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A Method of Predicting the Combustion Status of Pulverized Coal-Fired Boiler Using Furnace Negative Pressure

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Abstract **Original Research Article**

The change in combustion state in the furnace is necessarily reflected in the furnace negative pressure, and the correlation between combustion state and furnace negative pressure inside the furnace is important for the normal operation of the boiler to be established between typical combustion conditions such as normal ignition, ignition delay and extinction of pulverized coal flame. In this paper we have analysed the relationship between the furnace negative pressure and the main parameters of the boiler based on the analysis of the variation of the furnace negative pressure reflecting the combustion state in the furnace of pulverized coal boiler, using statistical techniques, and establishes a method to estimate the steady state of combustion in the furnace. The proposed method is particularly suited to the characteristics of pulverized coal boiler furnaces fuelled by low-load combustion and low-rank coal, and has important practical significance.

Keywords: furnace negative pressure, combustion status, pulverized coal-fired boiler, low load, low-rank coal.

1. INTRODUCTION

As society developed, the conflict between energy development and environment has further intensified. Developing new energy is a strategic option to reduce carbon emissions, change economic structure, and gain sustainable development path [1].

Many power generation plants using renewable energy have been generated, and as a result, thermal power generation has gradually turned into a large parameter, a low load operation and a soft peak operation in the former high load operation mode.

The stability of the power plant in the new operation mode is becoming an important issue [2]. Due to the difference between the initial nominal and operating conditions of the boiler design, combustion fluctuations will occur in the boiler furnace when under low load or mild peak operation, and will have some effect on the stable operation.

The current method for determining the combustion safety of a boiler furnace mainly focuses on three methods: furnace negative pressure, flame detection and flame imaging [3]-[5].

Among them, the furnace negative pressure is an important characteristic of the combustion state of the furnace. This parameter not only determines the relationship between the amount of air and coal entering the furnace and the output gas, but also can directly reflect the change of combustion process.

In particular, the study of the negative pressure characteristics of the furnace at different loads of the boiler helps to optimize the combustion stability control. Combustion is a complex dynamic process, accompanied by physical and chemical reactions and energy release [6].

The variation of furnace negative pressure is influenced by many factors [7].

For example, changes in primary, secondary and tertiary air, coal quality, control orders, and combustion conditions all affect the negative pressure.

In [8], two indicators of combustion order and symmetry order are obtained based on the furnace negative pressure and a mathematical model is established to evaluate the combustion stability of the furnace.

However, this model has the disadvantage of relatively complex calculations and lack of correlation with boiler parameters.

In this paper, a mathematical model between ignition delay or extinction of pulverized coal flame and furnace negative pressure change is developed, a corresponding numerical relationship between ignition delay or extinction and furnace negative pressure change is derived, and a method for judging the combustion behaviour of the furnace using furnace negative pressure is described.

2. Mathematical modelling of furnace negative pressure variation and extinction prediction in furnace

2.1 Mathematical modelling of furnace negative pressure variation

The air flow rate into the furnace, the pulverized coal rate and the hot gas flow rate out of the furnace are kept in equilibrium, while the furnace negative pressure remains stable when the fluidising gas state in the furnace is unchanged. However, as the combustion process is fluctuating, the furnace negative pressure also fluctuates. During boiler operation, this range of furnace negative pressure fluctuations is usually less than ±50 Pa and does not exceed ±100 Pa. However, when the combustion state in the furnace changes sharply, the fluctuations in the furnace negative pressure become much larger, and these sudden changes and directions must reflect the combustion state in the furnace.

To model the furnace negative pressure variation, the following assumptions are made:

First, the mixture in the furnace can be considered to consist of the original hot gas, the newly generated combustion products and the pulverized coal air flow supplied, and their effect on the furnace negative pressure follows the gas partial pressure law.

Second, when the flame temperature inside the furnace is constant, the mixture gas component can be considered as ideal gas and the ideal gas equation of state is satisfied.

Third, in stable operation, the heat exchange between the mixture gas in the furnace and the water-cooled wall is almost constant, so neglecting the change, the heat exchange between the hot gas and the pulverized coal air flow obeys the heat balance law.

Based on these assumptions, the process of changing the furnace negative pressure due to ignition delay or extinction of pulverized coal air stream can be considered as two mutually independent processes.

2.1.1 Variation of furnace negative pressure with delay of pulverized coal ignition.

The initial values of temperature, volume flow rate and pressure before the pulverized coal air flow of each burner enters the furnace are T_{i0}, Q_{i0} and p_{i0}, respectively. In this situation, the furnace is filled with hot gases flowing in, some of which are original hot gases, V_{y0}, T_{y0} and p_{y0}, respectively, while the other part is the combustion products of N pulverized coal air flows, and the volume flow rate, temperature and pressure of the combustion products corresponding to each pulverized coal air stream are Q_{ir0}, T_{ir0} and p_{ir0}, respectively. Considering that the pressure and temperature of the new combustion product are essentially the same as the state of the hot gas, $T_{ir0}=T_{y0}$ and $p_{ir0}=p_{y0}$ are obtained.

