Analysis of Combustion Stability Based on the Negative Pressure Characteristic of Furnace

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Abstract. Under the low load and flexible peaking operation mode, it is very important to maintain the stable of the thermal power unit. To study the combustion characteristics of the unit under steady condition. We take a 600WM thermal power unit for example to illustrate the mechanism of the influence of combustion stability on the furnace negative pressure. The correlation coefficient method was used to analyze the relationship between related factors and negative pressure fluctuations. After eliminating the disturbance factors, the negative pressure fluctuation caused by combustion was studied. Combining the negative pressure power spectral density with the load and first-order components of the load, we establish a two-tuples combustion model. Two indicators of combustion-order and symmetry-order were established to evaluate the furnace combustion stability. Extracting the operating characteristics of two-tuples model during stable combustion and unsteady combustion. We found that the combustion-order when the combustion is stable is smaller than the combustion-order when the combustion is not stable, and the symmetry-order tends to be stable, and the symmetry of the two-tuples distribution is good. The combustion characteristics have guiding significance for the determination of the subsequent operational stability control strategy.

1. Introduction
With the development of society, the conflict between energy development and the environment has further intensified. China's energy structure is facing adjustment and upgrading. Developing new energy power is a strategic choice for reducing carbon emissions, transforming the economic model and taking a sustainable development path [1]. A large number of wind turbines and photovoltaic power stations are connected to the power grid. The random nature of new energy power generation gradually emerged. The random nature of new energy load fluctuations requires the entire grid to increase flexibility to accommodate rapid dispatch. As a result, China's thermal power generation has gradually changed its previous large-parameter, high-load operating mode and gradually shifted to low-load operation and flexible peaking operation [2]. Under the new mode of operation, the stability of the unit operation has become the focus [3]. Due to the inconsistency between the initial rated conditions and the operating conditions of the boiler design, when the unit is under low-load or flexible peaking operation, it will cause combustion fluctuations, which will have a certain impact on
the stable operation of the boiler. The current method for determining the boiler stability is mainly focused on three methods, furnace pressure, fire detection, and flame images [4]-[6]. Among them, the furnace negative pressure is an important characterization of the furnace combustion state. This parameter not only determines the relationship between the inlet and outlet of flue gas in the furnace, but also can directly reflect the changes in the process of combustion [7][8]. The low-load operation and deep-level regulation of the thermal power unit are more and more widely used. The study of the furnace negative pressure characteristics under different loads of the boiler helps to optimize the combustion stability control.

2. Furnace Negative Pressure Fluctuation Mechanism Analysis

Combustion is a complex dynamic process, accompanied by physical and chemical reactions and energy release [9]. The change of furnace negative pressure is affected by many factors [10]. For example, primary air, auxiliary air, changes in coal quality, man-made coordinated control commands, and fluctuations in combustion conditions all affect negative pressure. However, there are two main factors that cause negative pressure change:

1) Effect of flue gas and air system on negative pressure
2) Effect of combustion process on negative pressure

There are two different mechanisms in the combustion process [11]: Firstly, the fuel flow premixed by fuel and air enters the furnace and rises to the ignition point in the furnace. Deflagration occurs and the volume expands rapidly causing the pressure increasing. Secondly, the mixture of fuel and air begins to heat up, the combustion reaction proceeds slowly, no deflagration occurs, and the pressure fluctuation of the combustion field is small. However, the combustion in both modes will cause the air fluctuation in the blast pipe. The fluctuation of the air will lead to the fluctuation of the flame, which will cause the “combustion oscillation” [12]. By analyzing the power spectrum signal of negative pressure, the characteristics of negative pressure in different combustion states can be obtained [13].

Both mechanisms of the combustion process cause pressure fluctuations in the furnace. It is known from literature [14] that the forcing equation for the pressure oscillation of the combustion gas is:

\[
\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \Delta^2 p = \left( \frac{r - 1}{C^2} \right) \frac{\partial q}{\partial t} + \nabla \left[ \rho u (\nabla u) \right]
\]

In the formula:
- \(\rho\)-Microelement gas density, kg/m\(^3\);
- \(U\)-gas flow rate, m/s;
- \(P\)-combustion chamber gas pressure, Pa;
- \(q\)-fuel burns to release heat per unit volume, J/m\(^3\);
- \(T\)-temperature in the furnace, \(^\circ\)C;
- \(C\)-sound speed, m/s;
- \(R\)-adiabatic index.

