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FUZZY CONTROL FOR HEAT RECOVERY SYSTEMS OF CEMENT CLINKER COOLER

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ABSTRACT

A fuzzy logic controller of the heat recovery systems of cement clinker grate cooler is presented in this paper. The development and tests of the proposed fuzzy controller have been implemented in a cement plant in Guangdong, China. Cooling is performed by blowing fresh air underneath the grate cooler plate and heat recovery is obtained by outlet pipe extracting the hot air. However, continuous fluctuation of both the clinker inlet temperature and flow rate, in conjunction with the practical unfeasibility of direct measurements of such parameters, makes it difficult to extract air at constant temperature, this being the only parameter that can be monitored for process control. In this situation, fuzzy logic control offers an advantage over conventional control techniques in implementing the control rules. Drawing on a previously developed unsteady-state real-time heat exchange model of cement clinker grate cooler operation, the paper describes the development and optimization of the control system along with tests of its performance.

Keywords: *Fuzzy Control, Heat Recovery, Cement Clinker Cooler*

1. INTRODUCTION

In industries like chemical, metallurgical, material, etc., the cooling of solid particulate often causes a great deal of energy waste. Advances in energy saving techniques have made it possible to reduce production costs in heat recovery process, which is the most important energy saving process in the cement industry. In fact, 30-40% [1]-[4] of the total heat input of dry-process cement clinker rotary kiln production line is not being used, and 20-30% [1] of the total heat input of cement clinker cooler is discharged into the atmosphere as sensible heat of exhaust air.

Heat recovery from air-cooled cement clinker cooler is usually accomplished by one or more outlets extracting the waste hot air. Nevertheless, it is hard to recover waste heat at constant temperature because the operating conditions of clinker cooler rarely maintain the steady state. Frequent fluctuations of inlet temperature (T_{ci}) and flow rate (F_{ci}) of clinkers cause large variations of thermal load at the clinker inlet. As a consequence, in order to ensure constant target temperatures of the exhaust air ($T_{ea,\ t}$), recovery air ($T_{ra,\ t}$) and secondary air ($T_{sa,\ t}$), control actions on the cooling air flow rate underneath the grate plate must be taken according to the state of clinker grate cooler at any given time.

Control law of cooling air using T_{ci} and F_{ci} fluctuations as input variables is limited by complex transient phases in the heat exchange behavior which propagate along the cooler, especially when multiple outlets are involved. Moreover, as the real time T_{ci} and F_{ci} variations are difficult to measure, we only have transient temperature values of exhaust air (T_{ea}), recovery air (T_{ra}) and secondary air ($T_{sa,\ t}$) as effective input parameters for the control system. As a result, controlling of cooling air flow rate (F_c) can be adjusted depending on real time values of the extracted air (exhaust air, recovery air) temperature.

In this application, it is impossible to obtain the simple analytical model which directly correlates T_{ea} (and T_{ra}) with F_{c1} (and F_{c2}), even if real time conditions of the clinker cooler are known. Methods based on traditional PID rules, response surface, neural networks, expert systems, etc. are unable to define the control law because of the complexities in heat exchange and heat recovery and large fluctuations of operating conditions. Fuzzy logic, instead, seem to be the most appropriate approach especially when no adequate mathematical model for a given problem is easily found or when non-linearities and multiple parameters exist [5]-[8], as in the present application. Furthermore, fuzzy systems, when applied to these problems, have faster and smoother responses than conventional approaches [7].

Having this in mind, a heat recovery control algorithm based on fuzzy theory has been researched, which focuses on a set of heuristic decision rules. In order to carry out the fuzzy controller synthesis and tests in absence of appropriate thermal transient experimental data, a heat exchange dynamic model developed in a previous study [9] has been used for cooling bed simulation. The model shows the dynamics between pressure below the grate and speed of the grate, and is applied to a process of similar logic from paper [10]. Although fuzzy controller and PID-Fuzzy controller [11] for cooler is studied and applied, the control response to increase speed of the grate is based on pressure below grate. Based on the model of pressure and speed, a new model of controlling cooler is established in this article, which introduces more factors, such as temperatures of the exhaust air ($T_{ea,\,t}$), recovery air ($T_{ra,\,t}$), secondary air ($T_{sa,\,t}$) and etc. The addition of new factors makes the new model more suitable for the controlling of cooler under extreme conditions.

