AUTOMATIC COMBUSTION CONTROL FOR A GASIFYING AND DIRECT MELTING FURNACE

Kazuro Tsuda, Minoru Tanabe, Hiroyuki Shimamoto

JFE R&D Corp. 1-1 Minami-Watarida-cho, Kawasaki-ku, Kawasaki 210-0855 JAPAN

Abstract: JFE Engineering Corp. developed a high-temperature gasifying and direct melting furnace as a completely new waste treatment system that meets the requirements of a recycling-based society. In 2003, the company completed the delivery of the first plants on order. From a control point of view the plant has long and variable time lag depending on a height of waste in the furnace. This paper presents an outline of the completed plants and describes the control system in which online model prediction is effectively combined with rule-based control. Operational results with the control system show the effectiveness of the system. *Copyright © 2005 IFAC*

Keywords: Automatic process control, Model based control, Predictive control, Temperature control, Rule-based systems

1. INTRODUCTION

1.1 Overview of the state of waste disposal in Japan

In the resource recycling society in the 21st century, recycling of garbage and the further efficient energy recovery are called for aiming at environmental impact mitigation in addition to detoxication and volume reduction of ashes. About 50 million ton per year of waste is discharged and volume of about 70% is reduced by incineration in Japan. Toxic substances and handling of the incineration ash pose a big problem. Moreover, the incineration processing itself is difficult for the industrial waste discharged about 400 million ton per year and the lot reservation for land reclamation is becoming difficult.

1.2 Technical characteristics of high-temperature gasifying and direct melting furnace

This furnace employs a new combustion technology developed from a combination of the melting technology employed in blast furnaces and nurtured through iron making operation and fluidized bed combustion technology well proven in waste incineration field. The furnace has the following characteristics (Arita, *et al*., 2003; Matsudaira, *et al*., 2004).

(1) Stable treatment of wide variety of solid wastes: The use of coke as a supplementary heat source

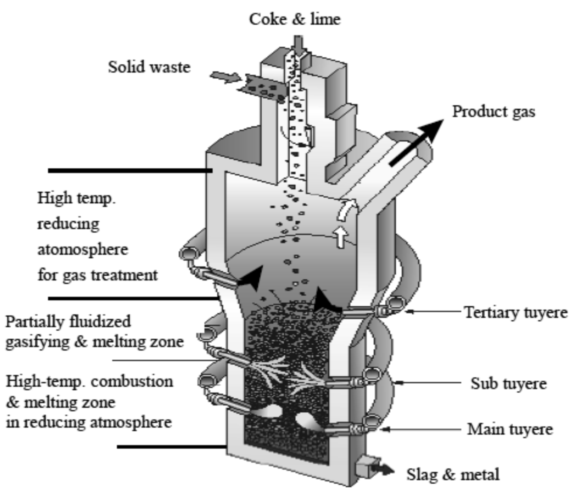

Fig. 1. Schematic diagram of high-temperature gasifying and direct melting furnace

allows stable gasification and melting of wide range of solid wastes without being affected by their ash rates and calorific values.

(2) Minimal environmental load during treatment:
Two-stage control comprising high-temperature reduction combustion in the melting furnace and high-temperature oxidization combustion in the secondary combustion furnace allows for control of dioxins. The use of limestone for basicity control ensures a low hydrogen chloride concentration.

(3) Reduction of waste volume and minimization of treatment costs:
Non-combustible components of the wastes are tapped continuously out of the furnace and form a high-quality slag that is recovered for use in a variety of applications. Thus the volume of materials remaining is considerably reduced and only fly ash from the dust collector requires final disposal. The use of low air ratio combustion in the furnace improves the power generation efficiency.

1.3 Structure of high-temperature gasifying and direct melting furnace

Fig.1 shows the structure of the high-temperature gasifying and direct melting furnace. The introduction of oxygen-enriched air from the main tuyeres promotes high-temperature combustion in the high-temperature combustion and melting zone at the lower portion in the furnace, thus melting the non-combustible components of the wastes as a slag. The slag can be tapped continuously as shown in Fig.2. Continuous tapping is the most attractive feature for operators because it makes the operational load substantially low as compared with intermittent tapping. Introduction of air from the sub tuyeres and the combustion gas from the high-temperature combustion and melting zone ensures that combustion is maintained at a temperature of between 650 and 750°C in the partially fluidized gasifying and pyrolysis zone at the middle portion in the furnace, thus drying and pyrolyzing the wastes. The non-combustible components fall into the high-temperature combustion and melting zone at the lower portion in the furnace, while the volatile components are gasified and move upwards. Introduction of air from the tertiary tuyeres ensures that a high-temperature reducing atmosphere is maintained in the freeboard zone towards the top of the furnace, thus controlling the generation of dioxins in the gas, and pyrolyzing the tar component to produce gas that is easily handled.