In the formula, the two terms on the right side are the source of the excitation, one is the combustion of fuel in the combustion chamber to release heat, and the other is the stream turbulence in the combustion chamber. It can be seen that the fluctuation of the air flow and the state of combustion have a certain influence on the furnace pressure. In the following part, we will perform qualitative and quantitative analysis around the two items in combination with actual operational data, and extract the relationship between furnace pressure and combustion characteristics, and use the furnace pressure to characterize the stability of the furnace operation.

3. Correlation calculation of influence factors of furnace negative pressure

3.1. Feature selection and analysis

During the combustion process, the unit sends coal powder into the furnace through the primary air, and provides oxygen for combustion through the secondary air and the tertiary air. Taking a 600 MW
unit as an example, we relied on the DCS historical database of the power plant to conduct data mining on the operation records and extract the factors that characterize the relevant variables.

We take a period of about two hours of unit operating status data from the mass operation data. Taking the negative pressure and the primary air volume of the flue gas and air system as an example, the equal time interval sequence models of the original data are established respectively. As shown in FIG. 1 and FIG. 2, are the status charts of the negative pressure and primary air volume of the furnace.

From Fig. 1 and Fig. 2, we can observe the fluctuation of the negative pressure of the furnace and the primary air volume in the unit operation. In order to remove the interference and further observe the relationship between the two changes, the mean filtering of the negative pressure and primary air volume of the furnace was carried out respectively. And the random fluctuation of the short time was filtered out to further observe the correlation between two variables. Fig. 3 and Fig. 4 show the negative pressure and primary air volume of the furnace after the mean filtering.

Observing Figure 3 and Figure 4, we can see that there is a strong correlation between the fluctuation of the furnace negative pressure and the change of the primary air volume. At the same time, it is also confirmed that the turbulent flow in the combustion chamber is a direct stimulus source in the pressure change in the above theoretical derivation.

3.2. Correlation quantitative calculation and data preprocessing
In order to derive the specific relationship between negative pressure and the fluctuations of the wind-smoke system, the correlation coefficient was introduced in this part, which was first used by statistical indicators designed by the statistician Carl Pearson to measure the linear correlation between variables and the correlation coefficient. It is determined by formula (1):

$$r(X, Y) = \frac{Cov(X, Y)}{\sqrt{Var[X]Var[Y]}}$$

In the formula, X and Y are two-variable sequences. The closer the absolute value $|r|$ of the calculated correlation coefficient is to 1, the higher the correlation between X and Y.

Selecting data from the DCS history record, still taking negative pressure and primary air volume as examples, the unit has six burners, burners A, B, C, D, E, F, and each burner corresponds to a primary air flow measurement point. Select four negative pressure measuring points A1, A2, B1 and
B2 in the furnace. The correlation coefficient matrix was constructed to analyze the effect of primary wind of each burner on the negative pressure change of the furnace. The resulting data was scaled to eliminate the impact of dimension. The obtained primary air volume and negative pressure correlation coefficient matrix are shown in Table 1:

| Table 1 Correlation coefficient matrix |
|----------------------------------------|
| Correlation coefficient | A1 | A2 | B1 | B2 |
|--------------------------|----|----|----|----|
| A                        | 0.4394 | 0.4364 | 0.433 | 0.4577 |
| B                        | 0.9234 | 0.9217 | 0.9206 | 0.9272 |
| C                        | 0.674 | 0.6691 | 0.6701 | 0.688 |
| D                        | 0.9204 | 0.9185 | 0.9249 | 0.9283 |
| E                        | 0.9376 | 0.9348 | 0.9371 | 0.9452 |
| F                        | 0.9147 | 0.9124 | 0.9092 | 0.9189 |

From the correlation coefficient between each measurement point in Table 1, we can see that there is a large correlation between the negative pressure and the primary air volume, and the correlation coefficient between B, D, E, F burners and negative pressure exceeds 0.9. The primary air volume has a great influence on the negative pressure change in this area.

