Three-Dimensional Dynamic Modeling of a Tangentially Fired Utility Boiler Furnace

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Abstract: The tangentially fired utility boiler furnace is divided into several sections. The dynamic mathematical models for each section are presented. In the combustion zone, three-dimensional model is used, while for the upper sections, lumped parameter model is used instead. With the combination of different models, we can get detailed distributions of gas velocity, temperature, chemical species, heat flux, etc. in the furnace, but with less CPU time. The radiation through the interfaces of each section is considered. The furnace inlet boundary condition, which is exclusive for dynamic simulation, is also discussed. The dynamic response to the burner tilting up is simulated and discussed.

Key words: dynamic model, numerical simulation, boiler, furnace

Because of its flexibility and efficiency, computational fluid dynamics (CFD) is now widely used for the study of the utility boiler furnace[1,2], but most of the applications are concerned about its static performances, i.e. the distributions of the variables at certain load, which are time independent. On the other hand, for the CPU time limit, the furnace dynamic model is usually in the form of lumped parameter or multi-sectional lumped parameter (one-dimensional)[3], it can only simulate the general dynamics of the furnace, such as the total heat transfer, lumped outlet gas temperature and so forth, it is mainly used for real-time power plant training simulator.

Based on some reasonable simplifications, this paper tries to use CFD, plus with combustion and heat transfer models to get more detailed furnace dynamic simulation results, including the distributions of gas velocity, temperature, chemical species, heat flux, etc., in response to some disturbances. It is especially meaningful for engineering analysis of the dynamic performances of the furnace. The simulation results also provide a good reference for the lumped parameter dynamic model.

1 Description of the Furnace and Its Grid Arrangement

What to be modeled here is the tangentially fired furnace of a 300 MW utility boiler. Its schematic view is shown in Fig.1. Separated platen, rear platen and platen reheater are arranged successively in the upper part of the furnace. There are 5 level primary air

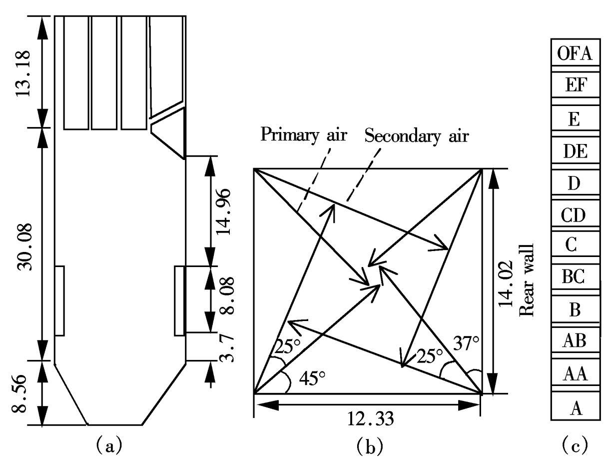

Fig.1 Schematic view of a 300 MW tangentially fired utility boiler furnace. (a) Furnace; (b) Burner horizontal arrangement; (c) Burner vertical arrangement (unit: m)

(fuel-air) burners (A,B,C,D,E) and 7 level secondary air burners (AA, AB, BC, CD, DE, EF, OFA) in all, arranged alternately at each corner (See Fig. 1(c)). The furnace is designed to run the upper 4 level (B,C,D,E) primary air (fuel-air) burners at economic continuous rating (ECR) load. To save CPU time, the furnace (See Fig.1(a)) is simplified as Fig.2 for modeling. In Fig.2, the whole furnace is divided into 6 sections. In section 1, three-dimensional mathematical model is used with a staggered non-uniform grid comprising 20 × 22 × 44 control volumes. While sections 2 to 6 use one-dimensional model, with lumped parameter model for each. The separated platen is located in sections 3 and 4, rear platen and platen reheater are in sections 5 and 6, respectively.

Received 2002-06-26.

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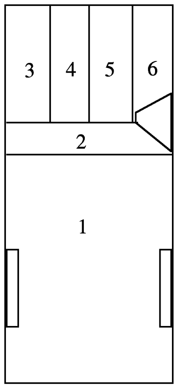

Fig.2 Furnace sections for modeling

The main considerations of the simplification mentioned above are as follows:

1) The bottom hopper of the furnace has little influence on the combustion, so the shape of this part is simplified to save CPU time.

