The Development of Feed-Forward Control Aided Method of the Boiler in an Integrated Steel Plant

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LDG (Linz-Donawitz converter gas) from the BOF (basic oxygen furnace) process is recovered to the LDG holder and then injected into the BFG (blast furnace gas) pipe network to form a mixed gas. Because the heating value of LDG is different from that of BFG, the LDG flow rate affects the heating value of mixed gas. The fluctuation of mixed gas heating value will also affect boiler operation, resulting in the main steam pressure being too high or too low. We use the plant data to develop three AI prediction models: the LDG holder level model, the LDG output flow rate model, and the mixed gas heating value model. According to the known future BOF production schedule, the developed prediction models can predict the future heating value of the mixed gas. The results show that the mean absolute error of the heating value of the mixed gas after five minutes is 2.96%. The heating value prediction result is used to be the set point of the boiler feedforward control system. The plant test results show that the main steam pressure fluctuation is reduced by 5.26%. The main steam emission is reduced from 116 minutes to 80 minutes per month, reducing the main steam emission by 36.6 tons. The steam production is increased by 1,350 tons per month, which can reduce the mixed gas emission by 1,350 kNm^3 per month.

Keywords: Heating Value, Mixing Gas, Cogeneration, Prediction, Feedforward Control

1. INTRODUCTION

LDG (Linz-Donawitz converter gas) from the BOF (basic oxygen furnace) process is recovered to the LDG holder and then injected into the BFG (blast furnace gas) pipe network to form a mixed gas (MIX). The BOF Process is a batch process and the LDG output flow rate is not continuous. Because the heating value of LDG is different from that of BFG, the LDG flow rate affects the heating value of mixed gas. When LDG is injected into the BFG pipe network, the heating value of mixed gas fluctuates between 750-950 kcal/Nm^3, and when there is no LDG injection, the heating value is stable at 750 kcal/Nm^3.

The boilers and turbine generators in the power plant use mixed gas to produce main steam and electricity. The fluctuation of mixed gas heating value will also affect boiler operation, resulting in high or low main steam pressure. Therefore, it is necessary to adjust the power loading frequently to smooth the change of the main steam pressure. If the loading is not adjusted immediately, the main steam pressure will be too high and emission will occur, resulting in energy waste. So, the prediction of LDG output and the change in the mixed gas heating value is necessary for boiler operation.

There is much scientific literature about the prediction of by-product gas. Zhang et. al.(1) developed a mathematical model for the optimal management of by-product gas, a mathematical model for the by-product gas holder, and the fuel supply system of a power plant in large iron and steel plants. They also established a real-time monitoring and information management system integrating the functions of monitoring, forecasting, analysis, and decision-making to achieve by-product gas supply and demand prediction, by-product gas holder level prediction, and fuel supply of boilers optimization control. After optimization, the gas emission decreases, and the operation fee is saved when the gas holder is in a safety zone and fuels are changed in boilers correctly. Jiang(2) found the main factors affecting the gas generation and gas consumption of branch plants through detailed research on the gas-generation mechanism and the consumption characteristics in branch plants of the main process in iron steel works. The indexes influenced by these main factors have been found in an energy-balance table of iron-steel works. Jiang took the gas system of the converter as an example and summarized the forecast model of gas based on the linear regression method. He took out a statistical expression of the callback converter gas, then, theorized a forecast model of the gas balance. Tang[3] proposed on paper a long-term prediction approach for the generated amount of Convener gas based on steelmaking production status estimation, in which the steelmaking production status estimation consists of two stages, feature extraction and feature fusion. In the first stage, the generated flow data of LDG is divided into some data segments at the same length, and then a matching template is used to extract the time and frequency domain characteristics of steelmaking production status. In the second stage, an improved version of the fuzzy C-mean clustering method, which integrates the prior process knowledge and the clustering objective function, is developed for feature fusion. Specifically, the characteristics extracted from different data segments are assembled to obtain a universal feature of steelmaking production status. Finally, the universal feature is used to reconstruct the generated flow data of LDG. Wang[4] proposed a new advanced predictive control method based on the basic PID control level to overcome the low effectiveness of classical dual-cross cascade control methods in the burning system. According to the inner relationship between the air/fuel ratio and oxygen content, the air/fuel ratio is optimized online using the rolling optimal technique. By converting the optimization problem to a controller-design problem, the disturbance of a heating valve can be conquered and the optimal burning conditions of the whole system can be achieved.

