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Automatic Combustion Control for a Gasifying and Direct Melting Furnace†

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Abstract:

The JFE Group has developed a high-temperature gasifying and direct-melting furnace as a completely new waste treatment system to meet the operational requirements of a recycling-based society. This plant is still difficult to control, however, as the time lag for operation is lengthy and varies considerably in accordance with the height of the waste in the furnace. In this paper we outline the completed plants and describe a control system that effectively combines online model prediction with rule-based control. The results of trial operations demonstrate the effectiveness of this control system.

1. Introduction

The resource recycling society of the 21st century will require new systems for the recycling of garbage and more efficient energy-recovery technologies capable of mitigating the environmental impact of waste incineration by detoxifying ashes and reducing ash volumes. The Japanese discharge about 50 million tons of waste per year domestically, of which 70% is reduced by incineration. Toxic substances and the handling of the incineration ash pose major challenges and moreover in the industrial field the waste discharged, now reaching upwards of 400 million tons of year, is basically difficult to process by incineration, and lots for landfill are becoming difficult to reserve.

Under these circumstances, the JFE Group developed a high-temperature gasifying and direct melting furnace as a completely new waste treatment system[1,2]. This furnace uses a new combustion technology based on a combination of two preexisting processes, one for melt in blast furnaces, nurtured through iron making operations, and one currently deployed for fluidized bed combustion and well proven in waste incineration.

2. Technical Features of the High-temperature Gasifying and Direct Melting Furnace

The furnace has the following characteristics[1,2].

(1) Stable Treatment of Wide Variety of Solid Wastes

The use of coke as a complementary heat source allows stable gasification and melt of a wide range of solid wastes without undue influences from the ash rates and calorific values.

(2) Minimal Environmental Influence

Two-stage control comprising high-temperature reduction combustion in the melting furnace and high-temperature oxidization combustion in the secondary combustion furnace allows for the control of dioxins. The use of limestone for basicity control ensures a low hydrogen chloride concentration.

(3) Reduced Waste Volume and Minimized Treatment Costs

Non-combustible components of the wastes are tapped continuously out of the furnace and form a high-quality slag that can be recovered for use in various applications. This approach considerably reduces the volume of materials remaining after combustion, and only the fly ash from the dust collector requires final disposal. The low-air-ratio combustion in the furnace improves the efficiency of power generation.

Figure 1 shows the structure of the high-temperature gasifying and direct melting furnace. The secondary

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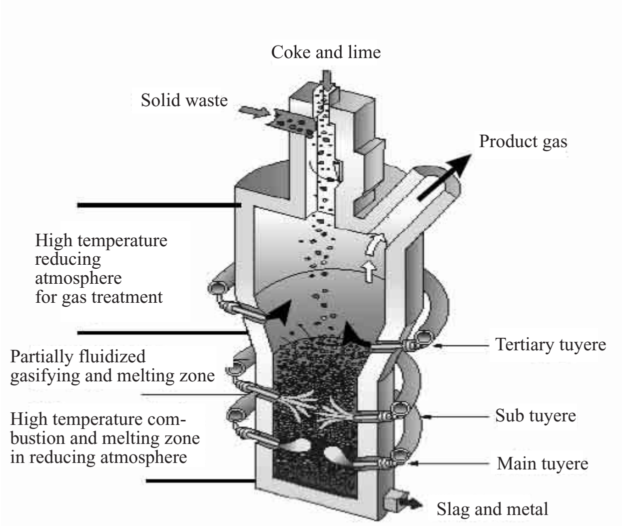

Fig. 1 Schematic diagram of high-temperature gasifying and direct melting furnace

combustion furnace, not shown in the figure, is located next to 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 segment in the furnace, thus melting the non-combustible components of the wastes as slag. The slag can be tapped continuously, as shown in **Photo 1**. Continuous tapping is an extremely attractive feature for operators, as it reduces the operational load to far lower levels than can be expected with intermittent tapping. The introduction of air from the sub tuyeres and the combustion gas from the high-temperature combustion and melting zone maintain the combustion at a temperature of about 600°C in the partially fluidized gasifying and pyrolysis zone at the middle segment in the furnace, thus drying and pyrolyzing the wastes. The non-combustible components descend into the high-temperature combustion and melting zone at the lower

Photo 1 Continuous tapping of molten slag

segment of the furnace, while the volatile components are gasified and move upwards. The air introduced from the tertiary tuyeres maintains a high-temperature reducing atmosphere in the freeboard zone towards the top of the furnace. This improves control over the generation of dioxins and pyrolyzing tar components in the gas produced, thereby making the gas easier to handle.