If N pulverized coal air flows ignite after t_2 from the time of injection into the furnace, the pulverized coal flow during that time can be considered as being fed into the furnace at the burner outlet state, and the volume of pulverized coal air flow supplied is:

$$V_0 = \sum_1^N Q_{i0} \times t_2$$

If normal ignition has performed after t_1, the volume is as follows:

$$V_1 = \sum_1^N Q_{i0} \times t_1 + \sum_1^N Q_{ir0} \times (t_2 - t_1)$$

If ignition is delayed compared to normal ignition, the volume of the reduced furnace mixture is calculated by

$$\Delta V_{01} = V_1 - V_0 = \sum_1^N (Q_{ir0} - Q_{i0}) \times \Delta t \qquad (1)$$

where $\Delta t = t_2 - t_1$

In case of ignition delay or extinction, the gas volume decreases to $V_{y0}+V_1=V-\Delta V_{01}$. According to Dalton's law, the pressure p_1 of the mixture gas in the furnace is

$$p_1 = p_{y0} / V \times (V - \Delta V_{01}) \qquad (2)$$

If the mixed gas pressure in the furnace at normal ignition is $p_0=p_{y0}$, the change in the furnace negative pressure due to ignition delay, Δp_{1r} is

$$\Delta p_{1r} = p_1 - p_0 = p_{y0} / V \times (V - \Delta V_{01}) - p_{y0} = p_{y0} / V \times (-\Delta V_{01})$$

Substituting Eq. 1 into the above equation, it is as follows:

$$\Delta p_{1r} = p_{y0} / V \times \sum_1^N Q_{i0} \times \Delta t \times (1 - Q_{ir0} / Q_{i0}) \qquad (3)$$

Considering the state change of pulverized coal air flow at the moment of combustion as an isobaric process, $Q_{ir0} / Q_{i0} = T_{y0} / T_{i0}$ and Eq. 3 can be written as

$$\Delta p_{1r} = p_{y0} / V \times \sum_1^N Q_{i0} \times \Delta t \times (1 - T_{y0} / T_{i0}) \qquad (4)$$

From Eq. 4, the larger the time Δt, the number of pulverized coal air flows N with ignition delay or extinction and T_{y0} / T_{i0}, the larger the value of the change in the furnace negative pressure due to ignition delay. The larger the furnace volume V, the smaller the value of the negative pressure change.

2.1.2 Variation of furnace negative pressure by changing the mixer temperature in the furnace

Within the ignition delay time, Δt, the pulverized coal air flow injected into the furnace absorbs heat from the high temperature gas in the furnace, so the high temperature gas temperature gradually decreases and the temperature of pulverized coal air flow increases. Overall, the mixing temperature in the furnace decreases. Assuming the reduced mixer temperature to T_h, the furnace negative pressure value p_{1c} due to the temperature change is

$$p_{1c} = p_{y0} \times (T_h / T_{y0}) \qquad (5)$$

The corresponding value of the negative pressure variation in the furnace is

$$\Delta p_{1c} = p_{1c} - p_{y0} = p_{y0} \times \left(T_h / T_{y0} - 1\right) \quad (6)$$

For Eq. 6, the larger the Δt, the smaller the T_h, so the larger the variation of the furnace negative pressure due to the gas temperature change.

From Eq. 4 and Eq. 6, the total furnace negative pressure change value, Δp_1, caused by ignition delay or extinction, can be written as the sum of the furnace negative pressure values due to ignition delay and temperature change as follows:

$$\Delta p_1 = p_{y0} \times \left[\sum_1^N Q_{i0} \times \Delta t \times \left(1 - T_{y0} / T_{i0}\right) / V + \left(T_h / T_{y0} - 1\right) \right] \quad (7)$$

To make the analysis of the furnace negative pressure variation more convenient, we consider the initial flow rate and temperature of N pulverized coal air streams where ignition delay or extinction occurs, and denote Q_{i0} as Q_0 and T_{i0} as T_0. Then Eq. 7 is simplified as follows.

$$\Delta p_1 = p_{y0} \times \left[N \times Q_0 \times \Delta t \times \left(1 - T_{y0} / T_0\right) / V + \left(T_h / T_{y0} - 1\right)\right] \quad (8)$$

