Numerical Simulation of Internal Flow in Direct Burning Coal-fired Hot Flue Gas Furnace

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Abstract. In this paper, a direct burning coal-fired hot flue gas furnace is taken as the research object. By using the SIMPLEC algorithm and the pressure based implicit solver in the analysis software FLUENT, the temperature, velocity and pressure distribution cloud chart and the CH4, CO, O2 and CO2 content distribution clouds are obtained by the numerical simulation of the gas solid two phases in the direct burning hot flue gas furnace. Through analysis, the high temperature zone in the hot flue gas furnace is the combustion area in the combustion chamber. There is a large amount of volatile matter in this area. The volatiles burn up a lot of oxygen rapidly and release carbon dioxide and heat. At the primary settlement, the radiation temperature of the reflected arch is higher, and more burnt particles are settled. The hot smoke flow in the whole hot flue gas is under negative pressure, and the flow is smoother. The flow in the furnace is relatively gentle, and the flow velocity and turbulence energy are large at the two turns. After the secondary sedimentation, the temperature gradually decreases and the output hot flue gas is substantially clean.

1. Introduction
Hot flue gas furnace is an efficient and energy-saving heating device. It mixes the hot flue gas produced by combustion with air, and then outputs hot flue gas with different temperatures and different cleanliness levels in conjunction with dryer. It dries materials directly in contact with materials, and is widely used in building materials, chemical industry and other fields. In recent years, numerical simulation theory and methods have become a powerful tool for developing combustion technology and guiding the design and performance optimization of combustion devices [1,2]. Xu Minghou et al. [3,4] carried out a large number of numerical simulation and experimental tests on the combustion process of front wall combustion boilers under different working conditions, and the results were not very different. Fan Jianren et al. [5-7] used flow, combustion and heat transfer comprehensive model to simulate the combustion process in boilers with different capacity and combustion modes in detail. The research results provide a theoretical basis for the structural design and improvement of this type of combustion vessel. Through numerical simulation of gas-solid two-phase flow in direct-fired coal-fired hot flue gas furnace, the problems encountered in the process of direct-fired coal-fired hot flue gas operation and the improvement of fuel utilization efficiency are provided. At the same time, it also provides a reference theoretical basis for the structural design and improvement of this type of hot flue gas furnace.
2. Structure of Direct-fired Coal-fired Hot Flue Gas Furnace
According to the structure parameters and two-dimensional CAD engineering drawings of the direct-fired coal-fired hot flue gas furnace, the three-dimensional solid model is appropriately simplified and drawn by SolidWorks software, as shown in Figure 1. The analysis model consists of a primary settlement reflection arch, an inlet, a combustion chamber, a secondary settlement windshield, a settlement chamber and an outlet.

![Figure 1. Three-dimensional Model of Direct Burning Hot Flue Gas Furnace](image)

Considering the complexity of the model, in order to get high quality meshes and more accurate analysis results, the model is divided into two parts: segmentation and recombination. According to the structure of hot flue gas stove, the whole model is divided into five regular blocks, while the regular model is easy to be divided into structured grids. The structured grids not only have better quality than unstructured grids, but also have easier convergence of simulation results and reduce calculation errors and distortion of results.

3. Setting of Flow Field Analysis and Solution

3.1. Flow field analysis
The flow process of fuel combustion and gas generation in hot flue gas furnace conforms to the laws of mass conservation, momentum conservation, energy conservation and component conservation.

1. The mass conservation equation can be expressed as follows: the increase of mass per unit time in a fluid microelement is equal to the net mass flowing into the microelement at the same time interval. The general form of mass conservation equation is:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = S_m
\]  

Formula: \( \rho \) is density, unit kg/m³, \( t \) is time; \( \mathbf{V} \) is velocity vector, the source term \( S_m \) is the mass added to the continuous phase.

2. The law of conservation of momentum can be expressed as follows: the rate of change of fluid momentum to time in a microelement is equal to the sum of forces acting on the microelement by external forces. According to the expression of this law, the momentum conservation equation can be obtained:

\[
\frac{\partial (\rho \mathbf{V})}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = -\nabla p + \nabla \cdot (\tau) + \rho g + F
\]  

Formula: \( p \) represents the pressure on the fluid microelement, \( g \) and \( F \) represents the gravitational and other external volumetric forces acting on the microelement respectively, \( F \) also contains other model-related source terms, \( \tau \) are the viscous stress tensors acting on the surface of the microelement due to the molecular viscous effect.

3. The essence of the law of conservation of energy is the first law of thermodynamics. The law can be expressed as follows: the increase rate of energy in the microelement is equal to the net heat flux into the microelement plus the work done by the volume force and surface force on the microelement. The energy conservation equation is:
\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho E) = \nabla \cdot \left( k_{\text{eff}} \nabla T - \sum_j h_j J_j + \left( \tau_{\text{eff}} \cdot \nabla \right) \right) + S_i
\]  

Formula: \( E = h - p / \rho + v^2 / 2 \) represents the total energy of the bulk microaggregates, \( k_{\text{eff}} = k_i + k \) represents the effective thermal conductivity, \( J_j \) is the diffusion flux of component \( j \), \( S_i \) is the heat source term.