3. Overview of the Automatic Combustion Control (ACC) System

3.1 The Need for an Automatic Combustion Control System

As mentioned above, JFE Group's gasifying and direct melting furnace consists of a melting furnace and secondary combustion furnace. Though the new waste treatment system has many attractive features, it is subject to an intermingling of many reactions and states during operation[3,4]. The system therefore requires the monitoring and control of many process states at the same time. When the system operated manually, the operator can be overburdened and stable operation can be difficult to maintain. The automatic combustion control (ACC) equipment we developed for the gasifying and direct-melting furnace is an effective solution for mitigating the operator load and preserving stable operation. The most important function of the ACC is to maintain continuous tapping by controlling the temperature of the molten slag for fluidity.

The process from the charging of waste to the discharge of molten slag takes several hours in the melting furnace. The height of the loaded waste must also be stabilized, as this is the parameter that determines the heat-exchange time between the charged waste and high-temperature gas. If the heat-exchange time is insufficient, the waste cannot be heated to a temperature sufficient to avoid suspensions in the continuous tapping. When the product gas from the melting furnace moves into the secondary furnace, meanwhile, the rate at which it burns fluctuates by several minutes.

In order to control the two furnaces at different time scales simultaneously, the control system is designed with two parts: a fuzzy controller operated based on model predictions for the melting furnace, and a normal fuzzy controller operated based on the knowledge of the traditional stoker-type incinerator for the secondary incineration furnace[3,4]. In this paper we focus on the former, the ACC for the melting furnace.

3.2 ACC for the High-Temperature Gasifying and Direct Melting Furnace

The manipulated variables for the plant are the

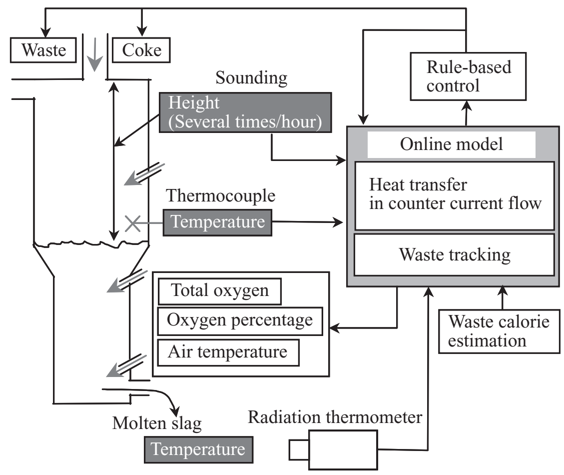

Fig. 2 Schematic diagram of ACC with online model for prediction

(1) air temperature, (2) oxygen percentage, (3) total oxygen, (4) throughput of waste, and (5) coke ratio. The observation variables are (1) the temperature of the molten slag, (2) the height of the charged waste, and (3) the temperatures of the respective parts of the furnace. The control target is to keep the molten slag at a constant reference temperature. The long and variable residence time constitutes the biggest challenge in controlling the temperature of the molten slag, as the control action is not reflected immediately in the state and the system tends to overshoot and lose stability.

To avoid overshoots and instability, the system employs a method of rule-based control based on online model predictions, as shown in **Fig. 2**. In addition to the various kinds of present process values, the predicted values from the online dynamic model of the plant are taken into account.

