Slaging Analysis Based on Boiler Wall Temperature at PLTU Paiton Unit 3

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ABSTRACT

Slagging on the surface of boiler walls in power plants is still a serious problem which reduces thermodynamic efficiency and threatens the operation of generating units. In this research paper, a slagging diagnosis method based on analysis of vibration signals from tube panels is proposed to monitor slagging conditions. We fabricated the tube panel tube according to the actual structure of the heating panel in the laboratory to study the relationship between the vibration signal and various slagging conditions and air velocity. Root Mean Square (RMS) in the time field and waveform breakdown in the frequency field are used to extract features from the vibration signal and predict slagging conditions without being turned off. It was found that the RMS value of the panel tube signal decreased with increasing slagging weight, especially at low air speeds. The relative signal energy at a certain frequency will experience a significant change after the panel tube is slagged. To verify the experimental results on changes in the panel tube vibration signal under various slagging conditions, we succeeded in demonstrating our laboratory results through analysis of the vibration signal from the heating panel tube at PLTU Unit 3 Paiton, Probolinggo Regency, East Java. This shows that the vibration signal between the heater and the boiler wall can be collected and used for the diagnosis of slagging in a running coal boiler. Our study is promising for the prediction of slagging and further mitigating the risk caused by slagging of exchange panels in boilers.

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1. INTRODUCTION

Currently the use of coal fuel in PLTU boilers is the most widely used, because of its availability which is still capable for the next 50 years [1] especially in PLTU Paiton unit 3. In Steam Power Plants (PLTU), the boiler is a pressure vessel that functions to convert water into steam at high pressure and temperature [2], especially in PLTU Paiton unit 3. Coal burning in the power plant is expected to continue to be used for power generation in the coming years. In coal burning, slagging and ash deposition are a set of serious operational problems associated with power plant boilers [3]. Slagging itself not only affects heat transfer within the boiler, but also causes mechanical damage and failure of the water/steam cycle [4].

With deep understanding of the slagging mechanism and slagging process in boilers, various diagnostic indexes and techniques based on coal properties are proposed, according to a large amount of test data and engineering practice [5], [6]. Coal properties such as temperature in the ash mixture, properties and chemical composition of the ash before being used as a predictive indicator of slagging in coal-fired boilers [7]-[11]. However, the influence of boiler operation is negligible even though researchers can predict and diagnose slagging problems in coal-fired boilers with the help of indexes based on coal properties. In addition, the prediction and diagnosis accuracy based on this index should be improved [12], [13].

In fact, boiler operational factors such as coal fineness, air temperature, firing angle, excess air and frequency will affect the slagging conditions on the heating surface, whereas the traditional slagging index based on coal properties has no impact on these factors. into consideration [14], [15]. Slagging diagnostic methods based on heat flow measurements are proven to work, but the installation of heat flow measurements requires a transformation of the heating surface structure [16], [17]. The cost of the transformation is estimated to be enormous. Corey Cantrell [18] made a calculation model using the heat transfer effectiveness method. The cleanliness factor used for the diagnosis of slagging is calculated based on the energy balance model. Given the empirical equations and parameters in the prediction model has low precision. Meanwhile, several special devices have been applied in the diagnosis of slagging on heating surfaces in coal boilers. A special infrared camera equipped with a filter is used for the diagnosis of heating surface slagging by means of a flame [19]. Wicker [20] showed that changes in weight caused by slagging can change the strain value of the tube which causes changes in electrical resistance. The electrical resistance of the tube can be used as an indicator for the diagnosis of slagging.

The heating panel tube is actually a heat exchange device in a coal boiler. Heat is transferred from the high temperature flue gas to the steam inside. The flow of exhaust gas outside and inside steam will induce vibration of the panel tube [21], [22]. Since the 1950s, researchers have carried out in-depth and continuous studies of the vibration mechanism of the tubes in heaters. Pettigrew [23], [24] conducted a flow-induced study on tube vibration excitation induced by released vortices, in 2003. The scope of application of the vibration model was obtained. Taylor [25] and Katinas [26] studied the large shocks of tube vibrations in the laboratory, and obtained the corresponding tube vibration response and vibration characteristics. Granger [27] discussed the phenomenon of fluid elastic excitation and established an approximate model of fluid elastic instability, especially for sweeping beam working conditions in industry. The study of tube vibration in this heat exchanger helps to understand the vibration mechanism and effectively resist damage to the tube caused by vibration. In addition, researchers also utilize fluid-induced vibrations of heat exchangers to increase heat transfer efficiency [28]. Lin [29], [30] proposed that fluid-induced vibration can change the working conditions of the heating surface flow, increase fluid turbulence, thin fluid boundary layer and finally improve the heat transfer efficiency of the heat exchanger.