1.4 Necessity for automatic combustion control system

However, since many reactions and states are intermingled at one furnace unlike the conventional stoker type incinerator, an operator needs to supervise many process states simultaneously. For this reason too much burden would be placed on an operator under a manual operation and keeping of stable operation would become difficult. Then, Automatic Combustion Control (henceforth, ACC) equipment for gasifying and direct melting furnace was developed for the purpose of mitigation of operator load and preservation of stable operation. The most important function of ACC is keeping on the continuous tapping by controlling the temperature of molten slag for fluidity. This paper reports the outline of gasifying and direct melting furnaces, the feature and the details of the developed ACC equipment and a system operation situation.

2. OVERVIEW OF AUTOMATIC COMBUSTION CONTROL (ACC) SYSTEM

2.1 ACC for secondary combustion furnace

Product gas of high-temperature gasifying and direct melting furnace includes CO gas and the CO gas should be completely burnt in second combustion furnace shown in Fig.3. From control point of view two furnaces have completely different characteristics. In melting furnace, it takes about several hours from charge of waste to discharge of molten slag. On the other hand, in a secondary combustion furnace product gas coming from the melting furnace burns with the fluctuation at the rate of several minutes. The point for maintaining stable

Fig. 2. Continuous tapping of molten slag

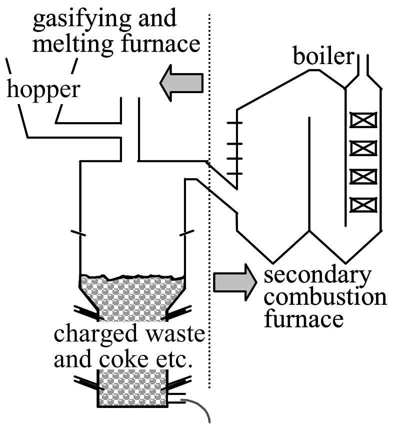

Fig. 3. Schematic diagram of total incinerator including secondary combustion furnace

operation in secondary combustion furnace is to perform quick adjustment of the amount of combustion air. This task cause an operator's load heavy without any automatic combustion control.

For avoiding such a situation JFE R&D Corp., in corporation with JFE Engineering Corp., has newly developed ACC system for the gasifying and direct melting furnace, in addition to ACC system for secondary combustion furnace that is similar to ACC for conventional stoker type incinerator (Fujii, *et al*., 1997, 2001). Moreover, the following two rules were taken into account as a control rule of a high-temperature reducing zone and a secondary combustion furnace.

(1) A rule of making a part of the combustion perform in a high-temperature reducing zone that reduces the combustion load of a secondary combustion furnace when the combustion load in a secondary combustion furnace is high.
(2) A rule that controls temperature distribution in the secondary combustion furnace by manipulating plural nozzles.

Thus the temperature and the exhaust gas behaviour of each part are appropriately adjusted by these control rules.

2.2 ACC for high-temperature gasifying and direct melting furnace

In this paper ACC system for the gasifying and direct melting furnace will be focused on. For keeping the stable continuous tapping in a melting furnace it is important to secure fluidity by controlling tapping temperature appropriate. For controlling the temperature of molten slag, the following problem should be solved.

(1) Long residence time:
In a gasifying and direct melting furnace it takes about a few hours from a waste charge to molten slag discharge. In other words, it is the plant with long time lag.
(2) Variable residence time
Because the property of waste always varies the speed of combustion also varies and, as a result, pile height varies. So the value of time lag is not fixed and can be varied while operation. This is critical for the plant because even when the waste coke ratio is changed intentionally the dominant state change happens only after the point reaches the bottom where oxygen-enriched air is injected. Especially change of Manipulated variable, for example, change of oxygen injection, causes fluctuation of pile height.