2) The combustible matter has almost burnt out in section 1, the remainder, if any, burns away in section 2.

3) Because many platens are arranged in sections 3 to 6, the distributions of gas velocity and temperature are very complex. It will need much finer grid and of course much more CPU time, to get reasonable results.

2 Mathematical Model

2.1 Three-dimensional model (for section 1)

2.1.1 Gas conservation equations

The conservation equation of gas mass, momentum, energy, chemical species, etc. can be expressed as[4]

$$\frac{\partial}{\partial t}(\rho\varphi) + \mathrm{div}(\rho \boldsymbol{v}\varphi) = \mathrm{div}(\Gamma \mathrm{grad}\varphi) + s \quad (1)$$

where $t, \rho, \boldsymbol{v}, \Gamma, s$ are time, gas density, velocity, effective viscosity and source term, respectively; φ is the variable to be solved. The k-ε model is employed for the turbulent viscosity, so turbulent kinetic energy k and turbulent dissipation ε are also included in φ.

2.1.2 Particle momentum equation

The particle phase is modeled with Lagrangian method. Particle trajectories are tracked throughout the computational domain. The particle velocities are solved by

$$m_{\mathrm{p}}\frac{\mathrm{d}v_{\mathrm{p}i}}{\mathrm{d}t} = \frac{c_{\mathrm{d}}\rho_{\mathrm{g}}}{2}(v_{\mathrm{g}i} - v_{\mathrm{p}i})\left|v_{\mathrm{g}i} - v_{\mathrm{p}i}\right|A_{\mathrm{p}} - m_{\mathrm{p}}g_i \quad (2)$$

where m_{p}, $v_{\mathrm{p}i}$, A_{p} are particle mass, velocity and area, respectively; c_{d} is the drag coefficient; ρ_{g} is gas density; $v_{\mathrm{g}i}$ is gas instantaneous velocity; g_i is gravitational acceleration, subscript i represents coordinate direction x, y and z.

Unlike static model, the particle flow here is the function of both the trajectory and the time. So as to simulate the reality that the dynamic variation of the coal flow through the burner is unable to affect those having already been in the furnace.

2.1.3 Coal devolatilization and combustion

Coal devolatilization is modeled by[5]

$$\frac{\mathrm{d}V}{\mathrm{d}t} = (V_{\max} - V)K\exp\left(-\frac{E}{RT}\right) \quad (3)$$

where $V_{\max}$ is the maximum of the volatile evolved from coal; R is the universal gas constant; pre-exponential factor K and activation energy E are the functions of temperature.

Char combustion is governed by both oxygen diffusion rate k_{d} and chemical kinetic rate k_{c}, the overall reaction rate R_{c} is expressed as

$$R_{\mathrm{c}} = \frac{P_{\mathrm{ox}}}{1/k_{\mathrm{d}} + 1/k_{\mathrm{c}}} \quad (4)$$

where P_{ox} is the partial pressure of oxygen in the gas.

Gas phase turbulent combustion process is modeled with EBU-Arrhenius model, and radiation heat transfer is calculated with six heat-flux model[6].

2.2 One-dimensional (multi-sectional) model (for sections 2 to 6)

Lumped parameter model is used for sections 2 to 6. In addition to the mass and energy carried by gas flow, the radiation heat transfer through the section interface is also considered. The energy conservation equation is

$$\frac{\mathrm{d}(m_{\mathrm{g}}h_{\mathrm{g}})}{\mathrm{d}t} = \sum f_{\mathrm{i}}h_{\mathrm{i}} - \sum f_{\mathrm{o}}h_{\mathrm{o}} + Q_{\mathrm{f}} - Q_{\mathrm{c}} - Q_{\mathrm{r}} \quad (5)$$