The main problem in boilers is caused by the formation of deposits that stick to the surface of the heat transfer medium from the flue gas to the steam in the heat exchange tube. The presence of slagging on the heat transfer surface will reduce the heat absorption capacity. A decrease in heat absorption capacity is indicated by an increase in flue gas temperature, which will cause a decrease in steam and boiler efficiency, so that the implication affects the consumption of the amount of fuel used. As a result, the slagging process that attaches to the boiler wall experiences corrosion, thus shortening the life of the boiler walls and pipes [31].

Due to the important role of coal-related industries in the energy sector and the global environment [36], [37], how to increase power plant efficiency and reduce coal consumption of coal-fired power plant boilers is one of the technical challenges [38]. Slagging and fouling problems caused by ash are difficult to avoid for coal-fired boilers because coal always contains mineral ash. Slagging and fouling can result in a serious reduction in heat transfer performance and the alkali metal salts in the precipitated slag can cause corrosion problems [39], [40].

In this research, a method of slagging diagnosis based on vibration signal analysis of heating panel tubes in coal-fired boilers is proposed. Experimental facilities built in the laboratory include panel tubes in reduced proportions. Vibration signal features with various slagging conditions and air velocity are extracted. The relative energy distribution is analyzed under different slagging conditions. Finally, the vibration signal from the heating panel tube in Unit 3 of PLTU Paiton, East Java. The feature changes and the relative energy distribution of the signals are consistent with those in the laboratory, which proves that a method based on the analysis of heating panel tube vibration signals can be carried out.

2. METHODS

2.1. Boiler Usage Flow

The research was conducted at the Paiton Unit 3 Steam Power Plant which is located in Probolinggo Regency, East Java Province, Indonesia. The object of this research is diagnosing slagging based on signal analysis of heating panel tube vibrations in coal-fired boilers. The research procedure describes the research steps in outline and can be seen in Fig. 1.

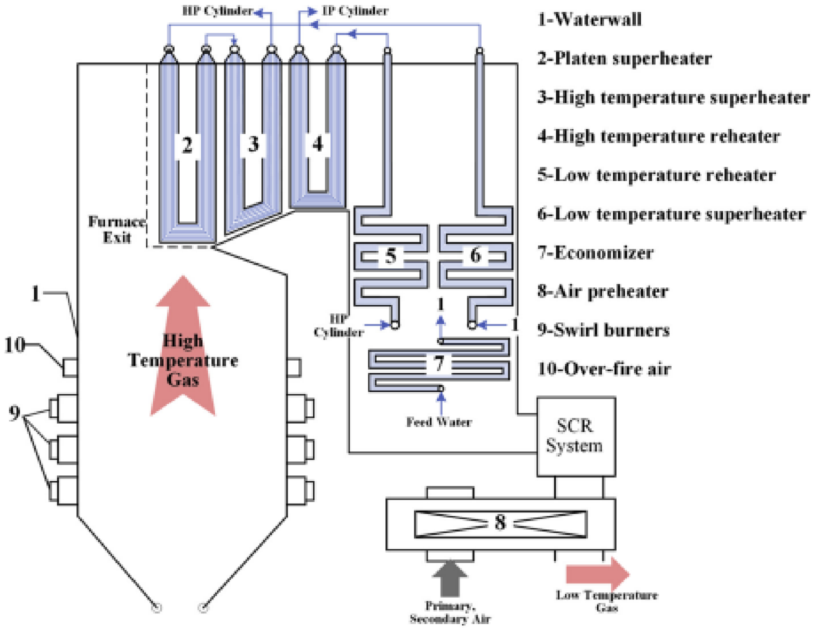

Fig. 1. Boiler Usage Flowchart

2.2. Case Study

The research case study was carried out at PLTU Paiton unit 3, Probolinggo Regency, East Java Province, which will analyze slaging based on the boiler wall temperature. For this case, the type of boiler type one through will be analyzed. As shown in the Fig. 2, the boiler is designed as a P type layout with single combustion chamber, balanced arrangement and solid descaling device. The main heat exchange surfaces include a waterwall, three heating stages, a two stage reheater, an economizer and two rotary air preheaters.