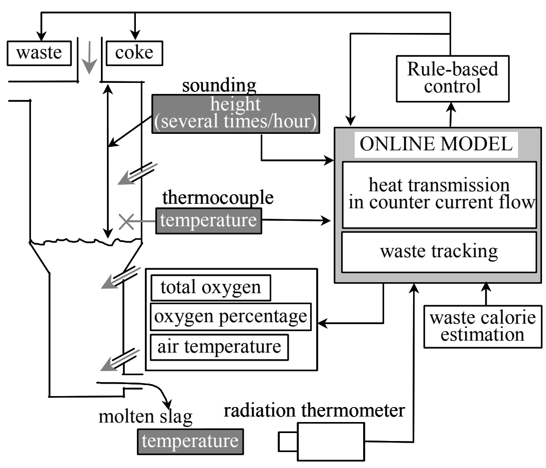

Fig. 4. Schematic diagram of ACC with online model for prediction

As mentioned above pile height is one of the most important states, and is a important factor which determines the heat-exchange time between charged waste and high-temperature gas. If sufficient heat-exchange time is not secured, sufficient temperature rise of waste will become impossible, thus, continuous tapping will be suspended. So it is necessary to maintain the pile height of waste appropriate, and to stabilize the temperature of molten slag.

The concept of rule-based control with online model prediction is shown in Fig.4. In addition to the various kinds of present process values, the predicted values from the online dynamic model of the plant built in ACC are taken into account. The dynamic characteristics of a melting furnace are described by the heat transfer in countercurrent flow model. The waste charged in from the top descends to high-temperature combustion and melting zone from partially fluidized gasifying and melting zone and performs a heat exchange from the high-temperature gas going up through the furnace. As a result of the heat exchange, the temperature of the descending waste rises and incombustible part carries out melting. In a model, the waste charged in unit time is treated as a cell. Since heat exchange and temperature change, as a result, are simulated for every cell, the waste charged into a certain time can be traced for the temperature and the position at any time. Generally in case of the process with long time lag, it takes long time for states to become stable once after the states have errors. On the other hand, the model prediction makes the ACC to act quickly against the undesirable deviation.

3. CONFIGURATION OF ONLINE MODELS AND RULE-BASED CONTROL

3.1 Waste tracking model

The conceptual diagram of a waste tracking model is shown in Fig.5. The waste charged in for definite periods of time, for example in 5 minutes, is treated as a cell or a layer in this model. As an attribute of a cell, the weight of each charge (waste, coke, lime), each component percentage(a part that can be dry-distilled, fixed carbon, moisture and ash) and bulk density are taken into consideration. The weight can be measured actually when the waste is charged into the furnace and other values are treated as constant.

At the bottom of the furnace component of fixed carbon lose its volume mainly by next chemical formula.

$$C + \frac{1}{2}O_2 \rightarrow CO + Q \tag{1}$$

Components of ash also lose its volume by melting in proportion to the reaction described by (1). As a result of moisture evaporation, dry distillation, melting and discharge at the main tuyere point, each cell loses its volume and moves below. Pile height is computed from the information of each cell. In Fig.6 comparison between model estimation and actual measurement of pile height is shown. Here the actual measurement is conducted by sounding every 20 minutes. It is shown from the figure that the model estimation is done with good quality and as a result the waste tracking is also assumed to be good.