In this study, the fuzzy logic control is designed though the MATLAB Simulink and Fuzzy Toolbox. [10] Fuzzy Toolbox can fulfill a series of tasks based on fuzzy logic, including MATLAB functions, graphic visualization, and a Simulink block for analyzing, designing, and simulating systems. It supports graphic development of membership functions, inference rules, and defuzzification processes. The overall simulink model allows for a detailed representation of the clinker cooler control system enabling real time optimization of controller parameters by graphically modifying fuzzy rules and membership functions even when the simulation is running. The fuzzy control developed may be then directly employed in real heat recovery systems by using the measured values of T_{ea}, T_{ra} and T_{sa} as input, and calculating corresponding control signals for the cooling air throttling equipment and the grate drive equipment.

The development and computation processes of the fuzzy control system will be briefly presented in the paper, and the tests of the fuzzy controller on different operating conditions will be carried out in the heat recovery system of a real cement clinker plant.

2. ANALYSIS OF HEAT RECOVERY SYSTEMS

The schematic technological process of cooling and heat recovery of the clinker is shown in Figure 1. The clinker cooler have double group grates. Below the grates, there are six chambers without connection channel between each other, and each chamber is equipped with a fan to provide cooling air. Above the grates in cooler is a connection space. At the top of the cooler, there are two air outlets to discharge air.

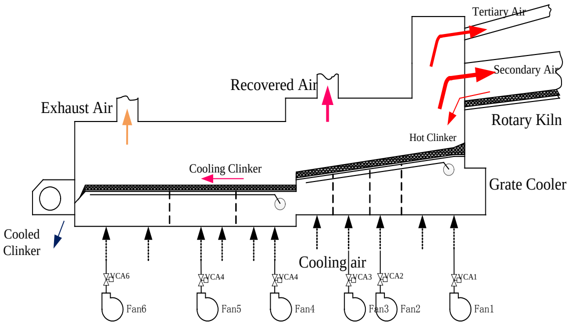

Figure 1: Technological process

The cement clinker falls into the grate cooler from the hood of kiln. The clinker moved from one end to the other on the reciprocating grates, and is cooled by the cooling air flowing through the grates before being discharged finally. The thickness of clinker on the grates depends on the flow rate of clinker from kiln and the speed of grates. The temperature of the discharged clinker depends on the flow rate of the cooling air, the flow rate and the temperature of the clinker from kiln, etc. The heat exchange between clinker and cooling air is completed here. The heated hot air is discharged thought multiple outlets. One part of the hot air enters kiln as secondary air for the fuel combustion; one part enters precalciner as tertiary air for the fuel combustion; one part flows though the AQC boiler as recovered air for waste heat recovery; and the rest is discharged directly into atmosphere as exhaust air.

The hot air recovered flows into the boiler to heat the working medium, and afterwards the air is released out of the boiler to combine with the exhaust air. Then all waste air enters the electrostatic precipitator for removing dust, and is discharged into atmosphere by the kiln hood exhaust fan.

3. CONTROL PROCESS DESCRIPTION AND DISCUSSION

3.1 DESCRIPTION OF CONTROL PROCESS

Clinker cooler is a very important piece of equipment in the complex cement production process that plays a significant role in stabilizing and improving performance of the production process both in relation to the speed of moving grates and the flow rates of fans. The function of cooler is to exchange heat between the hot clinker from the kiln and the cold air blown by the fans. The cooler control is to maximize heat exchange in a stable and permanent way, so three objectives must be achieved. First, the temperature of the clinker withdrawn from cooler should be as low as possible so as not to endanger transport and storage equipment. Second, the temperature of secondary air entering the kiln should be high and stabilized so as to maximize heat transfer and raise the calcination temperature in kiln [13]. Third, the temperature of the exhaust air should be controlled as low as possible to minimize heat loss.

There are ten variables to be controlled: six flow rates of cooling air, two flow rates of waste air, and two speeds of grates. The flow rate of cooling air is adjusted by the adjustable plates in front of each cooling air fan; the speed of grate is regulated by the speed of driving motor; and the flow rates of recovered air and exhaust air are adjusted by the air damper in the corresponding outlet.

