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循环流化床锅炉翼形墙受热面壁温特性分析

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摘 要: 以循环流化床锅炉中翼形墙 3 种典型结构 $\phi51\times5$ mm、$\phi42\times5$ mm 和 $\phi38\times5$ mm 为例, 分析了工质质量流率和参数对壁温的影响。结果表明, 质量流率是保证受热面安全运行的主控因素, 壁面与工质的温差随质量流率的增加而减小; 管件结构与工质出口温度对壁面与工质温差的影响不明显, 但管件结构对鳍片温度的影响较为明显; 压力仅在一定程度上对壁温有影响。为兼顾考虑低负荷下锅炉的安全与经济运行, 推荐翼形墙受热面内工质设计质量流率选取不宜低于 750 kg/(m^2·s)。本研究为翼形墙受热面的安全运行提供参考。

关 键 词: 循环流化床锅炉; 翼形墙受热面; 金属壁温; 质量流率

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引 言

循环流化床锅炉由于煤种适应性强等特点有广泛的市场[1]。各锅炉设计公司根据其自身优势分别推出了不同类型的循环流化床锅炉设计方案[2~7]。通过对循环流化床锅炉运行经验的总结, 认为对于 380 MW 及以下容量循环流化床锅炉, 可以不采用外置换热床, 仅在炉膛内布置翼形墙受热面就能够满足参数要求, 并能够有效简化系统[8], 在充分利用炉内空间、保证锅炉变负荷时的汽温特性和降低锅炉电耗等方面更具有综合优势[9]。

目前, 循环流化床锅炉炉膛内受热面的设计, 基本上沿用了煤粉炉的设计导则, 认为翼形墙是辐射受热面, 以质量流率控制壁温。平均质量流率通常选取 800~1 000 kg/(m^2·s)。实际上, 循环流化床锅炉中, 翼形墙受热面是以辐射换热为主, 对流换热占总换热量的 40%左右[10], 而且烟气温度相对于煤粉炉低而均匀。因此煤粉炉屏式受热面的设计不完全适用于循环流化床锅炉的翼形墙受热面。近年来, 部分锅炉的运行实践表明, 按照煤粉炉屏式受热面设计循环流化床锅炉的翼形墙受热面, 出现了超温问题[11]。本文针对循环流化床锅炉的传热特点和烟温分布, 研究了影响翼形墙受热面金属壁温的主要因素, 为其设计及安全运行提供参考。

1 研究对象

针对循环流化床锅炉炉膛内翼形墙受热面进行研究。翼形墙受热面为膜式壁纵向布置, 位于循环流化床炉膛上部, 沿炉膛宽向均匀间隔布置于炉膛前部, 对称分布。工质由入口集箱分别引入并联布置的翼形墙受热面, 在炉膛内一次上升, 进入炉膛顶部出口集箱, 再由蒸汽连接管道引出。翼形墙受热面由下部水平段与垂直段构成, 水平段敷设有耐磨耐火材料, 翼形墙受热面布置如图 1 所示。

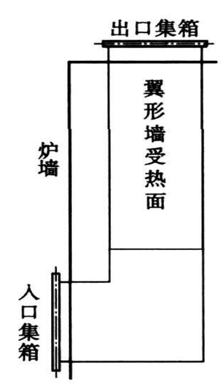

图 1 翼形墙受热面布置简图

针对工程上常见的几种参数, 对翼形墙受热面进行受热面壁温特性研究, 各参数如表 1 所示。在此基础上, 对 $\phi51\times5$ mm、$\phi42\times5$ mm 和 $\phi38\times5$ mm 3 种典型结构进行研究, 得到质量流率、管件结构、工质温度与压力参数对翼形墙受热面壁温特性的影响。

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表1　蒸汽参数

入口压力 /MPa	入口温度 /℃	出口温度 /℃	质量流量 /kg·s^{-1}
4.5	450	540	61.1
5.6	377	480	61.1
10.0	377	480	61.1
14.2	377	480	61.1
18.5	377	480	277.78

2　计算模型与计算条件

翼形墙受热面管内工质为蒸汽，各受热屏并联布置，工质在受热面内一次上升，根据翼形墙受热面内工质特性及其流程特点，该研究对象可以简化为并联管屏内单相工质的流动问题。由于循环流化床锅炉炉膛热负荷与物料浓度沿炉膛周向分布并不均匀[10,12]，因此布置在炉膛不同位置的受热屏会存在吸热量的差异。每屏内各根管子的结构并不相同，长度不等会导致较大的管间流量偏差[4,13]。