where m_{g}, h_{g} are gas mass and enthalpy of the section; f_{i}, f_{o} are the mass flow through the section inlet and outlet; the summation $\sum$ means that a section may have more than one inlet and/or outlet. For example, section 2 has three outlets (to sections 3, 4 and 5), and section 4 has two inlets (from sections 2 and 3). Q_{f} is the heat release of combustible matter (only considered in section 2), Q_{c} is the gas to metal convective heat transfer; Q_{r} is the radiative heat transfer and is solved by

$$Q_{\mathrm{r}} = \sigma a_{\mathrm{g}}T_{\mathrm{g}}^4 A - \sum \Phi a_{\mathrm{g}} \quad (6)$$

where σ is Stefan-Boltzmann constant; a_{g}, T_{g} are gas emissivity and temperature; A is the surface area of the section; $\sum \Phi$ is the summation of wall radiosity and the radiation incident on the interfaces.

3 Boundary Condition and Numerical Solution

Most of the boundary conditions for the dynamic model are just the same as those for static model. The main difference is at the inlet boundary, where the burner will tilt up and down in the dynamic simulation. It is difficult to keep the burner outlet coincident with the boundary of the control volume next to the burner, so the gas velocity through the burner cannot compromise between the fluxes of the mass and momentum at the inlet boundary. To solve this problem, an additional source term is used in this paper, that is to set the inlet flux zero, and transform it to the additional source term s_{add} of the control volume next to the burner.

$$s_{\mathrm{add}} = \rho |\boldsymbol{v}| A\varphi / \Delta V \tag{7}$$

where ρ, $\boldsymbol{v}$ are the gas density and velocity at the burner outlet; A is the burner outlet flow area; φ is the variable to be solved in Eq.(1); ΔV is the size of the control volume.

Eq.(1) is integrated in the computational cell to obtain finite-difference equation:

$$a_{\mathrm{P}}\varphi_{\mathrm{P}} = a_{\mathrm{W}}\varphi_{\mathrm{W}} + a_{\mathrm{E}}\varphi_{\mathrm{E}} + a_{\mathrm{S}}\varphi_{\mathrm{S}} + a_{\mathrm{N}}\varphi_{\mathrm{N}} + a_{\mathrm{B}}\varphi_{\mathrm{B}} + a_{\mathrm{T}}\varphi_{\mathrm{T}} + b \tag{8}$$

where

$$b = s_{\mathrm{c}}\Delta V + \varphi_{\mathrm{P}}^{0}\rho^{0}\Delta V/\Delta t \tag{9}$$

$$a_{\mathrm{P}} = a_{\mathrm{W}} + a_{\mathrm{E}} + a_{\mathrm{S}} + a_{\mathrm{N}} + a_{\mathrm{B}} + a_{\mathrm{T}} + \rho^{0}\Delta V/\Delta t - s_{\mathrm{p}}\Delta V + s_{\rho}\Delta V \tag{10}$$

where s_{ρ} is the source term of gas mass conservation equation, superscript 0 means the last step value.

Power-law scheme is used for the convective term discretization. Eq.(7) is solved with simpler algorithm[4].

4 Predicted Results and Discussion

Fig.3 and Fig.4 are the dynamic responses to the disturbance of burner tilting upward (from 0° to + 15° in 5?s). Fig.3 is the variations of the outlet gas temperatures of furnace, separated platen, rear platen and platen reheater (i.e. sections 2, 4, 5 and 6) from the steady state. Fig. 4 is the net heat flux variations of the furnace front wall (in section 1) after the disturbance. The (a), (b)and (c) of Fig.4 represent the states at the time of 0, 10, 20?s after the burner begin to tilt upward. So (a) is just before the disturbance (steady state), (b) is in correspondence with the maximum of the temperature variation (Fig. 3), and (c) is at the time when the gas temperature is about to reach a new steady state.