The speed of the group 1 grates is regulated according to the biggest pressure changes in chamber 1, 2 and 3. Similarly, the speed of the group 2 grates is regulated according to the biggest pressure changes in chamber 4, 5 and 6. In order to simplify the description, we take the pressure change in chamber 1 as the biggest pressure changes in first three chambers, and the pressure change in chamber 4 as the biggest pressure changes in last three chambers.

The amount of cooling air blown into each chamber is adjusted by the adjustable plates in front of cooling air fan depending on the air pressure in each chamber. The pressure of air in chamber is in direct proportion to the thickness of the clinker on the grate.

The flow rate of secondary air cannot be adjusted directly by valve or adjustable plate in the passage, but can be adjusted indirectly by the pressure at two ends of kiln. The flow rate of tertiary air can be adjusted directly by air valve in tertiary air pipe, but generally speaking no adjustment needs to be made so long as the rotary kiln is in normal operation. So we can only adjust the flow rate of recovered air and exhaust air for clinker cooling and heat recovery.

The relational graph is shown as Figure 2.

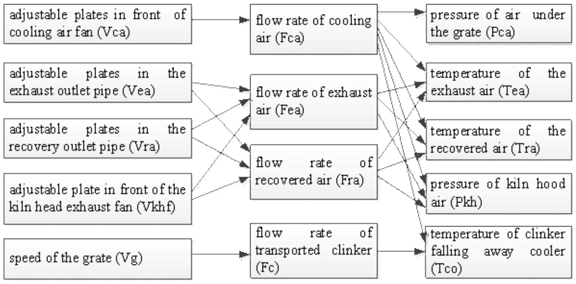

Figure 2: Coordinated control logic graph

3.2 DISCUSSION ON COOLER CONTROL

In order to recover heat from the cooler steadily by means of secondary air [13], tertiary air and recovered air, the clinker thickness on the cooler grates must be stabilized as well as the flow rates of cooling air from each fan. These factors must be considered in the control scheme, which are analyzed as follows.

Steady cooling air flow rate from fans is a fundamental requisite for cooler control. Although we have reliable equipment to measure air flow rates and fast actuators such as dampers, we still found it hard to control air flow rates in dynamic process because depending on the thickness of clinker and granularity of clinker, the damper will affect cooling air flow rate differently.

In order to stabilize the clinker thickness on the cooler grates, many problems inherent in the cooler and current technology must be carefully considered. Firstly, the flow rate of clinker from kiln cannot be measured directly. The fluctuation of flow rate makes it hard to guarantee the thickness of clinker on the cooler grates. Secondly the thickness of clinker on the cooler grates cannot be directly measured, but can be indirectly measured by the pressure below the grate. The pressure below the grate is related to clinker thickness, but it is also influenced by other factors such as the variations of clinker granularity and fan load. Thirdly, complex cooler has some limits on control actions such as grate speed. Finally, factors like relaxation, lag, inertia and nonlinearity increase the difficulty to control the speed.

To sum up, the control of cooler heat recovery system is complex since the control actions on the grate speed are affected by many factors, such as the clinker thickness on top of the moving grates and the flow rate of cooling air. Therefore, when developing control strategies, we must think about how to minimize the effects of clinker thickness.

3.3 CONTROL STRATEGY

From the above analysis, we know that the flow rates of cooling air and the speeds of grates are controlled by some measured variables. Control strategies for the clinker cooler can be developed based on the relations between controlled variables and measured variables.

The cooling air flow rate of fan 1 is determined by the measured values of cooling air pressure in chamber 1(P_{CA1}), recovered air temperature (T_{ra}) and secondary air temperature (T_{sa}). These measured parameters are also the control variables that should be maintained at the predetermined value fixed by the AQC boiler. It should be pointed out that the control system cannot calculate those immeasurable parameters through variables influencing the cooling process.