针对本研究对象，为简化计算条件，考虑到受热面间的吸热偏差（角部偏差为15%），取热负荷最高处的翼形墙受热面为计算对象。由于翼形墙受热面位于炉膛内，物料浓度和烟气的固体携带量较高，物料的热容量很大，炉膛上下温度较均匀。可以忽略炉膛温度沿周向与径向的差异，假设炉膛温度均匀，为893.0 ℃，且受热面宽度相对炉膛宽度而言较小，认为同屏各管间烟气侧换热系数相同，根据工程实际经验取148.0 W/(m^2·℃)。计算中保证同屏管间流量偏差在10%内。为比较同种蒸汽参数、不同结构时壁温特性的不同，计算中通过调整受热面积来保证不同的管结构下出口工质温度相同。

循环流化床锅炉燃烧室受热面的吸热量为：

$$Q=K\cdot H\cdot \Delta T \tag{1}$$

式中：Q—传热量，W；K—基于烟气侧传热平面的传热系数，W/(m^2·K)；H—烟气侧总面积，m^2；ΔT—温差，K。传热系数K受烟气侧换热系数、工质换热系数、金属材料物性和受热面结构等参数影响，其中烟气侧换热系数与工质换热系数对其影响最大。基于对循环流化床锅炉炉膛传热规律的分析与总结，可以将炉膛换热系数的计算简化为辐射换热与对流换热的线性叠加[10,12,14]。工质侧换热系数的计算可采用单相流体强迫对流换热计算方法：

$$\alpha_2=0.023\,\frac{\lambda}{d}Re^{0.8}Pr^{0.4} \tag{2}$$

式中：α_2—管壁与工质的换热系数，kW/(m^2·℃)；λ—水的导热系数，kW/(m^2·℃)；d—管子内径，m；Re—工质雷诺数；Pr—普朗特数。

工质在管内流动时要克服一定的阻力，总阻力Δp包括重位压降Δp_{zw}、摩擦压降Δp_{mc}、局部压降Δp_{jb}与加速压降Δp_{js}：

$$\Delta p=\Delta p_{zw}+\Delta p_{mc}+\Delta p_{jb}+\Delta p_{js} \tag{3}$$

压降计算与壁温计算参考电站锅炉水动力计算标准方法[15]。计算中涉及到的工质物性采用1985颁布的水蒸气热物性参数。在此基础上，对循环流化床锅炉的翼形墙受热面进行壁温特性分析，考虑质量流率、管件结构、出口工质参数以及压力条件对翼形墙受热面壁温特性的影响，为其设计选型提供一定的依据。

3　结果分析与讨论

3.1　质量流率的影响

图2为不同压力和温度下ϕ42×5 mm管壁与工质温差dt和平均质量流率G的关系曲线。从图2中可以看到，随着质量流率的增加，温差均单调降低，但变化率逐渐减小。质量流率越大，工质与金属换热越剧烈，则壁温越接近工质温度，在吸热量相同的条件下，质量流率越大，壁温越低，越不容易发生壁温超温现象。质量流率过低，可能发生传热恶化现象，使得壁温状况恶化。

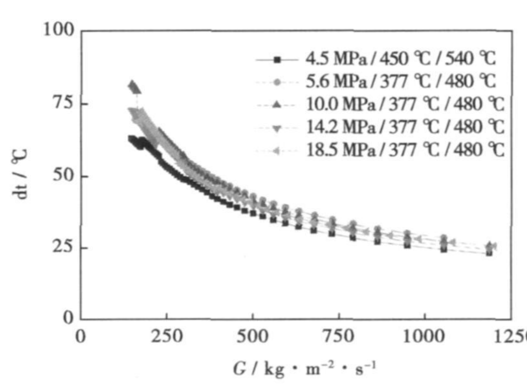

图2　质量流率对壁面与工质温差的影响
管子尺寸：ϕ42×5 mm，s=50 mm

从图2中可以看到，当质量流率高于750 kg/(m^2·s)时，各条件下温差dt均低于30 ℃；当质量流率低于250 kg/(m^2·s)时，各条件下的温差均高于50 ℃，且温差与质量流率关系已存在不稳定现象。因此必须严格控制质量流率。若考虑低负荷运行，一般的100%B—MCR质量流率不宜低于750 kg/(m^2·s)。