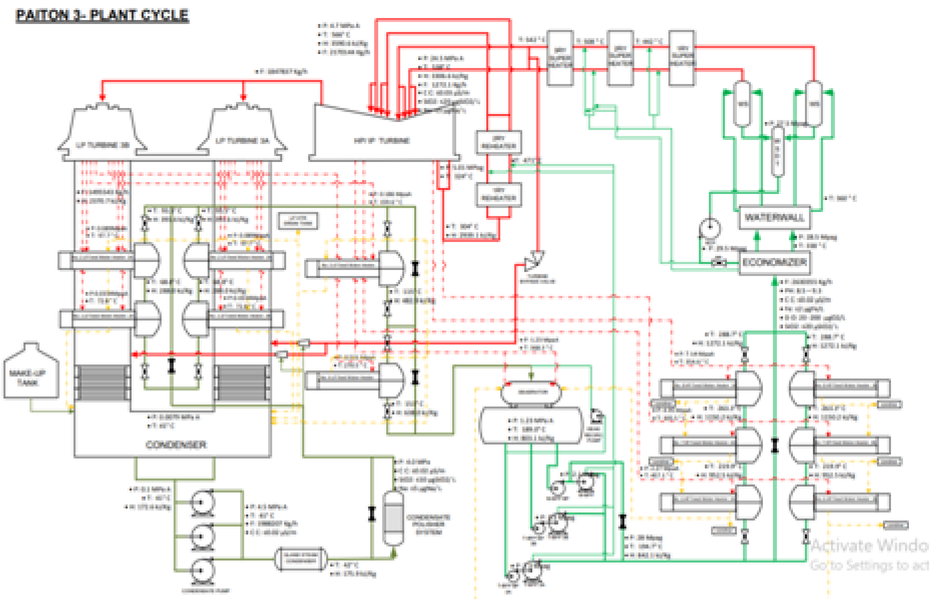

Fig. 2. Slagging Unit 3 Monitoring Flowchart of PLTU Paiton Probolinggo, East Java.

The arrangement of the burners and the wall temperature of the boiler is illustrated in Fig. 3. The wall-fired combustion system contains three rows of vortex burners and one row of air nozzles over the flames. There are 98 waterwall soot blowers arranged in six rows. From bottom to top, soot blower rows A~C are arranged on only the two side walls (excluding the front and back walls), and soot blower rows D~F are arranged on the four walls above the burners. Due to consideration of conserving steam energy, the current soot blowing strategy in the power plant is for the D~F lines of the soot blowers to be activated two or three times a day while the A~C lines of the soot blowers are activated about once every three days. In each soot blower operation for a water wall, all soot blowers are sequentially activated and two soot blowers installed symmetrically on the wall face-to-face are activated for 90 seconds at the same time. Therefore, the normal operating duration of line blowers D~F is approx. 54 minutes (72 ÷ 2 90 seconds) while the overall duration of all blowers (A~F) is approx. 73.5 minutes (98 ÷ 2 90 seconds). Steam for soot removal is extracted from the outlet of the platen heater.

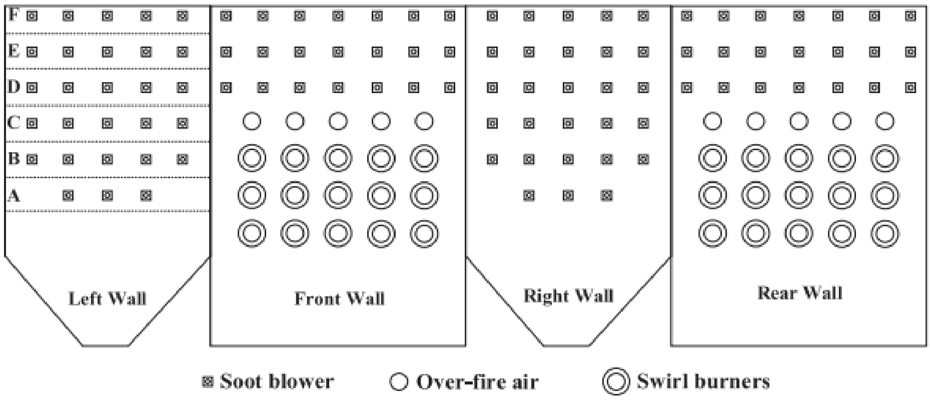

Fig. 3. Burner arrangement

In this work, sequential operating data of utility boilers are collected for modeling and analysis, mainly including parameters related to steam properties, flue gas and combustion performance. Coal samples burned on different days were collected and used for proximate and ultimate analysis. The moment and duration of waterwall operation that emits soot is recorded. Most of the data collection interval is 60 seconds, while the data collection interval in the first 600 seconds after the waterwall soot blowing operation is 10 seconds. Data preprocessing is done to reduce analysis errors. Outliers are detected when the average value of the data collected is greater than three times the standard deviation and is replaced by a smoothed average value [20], [21].

2.3. Vibration Signal Analysis Process

Heating panel vibrations are induced by various excitations, making it difficult to intuitively derive the panel tube vibration signal features under various slagging conditions and flow velocity according to the waveform only. Signals need to be processed for feature extraction to predict slagging conditions. The following is a vibration signal processing method based on time field and frequency field analysis:

1. Root Mean Square in the Time Field

Root Mean Square (RMS) is used to analyze the nature of the vibration signal in the time field. Different RMS values mean different energies of all sampled signals. For discrete time series with effective lengths, such as $x_0, x_1, x_2, \ldots$, the definition of RMS can be explained as follows:

$$X_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \tag{1}$$

where N is the number of sampling points and *x(i)* is the corresponding accelerating amplitude of the sampled signal.

