Advanced Industrial Control Using Fuzzy-Model Predictive Control on a Tunnel Klin 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 model predictive control occurs at regulation level of energy conversion and heating process. Fuzzy control is involved on the second control level on the basis of products quality control. The proposed control system has been simulated in MATLAB Simulink on a model from the factory for clay-brick productions "KIK" in Kumanovo. A suitable and intelligent automation can save energy and therefore costs. Copyright © 2011 IFAC

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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.

The overall control task is to drive the process to the desired thermodynamic equilibrium 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. 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.

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" KUMANONO 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 of natural gas batteries and air batteries. Natural gas batteries consist of 15 burners and one place for thermocouple. Air batteries also consist of 15 air distributors. Along the kiln there are central gas and air supply systems. Air is supply from one fan with capacity 7500m³/hour. Natural gas consumption is around 8-10 Nm³/hour continuous work. Maximal temperature in burning zone is 1200°C.

The kiln consists of three zones: preheating zone, firing zone and cooling zone, Fig. 1. 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. 2. 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.
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°C, to dark-red if the firing is on 1180°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°C, to olive green if the firing is on 1180°C. If the temperature in the firing zone is higher than 1200°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°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°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 micro cracks 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 micro crack or whole network of cracks which lead to product destroying. If on the product doesn’t exist micro cracks, it give clear sound on the blow. In opposite it gives dully and unclear sound. Another way for detection of micro cracks is wetting of the clay bricks. If the micro cracks exist they clearly are showed as a wet parts, and rest of brick surface will be dry. One of the main reasons for micro cracks 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 MPC 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. 1).

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, \( r_2 \), 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.

The fuzzy logic sets were defined in our previous work and it is conventional Mamdani multivariable controller with four inputs and three outputs. Controller inputs are: product colour, product dimension, porous, and energy consummation, in our case gas consummation. Outputs are: temperature profile in firing zone and damper position.
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 model predictive control with decentralized feedback. The temperature profile in the firing zone is controlled with 6 burners as defined in Section 3. 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 through the damper position.

The objectives of this layer are to implement quality control using model predictive controller. In our previous work (Stankovski et al. 2005) we have used ON-OFF controllers at this level combined with decoupling method. Now, when implementing MPC we do not need to decouple the plant, because the MPC controller takes into consideration all input-output interconnections in the system.

The control system architecture is presented on figure 3, and defines a two level, fuzzy – model predictive controller.

Fig 3. Schematic of the proposed control architecture

5. EXECUTIVE CONTROL LAYER – FIRST LEVEL WITH MODEL PREDICTIVE CONTROLLER

A basic structure of MPC is presented in Fig 4. The control input trajectory over the control horizon is determined in the algorithms on the basis of the model, by minimizing a cost function. In order to obtain proper results, we must to incorporate constraints on the system we want to control. The cost function in general consists of two parts: differences between the set points and the predicted outputs and is known as the cost of predicted control errors and the penalties for the changes of the control value. The most common used quadratic cost function can be formulated as in (1).

$$J(k) = \sum_{p=0}^{N_p} \delta_p \left[ w(k+p | k) - y(k+p | k) \right]^2 + \sum_{p=0}^{N_p} \lambda_p \left[ \Delta u(k+p | k) \right]^2$$

(1)

Fig. 4. Basic structure of MPC

The transfer functions between the input/output channels are in the form: $T = \frac{B}{s^2 + A}$, where $A$, $B$ and $T$ are the parameters to be identified.

The idea is to use one function not only to minimize the output errors, but in a way to keep the changes of the control value at the minimum. The notation in (1) is obvious, and the control horizon must satisfy the constraints $0 < N_u \leq N_p$. It is usually assumed that $N_u < N_p$ in order to get decreased dimensionality of the optimization problem which leads to a smaller computational load. The value of $\lambda$ differs depending on the process that we want to control and determine how big control change we will allow to be performed at one step of the algorithm. The predicted control values are obtained with minimizing the cost function. Nevertheless the quality of MPC depends mostly on the model for the controlled plant. In this paper, the model we use has 7 inputs (6 fuel flows into the burners and damper set point) and 13 outputs ($T_1$-$T_{12}$ and damper position). The model structure is presented on Fig 5. For more on MPC and the MPC industrial applications please refer to Camacho and Bordons, 2004.
6. SIMULATION RESULTS

In order to achieve good quality control in this study we combine an automated measurement system, which measures the colour of the bricks and the fuel consumption, with results of a laboratory tests done on daily basis. All these parameters are delivered in normalized form to a fuzzy logic controller installed on the PC in the operating room. From these parameters the fuzzy logic controllers derives the optimal temperature profile for the “firing zone” and the desired damper position.

We have designed a simulation in MATLAB Simulink (Fig. 6) to confirm that the proposed control architecture has many advantages over the conventional control of such processes. The quality control layer dynamically defines the referent temperature of the firing zone (Fig. 7).

The model was derived with identification with the data from the real plant. The transfer function for the direct I/O connections is $e^{-2.5s}(12 / (0.3s + 1))$. In the MPC algorithm the weights of the outputs in the firing zone are biggest (value $\delta_9 = 0.8$) and the weights of the temperatures in the preheating and cooling zones have lower values ($\delta_1 = 0.3, \delta_{10} = 0.3$). This means that the controller will react more on the errors in the firing zone than on the errors in the preheating and cooling zones. The set point in firing zone is set to 970 Celsius degrees.

The results of these simulations are presented on Fig 8 these results are given into summarized form because there are not big differences in the grouped signals. It is obvious that the controller drives the system to the steady state. It has minimal overshoot which is very important for the quality of the brick products. The fuel consumption (Fig. 9) is reduced compared to the data from the real-time operation in the factory.

This algorithm enables the engineer to replace the conventional decoupling control of MIMO processes with MPC, which is more intuitive and easier to understand. Additionally the MPC has “built-in” methods for compromising the quality of control with the cost of the control action which is extremely important for industrial processes with high consumptions of energy.

Fig. 6. Simulink model for the proposed Fuzzy-MPC control architecture

Fig. 7. Referent value change due to quality control layer

Fig. 8. Simulation results of the two level fuzzy – MPC
7. CONCLUSIONS

In this paper we discuss a two-level and set point-oriented controls in complex industrial heating plants, clay brick production (firing) in tunnel kilns. Special attention is given to model predictive control which is involved on the executive control level. The control system was simulated in MATLAB Simulink environment and the simulation results have been presented. These results have been satisfactory in means of quality of control, low fuel consumption and relatively easy implementation. The implementation of Fuzzy-MPC algorithm in real industrial heating plants will increase the productivity of the plant at some reduced fuel cost.

The future research will be oriented towards implementing a Fuzzy –MPC algorithm on a laboratory model of industrial furnace, and after that testing the developed control algorithm on real industrial processes.

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