3.2　管件结构的影响

为考察管件结构对温差 dt 的影响，在不同压力条件下，分别采用 ϕ38× 5 mm 和 ϕ51× 5 mm 的管子，并与 ϕ42× 5 mm 的管子进行对比，得到不同管结构下壁面与工质温差 dt 随质量流率 G 的关系曲线，如图 3 所示。相同压力时，各管结构下温差 dt 随质量流率的变化曲线基本重合。质量流率降至 250 kg/(m^2·s)，各结构下的变化曲线出现差异，并且温差 dt 均增大。质量流率过低，壁温越容易飞升。当质量流率降至 300 kg/(m^2·s)，对于各压力及各种结构，温差均高于 50 ℃。当质量流率进一步降低，温差 dt 随质量流率的变化越剧烈。从另一个角度说明了质量流率是温差 dt 的主控因素。

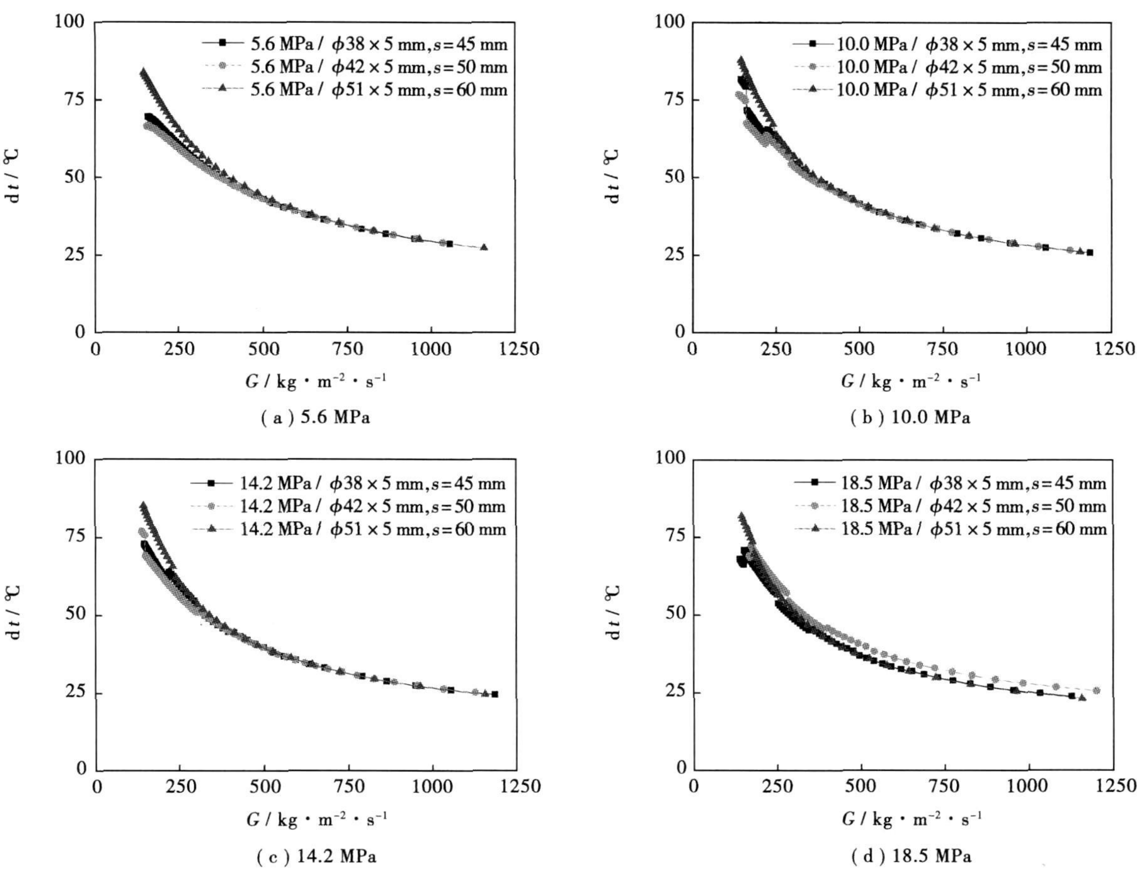

图 3 不同压力下管件结构对翼形墙壁温特性的影响(入口温度 T_{in} = 377 ℃，出口温度 T_{out} = 480 ℃)