The previous research showed that the production and demand management of the by-product gas system is a key issue for energy improvement in the steel plant. The output of by-product gas can be predicted by using process data. However, the gas system of each steel plant is different, so a customized prediction model must be developed. In this paper, we develop the feed-forward control-aided method of the boiler. The heating value of mixed gas is predicted by the production schedule of BOFs and related information. The predicted value can be used as the reference for boiler control.

2. METHOD

2.1 Time Delay Analysis of Pipe Network

LDG is recycled to the LDG holder and discharged to the power plant through the pipe network. Therefore, the time from LDG output to the power plant can be calculated according to the pipe diameter, length, and LDG flow rate. When the pipe network length L (m), diameter d (mm), cross-sectional area A (m^2), LDG flow rate F (Nm^3/h), fluid temperature T (°C), and fluid pressure P (mm-H_2O) are known, the flow velocity v (m/min) and the fluid flow time t (min) can be calculated according to the following steps.

1. Flow unit conversion: convert flow units from Nm^3/h to m^3/h

$$F' = \left(\frac{10332}{10332+P}\right)\left(\frac{T+273}{0+273}\right)F \quad (1)$$

2. Calculate cross-sectional area:

$$A = \left(\frac{\pi}{4}\right)\left(\frac{d}{1000}\right)^2 \quad (2)$$

3. Calculate fluid velocity:

$$v = \frac{(F'/60)}{A} \quad (3)$$

4. Calculate flow time:

$$t = \frac{L}{v} \quad (4)$$

The flow time required for different pipe network sections can be calculated by giving the related data of the pipe network and fluid.

2.2 BOF Production Schedule Information

To predict the heating value of mixed gas based on the BOF production schedule, the schedule data must be converted into usable information. The content of the schedule files is re-analyzed through the program, and the start and end times of the BOF production are recorded in the database. The analysis steps are shown in Fig.1.

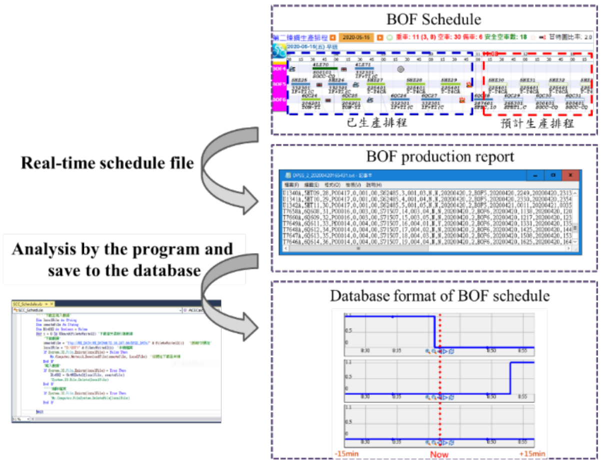


Fig.1. The analysis steps of the BOF production schedule.

2.3 Multiple Linear Regression

The multiple linear regression method and the ordinary least squares method are used to analyze the time delay, predict the LDG flow rate, and predict the heating value of the mixed gas. The basic concept of regression is to establish the relationship between the dependent variable (regression) and the independent variable (regressors). The coefficient of each variable is estimated from the given data. Assuming that the regression is y and the regressors are $x_2, x_3, \cdots, x_k$, the regression model can be expressed as:

$$y = \beta_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_k x_k + \varepsilon \quad (5)$$

Here, ε is the error and β is the coefficient. When there are n samples, the eq (5) can be expressed as:

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \quad X = \begin{bmatrix} 1 & x_{21} & x_{31} & \cdots & x_{k1} \\ 1 & x_{22} & x_{32} & \cdots & x_{k2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{2n} & x_{3n} & \cdots & x_{kn} \end{bmatrix}$$

$$B = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{bmatrix} \quad E = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} \quad (6)$$

$$Y = XB + E$$

The coefficient of each variable can be estimated by the ordinary least squares method:

$$B = (X'X)^{-1} X'Y \quad (7)$$

When the coefficient, B, is calculated, the predicted value, $\hat{Y}$, can be expressed as:

$$\hat{Y} = BX \quad (8)$$

2.4 Research Steps and Calculation Flowchart

The production process of LDG is as follows: LDG is recycled to the LDG holder from the BOF process. Then, the LDG output flow rate is controlled by the level of the LDG holder. According to the LDG output procedure, three models must be established to predict the heating value of mixed gas from the BOF production schedule.

Among the available information, only the BOF production schedule is available in future information. Therefore, the procedures for predicting the heating value of mixed gas are as follows:

1. Calculate the estimated value of the LDG holder level by using the BOF production schedule.
2. Calculate the estimated value of the LDG output flow rate by using the estimated value of the LDG holder level.
3. Calculate the estimated heating value of mixed gas by using the estimated value of the LDG output flow rate.

Fig.2 shows the research steps and calculation flowchart.

3. RESULTS AND DISCUSSION

The research subject was the #2 power plant. The prediction results and plant test results are described as follows.

3.1. Theoretical Analysis of Time Delay Effect

The distance from the LDG output point to the #2 power plant is about 650 meters (LDG pipeline: 360 meters, BFG pipeline: 290 meters). The diameter of the LDG pipeline is 1,600 mm, and the diameter of the BFG pipeline is 3,800 mm. Assuming that the LDG output flow rate is 40,000 Nm^3/h, and the gas demand of the #2

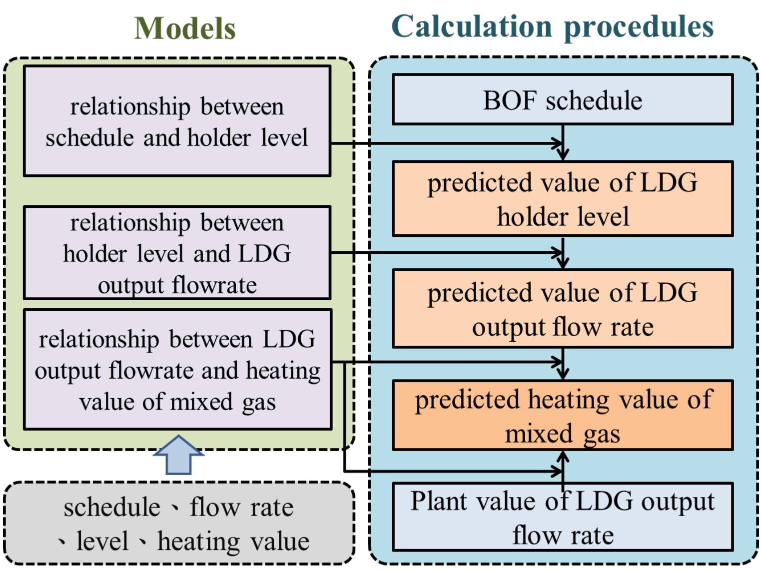


Fig.2. The flow chart scope of research steps.

power plant is 300,000 Nm^3/h. The calculation results from 2.1 show that it takes about 2 minutes from the output point to the #2 power plant.

3.2. Data Analysis of Time Delay Effect

Theoretical analysis results show that the LDG output to the #2 power plant is about 2min. We also use process data to analyze the time delay effect. When there is no time delay, the LDG flow rate at time t corresponds to the heating value of mixed gas at time t. When the time delay is 1 minute, the LDG flow rate at time t corresponds to the heating value of mixed gas at time t+1. The historical data show that when the time delay is 2-3 minutes, the relationship between LDG flow rate and heating value of mixed gas is the highest (Fig.3).

3.3. Relationship Between LDG Flowrate and Heating Value of Mixed Gas

The process data (Fig.4) shows that the change in the LDG flow rate is highly consistent with the change

Table 1 The time delay of LDG flow.