For N pulverized coal air flows with ignition time t_1, the ignition was only performed after t_2 for some reason, and there was no combustion reaction before ignition, so neglecting the change of V_{y0} during t_1, we can write by thermal equilibrium as

$$\sum_1^N Q_{i0} \times \Delta t \times c_{ipm} \times \left(T_h - T_{i0}\right) = V_{y0} \times c_{py} \times \left(T_{y0} - T_h\right) \quad (9)$$

where c_{ipm}-average specific heat of i-th pulverized coal air flow, kJ/(m^{3}K)

c_{py}- average specific heat of high temperature gas in furnace, kJ/(m^{3}K)

From Eq. 9, if the specific heat ratio of the hot gas is $c_i = c_{ipm}/c_{py}$, the temperature of the reduced mixture can be obtained by

$$T_h = \left(V_{y0} \times T_{y0} + N \times Q_0 \times \Delta t \times c_1 \times T_0\right) / \left(V_{y0} + N \times Q_0 \times \Delta t \times c_1\right) \quad (10)$$

In the above equations, Ty0 is obtained by thermal calculation, and the volume of the hot gas is $V_{y0}=V-N \times Q_0 \times t$ or $V_{y0}=V-N \times Q_0 \times \Delta t$. Solving Eq. 8 , Eq. 10 gives the values of the furnace negative pressure change with different ignition delay times Δt.

2.2 Computational examples and analysis for predicting furnace fire extinction

The important factors for ignition delay or extinction are ignition delay time, Δt, and number of burners N, where ignition delay occurs.

For example, in the 670t/h pulverized coal-fired boiler the relationship between ignition delay time, burner number and the calculated furnace negative pressure validation value with Eq. 8 at the initial flow rate Q_0 of pulverized coal air is shown in Table 1.

Table 1 Relationship between Δt, N and Δp_1

Δt, s	N			
	1	2	3	4
0.05	-1.9	-3.9	-5.8	-7.7

0.1	-3.9	-7.7	-11.6	-15.5
0.2	-7.7	-15.5	-23.2	-31.0
0.5	-19.4	-38.7	-58.1	-77.4
0.8	-31.0	-61.9	-92.9	-123.9
1	-38.7	-77.4	-116.1	-154.8

Table 1 shows that, under certain ignition delay times, for example, at $\Delta t \le 0.2, N \le 4$, the furnace pressure variation caused by the delay of ignition of several pulverized coal air streams are not large. This riser negative pressure fluctuation is small compared to the effect of other burners, and therefore, the effect on the combustion stabilization of the boiler is not significant. On the other hand, if $N \le 2$, the extinction of pulverized coal air stream has little effect on other burners in the furnace. However, in case of $\Delta t \ge 0.8, N \ge 2$, the furnace negative pressure variation is larger than 50 Pa, which affects the normal operation of other burners, in the case of $\Delta t = 1, N \ge 3$, the furnace negative pressure change is larger than 100 Pa, which is instantaneously propagated to the combustion state of other burners, leading to the flame extinction accident. Therefore, special care should be taken when the magnitude of the furnace negative pressure fluctuation is more than 100 Pa during operation.

Through the mathematical modelling and computational examples in the previous section, the furnace negative pressure fluctuations are caused by the ignition delay or extinction of pulverized coal air flow in the furnace, and their magnitude depends on the ignition delay time or the number of pulverized coal burner jet flows extinguished.

In practice, the furnace negative pressure variation is unavoidable even in a stable ignition state, and therefore, it is difficult to estimate the flame extinction by the absolute magnitude of the furnace negative pressure. However, the change of the furnace negative pressure fluctuation makes it possible to predict the early behaviour of flame instability.

Generally, the standard deviation indicates the steady state of the sample series, and the value of the variance of the furnace negative pressure is considered to represent the steady state of the furnace.

Using the operational history data of the 670 t/h pulverized coal-fired boiler, the analysis of the furnace negative pressure distribution shows that the furnace becomes unstable when the dispersion value is more than 20, and the probability of causing extinction increases.

The calculation equation of furnace negative pressure deviation is as follows:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(p_i - \bar{p}\right)^2} \qquad (11)$$