3.3 Waste Tracking Model

Figure 3 is a conceptual diagram of a waste tracking model. The waste charged in for a specific period of time, for example, in 5 minutes, is treated as a cell or a layer. The weight (waste, coke, lime), percentage of each component (parts that can be dry-distilled, fixed carbon, moisture, and ash) and bulk density are taken into consideration as attributes of a cell. The weight can be actually measured when the waste is charged into the furnace, and the other values are treated as constants. The fixed carbon component at the bottom of the furnace loses volume mainly via oxidization. The ash component also loses volume, via melting in proportion to the oxidization. As a result of moisture evaporation, dry distillation, melting, and discharge at the main tuyere point, each cell loses volume and moves downward. The pile height is calculated from the thickness of each cell.

3.4 Heat Transfer Model

The waste charged in from the top descends from a partially fluidized gasifying and melting zone to a high-temperature combustion and melting zone. As it descends, it undergoes a heat exchange with the high-temperature gas traveling up through the furnace. As a result of this heat exchange, the temperature of the descending waste rises and the incombustible component melts.

This model of heat transfer in the countercurrent flow (**Fig. 4**) calculates the heat exchange of the charged waste, a coke layer, and high-temperature gas, and estimates and predicts the temperature of the waste and the coke layer.

The assumptions of this model are as follows:

- The gas flow is steady.
- The gas flow rate is constant at all points in the furnace.
- The specific heat of the waste is constant.
- The reaction at the main tuyere is described by $2C+O_2 \rightarrow 2CO$.
- All O_2 reacts at the main tuyere.
- The reaction at the sub tuyere is described by $2CO+O_2 \rightarrow 2CO_2$.
- The heat transfer coefficient in cells containing water differs from that in cells without water.

The model shown in Fig. 4 considers the heat exchange of the high-temperature gas and the cell with a height dz. As the velocity of the gas flow is quite high relative to the velocity of the waste flow, the gas temperature is treated as a function of height and only the

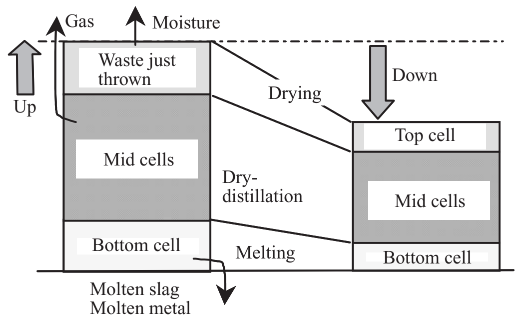

Fig. 3 Conceptual diagram of waste tracking model

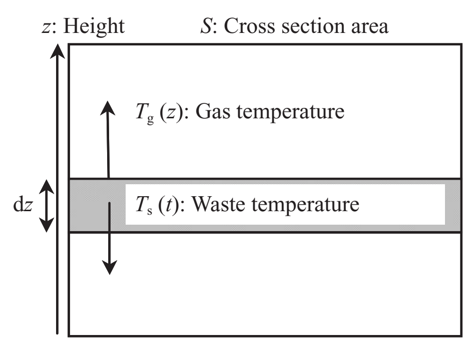

Fig. 4 Heat transfer in countercurrent flow model

waste cell temperature is treated as a function of time. The heat quantity exchanged during the unit time dt is described as shown in Eq. (1). The waste cell temperature is calculated by integrating Eq. (2) along the time. The gas temperature is deduced from the waste cell temperature and Eq. (2) (which considers the velocity of the gas).

$$h \cdot a \cdot S \cdot \mathrm{d}z(-T_s(t)+T_g(z))\mathrm{d}t = C_s \cdot S \cdot \mathrm{d}z \cdot \mathrm{d}T_s(t) \quad \cdots\cdots (1)$$

$$C_g \cdot V_g \cdot \mathrm{d}t \cdot \mathrm{d}T_g(z) = C_s \cdot S \cdot \mathrm{d}z \cdot \mathrm{d}T_s(t) \quad \cdots\cdots (2)$$

The notations in Eqs. (1) and (2) are as follows:

- h: Heat transfer coefficient (J/m^{2}K)
- a: The gas contact surface per waste unit volume (m^2/m^3)
- S: The cross section of waste cell (m^2)
- z: Coordinates of height direction (m)
- t: Time (h)
- T_s(t): Waste cell temperature (K)
- C_s: Specific heat of waste cell (J/kgK)
- T_g(z): Gas temperature (K)
- C_g: Specific heat of the gas (J/Nm^{3}K)
- V_g: Velocity of the gas (Nm^3/h)

The heat transfer coefficient h differs between object cells with and without moisture. The value is determined by comparing a model output with an actual molten slag temperature measured in the in-company demonstration plant.

