and natural I/O operating modes and which, interacting with the controlling infrastructure in the process real-time, provide the way the complexity of sensor-actuator problem be properly resolved by natural ordering of I/O modes and respective input-output variable pairing (Dimirovski, *et al*. 1996, 2000, Stankovski, 1997, Stankovski, *et al*. 1998a, b, c, d, 1999, 2000).

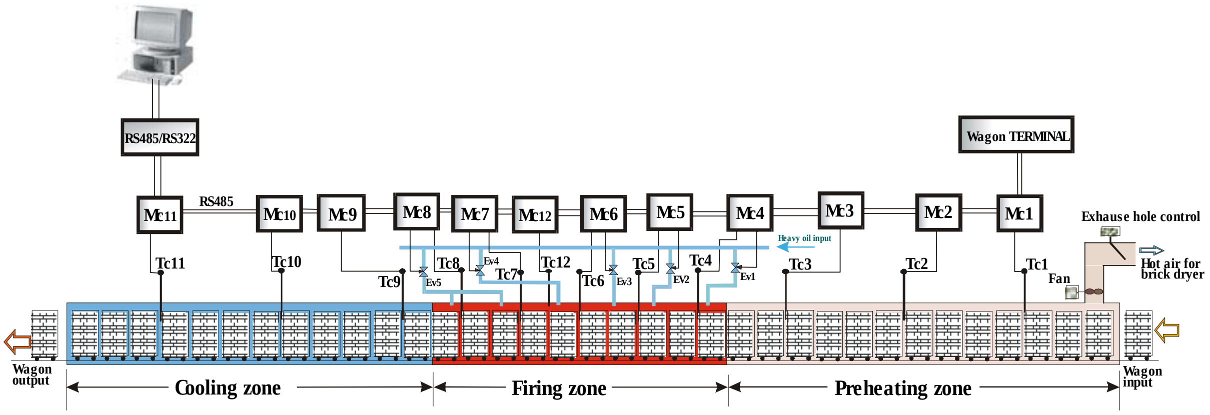
2. "KIK" KUMANOVO TUNNEL KILN FOR A BRICK PRODUCTION

One of the main parts of the brick plant production is tunnel kiln. One tunnel kiln for a brick production is located on the main plant in factory "KIK" Kumanovo. This kiln is in rectangular tunnel form and it was installed more than ten years ago. Floor of the kiln is formed with special fire-resistant wagons. There are special channels inside the kiln walls for air-cooling. Main characteristic of this kind of tunnel kilns is the fixing points fire and bricks wagons moved across the kiln (for the difference of ring kilns where bricks wagon are fixing and fire moved from the beginning to the end of the kiln).

Kiln has next characteristics: 96m long, 4.75m width and 1.85m high, 35 wagons capacity, (250.000 ENF (units normal format) bricks in the kiln in one moment and with 30 - 50 millions ENF per year).

There are eight burners groups (six of them are active) located on the firing zone of the kiln. Each of them consists natural gas batteries and air batteries. Natural gas batteries consist 15 burners and one place for thermocouple. Air batteries consist also 15 air distributors. Along the kiln there are central gas and air supply systems. Air is supply from one fan with capacity 7500m^3/hour. Natural gas consumption is around 8-10 Nm^3/hour continuous work. Maximal temperature in burning zone is 1200^{o}C.

The kiln consists three zones: preheating zone, firing zone and cooling zone, Fig.I. Outlet of the kiln is opened and cold air enters here and passes away the kiln. On this way it cools bricks in cooling zone and continues in firing zone and together with waste gases continue across the preheating zone and heat bricks. Exhaust with fan for aspiration of waste gases is located on the beginning of the preheating zone. On the exhaust pipe there is a damper for air flow control. Heat for preheating in preheating zone comes from firing zones. All burners are located only in firing zone. Typical temperature profile along the kiln we can see on Fig.II. Wagons with bricks input in the kiln discrete in process named "suppressing". The wagon is suppressing every 30 to 90 minutes depending of type of the bricks.