	LDG pipeline	BFG pipeline
Diameter (mm)	1600	3800
Cross area (m^2)	2.01	11.34
Length (m)	360	289
Flow rate (Nm^3/h)	40,000	300,000
Flow velocity (Nm/min)	331.6	440.9
Pressure (mm-H_2O)	940	800
Temperature (℃)	35	35
Flow rate (m^3/h)	41,365	314,138
Flow velocity (m/min)	342.9	461.6
Time (min)	1.09	0.66

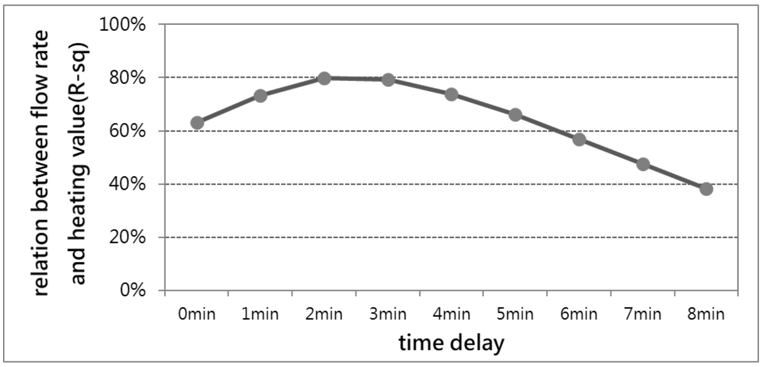


Fig.3. Time delay analysis by using process data.

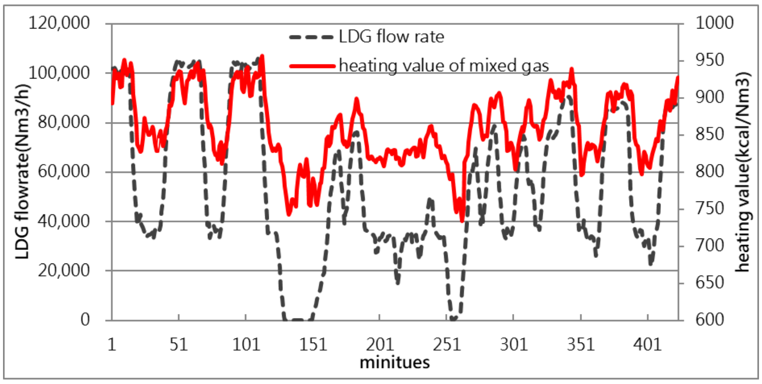


Fig.4. The trend of LDG flow rate and heating value of mixed gas.

in the heating value of mixed gas.

The LDG output flow rate is normally controlled at 30,000~40,000 Nm^3/h and 70,000~90,000 Nm^3/h. The LDG flow rate is classified into high flow and low flow ranges based on the boundary condition, 40,000 Nm^3/h. Considering a 2-minute time delay, the relationship between LDG flow rate and the heating value of mixed gas was established by using high flow and low flow range data, respectively. Fig.5 shows the results. In the low flow data, the model r-sq is 67.9%, the root mean square error (RMSE) is 20.9, and the mean absolute percentage error (MAPE) is 2.1%. In the high flow data, the model r-sq is 72.9%, the RMSE is 18.57, and the MAPE is 1.7%. MAPE of the two models shows that the models are accurate. The heating value of mixed gas can be predicted when the LDG flow rate is given.

Fig.6. shows the prediction results using the test data. RMSE is 36.72, MAPE is 3.4%, and the maximum error is 10%. In Fig.6, it can be found that when the predicted value is stable, the actual value still changes. There are two reasons for this phenomenon: 1. The fluctuation of the heating value of LDG and BFG. 2. The mixing of LDG and BFG is inhomogeneous. The first part can be solved by the use of the dynamic intercept term, the average of BFG heating value, in the model. The mixing results cannot be known, so the effect of the second part can only be regarded as the error term.