where N- number of furnace negative pressure samples

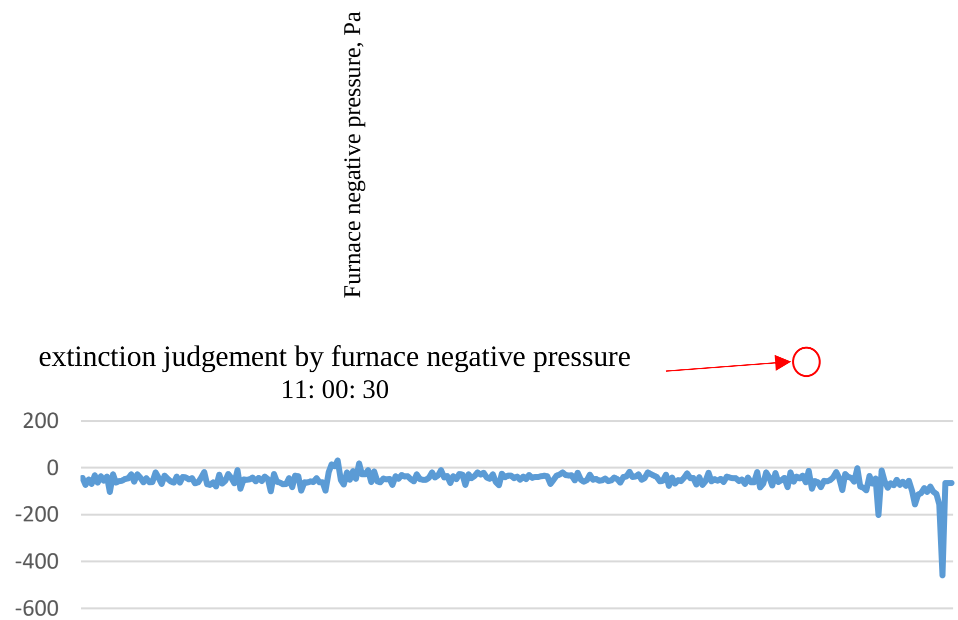
p_i- furnace negative pressure, Pa

$\bar{p}$ -average of furnace negative pressure sample values, $\bar{p} = \frac{1}{N}\sum_{i=1}^{N} p_i$

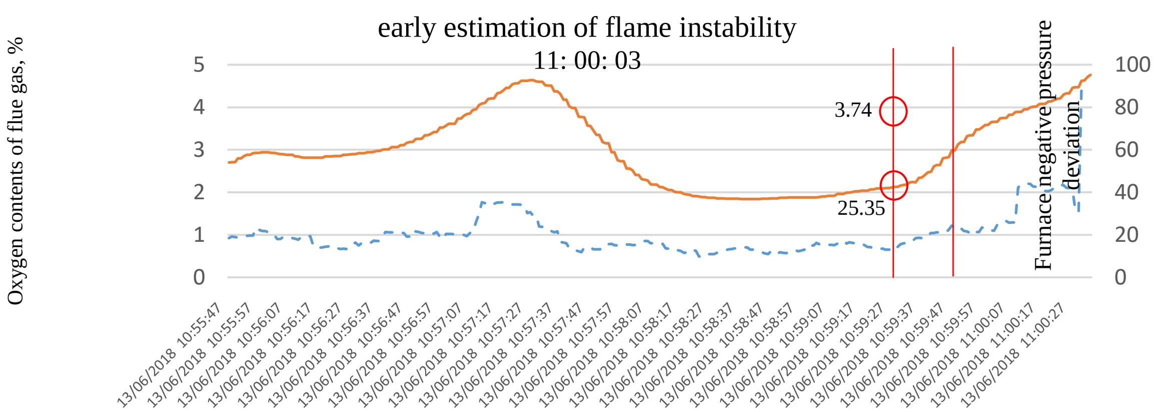
During boiler operation, even under stable conditions of actual flame, a transient variation of furnace negative pressure can occur due to various random factors such as damper operation or the fluctuation of the coal feed rate, and there are often cases where the flame instability is misestimated by the furnace negative pressure deviation alone.

The measured oxygen content in the flue gas is a factor that reflects the combustion process by mixing pulverized coal and air in the furnace, and considering it together with the furnace negative pressure deviation, it is possible to more accurately estimate the flame instability.

Figure 1 below shows an example of extinction estimation by furnace negative pressure and early prediction of flame instability by negative pressure deviation and oxygen contents during boiler operation.



a) Extinction judgement by furnace negative pressure



b) early estimation of flame instability by furnace negative pressure deviation and oxygen contents of flue gas

Fig. 1. Sample of judgement of flame extinction and early estimation of flame instability

Fig. 1 shows that the flame instability was already predicted by 11:00:30 when the furnace negative pressure dropped to -430Pa, with 25.35 furnace negative pressure dispersion at 11:00:03, 27s before and 3.74% oxygen contents in the flue gas. If the ignition device is turned on at this very moment, it can prevent the extinction and maintain a steady state.

3. R/S analysis and Hurst exponent calculation

An important aspect of the analysis of the furnace negative pressure is to solve the question of whether the furnace negative pressure can reflect the safety of the entire furnace. This paper has described the use of the Hurst exponent and the R/S analysis, one of the data analysis methods, to analyse the relationship between the furnace negative pressure and the parameters that indirectly reflect the furnace state of the boiler.

The calculation method of Hurst exponent is as follows.