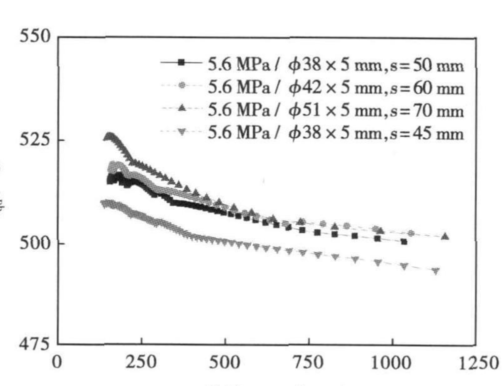

图 4 管件结构对水冷壁管鳍片中心温度的影响(入口温度 T_{in} = 377 ℃，出口温度 T_{out} = 480 ℃)

同时考察了 5.6 MPa 条件下管件结构对鳍片中间温度 t_{qd} 的影响，如图 4 所示。鳍片中间温度的大小同时受到管径和管节距 s 的影响。管子直径增大，其管节距 s 与鳍片高度也相应增大，相同质量流率条件下的鳍片中间温度升高。管径相同时，管节距越大，在出口工质温度相同时，相同质量流率对应的鳍片中间温度越高。随着质量流率的增大，鳍片中间温度均逐渐降低。

鳍片中间温度不仅与管径有关，也与管节距即鳍片宽度有关，两者必须同时考虑。

3.3 不同工质出口温度的影响

针对相同的管子尺寸 ϕ38× 5 mm，考察了各压力下不同工质出口温度对温差－流量特性的影响。

在各压力下,保持工质入口温度不变,将工质出口温度 T_{out} 从 480 ℃提高至 510 ℃,得到壁面与工质温差 dt 随质量流率 G 的变化曲线,如图 5 所示。可以看到,质量流率高于 250 kg/(m^2·s)时,不同工质出口温度下的温差与质量流率关系曲线基本重合,但工质出口温度较高的情况下,壁面的绝对温度也相应提高。当质量流率进一步降低时,工质出口温度的影响开始变得明显,此时出口工质温度越高,壁面与工质温差越大。因此合理设计翼形墙受热面的出口温度也是控制壁温的重要方面。对于不同的出口温度,为保证低负荷安全性,则应该根据不同结果选用不同的材料。