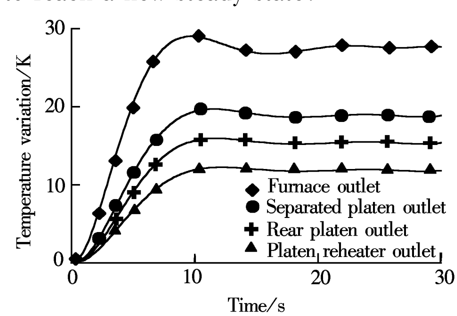

Fig.3 Dynamic responses of furnace and each platen outlet gas temperature to burner tilting up 15°

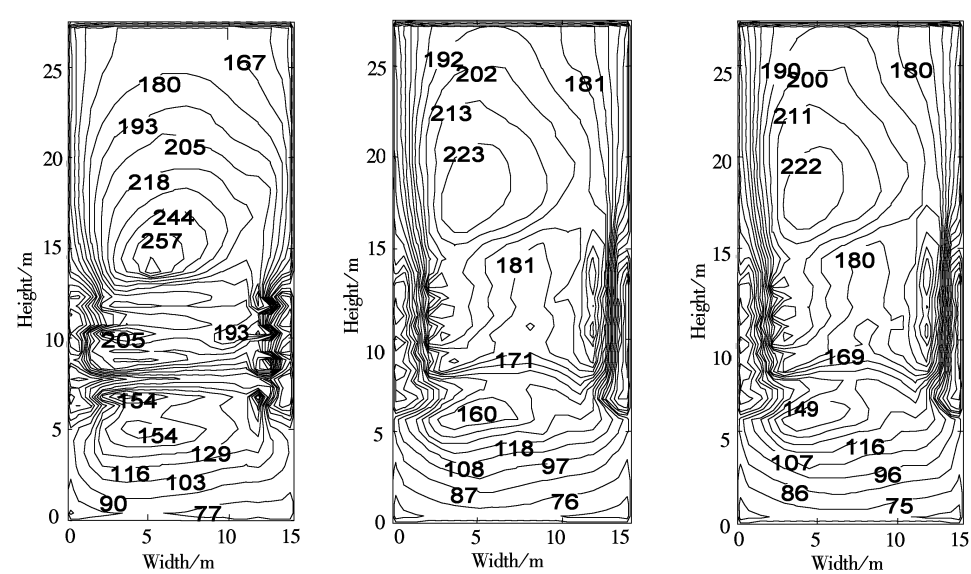

Fig.4 Variation of furnace front wall net heat flux (kW/m^2) in response to burner tilting up 15°

At steady state, the outlet gas temperatures of the furnace, separated platen, rear platen and platen reheater are 1607, 1419, 1316, 1201?K, respectively. Along with the burner tilting upward, the outlet gas temperatures of each section rise. Because the gas to metal heat transfer increases with gas temperature, the maximum of gas temperature variation decreases successively from sections 2 to 6.

Because of the rise of the fire center, the gas temperature of the lower part of the furnace decreases gradually (Fig.4), and this inversely affects the increase of the furnace outlet gas temperature, there is a hump of gas temperature in Fig.3. The furnace outlet gas temperature increases about 28 K after the disturbance, this is reasonable in comparison with Ref.[7].

5 Conclusion

Three-dimensional dynamic modeling of the utility boiler furnace is a useful way for the study of the furnace dynamics, and so for the improvement of the design and operation of the boiler. At present, it is a practical way to make some reasonable simplifications for the dynamic modeling to take less CPU time, but still get more detailed simulation results. To get better fidelity, some special factors should be considered in the dynamic simulation, especially in the furnace inlet boundary conditions for both gas phase and particle phase.

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切圆燃烧电站锅炉炉膛的三维动态模拟

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摘 要 切圆燃烧电站锅炉炉膛被分成了多个区段,对每个区段建立了各自的动态数学模型.在燃烧区段,采用了三维动态模型,而在炉膛的上部采用了集总参数动态模型.通过采用这种不同类型的模型组合方式,既可以得到动态模拟过程中烟气的速度、温度、组分、热流量等在炉内的分布情况,又可以节省计算时间.模型中考虑了各区段之间的辐射换热.对炉膛入口边界条件在动态计算时要注意的问题作了分析.对燃烧器摆角向上扰动的动态响应过程作了模拟计算,并对结果进行了讨论.

关键词 动态模型,数值模拟,锅炉,炉膛

中图分类号 TK224.1