Mci - Temperature microcontrolers
Tci - Termocouples
Evi - Electro valves

Fig.I Bricks tunnel kiln with control system

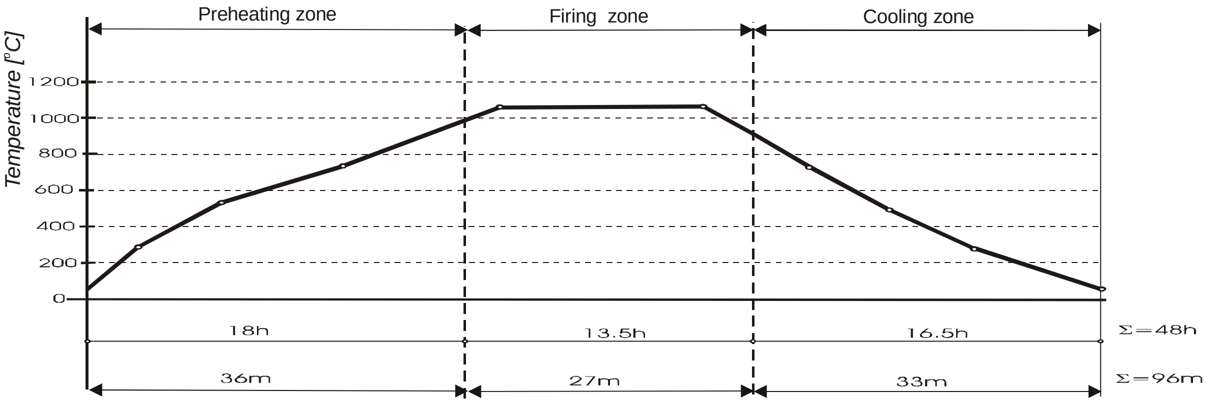


Fig.II Temperature profile in the tunnel kiln

Kiln has 35 positions (sections) and every wagon stay in every position during the time between two suppressing. Preheating zone has 13 sections, firing zone has 10 sections and cooling zone has 12 sections. At each section it is important to keep a good control of the temperature profiles.

3. MAIN PRODUCT CHARACTERISTICS

Quality of the products, in our case clay bricks, depends not only from the process of firing, but also from process of drying which is before. All the time we suppose that the process of drying is completely finished, and all defects in the bricks are results of the process of firing.

Quality assessment is on the bases of next features:

- color of clay bricks
- porous of clay bricks
- deformation of the dimension of clay bricks
- mechanical characteristics (hardness)

Here we will explain these products characteristics:

3 . 1 Color of clay bricks

The color of the final product, clay-bricks depends of two factors: chemical composition of clay from which bricks are made and firing temperature of the firing zone in the kiln. From the aspect of the chemical composition, bricks color depends from the quantities of Fe2O3 + FeO (iron oxide), in the clay mixture. If the percent of the iron oxides is in low level, bricks color is red if the firing is on 920^{o}C, to dark-red if the firing is on 1180^{o}C. From the other side, if the percent of the iron oxides in the clay mixture is in high level, bricks color is red-yellow if the firing is on 920^{o}C, to olive green if the firing is on 1180^{o}C. If the temperature in the firing zone is higher than 1200^{o}C, than bricks color transcends to dark brown. In that case product (clay-bricks) is overdone. If the brick satisfy other quality characteristic than only problem is increasing of energy consummation.

Measuring of the brick color is with unit for color detect, which give signal from 4-20mA, as a represent of red color. 4mA represent red-yellow and 20mA represent dark red. This signal goes directly to the analog input of the computer controller. Frequency of this measuring is ones per every wagon (10-20 measuring per day, depending from the number of the wagons).

3 . 2 Porosity and water absorption

Porosity is variable which changes depending on the firing temperature of the clay. Increasing the temperature of firing over 750^{o}C, porosity decreases evidently. This results in the decreasing of ability of water absorption. Well fired product has water absorption of 8%, and the higher limit is 15%. Values smaller than 8% are result of very high firing temperature in the firing zone (over fired product).

Testing of the porosity is in the laboratory, and it happens ones time per day, and result of this test is enter on the system directly on the controller also ones time per day, on the finishing of first shift.

3 . 3 Deformation in final products

During firing process in the different temperature intervals linear reducing and linear expanding happens. If final product swells, the reason is sudden increase of temperature in the preheating zone of the kiln. Very high temperature in the firing zone (around 1300^{o}C) results in product melting or deformation of originally products shape.

Measuring of the dimension of the brick is making manually from workers on every wagon. The worker enters data for brick dimension in the computer terminal located on the kiln outlet.

