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Discussion on calculation method of natural frequency of flue design in thermal power plant based on temperature field simulation

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Abstract: The vibration of the boiler tail flue not only leads to tearing and steam leakage at the welding point between the superheater and manhole, but also makes the acoustic soot blower in the tail flue basically unable to be put into operation, which seriously affects the safe operation of the unit. In order to reduce the size of external reinforcing ribs, the minimum number of internal struts should be used in large section flue. By means of temperature field simulation, the author adds a flow guide device at the junction of the down flue and the horizontal flue to forcibly guide the flue gas to the convection heat exchange area. The simulation results show that the vertical velocity field distribution of the horizontal flue tends to be uniform after adding the diversion device. Measures should be taken to prevent the vibration of the inner strut, such as selecting the inner strut with appropriate specifications; Install fins on the inner strut; Change the natural frequency of the inner strut; Select appropriate flue gas flow rate, etc.

1. Introduction

With the expansion of unit capacity in thermal power plant, the cross-sectional area of flue also becomes larger. At present, most of the flues in power plants are rectangular flues. As the flues become larger, the corresponding reinforcing ribs, internal struts and other reinforcing members also become larger, which directly leads to a substantial increase in the amount of flue works [1]. The vibration of the tail flue of the boiler not only leads to tearing and steam leakage at the welding place between the superheater and manhole, but also makes the acoustic soot blower in the tail flue basically unable to be put into operation, which seriously affects the safe operation of the unit [2]. Through the simulation study of temperature field, the causes of flue vibration in thermal power plant are analyzed and verified by calculation, and the measures to eliminate the vibration are formulated according to the calculation results.

2. Vibration mechanism of tail flue with inner strut

In the conventional flue design, the vibration of the inner strut has not been paid attention to, and the design only needs to meet the strength conditions. However, in the design of anti-corrosion flue, the inner strut should not only meet the strength condition, but also meet the condition that no vibration can be generated. The reason is: because the inner wall of the flue is coated with lining, even slight vibration may cause the inner lining of the flue to fall off after a long time, eventually leading to flue corrosion [3-4].

The vibration of boiler tail flue is complicated, and the main factors that cause the vibration of tail flue are the frequency of sound standing wave of flue, the shedding frequency of Karman vortex generated by flue gas flowing through tube bank, and the natural frequency of heating surface tube bundle [5]. When the flue gas flows through the heating surface, its standing wave frequency and vortex shedding frequency are coupled with the natural frequency of the equipment or a certain order of acoustic standing wave frequency, that is, resonance occurs.

3. Model building

The whole boiler is very huge, with the full size of 30 m in the horizontal and vertical directions, while the outer diameter of the cooling water pipe on the inner wall of the flue is only 38 mm, a difference of three orders of magnitude. Such a large size span requires very high grid division. In addition, in addition to the main structural components, there are various doors, holes and many accessories on the furnace wall, so the structure is quite complicated. Whether from the point of view of simulation cost or research object, reasonable simplification is very necessary in the modeling process.

Therefore, the following agreements are made on the establishment of the geometric model of the boiler:

(1) All dimensions are rounded to the nearest whole number (in mm);

(2) Ignore the increase of flue gas flow caused by air leakage, and ignore the smoke carried in flue gas;

(3) Only the main flow area of flue gas is modeled, ignoring the doors, holes and other accessories on the furnace wall, which are all equivalent to the water wall surface;

(4) The cooling water pipe is omitted, and the cooling wall is replaced by a plane;

(5) Five groups of heat exchange tube bundles in convection zone are replaced by porous media.

According to people's most conventional understanding of thermal efficiency, the percentage of high-temperature flue gas heat absorbed in the flue to the total input heat is the thermal efficiency of the flue [6], so the thermal efficiency of the flue can be calculated by the temperature difference of flue gas at the inlet and outlet:

$$\eta_k = \frac{T_J - T_C}{T_J} \times 100\% \tag{1}$$

Where, η_k is the thermal efficiency of flue, %; T_J is the smoke inlet temperature, ℃; T_C is the outlet temperature, ℃.

In order to focus on studying the influence law of improving flue structure on the change of flue gas flow field and temperature distribution, only the layout of flue in flue is optimized, and the position of stove and chimney that people are used to is not changed. Without considering the random influencing factors, the diffusion degree of flue gas and the temperature difference of flue gas at the inlet and outlet of the flue reflect the amount of heat absorbed in the flue, and then reflect the thermal efficiency of the flue.

In order to comprehensively analyze the flow state, temperature distribution and temperature change of high-temperature flue gas, three horizontal sections with different elevations were selected for research: The horizontal section of the flue 0.2 m away from the cushion soil layer to analyze the distribution of flue gas flow field after high-temperature flue gas enters the flue through the flue inlet;

The horizontal section of the center of the outlet 0.3 m away from the cushion soil layer is used to study the flow of high-temperature flue gas in the flue and the temperature distribution of the outlet; 0.42 m away from the cushion layer and close to the horizontal section at the bottom of the flue to analyze the heat exchange efficiency between the high-temperature flue gas and the flue.

