文章编号:1001-2060(2001)06-0650-03

利用Monte Carlo方法对循环流化床锅炉炉膛传热的数值计算

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摘 要:作者对循环流化床锅炉炉膛传热进行数值研究,所建模型考虑轴向和径向颗粒浓度分布的影响。模型计算揭示烟气温度和热流密度在炉膛内的分布变化。计算结果表明在循环流化床锅炉炉膛传热计算中,颗粒相的对流换热不能忽略。

关 键 词:循环流化床锅炉;传热;Monte Carlo方法

中图分类号:TK224.1 文献标识码:B

符 号

a—常数

Ar—阿基米德数, $Ar = d\rho_g(\rho_s-\rho_g)g/\mu_g^2$

n—颗粒数密度

Pr—普朗特数, $Pr=\mu_g C_g/\lambda_g$

R—通用气体常数

Z—常数

ε_s—颗粒浓度

ρ_g—气体密度

ΔV—计算单元体积

α—传热系数

a_y—烟气吸收系数

C_g—气体比热

d—颗粒粒径

Nu—努谢尔特数, $Nu=\alpha d/\lambda_g$

Q—热流率

T—温度

ε_p—发射率

ρ_s—颗粒密度

μ_g—气体动力粘度

ΔS—计算壁面单元面积

λ_g—气体导热系数

下脚标

in—流进

p,s—颗粒

out—流出

g—气体

1 前言

循环流化床锅炉具有燃料适应性广,能够燃烧其它燃烧方式难以正常燃烧的各种燃料,如劣质无烟煤、褐煤、油页岩、矸石等。通过采用低温、分级燃烧方式以及添加石灰石脱硫剂,可降低烟气中SO_x和NO_x的浓度。循环流化床锅炉具有良好的负荷调节能力,能实现调峰的目的。另外,循环流化床技术在其它工业领域,如化工行业等都得到了广泛地应用。

在循环流化床锅炉中,燃烧效率和烟气中SO_x、NO_x排放受温度水平控制,而炉膛内温度水平取决于颗粒及烟气的传热性能。除了高温烟气辐射换热之外,高温高浓度颗粒也具有高的辐射成份。炉膛高温气固两相辐射换热直接影响到锅炉性能以及锅炉总体布置等。因此有必要进行循环流化床锅炉炉膛内传热性能的理论研究,并校核其炉内温度水平。

2 理论模型

为了模拟循环流化床炉膛内辐射及对流换热,作如下假设:(1)系统为稳定状态,各参数不随时间而变。(2)颗粒粒径均匀分布。炉内颗粒浓度按二维分布考虑,颗粒轴向平均浓度按下式计算:

$$\frac{\varepsilon_s(h)-\varepsilon_{s\,a}}{\varepsilon_{s,\infty}-\varepsilon_s(h)}=\exp(-ah) \tag{1}$$

式中,h为炉膛高度。由上式可见,沿炉膛高度平均颗粒浓度按指数规律衰减。径向颗粒浓度分布按下式确定:

$$\varepsilon_s(r)=1-[1-\varepsilon_s(h)]^{0.19+r^{2.5}+3r^{11}} \tag{2}$$

式中,r为无因次径向距离。当r为0时,由上式可得炉膛中心颗粒浓度:

$$\varepsilon_s(0)=1-[1-\varepsilon_s(h)]^{0.19} \tag{3}$$

当r为1.0时,可得炉膛壁面处颗粒浓度:

$$\varepsilon_s(1)=1-[1-\varepsilon_s(h)]^{4.19} \tag{4}$$

由此可见,炉膛壁面处颗粒浓度高于炉膛中心,形成炉膛中心稀、壁面附近处浓的颗粒浓度分布特性。

在壁面附近,高颗粒浓度分布特性使得颗粒对流传热具有明显的作用。气固两相与壁面的对流换热需要同时考虑气相和颗粒相的对流传热。烟气与受热壁面和颗粒与受热壁面的对流换热按下式计算:

$$Nu_{gw}=0.009\,Pr^{0.333}Ar^{0.5} \tag{5}$$

$$Nu_{pw}=(1-\varepsilon_s)z(1-e^{-N}) \tag{6}$$

收稿日期:2000-03-28; 修订日期:2001-04-04

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其中，

$$z = \frac{\rho_s C_p}{6\lambda_g}\left[\frac{gd^3(\varepsilon_s - \varepsilon_{s\,max})}{5(1-\varepsilon_{s\,max})(1-\varepsilon_s)}\right]^{0.5} \tag{7}$$