In order to better reflect the combustion stability through the furnace negative pressure characteristics, it is necessary to eliminate the influence of the flue gas and air system on the change of the negative pressure. The main parameters of the gas and air system directly related to the furnace negative pressure are primary air, auxiliary air and air flow rate of fan. We carry out Schmidt-orthogonalization of these variables.

Schmidt orthogonalization decouples variables by orthogonal calculations between vectors. Let \( \alpha_1, \alpha_2, ..., \alpha_m (m \leq n) \) be a linearly independent vector set in \( \mathbb{R}^n \), if:

\[
\beta_1 = \alpha_i
\]

\[
\beta_i = \alpha_i - \frac{\langle \alpha_i, \beta \rangle}{\langle \beta, \beta \rangle} \beta
\]

\[
\beta_s = \alpha_s - \frac{\langle \alpha_s, \beta \rangle}{\langle \beta, \beta \rangle} \beta - \cdots - \frac{\langle \alpha_s, \beta_{s-1} \rangle}{\langle \beta_{s-1}, \beta_{s-1} \rangle} \beta_{s-1}
\]

Then \( \beta_1, \beta_2, ..., \beta_m \) is an orthogonal vector group, if it is then:

\[
ed_i = \frac{\beta_i}{\| \beta_i \|} (i = 1, 2, \ldots, n)
\]

A standard orthogonal vector set \( e_1, e_2, ..., e_m \) is obtained, and this vector set is equivalent to \( \alpha_1, \alpha_2, ..., \alpha_m \). After eliminating the influence of the fluctuation of the flue gas and air system on the negative pressure through orthogonalization, the time series of negative pressure is shown in the figure 5:

![Fig.5 Negative pressure sequence (Standardization)](image)

![Fig.6 Elimination of disturbances](image)

Figure 5 shows the sequence of negative pressure after standardization. The negative pressure sequence is orthogonalized. Remove the influence of the primary and secondary winds and the induced draft fan air flow. The resulting sequence is shown in Figure 6. Observed directly from the
figure, the fluctuation of the negative pressure is reduced after the influence of the fluctuation of the flue gas and air system is removed. The main factor causing this sequence fluctuation at this time is the combustion process and stability of the furnace. By analyzing this sequence, the stability of the furnace combustion process can be judged from the side.

4. Negative pressure spectrum analysis and establishment of stability characteristics

Furnace negative pressure needs to be maintained between -40 and -60 Pa. Therefore, the furnace pressure contains the DC fundamental component. The fundamental component has a great influence on the analysis of the furnace spectrum. In the frequency spectrum analysis, the fundamental component needs to be removed. The 200 s time window is used to perform zero-average processing on the negative pressure signal to remove the DC component. The Fourier transform can be used to obtain the furnace negative pressure spectrum information of the time window.

To measure the amount of energy carried by each frequency component, power spectral density was introduced. According to the Winner-Khintchine formula, the power spectral density $S_{xx}(f)$ of the discrete stochastic process is:

$$S_{xx}(f) = \sum_{k=-\infty}^{\infty} r_{xx}[k]e^{-jk2\pi f}$$

(6)

Among this:

$$r_{xx}[k] = \mathbb{E}[x[n]x^*[n-k]]$$

(7)

The frequency corresponding to the spectrum peak of the power spectrum is the main frequency of the power spectrum, and the main frequency represents the frequency with the maximum carrying capacity of the negative pressure fluctuation in this period. The distribution of the main frequency will have different characteristics under different operating conditions. Therefore, combining the operating condition information and the main frequency can characterize the combustion characteristics in the current operating state.