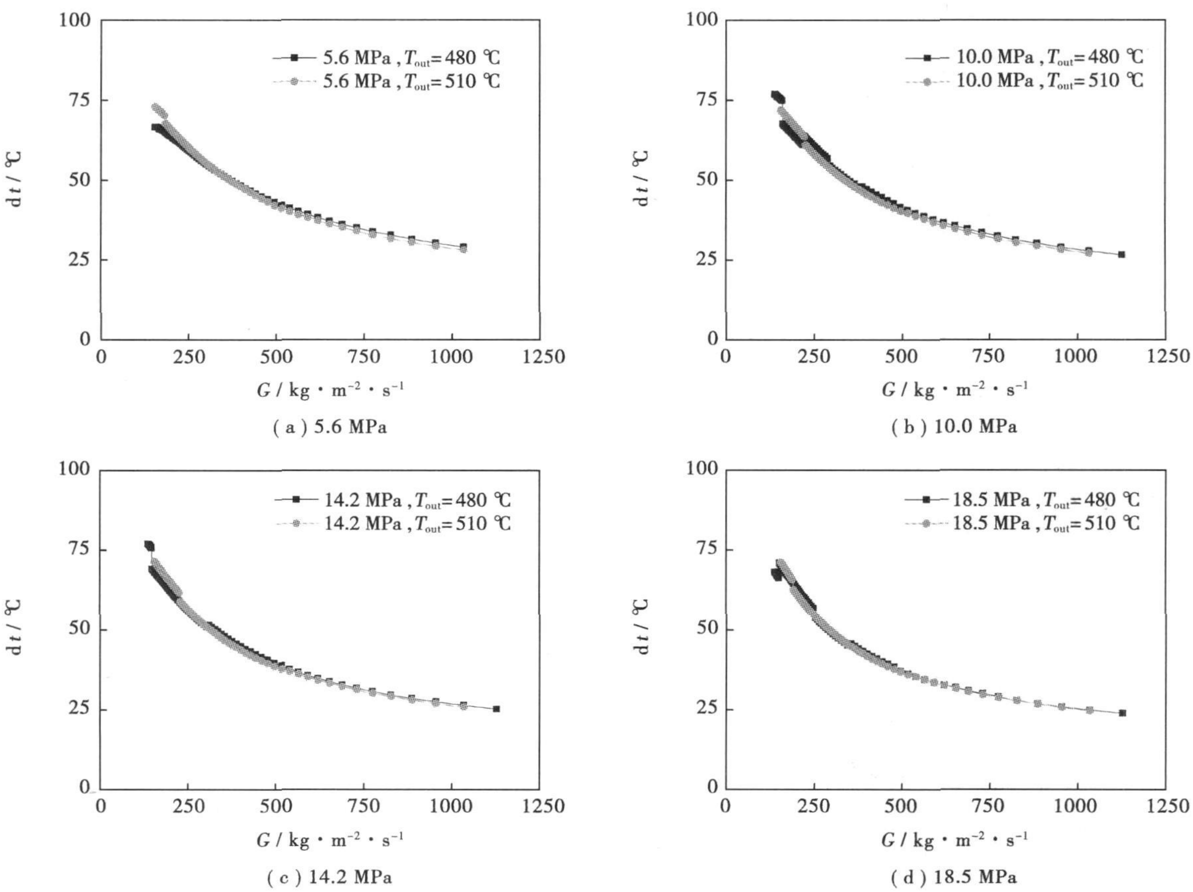

图 5 工质出口温度对翼形墙温度特性的影响(管子尺寸:ϕ38×5 mm,s=45 mm)

3.4　压力的影响

根据图 2～图 5 的结果考察压力对壁温特性的影响。不同压力条件下,壁面与工质温差 dt 均随质量流率 G 的增加而单调降低。随着质量流率的增加,各压力下的温差—质量流率曲线则趋于重合,即压力对温差特性影响减弱。从图 2 中可以看到,对于相同的温度条件,随着压力的升高,相同质量流率下的温差越小;且质量流率越大,不同压力下的差别越小。当质量流率为 250 kg/(m^2·s)时,各压力下温差的差异为 11 ℃内,而当质量流率为 1 000 kg/(m^2·s)时,差异仅为 2 ℃。因此,随着质量流率的增加,各条件下的温差与质量流率关系曲线越接近。

考察了管子尺寸为 ϕ38×5 mm 时压力对鳍片中间温度 t_{qd} 的影响,如图 6 所示。从图中可以看到,系统压力从 5.6 MPa 变化到 18.5 MPa,质量流率高于 250 kg/(m^2·s)时,t_{qd} 随 G 的变化曲线几乎重合,可以认为在此质量流率范围内系统压力对 t_{qd} 变化的影响并不明显。

4　结　论

对循环流化床锅炉炉膛内的翼形墙受热面在不同条件下的壁温特性进行研究,得到以下结论:

(1) 壁面与工质温差随质量流率的增加而降低。相同工质出口温度的条件下,质量流率是控制壁面与工质温差的主要因素,进而控制壁面温度在

安全范围内。

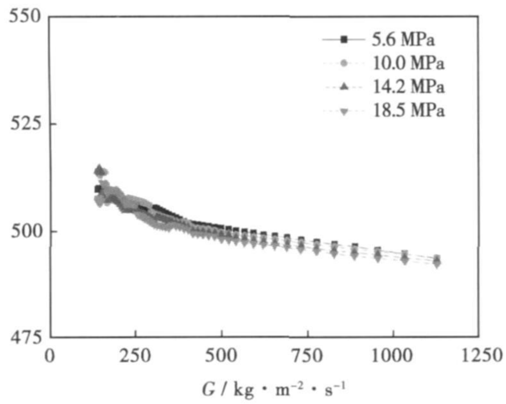

图 6 压力对翼形墙管鳍片中心温度的影响（管子尺寸：ϕ38×5 mm，s=45 mm）入口温度 T_{in}=377 ℃ 出口温度 T_{out}=480 ℃

（2）管件结构对翼形墙出口的壁温影响不大，相同压力时的壁面与工质温差随质量流率的变化曲线基本重合；但鳍片中间温度同时受到管径和鳍片宽度的影响。

（3）同种管件结构下，工质出口温度对温差—流量特性几乎没有影响，但影响壁面的绝对温度。

（4）压力在一定程度上影响翼形墙的温差特性，但压力不是影响翼形墙管鳍片中间温度的主要因素。

（5）为保证在满负荷与低负荷情况下翼形墙受热面的壁面温度都位于允许范围内，并同时考虑经济性，推荐流化床锅炉炉膛内的翼形墙受热面设计质量流率不宜低于 750 kg/(m^2·s)。