含有颗粒的烟气的辐射换热取决于系统的几何条件、颗粒浓度以及烟气和颗粒的辐射特性。热辐射体的衰弱系数、反射率按下式计算：

$$\beta = a_y(1-\varepsilon_s) + \frac{\varepsilon_p \pi d^2 n}{4} + (1-\varepsilon_p)\frac{\pi d^2 n}{4} \tag{8}$$

$$\omega = \frac{(1-\varepsilon_p)\pi d^2 n}{4\beta} \tag{9}$$

烟气和颗粒与受热壁面的能量方程可用下列方程表示。

气相单元：

$$Q_{r,out,g} + Q_{c,gw} + Q_{c,gp} + Q_{f,out,g} = Q_{f,in,g} + Q_{h,g} + Q_{f,in,g} \tag{10}$$

颗粒相单元：

$$Q_{r,out,p} + Q_{c,pw} + Q_{f,out,p} = Q_{r,in,p} + Q_{h,p} + Q_{c,gp} + Q_{f,in,p} \tag{11}$$

壁面单元：

$$Q_{r,out,w} + Q_a = Q_{r,in,w} + Q_{c,pw} + Q_{c,gw} \tag{12}$$

其中，

$$Q_{r,out,g} = 4\sigma a_y(1-\varepsilon_s)T_g^4\Delta V \tag{13a}$$

$$Q_{r,out,p} = 4\sigma a_p T_g^4 \Delta V \tag{13b}$$

$$Q_{r,out,w} = \sigma\varepsilon_w T_w^4 \Delta S \tag{13c}$$

每一部分吸收的辐射能由下式计算：

$$Q_{r,in,j} = \Sigma RD(I,J) Q_{r,out,j} \tag{14}$$

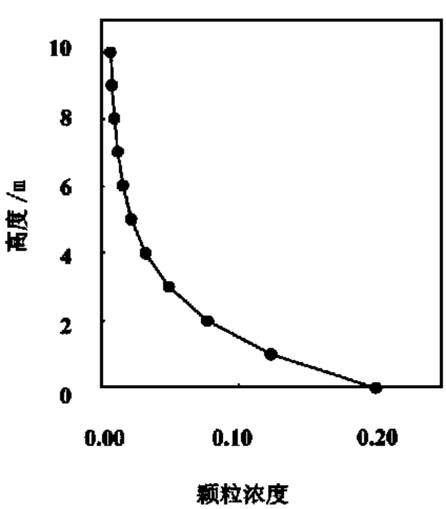

图 1　轴向颗粒浓度分布

其中 $RD(I,J)$ 的值定义为由 I 部分发生的辐射能与被 J 部分吸收的辐射能之比（每个部分均处于烟气和颗粒的辐射介质中或受热壁表面）。其值由 Monte Carlo 方法确定。

3　计算结果和分析

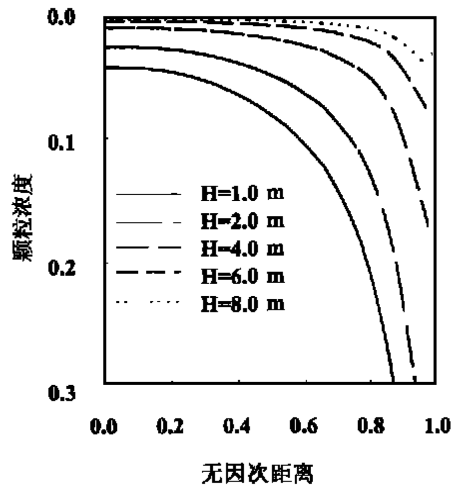

图 2　径向颗粒浓度分布

计算对象取自某 35 t/h 循环流化床锅炉。锅炉设计主要参数是：锅炉蒸发量 35 t/h，过热蒸汽压力和温度分别为 3.82 MPa 和 450 ℃，给水温度 105 ℃，燃用燃料为一类烟煤，燃料成份如下：C_{ar} = 38.46％，H_{ar} = 2.16％，O_{ar} = 4.65％，N_{ar} = 0.52％，S_{ar} = 0.61％，A_{ar} = 43.1％，W_{ar} = 10.5％，Q_{net} = 13 535.9 kJ/kg。炉膛高度为 10 m，宽度为 4 m。在高度 7 m 处，后墙受热面折向炉膛，形成折烟角。炉膛烟气平均速度为 4 m/s。表 1 给出计算中所需的主要计算参数。