In the model, the waste charged in unit time is treated as a cell. Since heat exchange and temperature change are simulated for every cell, the waste charged in over a certain period of time can be traced to determine the temperature and position at any time. In processes with long time lags, it generally takes a long time for a state to reach stability once it has been disrupted by error. With the model prediction, on the other hand, the ACC acts moderately without any overshoot against unwanted deviations.

3.5 Validation of the Online Model

The authors compared the actual measurement and model output in order to evaluate the validity of the online model. **Figure 5** shows a comparison of the model estimation and the actual measurement of the pile height. The actual measurement was conducted by sounding every 20 min. As the figure demonstrates, the model estimation produces accurate results and thus can be assumed to track the waste well.

Figure 6 shows a comparison of the model estimate of the molten slag temperature and temperature actually measured. In this case oxygen percentage is changed stepwise at 3 h and the temperature of the combustion gas at the main tuyere rises to a high level as a result. The temperature of the waste cell thus rises to a high level gradually, reaching a constant state at 5 h. Though the actual measurement deviates somewhat as a result of fluctuation in the caloric value of the waste, the estimate of the molten slag temperature is accurate enough to reflect the average behavior.

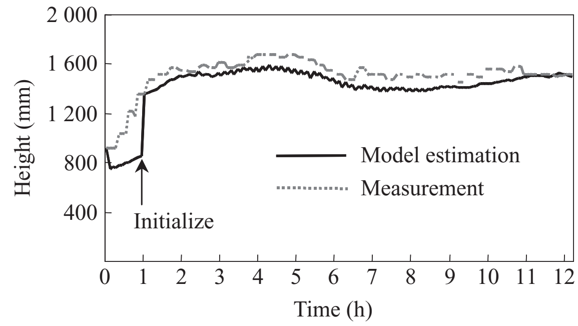

Fig. 5 Comparison between model estimation of height and actual measurement

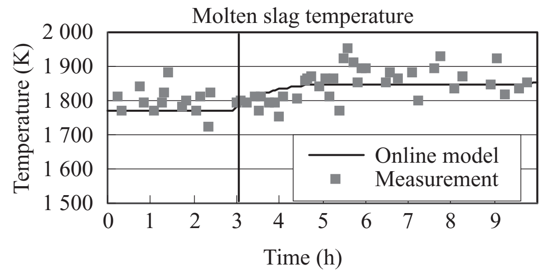

Fig. 6 Comparison between model estimation of molten slag

3.6 Rule-Based Control with the Online Model for Prediction

Figure 7 is a schematic diagram of a rule-based control algorithm with the online prediction model. The figure describes how the manipulated variables are adjusted when the slag temperature is going to be low. The judgment for low temperature is made by actual measurement and the output of the online model. With the application of the heat transfer model, the system can take a control action in advance. There are four manipulated variables in this case: the air temperature, oxygen percentage, total oxygen, and coke ratio. From an operational point of view, the temperature of the air from the main tuyere should be the first variable to be manipulated, given that it reacts with sufficient speed and costs the least among the four manipulated variables. The actual plant, however, is only capable of achieving maximum air temperatures within a limited range. If the first manipulation fails to bring about the desired increase in temperature, the oxygen percentage should be changed as well. The last manipulation for temperature rise is to increase the