In the control system, the deviations of recovered air temperature T_{ra} from the set point $T_{ra,t}$, secondary air temperature T_{sa} from the set point $T_{sa,t}$ and cooling air pressure in chamber 1 P_{CA1} from the set point $P_{CA1,t}$ are assumed as input variables. The speed of the grate 1 S_{G1} and the adjustable plates in front of cooling air fan 1 V_{CA1} are output variables.

$$\Delta T_{ra} = T_{ra} - T_{ra,t} \tag{1}$$

$$\Delta T_{sa} = T_{sa} - T_{sa,t} \tag{2}$$

$$\Delta P_{CA1} = P_{CA1} - P_{CA1,t} \tag{3}$$

Output variable uses the gain coefficient k_{SG1} to denote the intensity of the required control action, which provides the real time value of the control speed of the grate 1 $(S_{G1})_{new}$ by modifying the previous value $(S_{G1})_{old}$. The F_{SG1} is a function to calculate k_{SG1} with the deviations of measured variables from the set point, such as ΔT_{ra}, ΔT_{sa}, ΔP_{CA1}.

$$\left(S_{G1}\right)_{new} = \left(S_{G1}\right)_{old} * \left(k_{SG1} + 1\right) \tag{4}$$

$$k_{SG1} = F_{SG1}\left(\Delta T_{ra}, \Delta T_{sa}, \Delta P_{CA1}\right) \tag{5}$$

Also, the other output variable also adopts the gain coefficient k_{CA1} to denote the intensity of the required control action, which provides the real time value of the control adjustable plates in front of cooling air fan 1 $(V_{CA1})_{new}$ by modifying the previous value $(V_{CA1})_{old}$. The F_{CA1} is a function that calculates k_{CA1} with the incremental value ΔT_{ra}, ΔT_{sa}, ΔP_{CA1}.

$$\left(V_{CA1}\right)_{new} = \left(V_{CA1}\right)_{old} * (k_{CA1} + 1) \tag{6}$$

$$k_{CA1} = F_{CA1}\left(\Delta T_{ra}, \Delta T_{sa}, \Delta P_{CA1}\right) \tag{7}$$

Gain coefficients k_{SG1} and k_{CA1} are determined by ΔT_{ra}, ΔT_{sa} and ΔP_{CA1}. Therefore, the new values of S_{G1} and V_{CA1} are obtained by adding the changes to the values of the old ones. That is an incremental algorithm based on conventional discrete time controllers. The control law of the cooling air flow rate should be obtained at any transient situation. So the control speed of the grate 1 $(S_{G1})_{new}$ and adjustable plates in front of cooling air fan 1 $(V_{CA1})_{new}$ are updating continuously in each sampling period.

The cooling air flow rate of fan 4 is determined by two input variables: the cooling air pressure in chamber 4 (P_{CA4}) and the exhaust air temperature (T_{ea}). In the control system, the input variables are the deviations of exhaust air temperature T_{ea} from the set point $T_{ea,t}$ and cooling air pressure in chamber 4 P_{CA4} from the set point $P_{CA4,t}$, which are expressed as:

$$\Delta T_{ea} = T_{ea} - T_{ea,t} \tag{8}$$

$$\Delta P_{CA4} = P_{CA4} - P_{CA4,t} \tag{9}$$

Output variable uses the gain coefficient k_{SG1} to denote the intensity of the required control action, which provides the real time value of the control speed of the grate 2 $(S_{G2})_{new}$ by modifying the previous value $(S_{G2})_{old}$.

$$\left(S_{G2}\right)_{new} = \left(S_{G2}\right)_{old} * (k_{SG2} + 1) \tag{10}$$

Also, the other output variable uses the gain coefficient k_{CA1} to denote the intensity of the required control action, which provides the real time value of the control adjustable plates in front of cooling air fan 1 $(V_{CA4})_{new}$ by modifying the previous value $(V_{CA4})_{old}$.

$$\left(V_{CA4}\right)_{new} = \left(V_{CA4}\right)_{old} * (k_{CA4} + 1) \tag{11}$$

The k_{SG2} and k_{CA4} can be obtained through the F_{SG2} and F_{CA4} respectively. The F_{SG2} and F_{CA4} are the functions that calculate k_{SG2} and k_{CA4} with the deviations of measured variables from the set point, such as ΔT_{ea} and ΔP_{CA4}.

$$k_{SG2} = F_{SG2}\left(\Delta T_{ea}, \Delta P_{CA4}\right) \tag{12}$$

$$k_{CA4} = F_{CA4}\left(\Delta T_{ea}, \Delta P_{CA4}\right) \tag{13}$$

4. FUZZY CONTROL SYSTEM DEVELOPMENT

4.1 STATEMENT

Taking the heat recovery system of one outlet as example, we developed the fuzzy logic control system in this paper. In this case, how to recover the highest amount of heat by control strategies is our major concern. The cooling air flow rate is adjusted on the basis of the measured values of pressure beneath grate and extracted air temperature.