2. Spectrum Analysis

Spectrum analysis is a signal processing method that converts a vibrational signal from a time field into a frequency field. Useful information can be obtained in the spectral image, such as the frequency component of the signal and the amplitude distribution of each frequency component. The Fourier transform is the main analytical tool for the analysis of continuous and discrete time signals that is widely used today. For discrete time series with effective lengths, such as $x_0, x_1, x_2, \ldots, x_{n-1}$, the definition of the Fourier transform can be explained as follows:

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi kn}{N}},\ k=0,1,2,\ldots,N-1 \tag{2}$$

3. Relative spectrum wave analysis

Wavelet Packet Transform (WPT) is an extension of Wavelet Transform (WT), which provides complete level-by-level decoding of signals. This transformation is formed by a linear combination of waves. WPT denotes the permanent and temporary features of a signal with a desired time-frequency separation [32]. The wave consists of a set of wave functions that are coupled linearly [33]. The wave-based function library can be obtained as follows:

$$\begin{cases} u_{2n}(t) = \sqrt{2}\sum_{k\epsilon Z} h_k u_n(2t-k); \\ u_{2n+1}(t) = \sqrt{2}\sum_{k\epsilon Z} g_k u_n(2t-k); \end{cases} \tag{3}$$

The waveform implementation leads to a parsed tree structure, implying that the output of the low-pass and high-pass filters is parsed recursively. The waves can decompose the vibration signal from the heating panel into different frequency bands [34]. The two-level wave structure is shown in Fig. 4. The original signal is decomposed into four ranges of frequency bands. *'a'* and *'b'* in frequency band *T (a,b)* respectively represent the described level of the waveform and the serial number of the frequency band. After the wave is decomposed from the vibration signal $s(t)2^i$, it can be obtained after being described in layer *i*, so that *s(t)* can be expressed as:

$$S(t) = \sum_{j=0}^{2^i-1} f_{i,j}(t_j) = f_{i,0}(t_0) + f_{i,1}(t_1) + \cdots + f_{i,2^i-1}(t_{2^i-1}),\ j = 0,1,2,\ldots\ 2^i - 1 \tag{4}$$

where $f_{i,j}(t_j)$ is the vibration signal of the decomposition node reconstruction (i,j) in layer *i* with WPT. If the lowest frequency *s(t)* is 0, the highest frequency is ω_m, then the bandwidth of each frequency at decomposition level *i* is $\omega_m/2^i$.

According to the signal spectral analysis in Parseval theory [35], from (4), we can get the energy spectrum of the vibrational signal *s(t)* by wave analysis:

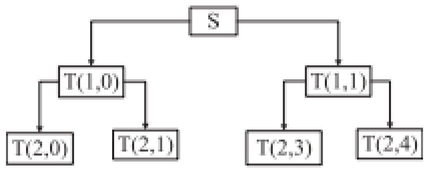

Fig. 4. Two Stage Wave Structure

$$E_{i,j}(t_j) = \int_T \left|f_{i,j}(t_j)\right|^2 dt = \sum_{k=1}^{m} \left|X_{j,k}\right|^2 \tag{5}$$

Where $X_{j,k}(j = 0,1,2,\ldots,2^i - 1\ ;\ k = 1,2,\ldots,m)$ is the discrete sampling point of the vibration construction signal $f_{i,j}(t_j), E_{i,j}(t_j)$ is the energy spectrum of node *j* in layer *i* with waves. From (5), the total energy of the vibration signal *s(t)* is:

$$E = \sum_{j=0}^{2^i-1} E_{i,j}(t_j) \tag{6}$$

The relative wave energy is the ratio of the energy of each frequency band to the total energy, which can be calculated as follows:

$$P_{i,j} = \frac{E_{i,j}(t_j)}{E} \times 100\% \tag{7}$$

3. RESULTS AND DISCUSSION

3.1. Slagging Panel Diagnostic Experiment

As shown in the Fig. 5, the experimental setup for slagging diagnosis only contains a reduced heating tube panel, a force draft blower, an air duct, an acceleration sensor, a signal collector and a signal acquisition system. And it is used for slagging diagnosis simulation in laboratory.