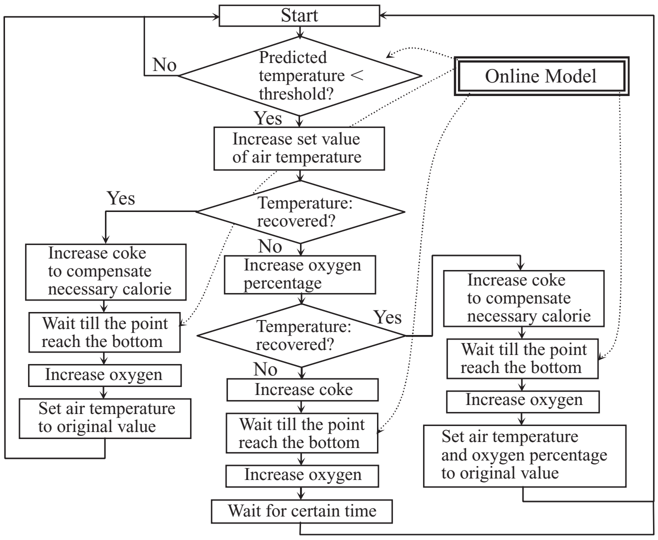

Fig. 7 Rule-based control algorithm with online prediction model

waste coke ratio. In this case, the quantity of oxygen should also be changed in order to keep the pile height at the same level. It is important to note here that the oxygen should never be increased while the waste coke ratio is being adjusted. Doing so would reduce the pile height, which in turn would lead to an unwanted reduction in the slag temperature. Instead, the oxygen should be increased when the point of ratio change reaches the main tuyere. The above-mentioned waste-tracking model calculates the optimal timing for the oxygen increase.

4. Operation Result of the Developed ACC

Figure 8 shows the difference in slag temperature with and without application of the ACC. The horizontal and vertical axes of Fig. 8 represent the molten slag temperature and the frequency distribution of the temperature measured every 5 seconds for 24 h, respectively. As the figure shows, the frequency distribution narrows as the temperature deviation shrinks. The top graph in Fig. 8 shows the results of the No. 1 furnace operated manually, and the middle graph shows the results of the No. 2 furnace operated with the ACC. The bottom graph shows the results of the No. 2 furnace operated manually four days after the operation plotted in the middle graph. In each case, the waste property was basically the same. It turns out that the slag temperature distribution is smaller with ACC than with operator operation. The standard deviation of the slag temperature is 90.5 degrees with the ACC and 109.3 degrees without the ACC. Under the ACC control mode, the temperature remains high, at around 1 773 K, and continuous tapping was maintained perfectly without disruption. The results indicate that the ACC can stabilize the slag temperature and thereby reduce the workload of human operators.

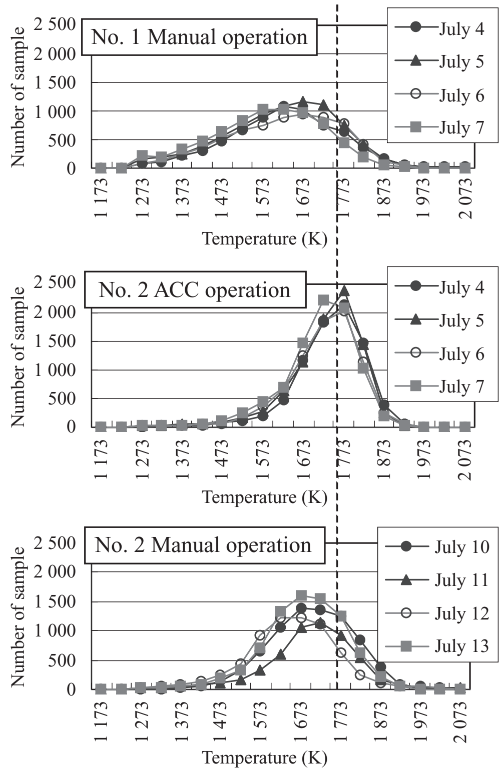

Fig. 8 Comparison of molten slag temperature with ACC and without ACC

5. Conclusion

This paper has described the development and testing of a high-temperature gasifying and direct melting furnace, one of the many environment-friendly technologies developed by JFE Engineering. The rule-based algorithm with the online model for prediction played a principal part in the control, and the temperature distribution of the continuous tapping slag from the furnace proved the accuracy of the control performance. All of the plants running with this control algorithm installed are now operating in good condition.

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