3 . 4 Mechanical hardness

One of the main characteristics of fired product is its mechanical hardness which is incomparable higher than the one of the nonfired but dried product. Increasing the firing temperature involves increasing of mechanical hardness. But the mechanical hardness depends not only of the temperature, but also from the chemical structure (composition) of the clay and the way it is shaped.

One of the main parameter for clay brick quality is air flow across the kiln. It is important not only for product quality, (product cooling in cooling zone and oxygen entering in the firing zone) but also for right time removing of waste gas.

Measuring of the mechanical hardness is on the laboratory, ones time per day, and result of this test is enter on the system directly on the controller also ones time per day, on the finishing of first shift.

3 . 5 Products defects as a result of problems in cooling zone

Biggest problem during bricks firing process is appearance of microcracks which are results of the straining as an occasion of volume changing during phase transformation of free quartz. On the clay brick can exist one microcracks or whole network of cracks which lead to product destroying. If on the product doesn’t exist microcracks, it give clear sound on the blow. In opposite it gives dully and unclear sound. Another way for detection of microcracks is wetting of the clay bricks. If the microcracks exist they clearly are showed as a wet parts, and rest of brick surface will be dry. One of the main reasons for microcracks appearance is taking out too much quantity of hot air. In that case we have underpression in the cooling zone, which result in uncontrolled temperature drop in cooling zone. This problem can be solved with control of the air flow across main air channel on the exhaust with damper.

3 . 6 Fuel consummation

One of the main characteristic of thermal processes is fuel consummation. It is important from the first because final price of the products direct depend from it. Reducing of fuel consummation in thermal processes is on the first place for control engineers. Our goal is products quality improves and fuel consummation reducing. In the case of "KIK" Kumanovo tunnel kiln there is one gas flow transmitter located on the main supplying gas line. It gives 4-20mA signal which can be used in control system. This signal goes directly to the control system continually.

4. TWO LEVEL SYSTEM ARCHITECTURE

Clay-bricks production is a critically dependent on the firing process at the kiln. Existed control systems apply first level local control, data acquisition and supervision and product quality is the second stage of the project and here is directly considered. The ultimate goal is the quality improvement of the bricks at the kiln output and fuel consummation reduction.

To reach this goal, this application incorporates a two-level hierarchical control structure: a PID or ON-OFF control to keep the temperature profile along the kiln as steady as possible, and a rule-based control which modifies the desired temperature and pressure profiles along the kiln so as to counter-act quality defects measured at the kiln output. Both levels interact with a database and a man-machine interface through a blackboard based system, where real-time issues have been addressed. On the other hand, monitoring of variables, treatment of alarms, data management and man-machine communication are important issues also considered in the application. An easy configuration of one two-level control system is incorporated in KIK Kumanovo Clay-Brick Company (Fig.I).

The two layers in the control structure (Dimirovski, *et al.* 2000, Pico *et al.* 1999, Stankovski, *et al.* 1998a, d, 2000) within hierarchical system architecture are:
Upper optimization layer computes the desired references, r_k, for the temperatures at each section along the kiln. These references are defined with the aim of counteract quality defects appearing at the bricks. It can be a rule-based control level, at which different actuation strategies can be defined by the operator, attending to the defect to be controlled and the kind of composition of the bricks.

Executive control layer is aimed to achieve that the actual temperature be equal to the desired reference at each section, i.e. $y_k = r_k$. To reach this goal, the coordinating control is an adaptive decoupling control with decentralized feedback.

Executive Control Layer. The executive control layer is a decentralized feedback multivariable control. The objectives of this layer are:

- To determine the control input u_k such that the output y_k of the process tracks a desired output vector r_k asymptotically, $\lim_{k \to \infty} = \left\| r_k - y_k \right\| \cdot$

- Decoupling. In this case, a control structure has to be defined so that the reference signal $r_{i,k}$ affects only one component $y_{j,k}$ of the output.
It should be noted that whether or not a multivariable system can be decoupled depends upon the relative degrees of the outputs with respect to the inputs, or alternately, upon the delay between each input-output pair and also the nature of interaction in the cross-paths of operating I/O modes. A conceptually simple approach to multivariable control design, is given by a two-step procedure in which we first design a compensator to deal with interactions, and then design a diagonal controller designed as if dealing with (practically almost) independent SISO systems.
Decentralized Feedback Control. The design of decentralized control systems involves two steps: first, the choice of pairings (control configuration selection) and second, the design (tuning) of each controller. In the particular case of the kiln, the choice of pairings is evident. Each main controller (Digital microprocessors controller based on MICROCHIP series chips PIC16C56) controls the set of burners placed in one section located on the firing zone, and the measured output is the section temperature.