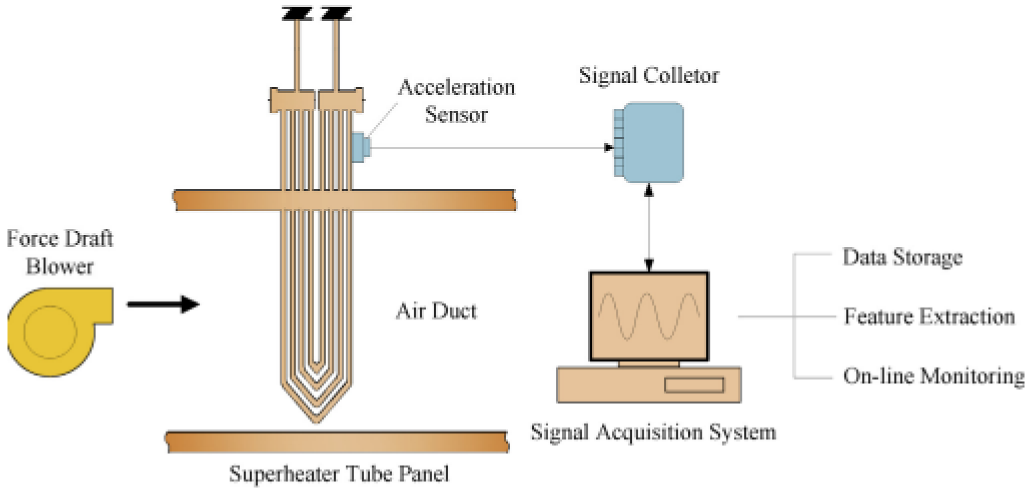

Fig. 5. Experimental setting of Slagging Diagnosis based on tube panel vibration signal

The reduced tube panel based on the actual structure of the heating panel is built in the laboratory. It is used to simulate real boiler tube panels under different slagging conditions. The tube panels and headers are suspended from steel frames in the laboratory by steel poles, leaving most of the tube panels in the air duct.

The speed blower is used to send air into dust continuously, simulating the flue gas flowing in the boiler. The air flow rate in the ducts can be controlled by adjusting the boiler exhaust opening. The vibration signal acquisition system consists of a vibration meter, a signal collector and a computer for analysis and data storage. Acceleration sensor LC01 is selected as vibration measuring device, which integrates traditional piezoelectric acceleration sensor and charge amplifier. This system will be simplified by having a sensor that can be connected directly to the collecting instrument. The signal collector used in the system is provided by the National Instrument Corporation. It has 4 signal channels with automatic sampling frequency adjustment filter in it. The vibration signal is converted into a digital signal at the highest frequency up to 51.2 kHz on each channel. This high performance signal collector is equipped with the aim of obtaining a signal close to that of a real tube panel vibration. Functions such as data storage, feature extraction, online monitoring, and spectrum analysis are accomplished by a LabVIEW-based computer program to cooperate with signal acquisition devices.

The heater is a heat transfer component with high temperatures in the boiler. The exhaust gas temperature around the heating panel is over 1000 ^{0}C. The sensor cannot work effectively in a high temperature environment for slagging monitoring and diagnosis. The air temperature near the outside of the boiler is only around 100 ^{0}C because of the thermal insulation layer. Thus the acceleration sensor was chosen to be installed in the tube section between the header and the thermal insulation layer of the furnace wall, ensuring it can work effectively and continuously.

3.2. Results of data in the laboratory

The different slagging conditions of the tube panels are simulated by depending on the weight of the slagging attached to the panel and the air velocity in the ducts in the laboratory. Tube panel vibration signals under different slagging conditions and air velocity were obtained. The maximum weight of slagging is 20% of the mass of the superheat panel, considering that slagging from the tube panels accumulates in the actual coal-fired boiler. According to the weight of the slagging attached to the tube panel, it can be divided into five grades, namely $\Delta m = 0, \Delta m = 5\%, \Delta m =, 10, \Delta m = 15$, and $\Delta m = 20\%$. Δm is the ratio of the slagging weight to the tube panel weight. Meanwhile, three types of air velocity in the channel are selected. The sampling frequency is 12.8 kHz.

The time domain waveforms of the tube panel vibration signals before and after slagging are given in Fig. 4. Both signals change over time periodically. Fig. 5 shows the RMS of the tube panel signal with various slagging weights and airspeeds. The RMS value of the tube panel signal increases when the airflow velocity increases from 8 m/s to 12 m/s. The increase in slagging weight has a negative effect on the RMS value.

In order to more effectively extract the slagging-varying features of the panel vibration signal, the vibration signal is transformed to the frequency domain for further analysis. A series of amplitude spectral images were obtained under different slagging conditions. Fig. 6 shows the amplitude spectrum of the tube panel signal under different slagging conditions at an airspeed of 12 m/s. It can be seen in Fig. 6 that the peak of the frequency spectrum of the vibration signal lies in the frequency band from 0 Hz to 400 Hz. Comparing Fig. 6(a) with Fig. 6(b), we can find that there are also some frequency spectrum peaks in the 500-3000 Hz frequency band when Δm=0. Conversely, the peaks located at the corresponding frequencies weaken or even approach zero as the slagging on the tube panels increases.