Setting a time series of equidistant intervals $\gamma_1, \gamma_2, \ldots, \gamma_n$, the mean value is $\bar{\gamma}_n = \frac{1}{n}\sum_{i=1}^{n}\gamma_i$

The cumulative deviation is $X_{n,i} = \sum_{j=1}^{i}\left(\gamma_j - \bar{\gamma}_n\right)$, and the difference between the maximum and minimum of the cumulative deviation is called the range (Rn), which is

$$R_n = \max X_{n,i} - \min X_{n,i} \qquad (12)$$

The standard deviation (Sn) of the time series is

$$S_n = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\gamma_i - \bar{\gamma}_n\right)^2\right]^{\frac{1}{2}} \qquad (13)$$

Therefore

$$R_n / S_n = an^H \qquad (14)$$

where *H*- Hurst exponent, *a*-constant

The Hurst exponent defined above represents the degree of time series correlation. The H value is regular with increasing signal, when H = 0.5, the time series is completely random, indicating a “ignorance property” and there is no correlation between the forward and the backward. When 0 H < 0.5, the time series decreases further and decreases in the past if it has increased in the past as "reverse persistence," and then decreases in the future, and when 0.5 < 1, the time series exhibits "persistence", which increases or decreases in the past, and remains in the future as well. When H approaches zero, the signal is chaotic and when H approaches 1, the signal is fairly smooth.

4. Calculation of Hurst exponent of furnace negative pressure and power generation unit output

It can be seen from Fig. 2 that the Hurst exponent of furnace negative pressure and Hurst exponent of power at steady load change steadily above 0.5.

Fig. 3 shows the relationship between the state change in the state of instability and the Hurst exponent. It can be seen from Fig. 3 that, when the load fluctuates unsteadily, the Hurst exponent of the furnace negative pressure and power also fluctuates unsteadily below 0.5.

This indicates that the furnace negative pressure includes the characteristics of evaluating the stability of the combustion state.

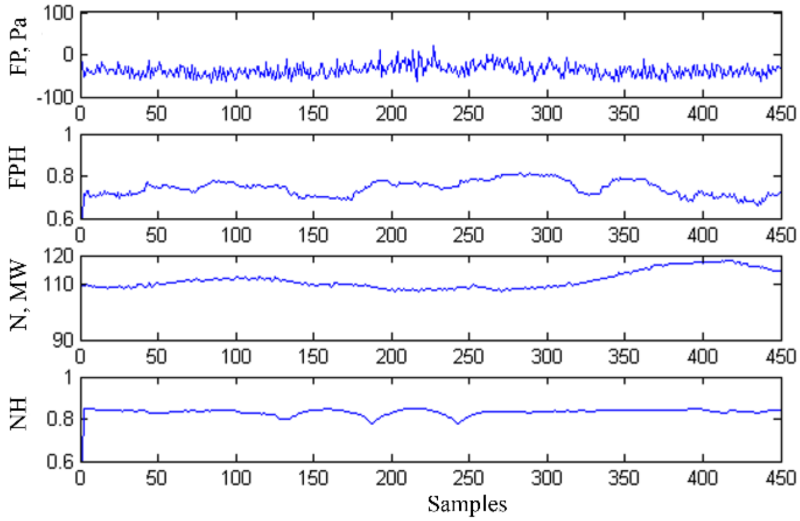


Fig. 2. Variation of Hurst exponent of furnace negative pressure and power in steady state

(FP-Furnace Negative Pressure, FPH-Furnace Pressure Hurst Exponent, N-Generator Power, NH-Generator Power Hurst Exponent)