The temperature profile in the preheating and cooling zones is controlled with hot and cold air circulation along these sections. For that reason we need regulate circulation of the air in the few manners: regulate width of the exhaust hole, or width of other holes along the whole kiln with motor control of the dampers.

5. QUALITY CONTROL LAYER - SECOND LEVEL WITH FUZZY LOGIC CONTROLLER

The main goal is to generate a set-points for the controlled kiln variables so that the quality defects at the output bricks can be corrected. Hence, we may summarize [2,4,5] the following design procedure:
- Select the kiln sections where an action should be applied. Usually it is firing sections reference temperature (temperature profile) and position of the dampers for air circulation. This is referred to as the strategy selection.
- Calculate, by means of a fuzzy rule base inference, the temperature modification to be applied in the selected sections. This modification is considered on the temperature difference between the upper and bottom profiles.
- Distribute the calculated gradient modification between the upper and bottom temperature profiles.
- Correct the temperature set-points of the left and right neighbours sections if the temperature gradient is too large.

Firing zone reference temperature or temperature profile is presented on Fig.III. Temperature curves which give best result of the products quality are located in one region presented on Fig.III, with width

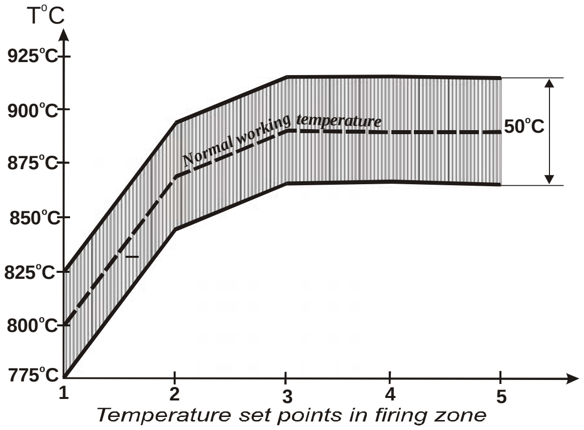


Fig. III. Temperature profile of set points in firing zone

50°C. There is one normal working temperature, and maximum and minimum temperature can have difference of 25°C, which mean zone of variation of referent temperatures in firing zone are 50°C (Fig. III).

Fuzzy logic controller is conventional Mamdani multivariable controller with four inputs and two outputs (Fig.IV). Controller inputs are: product colour u1, product dimension u2, porous u3, and energy consummation, in our case gas consummation u4. Outputs are: temperature profile in firing zone y1, and damper position y2.

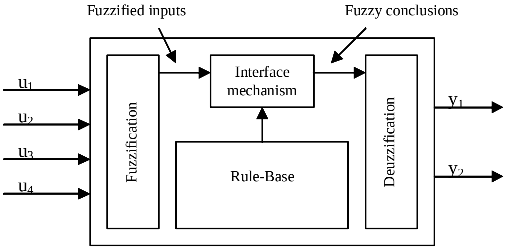


Fig. IV Second level fuzzy logic controller

Membership functions of input and output variables are presented on Fig.V.

Fuzzy logic sets are:

$BC=\{((u_1), \mu_{BC}(u_1)): u_1 \in [0,100]\}$
$BD=\{((u_2), \mu_{BD}(u_2)): u_2 \in [-8,8]\}$
$P=\{((u_3), \mu_P(u_3)): u_3 \in [0,20]\}$
$FC=\{((u_4), \mu_{FC}(u_4)): u_4 \in [-1,1]\}$
$T=\{((y_1), \mu_T(y_1)): y_1 \in [870,920]\}$
$DP=\{((y_2), \mu_D(y_2)): y_2 \in [0,100]\}$

When μ_{BC}, μ_{BD}, μ_P, μ_{FC}, μ_T, μ_{DP} are corresponding membership function defined as on Fig.V. We chouse next lingvistic variables:

$\tilde{u}_1$=“BrickColor”=$\{\tilde{U}_1^j : j = 1,2,3\}$ ={light, middle, dark};