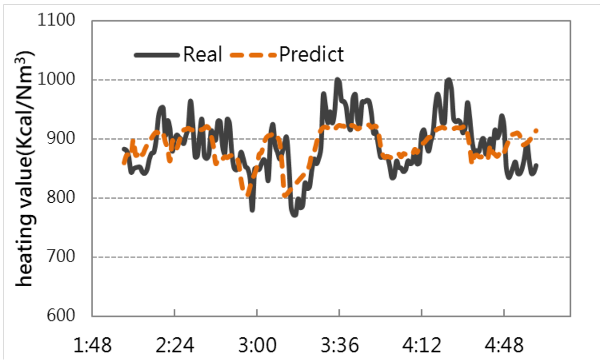
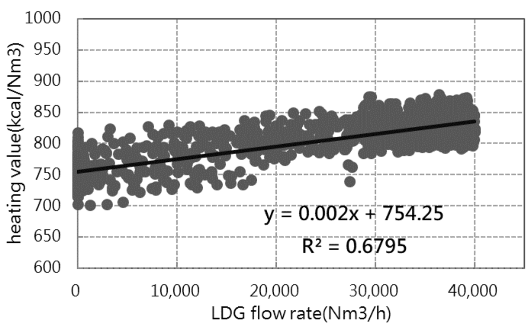


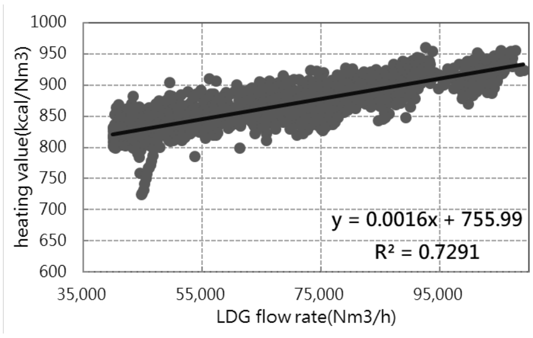
Fig.6. The predicted result of mixed gas heat value.

3.4. Relationship Between LDG Holder Level and BOF Production Schedule

The LDG holder level is classified into four stages, and the relationship between BOF production mode and level change can be calculated from the process data. Table 2. shows the average level change per minute in each stage. For example, If the BOF production number is 1 and the level is between 0 and 7.5 m, the average change in the level per minute is 0.36%. According to the data in Table 2, the LDG holder level can be predicted by giving the BOF production schedule. Fig.7 shows the 5-minute and 10-minute forecasts of LDG level. The



Low flow rate data



High flow rate data

Fig.5. The relationship between LDG flow rate and mixed gas heat value.

Table 2 The time delay of LDG flow

		BOF production number			
		0	1	2	3
Level range (m)		Level change (%/min)			
0	7.5	-0.22	0.36	0.60	
7.5	10	-0.46	0.35	0.56	0.66
10	15	-0.58	0.18	0.33	0.30
15	30	-0.63	0.00	0.30	0.26

5-minute forecast can successfully predict changes, but the 10-minute forecast cannot predict peak changes.

3.5. Relationship Between LDG Flow Rate and LDG Holder Level

The flow rate of LDG to the BFG pipe network is controlled by the LDG holder level and is pressurized by boosters. In addition, the operator will also determine the valve opening and the operation number of boosters according to the production schedule and liquid level. Therefore, the relationship between LDG flow rate and LDG holder level is corrected by the real process data. Fig.8 shows the new relationship between LDG flow rate and LDG holder level.

Based on Fig.8, the predicted value of LDG output flow rate is calculated with the predicted value of the holder level in Fig.7 Fig.9 shows that the trend of the predicted value after five minutes is similar to the real flow value. However, in the predicted value after ten minutes, some peaks cannot be predicted accurately.