Different amplitudes in the spectrum represent different signal energies. Therefore the vibration signal is decomposed by the wavelet package for further research on the signal energy distribution under different slagging conditions according to the nature of the amplitude spectrum. The relative energy distribution of the signals in various frequency bands is analyzed quantitatively.

From the amplitude spectral image in Fig. 6, it can be prejudged that the signal energy is mainly concentrated in the frequency band from 0 to 0.5 kHz. So we decompose all these vibration signals by 5-level decomposition by WPT and the frequency band distribution is shown in Table 1. Table 2 shows the relative energy distribution of the vibration signals without slagging at an airspeed of 12 m/s. As we can see, the relative signal energy in the 0-0.2 kHz and 0.2-0.4 kHz frequency bands accounts for 50.79% and 13.16% of the overall signal energy, while there is almost no energy in the high frequency bands. This is consistent with the results shown in Fig. 6. The amplitude spectrum of the heating panel signal is shown in Fig. 7 when the boiler load changes.

Fig. 8 shows the relative energy distribution of the panel vibration signals under different slagging conditions at an air speed of 12 m/s. The vibration signal energy is mainly concentrated in the D_1 frequency band regardless of the change in slagging weight.

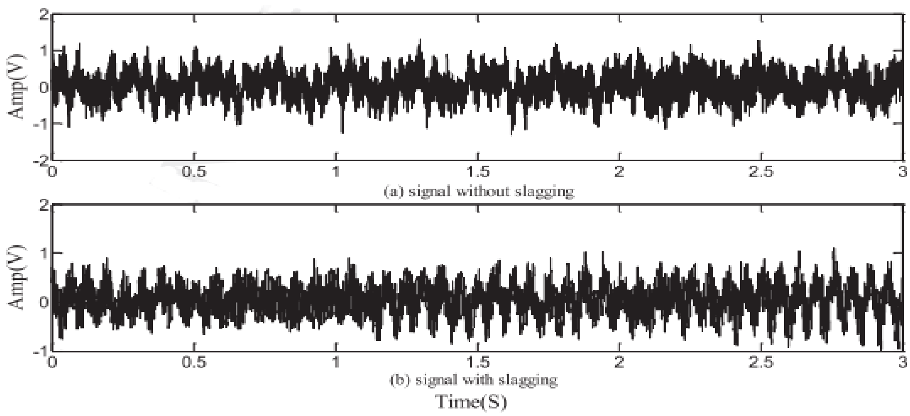

Fig. 6. The time domain waveform of the tube panel vibration signal in the laboratory

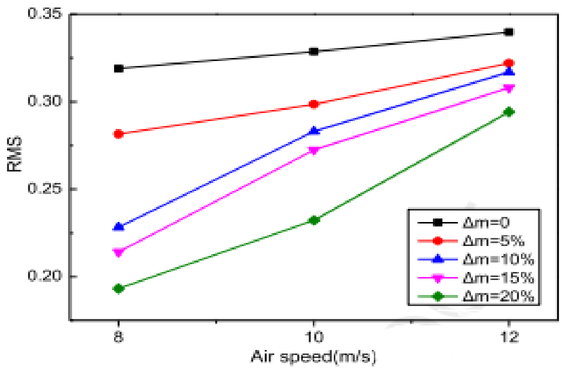

Fig. 7. RMS value of tube panel signal with variable slagging weight and air velocity