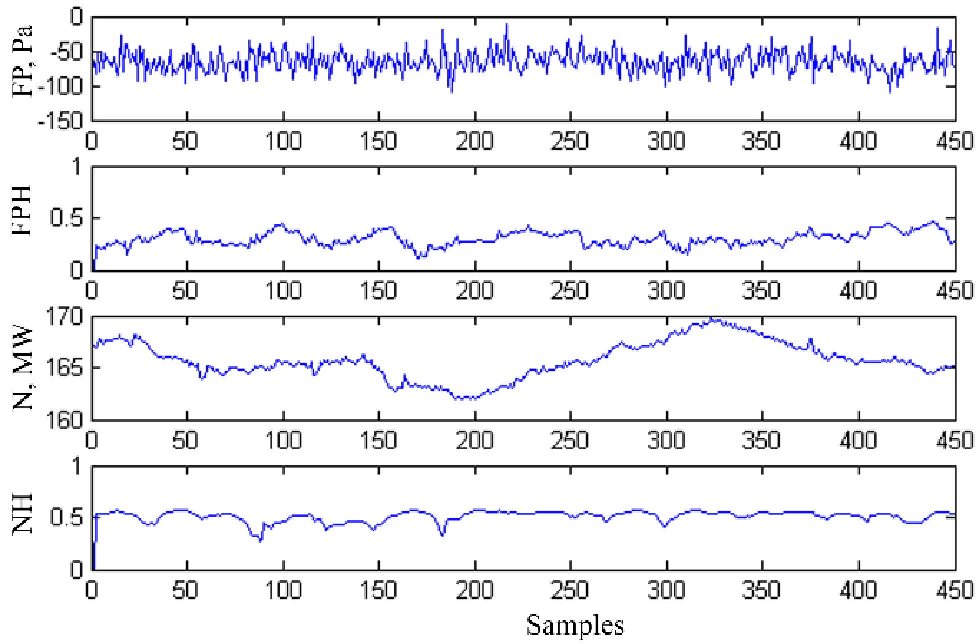


Fig. 3. Relationship of variation of Hurst exponent under unsteady load

5. Discussion on the safety evaluation of the furnace based on the furnace negative pressure signal

To evaluate the furnace safety based on the boiler's furnace negative pressure signal, the factors affecting the boiler's safety must be identified and the degree of variation of those factors must be taken into account.

5.1 Selection of parameters relate to combustion

The flame intensity and furnace negative pressure signals are limited only to the burner region and the top of the furnace due to the limitations of the installation location, so it is difficult to fully reflect the combustion behavior of the entire furnace. Considering that the heat energy is converted into the useful heat of the boiler in a very short time, the temperature, pressure, etc., characterizing the size of the steam and gas sides indirectly reflect the combustion behavior, and therefore, based on the relationship between these parameters and the furnace negative pressure, the effective power, drum pressure, main steam temperature, and the flue gas oxygen content signal are used to evaluate the furnace safety.

5.2 Indirect reflection of combustion safety

We selected four stages, 110 MW, 120 MW and 160 MW, depending on the generation power for 10 h of continuous operation. Each step was separated by 1 hour after and before. (Fig. 4)

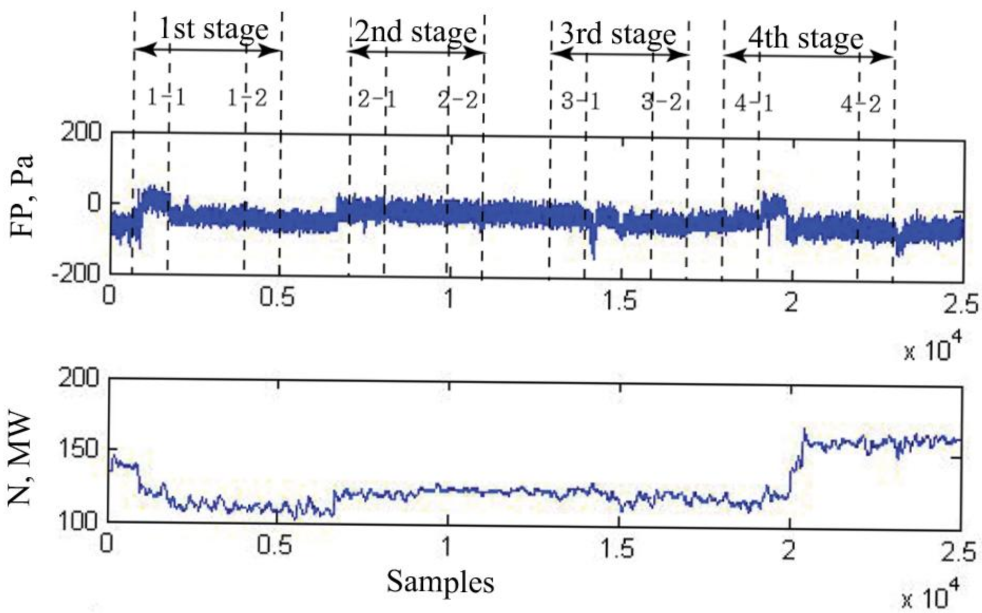


Fig. 4. Stage setup according to power

Table 2 Average and variance of the state variables in the steps

Stage	1-1	1-2	2-1	2-2	3-1	3-2	4-1	4-2
Sample Number	2000-3000	5000-6000	8000-9000	11000-12000	14000-15000	17000-18000	19000-20000	23000-24000

FP, Pa	AVG	-37.94	-51.44	-17.81	-21.07	-39.07	-43.92	-13.14	-67.46
	DEV	12.7035	14.7035	13.0778	11.1223	23.7276	12.0918	29.1837	19.4487
N, MW	AVG	111.98	109.81	120.02	122.72	122.86	125.89	120.94	159.38
	DEV	2.66706	3.6367	1.8705	0.9115	2.8902	2.2985	3.2437	2.613
P_d, MPa	AVG	9.83	10.21	10.0	10.26	10.28	10.37	10.19	11.75
	DEV	0.1676	0.2671	0.1377	0.0645	0.2099	0.1644	0.2145	0.1691
T_{SH},℃	AVG	520.9	530.8	522.0	524.2	517.8	514.1	525.1	510.5
	DEV	14.2015	12.9417	7.393	5.6245	14.2305	9.532	12.8368	11.1343

As can be seen from Table 2, the output power of each stage is basically identical, but the output power change is high in the last stage. However, the degree of stability is different, and the degree of stability is less than that of stability in each group. It is shown that combustion is stable if the parameters related to the operation of the boiler are in steady fluctuation. In particular, it is clearly seen that the fluctuation degree of the furnace negative pressure has a certain relationship with the fluctuation of the parameters that indirectly evaluate the stability of the boiler furnace.