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（编辑 滨）

employing an experimental study method with the change characteristics of different flow patterns being observed and analyzed. In addition, two types of improved pulsating heat pipe, favorable for securing a stable circulating flow of the working medium, were designed. The test results indicate that various flow patterns may occur in the pulsating heat pipe under different working conditions, namely, plug flow-, hybrid flow- and annular flow pattern, etc. The flow patterns feature self-adjusting characteristics to any change of heat transferred. To modify the symmetry and equilibrium of the flow passage of the pulsating heat pipe as well as the micro-pump effect of bubbles in the capillary diverging passage will be beneficial to attaining a stable single-direction circulating flow of the working medium. **Key words**: pulsating heat pipe, flow pattern, flow direction, structural improvement

场协同原理在对流换热中的应用方法＝**Methods for Applying Field Synergy Principle in Convection Heat Exchange**[刊，汉] / LENG Xue-li, ZHANG Guan-min, TIAN Mao-cheng, CHENG Lin (College of Energy Source and Power Engineering, Shandong University, Jinan, China, Post Code: 250061)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(3). —352～354

Proceeding from the basic concept of field synergy principle and in combination with a basic understanding of convection heat exchange, the authors have established a quantitative method for maintaining the great value and matching principles in the field synergy guidelines during the convection heat exchange process. The synergy angle definition was improved at a microelement unit on the heat exchange surface, enabling the field synergy principle more adaptive to the convection heat exchange treatment and improving the arithmetic average method for field synergy angles so as to evaluate the synergy performance. An integration average method was put forward to evaluate velocity-weighted integral synergy performance. A concept of synergy matching coefficient was proposed to assess the synergy matching performance. Non-dimensional C-V and K charts were used for analyzing the distribution of synergy matching performance. **Key words**: field synergy, convection heat exchange, synergy matching coefficient

大容量超临界和超超临界压力锅炉炉膛传热公式＝**In-furnace Heat Transfer Formula for Large-capacity Supercritical and Ultra-supercritical Pressure Boilers**[刊，汉] / ZHAO Ling-ling, ZHOU Qiang-tai (College of Energy Source and Environment, Southeast University, Nanjing, China, Post Code: 210096)//Journal of Engineering for Thermal Energy & Power. — 2009, 24(3). —355～361

Analyzed were two parallel-plane radiative heat exchange formulae, which serve as the basic formulae for calculating the radiative heat transfer of in-furnace flames to the surrounding waterwalls in a steam boiler. Derived was the radiation intensity weakening of a one-dimensional (radial direction on a cross section) radiative energy caused by the following factors when the energy is transferred from the furnace center to surrounding wall surfaces. The factors are: absorption of flame media, self radiation and dispersion action. On this basis, a formula for radiative heat transfer in furnace was also deducted with due consideration of the weakening of radiative energy along the cross section direction from the furnace center to the surrounding wall surfaces. By using the derived formula and currently available calculation methods, the furnace outlet flue gas temperatures were calculated respectively when supercritical and ultra-supercritical large-sized pulverized coal utility boilers are burning three kinds of typical bituminous coal with different ash contents. The calculation method was compared with other relevant methods and the deficiencies of the methods in question were analyzed. **Key words**: supercritical and ultra-supercritical pressure boiler, radiative heat transfer, radiative intensity, radiation weakening, pulverized coal boiler, in-furnace flame

循环流化床锅炉翼形墙受热面壁温特性分析＝**Analysis of the Heating-surface Wall Temperature Characteristics of a CFB (Circulating Fluidized Bed) Boiler Wing Wall**[刊，汉] / LI Yan, LI Wen-kai, WU Yu-xin, YANG Hai-rui (Education Ministry Key Laboratory on Thermal Sciences and Power Engineering, Department of Thermal Energy Engineering, Qinghua University, Beijing, China, Post Code: 100084)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(3). —362～366

With the three wing wall typical structures of a circulating fluidized bed boiler serving as an example, namely, $\phi 51\times$