4. Calculation of design natural vibration frequency of flue in thermal power plant

4.1 Structural stability calculation

Stability analysis is an important aspect of structural analysis, the purpose of which is to obtain the critical load of structural instability [7].

Take the slender bar as an example, the stable equilibrium state of the bar under central compression is transformed into unstable equilibrium state due to the gradual increase of axial force, and suddenly transformed from central compression state to bending compression state, which is called instability. The transition state from stable state to unstable state of the bar is called critical state, and the load in critical state is called critical load.

Taking beam members as an example, the node displacement of beam elements can be divided into two parts, namely axial displacement δ_a^e and bending displacement δ_b^e.

$$\begin{aligned}\delta_a^e &= [u_i, u_j]^T \\ \delta_b^e &= [w_i, \phi_i, w_j, \phi_j]^T\end{aligned} \tag{2}$$

After considering the influence of axial force, the stiffness matrix of the beam element becomes:

$$K^e = K_b^e + K_\sigma^e \tag{3}$$

Where, K_b^e is the bending stiffness matrix of the beam element, K_σ^e is the stiffness matrix increased due to the influence of axial force, which is called the geometric stiffness matrix because it has nothing to do with the physical constants of materials but only with the geometric dimensions of the element. When the axial force is tensile force, K_σ^e is positive, otherwise it is negative. The equilibrium equation of the system can be written as:

$$Kb_\sigma = P \tag{4}$$

The geometric stiffness matrix is proportional to the axial load. If the axial load increases according to the scaling factor λ, it is discrete, while pentahedron and hexahedron elements are mostly used for structures with regular shapes. Among the three orders, the quadratic element has more suitable calculation accuracy and calculation amount, and is widely used.

$$F = \lambda F_0 \tag{5}$$

The node of the entity has three translational degrees of freedom (u, v, w), which belongs to the non-bending element. Node force, surface force, volume force and temperature load can be applied on the element, but edge load cannot be applied.

It can analyze isotropic, completely anisotropic and orthotropic materials, and output the calculation results of displacement, stress, strain, strain energy, unit force and reaction force.

4.2 Calculation of vibration of inner strut in tail flue

The flue gas duct of thermal power plant includes flue, cold air duct and hot air duct. In the industry, the flue gas duct, raw coal pipeline, pulverizing pipeline and powder conveying pipeline are called six channels [8]. Flue refers to the flue from the outlet of boiler air preheater to the front of chimney; Flue gas recirculation pipeline; High temperature flue gas pipeline for drying coal mill; Low temperature flue gas pipeline and drying pipe from mixing chamber to coal mill inlet, etc. Among them, the design of reinforcing ribs is an important factor that affects the safety and economy of smoke duct system.

Although the circular flue gas duct has many advantages over the rectangular flue gas duct, it was seldom used in domestic large-capacity units in the past due to the limitations of the layout site, the imperfect design rules and supporting calculation methods for the reinforcing ribs of the circular flue gas duct in China and other factors.

Through a large number of experiments, it is found that the frequency f of vortex shedding mainly depends on the velocity V of the fluid and the diameter d of the cylinder, and the frequency of vortex shedding in the transverse flow around the cylinder can be calculated by formula (6).

$$f = SrV / d \tag{6}$$

Where Sr is the SteRohal number, which is only related to Reynolds number Re. When $Re > 100$ the SteRohal number is approximately equal to a constant, that is, $Sr = 0.21$.

When the frequency of Karman vortex is close to the acoustic natural frequency f_n of the air column of the inner strut, Karman vortex will excite the vibration of the air column, that is, resonance. If we know the natural vibration frequency of the inner strut, compare it with Karman vortex frequency and stagger the frequency, we can avoid the vibration.

The natural vibration frequency of the inner strut can be expressed as formula (7):

$$f_n = \lambda^2 \{9800EIM_0 / (9.8\rho A(M_0 + M_1))\}^{1/2} / 2\pi L^2 \tag{7}$$

Among them, λ——Vibration coefficient;

L——The length of the inner strut, mm;

E——Elastic modulus of inner strut material at working temperature, $\mathrm{N/mm^2}$;

I——Section moment of inertia of the inner strut, $\mathrm{mm^4}$;

M_0——The mass of the inner strut, $\mathrm{kg/m}$;

M_1——The mass of other substances (such as lining, water, etc.) attached to the inner strut, $\mathrm{kg/m}$;

ρ——The density of the inner strut, $\mathrm{kg/mm^3}$;

A——Cross-sectional area of the inner strut, $\mathrm{mm^2}$.