表 1　烟气和颗粒特性

颗粒粒径	d = 250 μm
颗粒密度	ρ_s = 1 300 kg/m^3
颗粒比热	C_p = 1.0 kJ/(kg ℃)
气体吸收系数	k = 1.2 l/m
颗粒黑度	ε_p = 0.7
壁面温度	T_w = 520 K
壁面黑度	ε_w = 0.8
波尔兹曼系数	σ = 5.668 7 × 10^{-8} W/(m^{2}K^4)

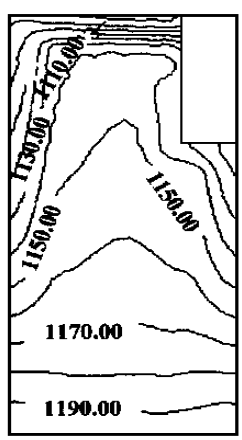

图 3　炉膛温度等势图

图 1 表示沿炉膛高度平均颗粒浓度分布。图 2 表示沿炉膛径向（局部）颗粒浓度分布。计算结果表明沿炉膛高度平均颗粒浓度逐渐下降，颗粒浓度在紧靠壁面处迅速增加，沿炉膛中心逐渐下降，在炉膛中心颗粒浓度最低。

图 3 表示炉膛温度等势图。图 4 表示在炉膛高度 0.25 m、0.75 m、1.25 m、1.75 m 和 2.25 m 处沿炉膛径向烟气温度分布图。由图可见，沿炉膛高度，烟气温度逐渐下降，在炉膛中心，烟气温度相对较高，沿炉膛壁面，烟气温度逐渐

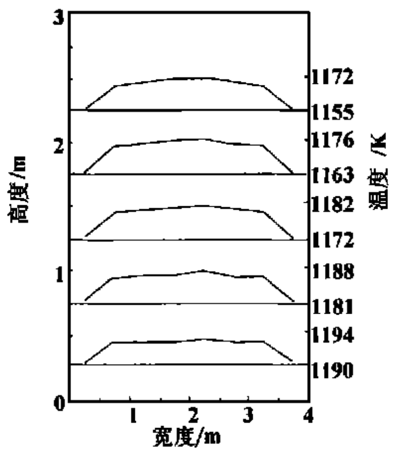

图 4　沿炉膛径向烟气温度分布

下降。由图 2 可见，在壁面处颗粒浓度较高，在炉膛中心区的辐射能被壁面附近高浓度悬浮颗粒屏蔽，同时壁面温度远远低于烟气温度，使得烟气温度在壁面处逐渐降低。

由方程(12)可见，壁面总热流密度由烟气与壁面的对流换热、颗粒与壁面间的对流换热和气固两相辐射换热组成。图 5 中分别给出烟气与壁面的对流换热热流密度 q_{cgw}、颗粒与壁面的对流换热热流密度 q_{cpw}、辐射换热热流密度 q_{rw} 和气固两相总换热热流密度 q_w 分布。由图可见，气体和颗粒对流分量和辐射换热分量沿炉膛高度逐渐下降，烟气对流分量沿炉膛高度的变化量相对较小。

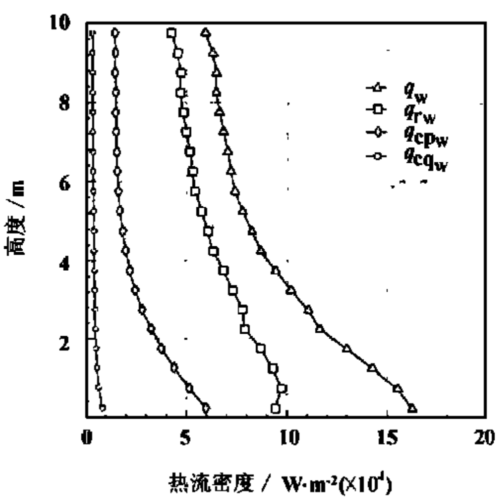

图 5　烟气和颗粒与壁面的对流热流密度和辐射热流密度的分布

在炉膛下部，颗粒对流分量相对较大，而在炉膛上部，颗粒对流分量的变化相对较小。这种变化主要是受颗粒浓度沿炉膛高度变化规律的影响。辐射换热分量沿炉膛高度逐渐下降，从而使壁面总热流密度沿炉膛高度逐渐下降。