However, the furnace combustion process is a dynamic process. Its working condition is not only closely related to the current state, but also related to the operating conditions of the previous working conditions. Therefore, it is difficult to reflect the stability of the combustion process based on the state of the furnace alone. It is also necessary to introduce a change in the state to correct the current state. To do this, we seek a first-order difference $\Delta load_t$ for the load:

$$\Delta load_t = load(t+1) - load(t)$$

(8)

The first-order difference sequence of the load can characterize the change trend and instantaneous change speed of the load in the current hour. Therefore, we combine the first-order differential and negative-pressure power spectrum frequencies of the operating point to form a dual group. The dual group can not only represent the change information of the working conditions, but also reflect the combustion characteristics. The dual group can be used to determine the combustion stability of the furnace. With the help of a large number of operating data of the unit, a dual-character model library can be built to effectively reflect the distribution of the combustion characteristics of the unit.

5. Combustion stability determination example

From the DCS operation history record of the unit, a large number of representative conditions are selected. Through the above-mentioned data processing process, a dual-group model of the first-order difference and main frequency of the load is established, and a dual model is established under multiple operating conditions to obtain a large number of analyzing the sample. The dual distribution map is shown in Figure 7.
The distribution characteristics of the dual points of operating conditions contain a large amount of information on the negative pressure of the unit and load and load fluctuations, which can reflect the combustion status of the unit to some extent. Observing from the figure, it can be seen that the characteristic points of the two-tuples are symmetrically distributed about the load first-order difference $\Delta load_n = 0$, and the unilateral approximation $\beta$-distribution. In order to better extract the dyad and characterize the combustion stability, we deal with the positive and negative data separately. Defining distribution feature points is calculated as follows:

$$
\begin{align*}
  x_c &= \frac{\sum_{i=1}^{n}(f_n \cdot \Delta load_i)}{n} \\
  y_c &= \frac{\sum_{i=1}^{n}(load_n \cdot f_i)}{n}
\end{align*}
$$

(9)  

(10)

Among these:

- $f_n$ — the number of operating point under the first-order differential of the fixed load
- $load_n$ — The number of differential points in the next-order fixed frequency.

On both sides of the semi-axes are the positive distribution and negative distribution feature points. Define the positive combustion order is the distance from the distribution feature point which locate on the right side of the x-axis to the origin. The opposite distribution feature points symmetrically to the positive semi-axes, and the distance between them and the positive distribution feature points is defined as a symmetry order. Sampling the operating data in the stable combustion conditions and the operating data in the unstable operating conditions, respectively, to find the positive combustion order and negative combustion order, the results are shown in Table 2:

| Condition status       | positive combustion order | negative combustion order | symmetry order |
|------------------------|---------------------------|----------------------------|----------------|
| stable combustion      | 8.41                      | 8.59                       | 0.26           |
|                        | 6.3                       | 10.48                      | 17.47          |
|                        | 6.31                      | 6.89                       | 0.33           |
|                        | 11.22                     | 11.76                      | 0.28           |
|                        | 10.69                     | 14.87                      | 18.34          |
| unstable operating     | 71.81                     | 80.39                      | 73.67          |
|                        | 50.68                     | 56.69                      | 36.17          |
|                        | 79.92                     | 100.44                     | 421.76         |
|                        | 25.34                     | 18.46                      | 58.42          |
|                        | 25.57                     | 21.5                       | 20.54          |

Comparing the data obtained in Table 2, it can be found that when the combustion is in a stable state, the symmetry order is small, indicating that the symmetry of the positive and negative semi-axes of the combustion characteristic point distribution is good, and both the positive combustion order and the negative combustion order are less than which in unstable conditions. Extract some representative working conditions from the DCS historical database to establish a data set, find the positive
combustion order and the negative combustion order under each working condition, draw the positive combustion order and the negative combustion order pair, as shown in Figure 8. Under consideration of certain fault tolerance, the combustion moments in stable conditions and the combustion moment values in unstable conditions are linearly separable. The figure shows the stable combustion area and the non-stable combustion area respectively.

![Fig.8 Stable/unstable characteristics distribution](image1.png)

![Fig.9 combustion symmetry-order](image2.png)

The area marked with “+” in the figure is the distribution of combustion moment values in stable conditions, and the area represented by “○” is the distribution of combustion moment values in non-steady conditions. When the unit is running stably, the combustion order value is distributed close to the origin, while in the unstable state, the combustion order is divergent and away from the origin. Another feature that compares the stability and instability of the combustion is the symmetry order. The symmetrical order under stable conditions and the symmetric order under unstable conditions are plotted, as shown in Figure 9.