The advantages of fuzzy control over other control method are obvious: [7][14][15]: it requires no mathematical model; there is no need to estimate the operating conditions; it shortens the development time of control system control; linguistic representation makes it convenient to optimize strategy and it enhances robustness by incorporating engineering know-how.

4.2 CONTROL CRITERIA

Two controllers are designed for controlling heat recovery system of clinker cooler. The first controller has three inputs and two outputs: cooling air pressure in chamber 1 (PCA1), temperature of the recovered air (TRA), temperature of the secondary air (TSA), speed of the grate 1 (SG1), and adjustable plates in front of cooling air fan 1 (VCA1). The logic diagram of controller Ⅰ is shown in Figure 3.

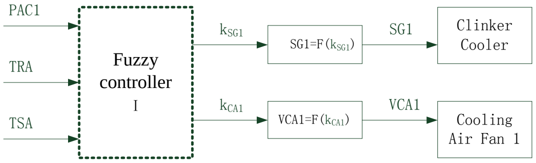

Figure 3: Fuzzy controller Ⅰ

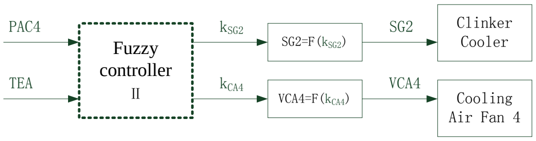

Figure 4: Fuzzy controller Ⅱ

The second controller has two inputs and two outputs: the deviations of cooling air pressure in chamber 4 P_{CA4} from the set point $P_{CA4,t}$ (, PCA4), the deviations of exhaust air temperature T_{ea} from the set point $T_{ea,t}$ (, TEA), speed of the grate 1 (SG2), and adjustable plates in front of cooling air fan 4 (VCA4). The logic diagram of controller Ⅱ is shown as Figure 4.

The fuzzy logic control process is shown in Figure 5. The first step is called as fuzzification, in which the real variables are translated into linguistic variables. The second step is called fuzzy inference, which defines a set of IF-THEN rules and provides linguistic results of output variables. The last step is called defuzzification, in which the linguistic results are translated into real variables.

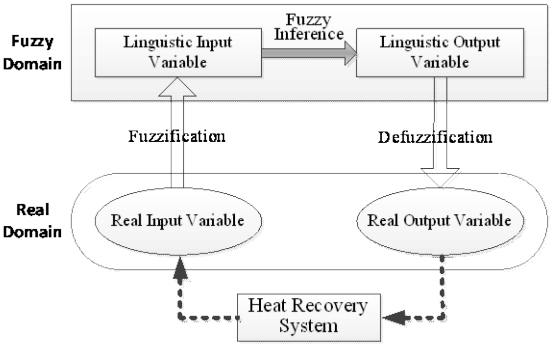

Figure 5: Fuzzy control processes

4.3 FUZZIFICATION

All the real input and output variables are translated into linguistic variables. The linguistic variables of ΔT_{ra}, ΔT_{sa}, ΔP_{CA1}, k_{SG1} and k_{CA1} are defined in terms of the following fuzzy sets: strongly negative (SN), negative (N), weakly negative (WN), zero (O), weakly positive (WP), positive (P) and strongly positive (SP). The degree to which real values of variables belong to a given fuzzy set is represented by membership functions. That is, ΔT_{ra}, ΔT_{sa}, ΔP_{CA1}, k_{SG1} and k_{CA1} crisp values may be represented on the horizontal axis of the function and membership degrees on the vertical axis. For example, the ΔT_{ra} determined membership functions are shown as Figure 6.