(4) For a definite system, the law of conservation of component mass can be expressed as: the change rate of the mass of a chemical component in the system to time is equal to the sum of the net diffusion flux through the system interface and the net productivity of the component formed or disappeared by chemical reaction. According to the expression of this law, the mass conservation equation of components can be obtained:

\[
\frac{\partial (\rho Y)}{\partial t} + \nabla \cdot (\rho Yu) = - \nabla \cdot J_i + R_i + S_i
\]

Formula: \( Y_i \) is the mass fraction of component \( i \), \( J_i \) is the diffusion flux of component \( i \), \( R_i \) is the net formation rate of the component consumed or produced by chemical reaction per unit volume of the system in unit time, \( S_i \) is the mass source term.

(5) The residual curve of the standard \( k-\varepsilon \) turbulence model is easier to converge, and the simulation results are more in line with the actual situation, so the standard \( k-\varepsilon \) model is chosen in this paper. Transport equation of standard \( k-\varepsilon \) model:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_{\varepsilon}} \right) \frac{\partial k}{\partial x_j} \right] + G_i + G_h - \rho e - Y_M + S_k
\]

\[
\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho e u_i)}{\partial x_i} = - \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_{\varepsilon}} \right) \frac{\partial e}{\partial x_j} \right] + C_{i_{\varepsilon}} \frac{\varepsilon}{k} (G_i + G_h) - G_{\sigma \varepsilon} \rho \frac{\varepsilon^2}{k} + S_e
\]

Formula: \( G_i \) is affected by turbulent kinetic energy caused by mean velocity gradient, \( G_h \) is affected by turbulent kinetic energy caused by buoyancy, \( Y_M \) is the effect of compressible turbulent fluctuation expansion on total dissipation rate, \( C_{i_{\varepsilon}}, C_{2_{\varepsilon}}, C_{3_{\varepsilon}} \) is an empirical constant. In Fluent, \( C_{i_{\varepsilon}} = 1.44, C_{2_{\varepsilon}} = 1.92, C_{3_{\varepsilon}} = 0.09, \sigma_{\varepsilon}, \sigma_t \) represent the Prandt number corresponding to turbulent kinetic energy and turbulent energy dissipation rate respectively. In this paper, \( \sigma_{\varepsilon} \) is taken as 1.0.

3.2. Setting of Solutions

Four solutions are provided in FLUENT, PISO algorithm is for unsteady compressible fluid, COUPLE algorithm is for pressure and speed coupling. Although it can accelerate the convergence speed, it consumes too much CPU for computer. SIMPLE algorithm is a semi-implicit method for solving pressure coupled equations of incompressible flow field. SIMPLEC algorithm improves and changes the flux correction algorithm, which can make the convergence of the solution process faster. The fluid studied in this paper can be regarded as incompressible fluid, and the flow rate is not high, so SIMPLEC algorithm is chosen. Pressure-based implicit solver is chosen as the solution method. Coal and its volatiles react in a hot flue gas furnace and produce high temperature flue gas. After mixing with air and settling, they are dried. This process conforms to the energy conservation, so the energy model is used in the simulation analysis process.

4. Simulation results and analysis
By analyzing the temperature distribution nephogram, it can be concluded that the whole combustion chamber is in a high temperature state, and the high temperature hot smoke flows to the outlet in the form of wave. Because there are a large number of coal volatiles and sufficient oxygen at the entrance, the volatilization separation starts quickly and then the coal is gradually heated, and then the coal begins to burn violently, so the combustion chemical reaction at the entrance is relatively strong, the highest temperature is about 1350K. The temperature of the combustor is about 845K, which is due to the fact that the combustor has no seam coal barrier and some cold air enters the combustor directly. In the coal seam at the entrance, some uneven fine high-temperature particles are blown up by the air. They will continue to burn and release heat with the volatile matter from the combustion chamber, which is transferred to the hot flue gas together with the heat radiated by the coal particles. A large number of high-temperature hot flue gas flows in the furnace. Because of the blockage of the secondary settling windshield, the hot air flow tends to be gentle, and the average temperature in the settling chamber is about 1000K. Finally, the high temperature hot flue gas after sedimentation flows out from the outlet, and the temperature is about 995K.