It can be seen from the figure that the distribution symmetry of the dual group becomes worse under non-steady conditions, and the symmetry order is larger than that under stable conditions, and the fluctuation is also larger than that during stable operation.

6. Conclusions
Under the operating mode of the power station boiler at this stage, the boiler combustion stability becomes an important guarantee for the safe operation of the unit. This paper proposes a set of methods to assess unit operating stability. Data processing is performed on negative pressure, the influence of related factors is filtered out, and then the power spectral density of each window is calculated. Two stability indexes are proposed based on the frequency spectrum characteristics of negative pressure fluctuations. Relying on the massive historical operating data of DCS to establish the operating characteristics model. Through this method, the stability of furnace combustion can be characterized by means of negative pressure characteristics, which has guiding significance for the subsequent further combination of economy and stability for optimization of the combustion scheme of the unit.

References
[1] Zhang Weibo, Pan Yuchao, Cui Zhiqiang, Zhang Weidong. Analysis on the development of new energy power generation in China[J]. Energy of China, 2012,34(04): 26-28+41.
[2] Liu Jizhen, Zeng Deliang, Tian Liang, Gao Mingming, Wang Wei, Niu Yuguang, Fang Fang. Control Strategy for Operating Flexibility of Coal-fired Power Plants in Alternate Electrical Power Systems [J]. Proceedings of the CSEE, 2015,35(21):5385-5394.
[3] Liu Jizhen, Yang Guangjun, Tan Wen, Fang Fang. Synthetic Evaluation on the Degree of Combustion Stability in Power Station Based on Data-driven[J]. Proceedings of the CSEE, 2007(35):1-6.
[4] Hao Zulong. Research on Recognition and Diagnosis of Utility Boiler Combustion State[D].
North China Electric Power University (Beijing), 2010.

[5] Gao Xiang, Luo Zhongyang, Chen Yafei, Zhou Jinsong, Ni Mingjiang, Ceng Kefa. Experimental Study on the Diagnosis of Combustion Using Micro-pressure Detection[J]. Power Engineering, 1998(04):28-32+15+88.

[6] Wu Yiquan, Song Yu, Zhou Huachun. State Identification of Boiler Combustion Flame Images Based on Gray Entropy Multiple Thresholding and Support Vector Machine[J]. Proceedings of the CSEE, 2013, 33(20):66-73+13.

[7] Xiao Jun, Wang Yiqing, Lv Zhenzhong. Study on Boiler Combustion Diagnostic Test Based on Micro-pressure Signal of Furnace[J]. Boiler Technology, 2002(07):12-15.

[8] Sun Lingfang, Gong Yuanyang. Research on Optimization Strategy of Boiler Combustion Chamber Draft of Thermal Power Unit[J]. Computer Simulation, 2017, 34(02):170-174.

[9] Zhang Xingang, Ren Jing, Xu Zhigao. Numerical Study on Self-excited Vibration of Turbulent Premixed Burner[J]. Gas Turbine Technology, 2007(03):23-28.

[10] He Lanhua, Ning Quan, Zheng Xianghong. Discussion on the Law of Vacuum Change in the Pulverized Coal-fired Boiler[J]. Technology Wind, 2014(10):201-202.

[11] Jin Qingming. Power Spectral Density Measurement of Flammable Pressure in Combustion Field[J]. Power Engineering, 1990(02):43-45+4-62.

[12] Wei Zhaolong, Guo Chaoling, Yang Yibo. Experimental Study on Stable Combustion Property of Coals [J]. Boiler Technology, 1999(10):6-9.

[13] Jin Qingming. Combustion-Induced Vibration of Furnace Wall[J]. Journal of Shanghai Institute of Machinery, 1989(04):51-57.

[14] Jiang Zhe, Guo hua. Spectrum Analysis of Cylinder Pressure of Internal Combustion Engine[J]. Transactions of Csite, 1989(03):251-258.