Figs. 5 - 8 show the diagrams of the state variables of each stage.

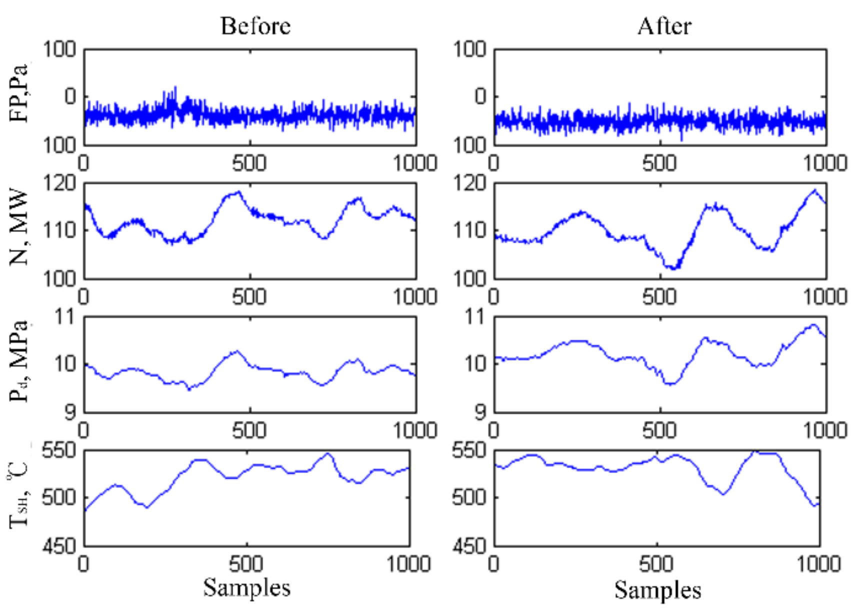


Figure 5. Parameter variation characteristics before and after 1st stage

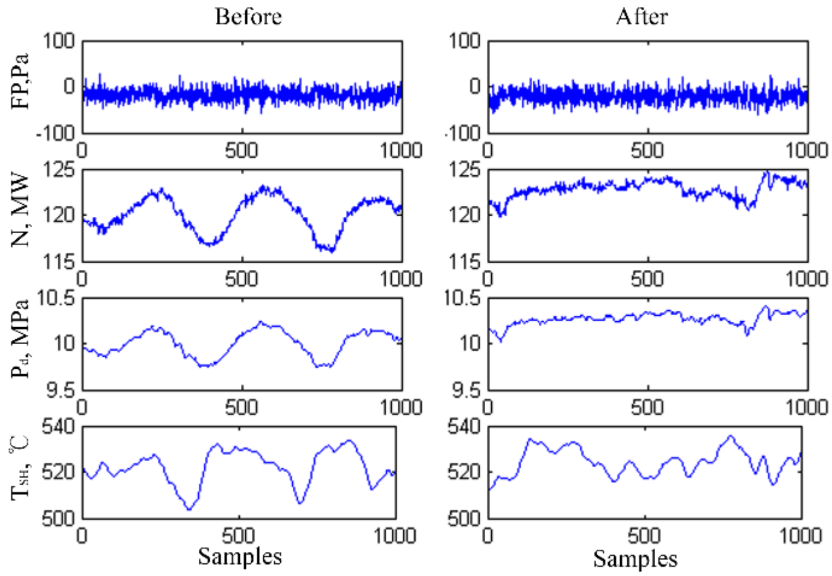


Figure 6. Parameter variation characteristics before and after 2nd stage

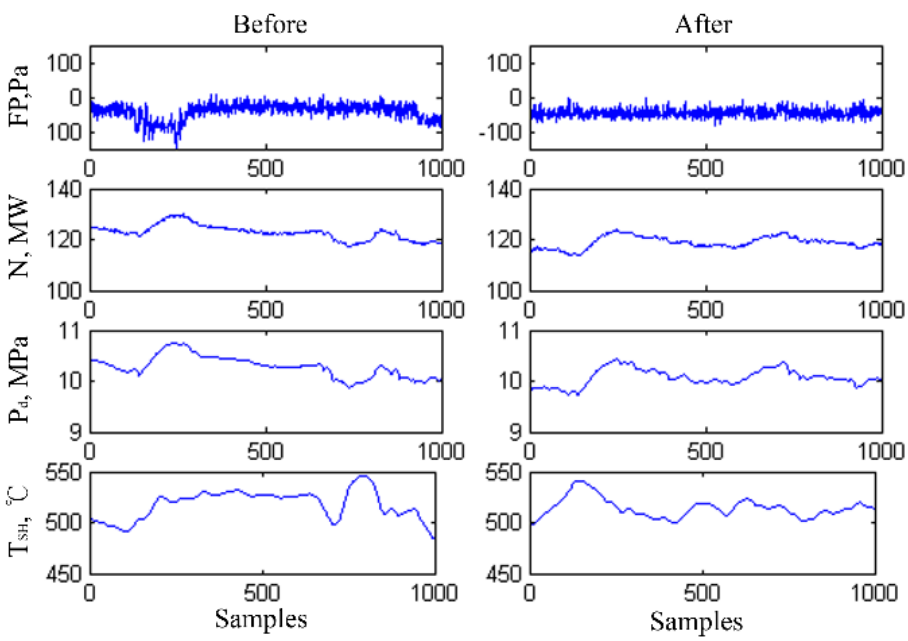


Figure 7. Parameter variation characteristics before and after 3rd stage

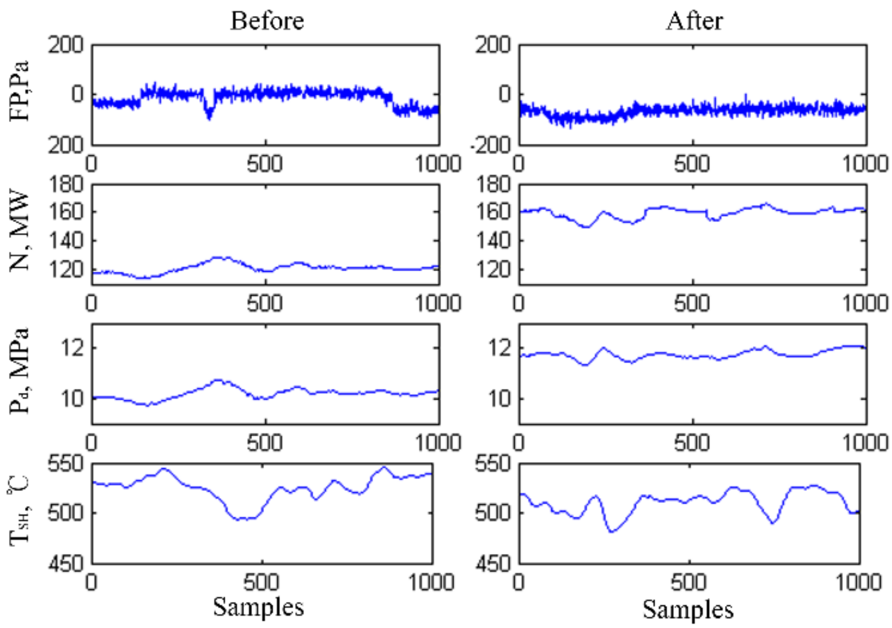


Figure 8. Parameter variation characteristics before and after 4th stage

Fig. 5 shows the hysteresis diagram of the furnace negative pressure, generating power, drum pressure and main steam temperature before and after 1st stage with an average power of 110 MW. The values given in Figs. 2 and 2 show that the first stage front has a smaller variance of all the parameters compared to the latter, indicating that the boiler furnace safety in the former is higher. Figures 6-8 show the stage states for the 120-160 MW average power in 2nd -4th stages .

It can be seen from Figs. 6-8 and Table 2 that the forward states in the two to four stages are less dispersive compared to the back states. This indicates that the combustion stability of the furnace was high.

6. Conclusion

1. In normal ignition conditions, the furnace negative pressure clearly exhibits regular small fluctuations.

2. When ignition delay or extinction of pulverized coal flame occurs, the degree of decrease of furnace negative pressure is related to the number of pulverized coal-air flows N and delay time Δt caused by ignition delay or extinction, which is higher in N and longer in Δt, the furnace negative pressure is lower and the furnace of the boiler becomes unstable. Therefore, when the furnace negative pressure is greatly reduced, special attention must be paid to prevent the boiler flame extinction accident from occurring due to combustion instability.

3. Predict flame instability by correlating the variation of furnace negative pressure dispersion and flue gas oxygen concentration, thus preventing extinction.

4.The furnace negative pressure is an important factor that directly reflects the combustion state in the boiler furnace, and the changing trend of the furnace negative pressure has a close relationship with the boiler primary parameters.

5.When the Hurst exponent of the furnace negative pressure is kept above 0.5, the boiler's parameters are kept stable, when the boiler's parameters are below 0.5, the boiler's combustion is disturbed and the boiler's parameters are not stable.

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