由图 5 计算结果可见，在炉膛下部，颗粒对流分量与气固两相辐射换热几乎是同一数量级。在炉膛上部，由颗粒和气体换热分量占总热流密度的 20% ~30%。所以，在循环流化床炉膛计算中，颗粒相对流换热不能忽略。

4　结论

建立了循环流化床锅炉炉膛内传热模型，可确定炉膛内烟气温度分布和壁面热流密度分布。计算结果表明辐射换热和烟气、颗粒的对流换热受颗粒浓度分布的影响很大。颗粒和烟气的对流换热占总壁面热流密度的 20% ~ 30% 以上。所以循环流化床锅炉炉膛内对流分量不能忽略，并且如果想得到循环流化床炉膛内气固两相的辐射及对流传热特性，应对每一方向上的颗粒浓度分布进行校核。

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tute of Thermal Energy Engineering under the Southeastern University, Nanjing, China, Post Code: 210096)//Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—637～640

The use of an advanced combustion diagnostic system can be conducive to an effective enhancement of utility boiler operation economy and safety. Through the collection of furnace flame images and by utilizing computer-based digital image processing techniques as well as the analysis method of an artificial neural network model a combustion diagnostic system of flame images has been developed for boiler No. 5 of Yongan Thermal Power Plant in Fujian Province. This system has provided meaningful quantified characteristics parameters, performing a highly effective probing of the combustion condition identification mechanism. As a result, a new method and approach for combustion diagnosis and optimized control is provided for utility boilers. **Key words**: utility boiler, combustion diagnosis, digital image, artificial neural network

火电机组锅炉过热汽温的约束模型预测控制研究＝**A Study of the Constrained Model Predictive Control for the Boiler Superheated Steam of a Thermal Power Plant** [刊, 汉] / JU Gang, CHEN Shao-bing, XU Zhi-gao (Power Engineering Department, Southeastern University, Nanjing, China, Post Code: 210096)//Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—641～643

Presented is a model predictive control algorithm with an input of hard constraints. With no need for on-line iteration solution or on-line matrix inversion the recommended algorithm features a simplified calculation method with a low on-line computation load. It has been employed for the simulation study of boiler superheated steam control of thermal power plants and proved to be highly effective. **Key words**: predictive control, constraint, boiler, superheated steam temperature

75 t/h 树皮一煤粉复合燃烧系统的建模与仿真＝**Model Building and Simulation of a 75 t/h Bark and Pulverized Coal-fired Boiler** [刊, 汉] / BAO Gang, DENG Su-bi, WANG Zu-wen (Pneumatics Technology Center under the Harbin Institute of Technology, Harbin, China, Post Code: 150001)//Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—644～645, 649

A 75 t/h boiler with a composite firing system operates on bark and pulverized coal. A model of the firing system has been set up with the combustion system serving as an object model. Meanwhile, a simulation of its control system was also conducted. **Key words**: fluidized bed boiler, simultaneous burning of bark and pulverized coal, mathematical model, control system simulation

压水堆核电机组二回路的反平衡单元分析法＝**Inverse-balance Element Analysis for the Secondary Circuit of a Pressurized Water Reactor-based Nuclear Power Plant** [刊, 汉] / LI Yun-ze, YAN Jun-jie, LIN Wan-chao (Power System Engineering Research Institute under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049), DENG Shi-min (Thermal Engineering Research Institute of National Electric Power Co., Xi'an, China, Post Code: 710032)//Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—646～649

On the basis of analyzing the effect of additional components on the incoming water factor of a heating unit derived is a general expression for the incoming water factor of the high-pressure heating unit of a secondary circuit. Through a detailed theoretical analysis and mathematical deduction an inverse-balance mathematical model was set up for the secondary circuit of a pressurized water reactor-based nuclear power plant. The foregoing has laid a theoretical basis for the inverse-balance element analytical method of the above-mentioned secondary circuit. Such an analytical method features a simplified calculation and an accuracy of the calculated results. Being convenient for manual calculations and programming-based electronic calculations, it represents one of the effective tools for the secondary circuit system design and energy-saving diagnosis. **Key words**: pressurized water reactor-based nuclear power plant, secondary circuit, heating unit, incoming water factor, heat release factor, inverse-balance element analytical method