The volatiles are mainly composed of hydrocarbons and hydroxides. CH₄ and CO with high volatile content were taken as the research objects in this paper. It can be seen from Figure. 3 and Figure. 4 that CH₄ and CO in volatile gases react with oxygen in combustion chamber. With the continuous combustion of chemical reactions, CH₄ and CO fuels are constantly consumed, and the content of CH₄ and CO fuels is higher at the entrance, until the end of the reaction, the content of CH₄ and CO fuels gradually tends to zero. The flow trend of combustion chemical reaction is along the outlet direction of hot flue gas furnace, and the mass fractions of CH₄ and CO are zero in settling chamber and outlet. In addition, the cloud of CH₄ and CO content distribution corresponds to the cloud of temperature distribution in Figure. 2. As the chemical reaction proceeds, the temperature increases and the fuel gas content decreases.
As can be seen from Figure 5 and Figure 6, the oxygen content is the highest at the entrance of the hot flue gas furnace and the CO₂ content is the lowest, because combustion chemical reaction is a process of gradually consuming oxygen to produce CO₂. Therefore, with the continuous reaction, the content of O₂ gradually decreases to the lowest value, the content of CO₂ gradually reaches the highest value and moves towards the outlet direction with the gas, and finally CO₂ diffuses throughout the hot flue gas furnace. The distribution patterns of CO₂ and CO₂ content in Figure 5 and Figure 6 also correspond to the distribution in high temperature zone.

Analyzing the velocity distribution nephogram, it can be concluded that the velocity at the entrance is small because the coal fuel layer has some hindrance to the gas. After passing through the fuel layer, a large amount of heat released by fuel combustion makes the temperature of combustion chamber rise sharply, while the space decreases due to the primary settlement reflection arch. In this case, the velocity of hot smoke at high temperature increases gradually. In the furnace, it flows smoothly to the outlet direction. When the high temperature hot smoke gas hits the secondary settling windshield, the velocity decreases, and increases again when passing through the settling chamber with reduced space, and then flows quickly to the outlet. At the exit position, the air velocity is higher, which is caused by the negative pressure at the exit and the smaller cross-section.

By analyzing the static pressure distribution nephogram of hot flue gas, it can be concluded that the static pressure of the gas in the combustion area of the combuster is larger and more uniform, which fully shows that this area is the combustion chemical reaction area, producing a large number of high temperature gases and filling the whole combuster, corresponding to the temperature distribution nephogram and the CO₂ content distribution nephogram. The non-uniform distribution of static pressure in the furnace is mainly due to the tendency of the hot smoke flow being blocked by the secondary settling windshield wall to move back, which can not flow smoothly to the outlet, resulting in the lower static pressure in the settling chamber.

The static pressure of the whole hot flue gas furnace is between -1000Pa and -100Pa, and the whole space is always in a negative pressure state, which helps the hot flue gas generated by combustion to be discharged from the outlet quickly. At the same time, it also prevents the high
temperature gas generated by the internal combustion of the hot flue gas furnace from diffusing to the exit of the fire gate, ash clearing door and air regulating valve, which not only ensures the combustion reaction can proceed smoothly in the combustion chamber, but also provides great convenience for the introduction of air from the inlet and the supplement of cold air from the air regulating port.

Dynamic pressure refers to the pressure caused by airflow, which can reflect the level of fluid flow and working force. It is closely related to the flow rate and gas density. It is the pressure that reflects the phenomenon of gas flow, and it is always positive. Analyzing the dynamic pressure distribution nephogram, we can get that the dynamic pressure value is not very large because the gas velocity in the combustion chamber is relatively small. At the exit of the combustion chamber, the dynamic pressure increases gradually until the air flow meets the secondary settling windshield, and then decreases. The dynamic pressure at the exit and the settling chamber is larger. The overall distribution form of dynamic pressure value corresponds to the velocity distribution nephogram in Figure 7, which reflects the flow state of high temperature hot flue gas in the hot flue gas furnace from the side.

5. Conclusion
(1) The combustion reaction of coal mainly occurs in the combustion chamber, and the high temperature zone is concentrated in the combustion area of volatile matter, which causes coal combustion. The fuel layer at the entrance is also in the high temperature zone and transfers heat radiation to the surrounding area. The most affected area by radiation temperature is the first-stage settlement reflection arch, which has a higher radiation temperature. The analysis of temperature field is very helpful to understand the temperature of combustion chamber, the location of high temperature area and the choice of refractories. It can also effectively control the phenomenon of coking and slagging in hot flue gas furnace.

(2) In the whole hot flue gas furnace, the velocity of hot flue gas in combustion chamber is smaller, and it increases at two settling turns, and reaches the maximum at the exit. Through the analysis of velocity distribution nephogram, the size, distribution and flow direction of fluid velocity can be obtained, which can effectively control the cleanliness of hot flue gas when it flows out from the outlet.

(3) The whole hot flue gas furnace is in a negative pressure state. The static pressure of the combustion chamber is the largest, and gradually decreases along the outlet direction. The distribution of static pressure in the furnace is uneven, and the static pressure at the outlet is the smallest. The distribution of dynamic pressure of hot flue gas is basically the same as that of velocity distribution nephogram, whereas the dynamic pressure value is high where the velocity is high. The analysis of pressure nephogram can get the degree of thermal damage and corrosion caused by high temperature hot flue gas on the furnace wall, which is convenient for timely replacement and maintenance.

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