5mm, ϕ42×5mm and ϕ38×5mm, analyzed was the influence of mass flow rate and parameters of the working medium on the wall temperature. It has been found that the mass flow rate is a dominant factor for securing a safe operation of the heating surfaces. The temperature difference between the wall surface and working medium decreases with an increase of the mass flow rate. The influence of the tubing structure and the outlet temperature of the working medium on the temperature difference between the wall surface and working medium is not evident, the influence of the tubing structure on the fin temperature, however, is relatively obvious. The pressure only affects the wall temperature to a certain extent. To consider both the safe and economic operation of a boiler at low loads, it is recommended that the design mass flow rate inside the wing wall heating surface should be chosen at a value not lower than 750 $kg/m^2 \cdot s$. The research results can well provide reference for the safe operation of wing wall heating surfaces. **Key words**: circulating fluidized bed (CFB) boiler, wing wall heating surface, metal wall temperature, mass flow rate

旋/直复合流化下循环流化床脱硫塔内的气液分布特性研究＝**A Study of Gas-liquid Distribution Characteristics in a Circulating Fluidized Bed Desulfuration Tower Under a Swirling/straight Composite Fluidization Mode**

[刊, 汉] / CUI Lin, MA Chun-yuan, DONG Yong, SONG Zhan-long (Engineering Research Center of Environmental Thermodynamic Process under Education Ministry, College of Energy Source and Power Engineering, Shandong University, Jinan, China, Post Code: 250061)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(3). —367 ~372

By using a laser-phase Doppler analyzer (PDA) and a dual-loop extraction-type thermocouple, tested was the liquid droplet and gas-phase temperature distribution law in a flue gas circulating fluidized-bed desulfuration tower under a swirling/straight composite fluidization mode. The measurement results show that the liquid droplet distribution in the whole drying process basically assumes a tendency of being more accumulative in the central zone and less so in the side wall zones. When compared with the conventional straight flow fluidization mode with the relative height H/D being greater than 2, the existence of a swirling flow can enhance the liquid droplet drying speed at various points in the tower on the whole. Moreover, the greater the swirling flow rate, the quicker the drying speed. In the nozzle-atomized zone, the flue-gas temperature distribution tends to assume a low value in the middle and a high one at the side walls. When the relative height H/D is lower than 2, the existence of a swirling flow can intensify the above tendency. The presence or absence of swirling flows, however, influences little on the gas phase temperature and distribution when the liquid droplets have been completely dried. From a comprehensive viewpoint, the swirling/straight composite fluidization mode can effectively ameliorate the wall-sticking phenomenon. **Key words**: circulating fluidized bed (CFB), swirling/straight composite fluidization, gas phase temperature distribution, liquid droplet distribution

船用高速齿轮齿根弯曲疲劳强度的计算＝**A Calculation of the Tooth-root Bending Fatigue Strength of a Marine High-speed Gear**[刊, 汉] / LI Xiu-lian (School of Automobile and Traffic Engineering, Jiangsu Technical Normal College, Changzhou, China, Post Code: 213001)// Journal of Engineering for Thermal Energy & Power. — 2009, 24 (3). —373 ~377

When a ship ploughs the high seas, its hull will produce a hogging or sagging bending deformation due to the action of water buoyancy and ship weight etc., which influences the strength and service life of gears arranged in the hull longitudinal direction. In the light of defects and deficiencies of traditional marine high-speed gears caused by neglecting the inter-tooth friction, centrifugal force and hull deformation during strength calculations, with the driving gear in the involute speed-up gearing unit arranged along the hull longitudinal direction serving as an object of study, derived for the tooth-root bending fatigue was a strength calculation formula with comprehensive consideration of inter-tooth friction, centrifugal force and hull deformation. Calculation cases show that the inter-tooth friction can lead to an increase of the tooth root bending stress by 9.98% with the centrifugal stress accounting for 11.18% of the tooth-root bending permissible stress, while the hull deformation may cause an increase in the tooth-root bending stress by 7.25%. **Key words**: inter-tooth friction, centrifugal force, hull deformation, spur gear, bending fatigue strength

基于动能法测量乏气送粉煤粉浓度的研究＝**A Study of the Kinetic-Energy Method-based Measurement of the Concentration of Pulverized Coal Transported by Exhaust Gas**[刊, 汉] / LI Ji-ming, ZHU Hong, LU Zhen-zhong