$\tilde{u}_2$=“BrickDimension”=$\{\tilde{U}_3^k : k = 1,2,3\}$ ={redused, normal, incrised};

$\tilde{u}_3$=”Porous”=$\{\tilde{U}_2^l : l = 1,2\}$ ={Nonporous, Porous};

$\tilde{u}_4$=”Fuel Consummation”=$\{\tilde{U}_3^m : m = 1,2,3\}$ = ={Low, Normal, Increased};

$\tilde{y}_1$=”Temperature”=$\{\tilde{y}_1^n : n = 1,2,3\}$ ={Low, Middle, High};

$\tilde{y}_2$=”Damper Position”= $\{\tilde{y}_2^p : p = 1,2,3\}$ ={Close, Middle, Open}.

The rules are with the form:

If $\tilde{u}_1$ is $\tilde{U}_1^j$ and $\tilde{u}_2$ is $\tilde{U}_2^k$ and $\tilde{u}_3$ is $\tilde{U}_3^l$ and $\tilde{u}_4$ is $\tilde{U}_4^m$ **then** $\tilde{y}_1$ is $\tilde{y}_1^n$ and $\tilde{y}_2$ is $\tilde{y}_2^p$

Or with the concrete values of linguistic variables:

If BrickColor is Light and BrickDimension is reduced and Porous is Nonporous and FuelConsummption is Low then Temperature is High and DamperPosition is Open

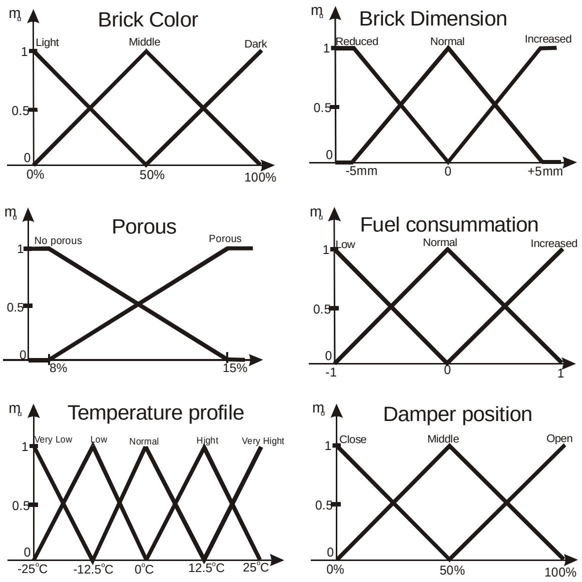


Fig.V Membership function of input and output variables

Definition of rule bases is on the basis of knowledge of technologist of the process, existing literature in this area and our experience with thermal processes and processes for clay brick production (Zadeh, 1980, Wang, 1997). The definition of strategies, rule bases and distribution coefficients is made using a simple syntax with a rules editor. On the other hand, a track of the fuzzy inference process can be obtained from the application. Perhaps, the application to *calibre control* is one of the best instructive examples illustrating the essentialities (Dimirovski, *et al.* 2000, Pico *et al.* 1999, Ribeiro *et al.* 1995).

Some of the input variables are change on every wagon suppression, e.g. every time when wagon come out from the kiln (brick colour, brick dimension), some of them change one times per day (brick porous) and some of them change continuously (fuel flow). Every time when we can have new values for any input variable we will have new values of output variables: temperature profile of set point values in firing zone and damper position.

6. SIMULATION RESULTS

We work simulation of the Second layer Fuzzy logic controller in MATLAB Fuzzy logic Toolbox. On the bases of our experience with processes of this kind and especially with clay brick production we find that our controller give us good results.

After implementation of this controller on the kiln we will adjust membership function of the input and output variable, and maybe some change in rules base.

7. CONCLUSION

In this paper we discus one two-level and set point-oriented controls in complex industrial heating plants, clay brick production (firing) in tunnel kiln. Special attention is give to fuzzy logic control which is involved on the second control level on the basis of products quality control. Fuzzy logic controller is Mamdani type with four inputs: quality of the products and process: brick colour, brick dimension, brick porous and energy consummation, and two outputs: temperature profile of set point values in firing zone and damper position for regulation of air flow across the kiln. The control system has been implemented in factory for clay-brick productions "KIK" in Kumanovo. A suitable and intelligent automation can save energy, improve the quality and therefore costs.

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