利用 Monte Carlo 方法对循环流化床锅炉炉膛传热的数值计算＝**Numerical Calculation of Heat Transfer in a**

Circulating Fluidized Bed Boiler Furnace by Utilizing a Monte Carlo Method [刊, 汉] / SUN Yong-li, HE Yu-rong, LU Hui-lin (Thermal Energy Engineering Department, Harbin Institute of Technology, Harbin, China, Post Code: 150001), TAN Xiu (Electric Power Scientific Research Institute of Jilin Province, Changchun, China, Post Code: 130021) // Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—650~652

A numerical study was conducted of the heat transfer in a circulating fluidized bed boiler furnace. The relevant model being set up takes into account the influence of the concentration distribution of axial and radial particles. The calculation of the model reveals the distribution variation of flue gas concentration and heat flux density within the furnace. The results of the calculation indicate that in the heat transfer calculation of a circulating fluidized bed boiler furnace the convection heat transfer of particle phase should not be neglected. **Key words**: circulating fluidized bed boiler, heat transfer, Monte Carlo method

燃煤工业锅炉湿式旋流烟气脱硫装置的数值模拟法优化设计=**Optimized Design of a Numerical Simulation Method for the Vortex Desulfurization Device of Wet Flue Gases of a Coal-fired Industrial Boiler** [刊, 汉] / QIU Zhong-zhu, XU Ji-huan, ZHANG He-sheng (Thermal Energy Engineering Department, Tongji University, Shanghai, China, Post Code: 200092) // Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—653~655, 676

Through the use of a k-ε dual equation model a numerical simulation was conducted of the vortex area speed and pressure field of a vortex wet gas desulfurization device. Meanwhile, with the help of a single-particle dynamic model the movement of liquid drops in the gas flow field was simulated, and by utilizing the numerical simulation method the structural parameters of the above-mentioned vortex device were determined. As a result, the optimized design of the vortex wet gas desulfurization was realized, contributing to a reduction of test expenses and a decrease in experimental work load. **Key words**: desulfurization device, vortex area, numerical simulation, structural parameter

船用蒸汽动力装置控制监测系统的研制=**The Development of a Control and Monitoring System for a Naval Steam Power Plant** [刊, 汉] / LI Lai-chun, LIU Fan-ming, et al (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—656~658, 674

Due to its complicated system, the presence of many equipment items and the large quantity of needed control parameters a steam power plant has a majority of its controlled objects not liable to be represented by simple mathematical models. During the operation of the plant many parameters are interrelated and involved in a complicated coupled relationship. Numerous controlled parameters cannot meet usage requirements if a single loop control is employed. Moreover, a naval steam propulsion plant features a high frequency of load changes and a wide range of such changes, resulting in a control system, the implementation of which demands sophisticated technical skills. In light of the above the authors present the composition and functions of a centralized control and monitoring system for a naval steam propulsion plant along with some innovative approaches of that system. **Key words**: naval vessel, steam power plant, automatic control

某汽轮机轴封汽外泄的原因分析及处理=**An Analysis of the Cause of a Steam Turbine Shaft Seal Leakage and Its Treatment** [刊, 汉] / Zhang Shao-bo (Cixi Thermal Power Plant, Cixi, Zhejiang Province, China, Post Code: 315300) // Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—659~660

After an analysis of the symptoms of shaft seal leakage and other abnormal conditions detected during the overhaul of a steam turbine the root cause of the leakage was identified and an economic, simplified and effective method proposed for its resolution. **Key words**: steam turbine, shaft seal, leakage rate, problem solving

轴向型粗粉分离器改进与完善=**Improvement and Advancement of an Axial Type Separator of Coarse Pulverized Coal** [刊, 汉] / LU Tai, CHOU Lin-qing, CHEN Fu, et al (Jilin Electric Power Institute, Jilin, China, Post Code: 131200), NIU Zhi-hong (Jilin Municipal Thermal Power General Co., Jilin, China, Post Code: 131200) // Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—661~663