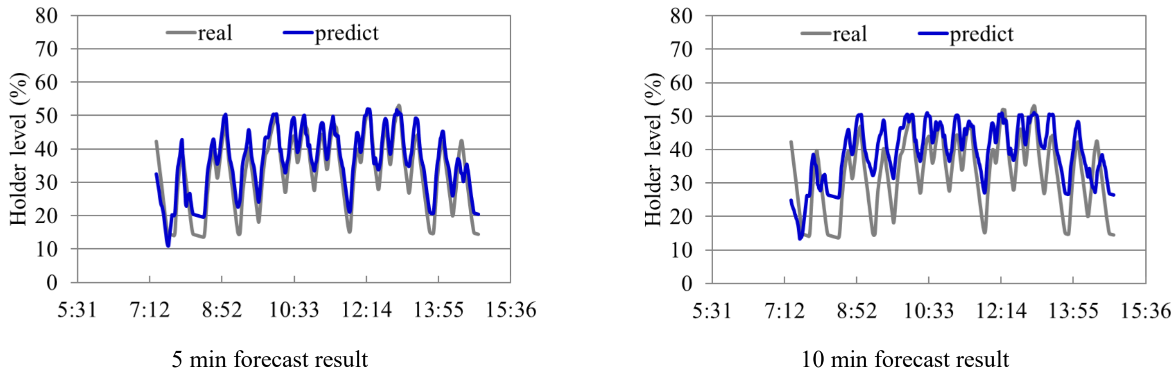


Fig.7. The predicted result of LDG holder level.

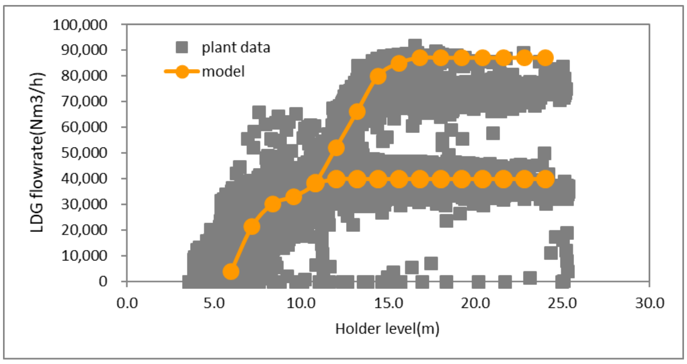


Fig.8. Relationship between LDG flow rate and LDG holder level.

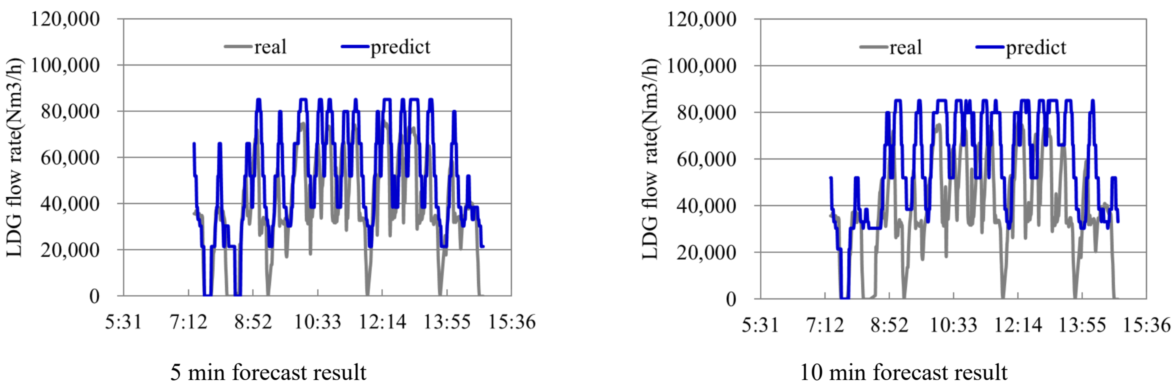


Fig.9. The predicted result of LDG flow rate.