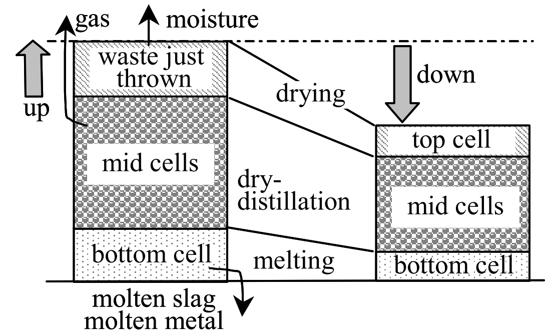

Fig. 5. Conceptual diagram of waste tracking model

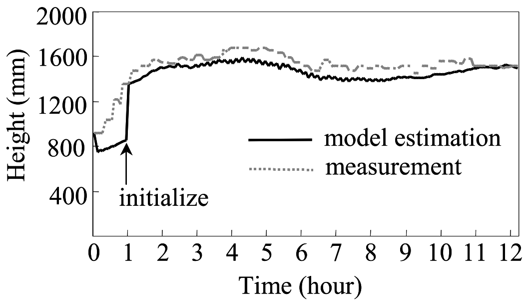

Fig. 6. Comparison between model estimation of height and actual measurement

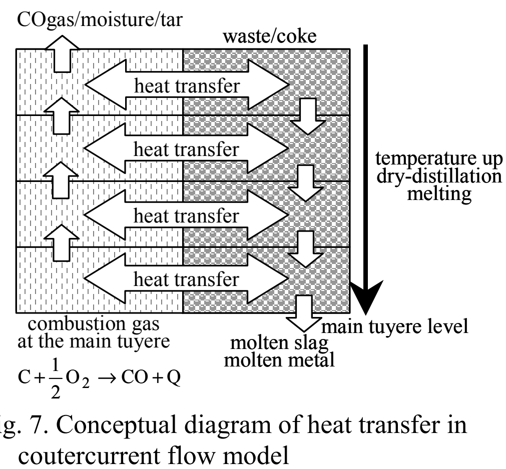

Fig. 7. Conceptual diagram of heat transfer in coutercurrent flow model

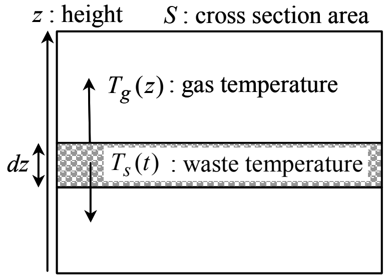

Fig. 8. Heat transfer in countercurrent flow model

3.2 Heat transfer in coutercurrent flow model

In a heat transfer in countercurrent flow model shown in Fig.7, heat exchange calculation of charged waste and a coke layer, and high-temperature gas is performed, and the temperature up of the waste and the coke layer is estimated and predicted. Hereafter, the basic equation that describes the heat exchange of cells is explained. As shown in Fig.8, the heat exchange of high-temperature gas and the cell which has dz height is considered. Since the velocity of gas flow is considerably high as compared with waste fall, gas temperature is treated as the function of a height and only waste cell temperature is treated as a function of time. Here, the calorie exchanged during the unit time dt is described as shown in (2). Waste cell temperature is computed by integrating the equation (3) along the time. From the waste cell temperature and Equation (3) including the velocity of the gas, gas temperature is induced.

$$h \cdot a \cdot S \cdot dz(-T_s(t) + T_g(z))dt = C_p \cdot S \cdot dz \cdot dT_s(t) \tag{2}$$

$$C_g \cdot V_g \cdot dt \cdot dT_g(z) = C_p \cdot S \cdot dz \cdot dT_s(t) \tag{3}$$

The notation in (2) and (3) are as follows:

h:	Heat transfer coefficient(kcal/m2K)
a :	The gas contact surface per waste unit volume(m2/m3)
S:	The cross section of a waste cell(m2)
z:	Coordinates of height direction(m)
t:	Time(s)
$T_s(t)$:	Waste cell temperature(K)
C_p :	Specific heat of waste cell(kcal/kgK)
$T_g(z)$:	Gas temperature (K)
C_g :	Specific heat of gas(kcal/Nm3K)
V_g :	Speed of gas (Nm3/s)

The heat transfer coefficient h has different value whether the moisture exist or not in an object cell, and determined by comparison of an actual molten slag temperature and a model output in the in-company demonstration plant. Fig.9 shows the comparison between model estimation of molten slag temperature and actual measurement. In this case oxygen percentage is changed stepwise at the time of 3 hour and the temperature of combustion gas at the main tuyere becomes high as a result. Then the temperature of waste cell becomes high gradually

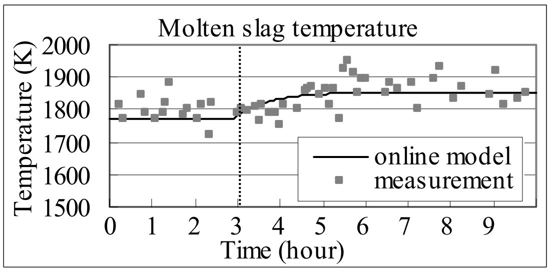

Fig. 9 Comparison between model estimation of molten slag temperature and actual measurement

and after two hours it reaches the constant state. Though the actual measurement has a measurement error and some deviation because of fluctuation of waste's calorie, estimation of molten slag temperature has enough quality in an average behavior.

3.3 Rule-based control with online model for prediction

Fig.10 is a schematic diagram of the rule-based control algorithm with online prediction model. The figure describes how the manipulated value is adjusted when the slag temperature is going to be low. The judgement for low temperature is done by actual measurement and the online model. With applying heat transfer in countercurrent flow model here the system can take an action in advance. There are four manipulated values in this case and those are air temperature, oxygen percentage, total oxygen and coke ratio. From the point of operational view air temperature from the main tuyere should be the first manipulation because it reacts fast enough and it costs the least among three. But the actual plant has a limitation of maximum temperature of the air. So if the first manipulation is not enough for temperature up then oxygen percentage should be changed too. The last manipulation for temperature up is to increase the waste coke ratio. In this case the quantity of oxygen should also be changed basically in order to keep the pile height at the same level. One should note that the timing of increase oxygen should not be completely simultaneous as waste coke ratio change. If this is the case, the pile height would become lower and the slag temperature would become lower which is undesirable in this case. Instead of that the timing of increase oxygen should be when the point of ratio change reaches main tuyere. Here above-mentioned waste tracking model decides the optimal timing to increase oxygen.