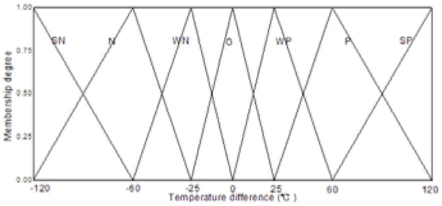

Figure 6: ΔT_{ra} membership functions

4.4 FUZZY RULE INFERENCE

The rules defining the relationship between fuzzy sets are expressed as IF (conditions of inputs) THEN (orders of outputs). The IF part is describes by one or more conditions, and determines the valid rules. The THEN part describes the control actions to be taken.

By computing fuzzy rules, the linguistic values of output can be obtained. The influence of ΔT_{ra}, ΔT_{sa}, ΔP_{CA1} on the output variable k_{SG1} and k_{CA1} is achieved through the rules. One part of rules is shown in Table I.

The influence of ΔT_{ea}, ΔP_{CA4} on the output variable k_{SG2} and k_{CA4} is achieved through the rules. One part of rules is shown in TableII.

Table I

Control rule table for k_{SG1} and k_{CA1} (TSA=O)

k_{SG1} k_{CA1}		PAC1						
		SN	N	WN	0	WP	P	SP
TRA	SN	WP N	P N	P SN	P SN	SP SN	SP SN	SP SN
	N	WP WN	WP N	P N	P SN	P SN	SP SN	SP SN
	WN	0 0	WP WN	WP N	P N	P SN	P SN	SP SN
	0	0 WP	0 WP	0 0	0 0	0 0	WP WN	P WN
	WP	0 P	0 P	0 WP	WP WP	WP 0	P 0	P WN
	P	0 SP	0 P	WP P	WP WP	P 0	P WN	SP N
	SP	0 SP	WP P	WP WP	P 0	P WN	SP N	SP SN

Table II

Control rule table for k_{SG2} and k_{CA4}

k_{SG2} k_{CA4}		PAC4						
		SN	N	WN	0	WP	P	SP
TEA	SN	0 SP	WP P	WP WP	P 0	P WN	SP N	SP SN
	N	0 SP	0 P	WP P	WP WP	P 0	P WN	SP N
	WN	0 P	0 P	0 WP	WP WP	WP 0	P 0	P WN
	0	0 WP	0 WP	0 0	0 0	0 0	WP WN	P WN
	WP	0 0	WP WN	WP N	P N	P SN	P SN	SP SN
	P	WP WN	WP N	P N	P SN	P SN	SP SN	SP SN
	SP	WP N	P N	P SN	P SN	SP SN	SP SN	SP SN

The fuzzy inference is performed from these rules, which mainly consists two parts: aggregation and composition. The aggregation determines the degree to which the IF rules are satisfied. And the composition uses the validity degree of the condition to determine the validity of the consequence. The computational results of the rules must be consistent with the actual condition. For example, when ΔT_{ra}=-100 ℃ , results strongly negative with a degree 0.65 and at the same time negative with a degree 0.35. The composition gives k_{SG1} and k_{CA1} strongly negative with a degree 0.65 and at the same time negative with a degree 0.35.

4.5 DEFUZZIFICATION

The defuzzification is the process of converting the output linguistic variables into numerical values. It is an important component of fuzzy modeling since it provides one part of the required symmetry between scalars and fuzzy sets. In this step, membership functions are once again used to translate the fuzzy output linguistic values into numerical values. It has to compromise the results given by different fuzzy sets recognized as valid for output linguistic variables in the previous step.

The Centre of maximum (COM) defuzzification algorithm [1] is adopted, which computes the output variables with the mean of k values corresponding to maxima of the valid membership functions, weighted by the respective inference result. For the previous example, k_{SG1} values corresponding to maxima of the valid membership functions strongly negative and negative are -0.1 and -0.06, respectively. Therefore, the crisp value of the output variable is k_{SG1}=(-0.1*0.65)+(-0.06*0.35)=-0.067; and similarly, when k_{SG1} values corresponding to maxima of the valid membership functions strongly negative and negative are -0.15 and -0.08 respectively, the other output variable is k_{CA1}=(-0.15*0.65)+(-0.08*0.35)=-0.1255.

4.6 MODEL IMPLEMENTATION

The described development steps of the fuzzy control system are carried out in the MATLAB SIMULINK, which supports graphical environment of all design phases of fuzzy logic systems. Integrating the fuzzy control algorithm with the previously developed dynamic simulation tool of the clinker cooler produces the overall model architecture for the heat recovery system in Figure 7.