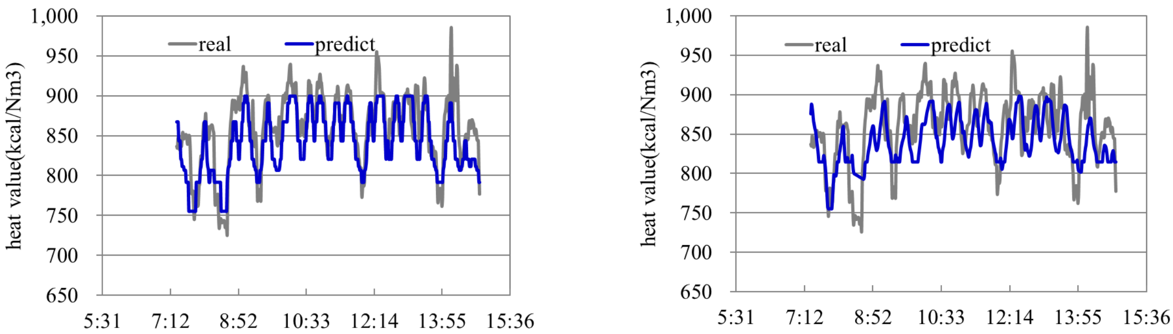
When the predicted value of the LDG output flow rate is known, the heating value of the mixed gas can be calculated by the relationship model between the LDG flow rate and the heating value in Fig.5. Fig.10 shows the prediction of the heating value of the mixed gas after 5 minutes using the predicted value of the LDG flow rate after 5 minutes, and the prediction of the heating value of the mixed gas after 10 minutes using the predicted value of the LDG flow rate after 10 minutes. The RMSE of the 5-minute forecast result is 32.5, and the MAPE is 2.96%. The RMSE of 10 min forecast result is 37.6, and the MAPE is 3.69%.

3.6. The User Interface and Plant Test Results

To achieve real-time calculation and display, the calculation method is built into the real-time database system. Fig.11 shows the user interface of the predicted heating value of mixed gas. This is the BOF production schedule in the next 10 minutes, the predicted value of the LDG holder level, the predicted LDG output flow rate, and the predicted value of the heating value of the mixed gas. The prediction result of the heating value is used to be the set point of the boiler feedforward control system. The plant test results show that the main steam pressure fluctuation is reduced by 5.26%. The main steam emission is reduced from 116 minutes to 80 minutes per month, reducing the main steam emission by 36.6 tons. The steam production is increased by 1,350 tons per month, helping to reduce the mixed gas emission by 1,350 kNm^3 per month.

4. CONCLUSIONS

The research proposed a feed-forward control-aided method of the boiler in an integrated steel plant. The heating value of the mixed gas after five minutes can be predicted by combining the LDG holder level model, the LDG output flow rate model, and the heating value of the mixed gas model. The prediction result of the heating value is used to be the set point of the boiler feedforward control system. The plant test results show that the main steam pressure fluctuation is reduced by 5.26%. The main steam emission is reduced from 116 minutes to 80 minutes per month, reducing the main steam emission by 36.6 tons. The steam production is increased by 1,350 tons per month, which can reduce the mixed gas emission by 1,350 kNm^3 per month.



5 min forecast result　　　10 min forecast result

Fig.10. The predicted result of the heating value of mixed gas.

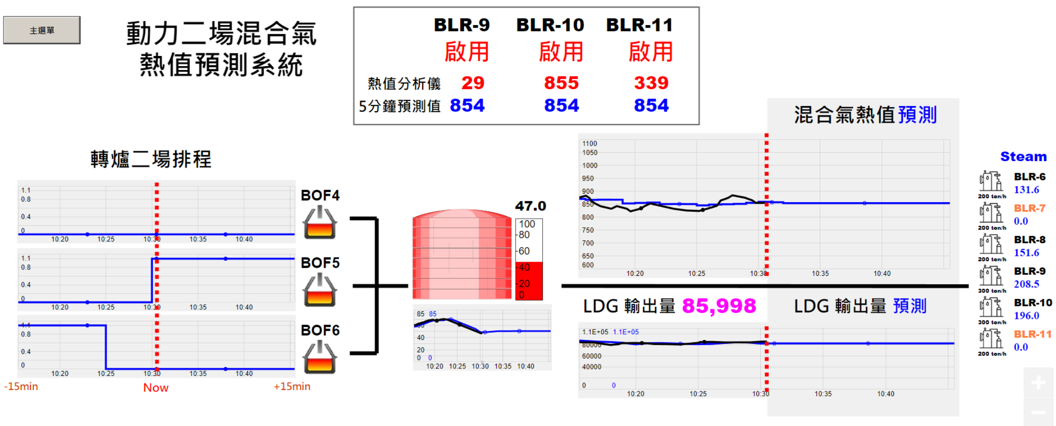


Fig.11. The user interface.

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