4. OPERATION RESULT OF THE DEVELOPED ACC

The slag temperature difference between when this ACC is applied and not applied is shown in Fig.11. The horizontal axis of Fig.11 indicates a slag temperature, while the vertical axis means frequency distribution of the temperature which is measured every 5 seconds for 24 hours. This means that the narrower the frequency distribution is, the smaller the temperature deviation is. In Fig.11 the upper figure shows the result of four days when the furnace is operated by ACC an operator. The lower figure shows the result of another four days (just after the first four days) when the furnace was operated by human operators. In both periods of time the waste property was basically same. It turns out that slag temperature distribution is smaller with ACC than with operator operation. Standard deviation of slag temperature is 90.5 degree with ACC and 109.3 degree without ACC. In addition under ACC control

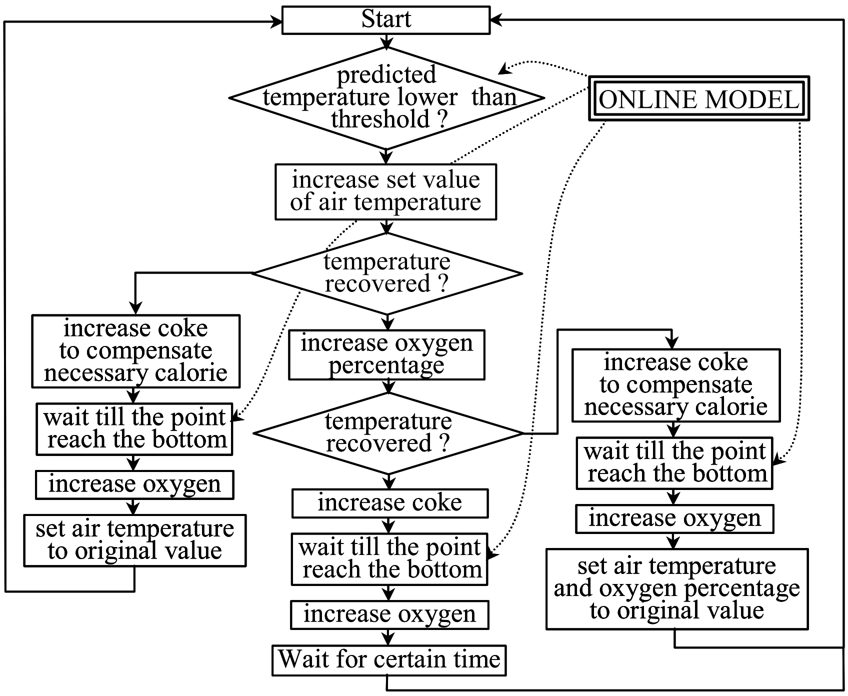

Fig. 10 Rule-based control algorithm with online prediction model

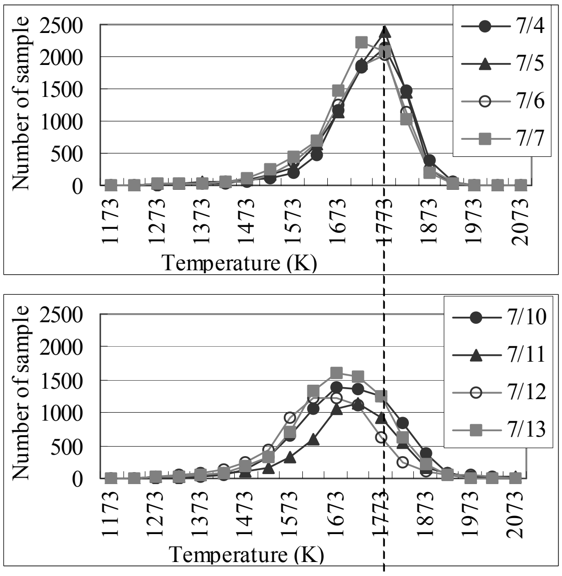

Fig. 11 Comparison of molten slag temperature with ACC and without ACC

mode temperature keeps high around 1723K and continuous tapping was done perfectly. This shows that slag temperature can be stabilized by applying this ACC and as a result it can contribute to work load reduction of an operator.

5. CONLUSION

This paper has described the development of high-temperature gasifying and direct melting furnace that is typical example of environment-friendly technologies at JFE Engineering Corp. From the control point of view the rule-based algorithm with online model for prediction play a principal part and the control performance was proven to be high enough by the temperature distribution of continuous tapping slag from the furnace. All the plants to which this control algorithm was installed are being operated in good condition.

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