Because the formula (7) is obtained by a simplified system, the practical factors of the combination of the inner strut as a whole and the inner wall of the flue are not considered. The actual engineering practice shows that:

As long as the frequency of Karman vortex formed by flue gas at the inner strut is not within $0.7-0.3f_n$, it indicates that there is no resonance, and at the same time, it makes up for the deficiency of formula (7).

4.3 General consideration for calculating natural frequency of flue

For the low flue, it can be calculated according to formula (8). For the flue with very low flue, it is also proposed that the natural frequency can be estimated approximately by smooth tube.

$$f_n = 0.4944 C_n \sqrt{EI / \left(W_e L^4\right)} \tag{8}$$

Among them, f_n——The n-th natural frequency of flue, Hz;

C_n——n-order frequency coefficient, dimensionless;

E——Young's modulus of material, MPa;

I——Section moment of inertia of the pipe, m;

W_e——Effective mass of flue per unit length, kg / m;

L——Take the maximum span length, m.

However, the theoretical calculation of natural frequency of flue given above is generally only applicable to low flue (such as threaded flue), and the ratio of flue height to base pipe diameter is less than 0.2. However, in order to improve the heat transfer efficiency, the flue used at present increases the height of the flue in design, and the ratio of the height of a part of the flue to the diameter of the base pipe is close to 0.5.

It can be seen that the flue has a greater influence on the quality and rigidity of the whole heat exchange tube than the traditional low flue, so the calculation of the natural frequency of the high flue needs further discussion.

5. Temperature field simulation analysis

In view of the unreasonable distribution of horizontal flue gas flow is caused by the design of right-angle structure at the joint of flue, in order to improve the flow field distribution, it is necessary to change the direction of flue gas flow, such as increasing the included angle between descending flue and horizontal flue to avoid the sharp turn of flue gas flow. From the actual situation, it is almost impossible to change the overall structure of flue.

In order to further compare the optimization effect of the deflector, the mass flow rate (kg/s) of flue gas passing through different sections before and after installing the deflector is extracted, as shown in Figure 1.

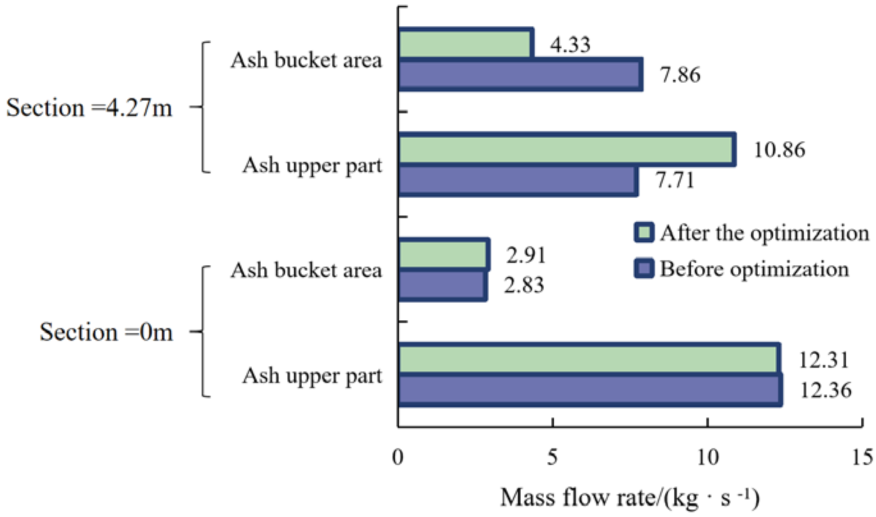

Figure 1: Flow rate of flue gas passing through different sections before and after installing deflector

It can be seen from Figure 1 that before and after installing the deflector, the distribution of flue gas flow through the cross section is almost the same. However, before optimization, less than half of flue gas can really enter the convection heat exchange area, and the remaining half can only pass through the ash hopper area and be discharged from the waste heat boiler after weak radiation heat exchange. However, after optimization, more than 2/3 of flue gas will pass through the convection heat exchange tube bundle, and the flow rate will increase by about 17.8%, and all of them are high-temperature flue gas with higher heat value, which can fully release heat through convection heat exchange.

6. Summary

With the enhancement of people's awareness of environmental protection, desulfurization in thermal power plants has attracted extensive attention. When designing desulfurization and anticorrosion flue, the vibration of inner strut should be paid attention to. Attention should be paid to the problems caused by not using internal struts in the tail flue and the mechanism of vibration caused by using internal struts. By establishing the temperature field simulation model, the distribution of flow field and temperature field under the design working conditions is obtained, and the distribution of flow field and temperature field in the horizontal flue is analyzed. It is considered that in the process of flue gas entering the horizontal flue from the down flue, due to the influence of inertia, the main stream of flue gas is concentrated in the lower part of the horizontal flue, that is, the ash hopper position, rather than the convection heat exchange area, which is extremely unfavorable for the realization of heat exchange function of waste heat boiler. Therefore, the optimization idea of setting deflector at the connection between the down flue and the horizontal flue is put forward.

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