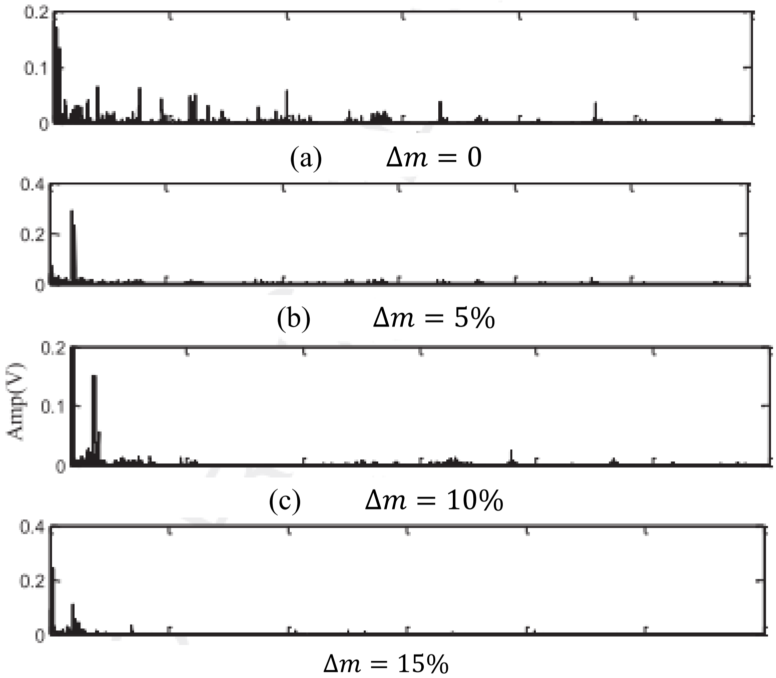

Fig. 8. The amplitude spectrum of the tube panel signal under different slagging conditions at an air speed of 12 m/s.

To help us better understand the energy distribution in the signal, the high frequency bands are integrated together as shown in Table 1-Table 3 each representing a different frequency band of the signal.

Comparing the relative energy distribution under different slagging conditions, it can be found that the relative signal energy in the D1 frequency band only accounts for about 50% of the total signal energy when $\Delta m = 0$. However, the relative signal energy in the D1 frequency band occupies almost 80%-90% of the total signal energy in the slagging condition. There is a sudden change in the relative energy in the D1 frequency band after the tube panel is peeled off. The characteristics of the same relative energy distribution of the panel vibration signal under different slagging conditions at an air speed of 10 m/s.

Table 1. Wavelet packet decomposition frequency bands.

Node	Frequency band/KHz	Node	Frequency band/KHz	Node	Frequency band/KHz	Node	Frequency band/KHz
T (5,0)	0-02	T (5,8)	3.0-3.2	T (5,16)	6.2-6.4	T (5,24)	3.2-3.4
T (5,1)	0.2-0.4	T (5,9)	2.8-3.0	T (5,17)	6.0-6.2	T (5,25)	3.4-3.6
T (5,2)	0.6-0.8	T (5,10)	2.4-2.6	T (5,18)	5.6-5.8	T (5,26)	3.8-4.0
T (5,3)	0.4-0.6	T (5,11)	2.6-2.8	T (5,19)	4.8-5.0	T (5,27)	3.6-3.8
T (5,4)	1.4-1.6	T (5,12)	1.6-1.8	T (5,20)	5.0-5.2	T (5,28)	4.6-4.8
T (5,5)	1.2-1.4	T (5,13)	1.8-2.0	T (5,21)	5.4-5.6	T (5,29)	4.4-4.6
T (5,06)	0.8-1.0	T (5,14)	1.2-2.2	T (5,22)	5.4-5.6	T (5,30)	4.0-4.4
T (5,7)	1.0-1.2	T (5,15)	2.0-2.2	T (5,23)	5.2-5.4	T (5,31)	4.2-4.4

Table 2. Relative energy distribution of the vibration signal without slagging on the tube panel with an air speed of 12 m/s

Frequency band/KHz	Relative Energy	Frequency band/KHz	Relative Energy	Frequency band/KHz	Relative Energy	Frequency band/KHz	Relative Energy
0-02	0.5079	1.6-1.8	0.0245	3.2-3.4	0.0010	4.8-5.0	0.0017
0.2-0.4	0.1316	1.8-2.0	0.0134	3.4-3.6	0.0025	5.0-5.2	0.0004
0.4-0.6	0.0993	2.0-2.2	0.0052	3.6-3.8	0.0022	5.2-5.4	0.0002
0.6-0.8	0.0646	2.2-2.4	0.0092	3.8-4.0	0.0015	5.4-5.6	0.0002
0.8-1.0	0.0355	2.4-2.6	0.0063	4.0-4.2	0.0021	5.6-5.8	0.0001
1.0-1.2	0.0255	2.6-2.8	0.0022	4.2-4.4	0.0011	5.8-6.0	0.0001
1.2-1.4	0.0248	2.8-3.0	0.0027	4.4-4.6	0.0006	6.0-6.2	0.0001
1.4-1.6	0.0306	3.0-3.2	0.0010	4.6-4.8	0.0017	6.2-6.4	0.0001

Table 3. Integrated frequency bands

Integrated Signal	D1	D2	D3	D4	D5	D6	D7	D8
Frequency band/KHz	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.6	1.6-2.4	2.4-4.4	4.4-6.4

3.3. Coal Boiler Wall Temperature Test Results

In order to verify the experimental results on feature changes of the tube panel vibration signal under various slagging conditions, the heating panel vibration signal from boiler #3 at Mitsubishi Power Generation Ltd was collected and analyzed. The boiler was built in 1984. And the load capacity of the boiler is 860 MW. The structure and arrangement of the heating panels are the same as those in the experimental setup in the laboratory. The acceleration sensor is mounted on the tube segment of the panel between the header and the furnace wall. Different boiler operational conditions are selected for vibration signal collection with boiler loads ranging from 0 MW to 860 MW. Table 4 shows the selected boiler loads. Signal collection is carried out after the heating tube panel slagging is cleaned. Therefore, the signal on the slagging condition on the boiler tube panel cannot be collected because the slagging has been removed on the running boiler. However, a signal collected without slagging on the panel can still verify the analysis in the laboratory to some extent. The sampling frequency was kept at 12.8 kHz during collection.