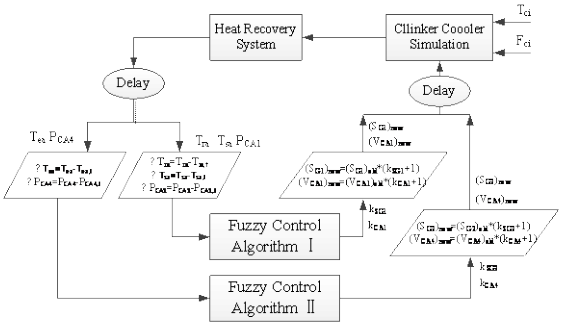

Figure 7: Overall model architecture of heat recovery system

The clinker cooler and heat recovery system model computes the temperature of the recovered air (T_{ra}) with the current values of the clinker inlet temperature (T_{ci}) and flow rata (F_{ci}), which are arbitrarily defined or imposed in a random fashion during the simulation running. The resulting T_{ra} value is compared with the target value $T_{ra,\ t}$ to obtain the value of the input variable ΔT_{ra}. The k_{SG1} and k_{CA1} output values of the fuzzy process are used to calculate the new speed of the grate 1 (SG1) and adjustable plates in front of cooling air fan 1 (VCA1) based on the equation described in control strategy part. The new values obtained from the clinker cooler simulation model are used to estimate the air temperature response in the subsequent sampling interval. In the real system, time delays may exist in both the measurement and the actual regulation of control actions. The delay in air temperature measurement is related with the volume of clinker cooler and the location of temperature sensor. The delay in grate speed is related with motor, pipeline length and the time the new speed value is required. In order to make the simulation model reflecting the actual situation, the k_{SG1} and k_{CA1} values are sent to the clinker cooler simulation model with a suitable and adjustable time delay. In the same, a delay is imposed on the measured air temperature signal received by the fuzzy control model.

The described approach may be implemented in real heat recovery systems adopting the control architecture shown as Figure 8.

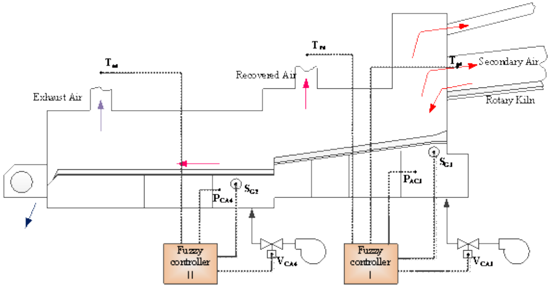

Figure 8: heat recovery system architecture

5. FUZZY CONTROL TESTS AND APPLICATION

The designed fuzzy controller has been tested in a cement plant. In case of flow rate fluctuations, we assume that a constant speed of the clinker grate will result in the variations of the clinker thickness. All of the scenarios mentioned above appear in the fuzzy control tests. The operation parameters of the clinker grate are shown as follows:

Clinker grate is 30m long, 4m wide;

Average overall cooling air flow rate is 12000Nm3/h at 20℃temperature;

Clinker temperature at bed inlet is about 1300℃;

Clinker temperature at bed outlet is about 90℃;

Recovery air temperature is 380℃;

Clinker grate bed speed ranges from 0 to 12 Reciprocating/min;

Clinker inlet flow rate ranges from 20 to 35kg/s;

Clinker thickness ranges from 450 to 750mm.

The fuzzy control method has been applied in a cement plant in Guangdong Provence with pure low temperature waste heat power generation system. The plant was operated under conventional control mode and fuzzy control mode for 72 hours respectively. The recorded data was selected and analyzed.

The comparison results of heat recovery system running in the fuzzy control mode and conventional mode are shown as Figure 9 to Figure 13 respectively.