Table 4. Operational Conditions and Boiler Loads

Operational Condition	**1**	**2**	**3**	**4**	**5**	**6**
Generator Load/MW	455	485	470	490	490	560
Operational Condition	**7**	**8**	**9**	**10**	**11**	**12**
Generator Load/MW	765	650	720	680	740	780

As illustrated in Fig. 9, the peak frequency spectrum of the heating panel vibration signal is at 1.8 kHz. This means that the vibrational energy is mainly concentrated in the same frequency band, which is the same as the characteristic amplitude spectrum distribution shown in the laboratory.

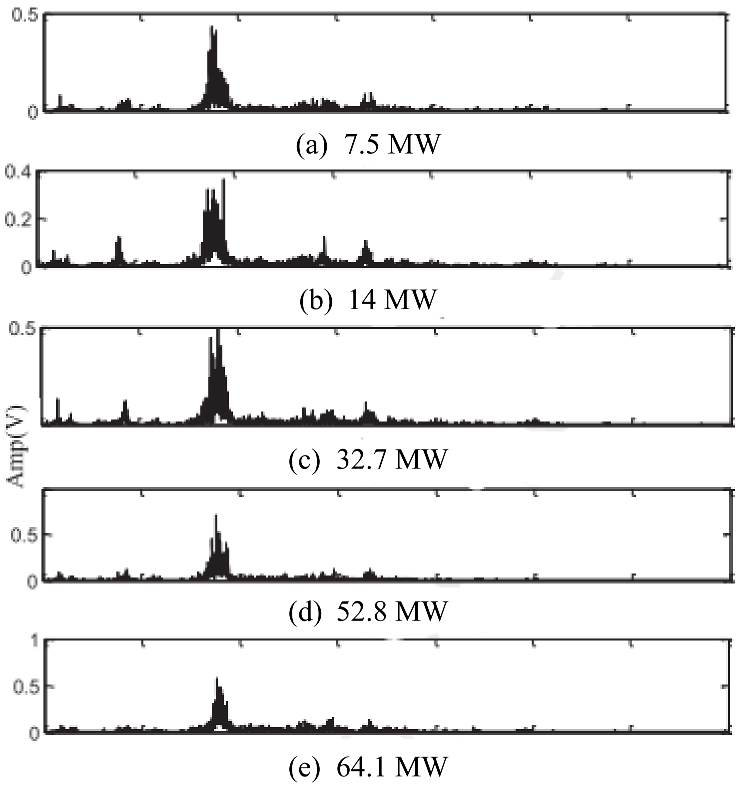

Fig. 9. Heating panel signal amplitude spectrum with variable boiler load

The RMS value of the vibration signal increases with increasing boiler load and feed air volume flow. According to the standard thermodynamic calculations, there is a proportional relationship between the exhaust gas velocity and the feed air volume flow. So it can be said that the RMS value increases with increasing exhaust velocity. This is in accordance with the characteristics of changes in the RMS value of the vibration signal which varies with air speed in the laboratory.

4. CONCLUSION

A slagging diagnosis method based on vibration signal analysis of heating tube panels in coal boiler walls has been proposed in this study. Tube panel vibration signals including time domain analysis were analyzed in the laboratory. The RMS value of the tube panel signal gradually decreases with increasing slagging weight when the air velocity in the channel is constant. Meanwhile, a decrease in airspeed can cause a decrease in the signal RMS value at the same slagging conditions. Vibration signals are also decomposed by transformations. The relative energy of the vibration signal is mainly concentrated at a certain frequency regardless of the slagging conditions. But the increase in the relative energy of that frequency signal after the tube panel is slagged, compared to that at the same frequency without slagging on the panel. These findings provide a possible method for the diagnosis of heating tube panel slagging. Vibration signals of heating tube panels at PLTU Paiton Unit 3 are collected and analyzed in the same way. The characteristics of the change in the RMS value with variable exhaust velocity and the characteristics of the relative energy distribution of the signals are consistent with what was analyzed in the laboratory. It is indicated that the tube vibration signal between the heater and the boiler wall can be collected and used for the diagnosis of slagging in a running coal boiler.

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