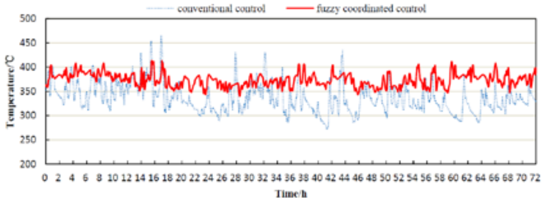

Figure 9: Temperature of the recovery air (TRA)

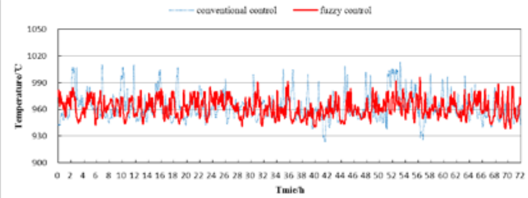

Figure 10: Temperature of the secondary air (TSA)

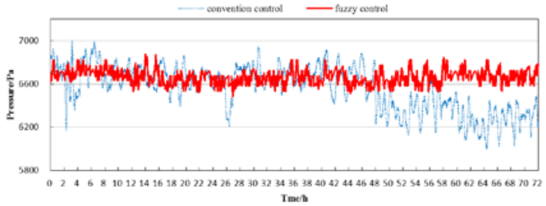

Figure 11: Pressure of cooling air in chamber 1 (PCA1)

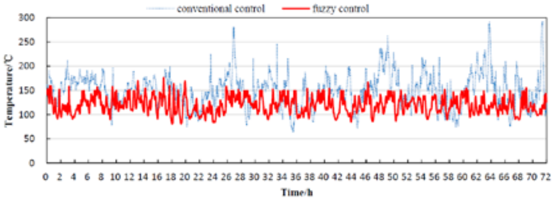

Figure 12: Temperature of the exhaust air (TEA)

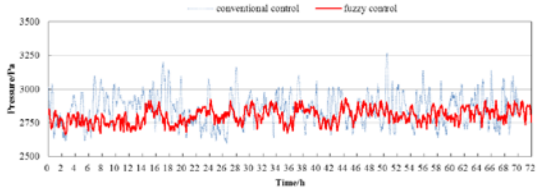

Figure 13: Pressure of cooling air in chamber 4 (PCA4)

As shown in Figure 9, the temperature of recovered air in the fuzzy control mode is higher and steadier than that in the conventional control mode in most of the time. So the average value of the recovered air temperature in the fuzzy control mode is higher than that in the conventional control mode, which means that more heat have been recovered.

It can be seen from Figure 10 that the temperature of secondary air of the heat recovery system in the fuzzy control mode is higher and steadier than that in the conventional control mode, which means that the steady temperature of secondary air is conducive to burning in rotary kiln.

Figure 11 shows that the pressure fluctuation of cooling air in chamber 1 of clinker cooler running in the fuzzy control mode is smaller than that in the conventional control mode. The steady pressure contributes to uniform cooling of clinker and the steady temperature of recovery air.

From Figure 12, it can be seen that the temperature of the exhaust air flowing out of the cooler in the fuzzy control mode is within the range of 100℃ to 150℃, and the average temperature is about 120℃. These values are lower than those in the conventional control mode. As we all know, the higher the temperature of the exhaust air is, the greater the heat loss there will be. So the fuzzy control method can effectively reduce the exhaust air temperature to reduce heat loss and create conditions for more heat recovery.

The pressure fluctuation curves of cooling air in chamber 4 in the fuzzy control mode and conventional control mode are shown in Figure 13. The pressure fluctuation in fuzzy control is smaller than that in the conventional control. The steady pressure ensures an appropriate flow rate of cooling air into cold clinker.

6. CONCLUSIONS

A temperature control system for heat recovery in cement clinker cooler has been presented in this paper based on fuzzy logic control method. Inlet temperature and flow rate of cement clinker cooler fluctuate greatly, which makes them difficult to measure. Control actions on the flow rate of cooling air and the speed of grates have been defined by using transient values of the pressure of air cooling air in chamber (PCA), recovered air temperature (Tra), secondary air temperature (Tsa) and exhaust air temperature (Tea). The superiority of the control system based on fuzzy theory has been tested under severe operating conditions, where complex transient phases in the heat exchange behavior propagate along the clinker cooler plate. As a result, the temperature of the extracted air (Tra, Tsa, Tra) has been quickly brought to Tt±10℃ and maintained in the range whatever the fluctuations of the clinker cooler thermal load are. Finally, the proposed control system may be readily implemented in the real heat recovery plant.

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