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循环流化床锅炉密相区内颗粒的横向扩散研究

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摘　要: 以热粒子作为示踪粒子, 用热电偶测量示踪粒子沿径向的变化, 在长 900 mm、宽 100 mm、高 5 200 mm 的循环流化床密相区进行了颗粒的横向扩散的研究。循环流化床密相区内颗粒横向扩散可用一维扩散模型来描述, 模型的计算结果与实验数据吻合很好。根据实验数据拟和得到颗粒的横向扩散系数 D_{sr}, 实验表明随着流化风速的增大和静止床高的增加, 横向扩散系数 D_{sr} 增大; 随颗粒粒径的增大, 横向扩散系数 D_{sr} 减小。最后给出了以流化风速、静止床高和颗粒粒径为影响因素的横向扩散系数 D_{sr} 的经验式。

关　键　词: 循环流化床; 横向扩散系数; 热示踪粒子
中图分类号: TQ021.1　　文献标识码: A

1　引言

颗粒混合、流体流动和化学反应机理构成了设计工业流化床的基础。五六十年代早期, 通常认为气固流化床内物料混合均匀, 流化床内各点的温度均匀。随着大型流化床越来越广泛的应用, 人们注意到床内温度和反应物浓度不是均匀分布的, 尤其在水平方向存在明显的梯度。对于我国目前广泛使用的正压集中给煤流化床锅炉, 如加入的燃料过多而不能迅速扩散, 就会出现给煤口区域燃料堆积。在燃煤流化床内, 煤粒挥发份生成的速率与床内颗粒混合的速率相近[1]。在脱挥发份期间, 如果煤粒未能充分扩散开来, 则会出现给煤区局部缺氧严重, 使得炉膛内燃烧恶化, 增加了可燃气体的不完全燃烧损失, 引起料腿燃烧或尾部受热面的积灰复燃。

随着流化床容量的增加, 床面积增大, 每个给煤点给煤量的增加, 这种情况更加突出。其本质是如何使燃料及时扩散到相应的床面上去, 以保持可燃物浓度的均匀分布。这说明, 床内燃料的横向扩散能力成为确定给煤点间距的基础, 而横向扩散系数是表征燃料横向扩散能力的重要参数。

有关循环流化床颗粒混合的研究文献并不多, 已有的实验一般采取注入示踪粒子并在不同距离处测量示踪粒子的浓度变化的方法。Rhodes 以食盐为示踪粒子, 定时骤然停机进行采样, 用蒸馏水溶解示踪粒子, 从溶液的导电性与示踪粒子的浓度之间的关系确定后者浓度[2]。Ambler 应用放射性粒子为示踪粒子[3], Avidan 用磁性粒子为示踪粒子[4], Kojima 采用 FCC 荧光染色和光导纤维技术, 分别进行了颗粒扩散的研究[5]。已有的大部分实验均集中于流化床提升管内颗粒整体混合特性的研究。示踪粒子注入口位于提升管的底部, 而测量点则远离密相区。密相区的流场、混合机理目前尚不清楚。Westphalen 在实验中发现密相区的混合在强度上远远大于上部区域[6]。由于此区域的混合特性在很大程度上影响了进料口的数目和间距的设计, 本文将着重研究密相区颗粒横向扩散的规律, 并寻找合适的模型来描述横向扩散现象。

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此外, 参比水柱的管道应该裸露在环境温度中, 即从单室平衡容器以下至水侧取样孔高度的管道不得施加伴热或者保温(根据实测, 有保温的管道管壁温度达 130 ℃, 而没有保温时仅为 30 ℃)。如果环境有结冰的可能时, 则应加强锅筒小室的密封和防冻。至于水侧取样孔以下引到变送器的两根管道应包在同一保温层内, 这段管道如果有结冰的可能时, 应加伴热防冻。

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(何静芳　编辑)

2 热粒子示踪剂

研究颗粒混合的示踪技术一般分为五类:(1)化学性质区分法;(2)放射性粒子法;(3)磁性粒子法;(4)升华法;(5)热粒子法。总体来讲,这些方法各有优缺点。化学性质区分法比较直观,但需骤然停机以便采样,从而破坏了床内的正常工况;第(2)~第(5)四种方法应用传感器可进行实时在线测量,从而避免了因骤然停机对床内工况的破坏。但第(1)~第(4)四种方法均存在同一问题,即从床料中分离示踪粒子相当困难。因此不得不经常更换床料,以消除残存示踪粒子带来的干扰,否则,连续混合实验会导致测量结果的偏差。升华法可以在连续工况下进行测量,但升华粒子在粒径和密度上和床料存在差异,从而难以真实反映床料的扩散。与之相比,热粒子作为示踪粒子具有以下优点:

(1) 示踪粒子性质与床料相同;

(2) 流化过程中在线测量示踪粒子的浓度;

(3) 同时测量床内不同位置的示踪粒子浓度。

热粒子与床料在粒径、形状、密度方面完全相同,运行后不必进行分离,几分钟后便与床料完全相同。在此短暂的时间内可进行多组测量,以获得准确的有代表性的数据。

应用热粒子为示踪剂研究床内颗粒的混合扩散,必须解决一先决条件,那就是微元内温度的升高与示踪粒子浓度的关系。Valenzuela 认为,由于固体物料与流化空气的热容量之比相当高,达 10^3 数量级,因此在较短的时间内,流化空气带走的热量与示踪颗粒带入的热量相比可忽略不计。空气与粒子间的对流换热系数较高,空气的热容量又很低,因此可近似认为在床内的任一点处的空气与颗粒具有相同温度[7],微元内温度的升高正比于示踪粒子的浓度。杨海瑞通过分析微元内的质量能量守恒,从理论上证明了在一定的条件下,微元内的温升与示踪剂的浓度近似成正比[8]。

由图 1 可看出,微元体的平均温度升高与空气的温升基本一致,且与微元体内示踪粒子的浓度增加近似成正比。应该考虑风速的影响,风速越大,空气带走的热量就越多,平均温度的升高将偏离与示踪粒子浓度的线性关系。由图 1 可以看出,在风速大于 5 m/s 时,由于空气的冷却效果增大,平均温度的升高明显低于示踪粒子的浓度。而在风速小于 5 m/s 时,平均温度的升高与微元体内示踪粒子的浓度增加是近似成正比的。

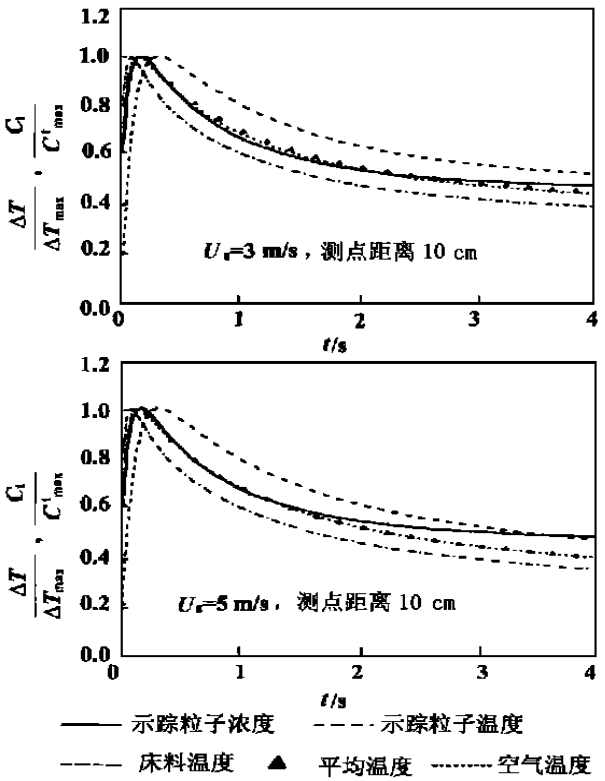
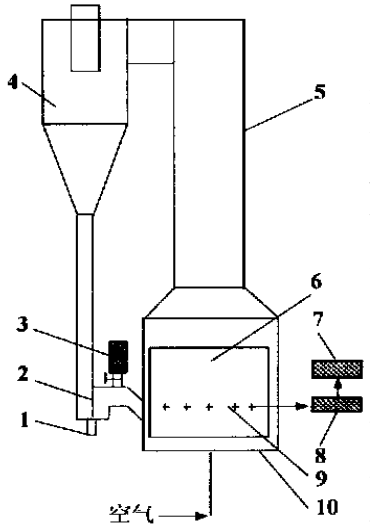


图 1 示踪粒子、床料、空气及平均温度的升高与示踪粒子浓度的比较



1— 松动风;2— J-F 阀;3— 加热炉;4— 分离器;5— 提升管;6— 观察窗;7— 计算机;8— 采集系统;9— 热电偶;10— 布风板

图 2 实验设备图

在本文的实验中,采用的风速范围是 2~4.5 m/s,满足平均温度升高与示踪粒子浓度存在线性关系的条件。研究循环流化床密相区内颗粒横向扩散,由于流化风速的提高,流化空气带走的热量相应增大。因此提高示踪粒子与床料的温差来降低温度的相对误差,同时缩短数据采集的时间。

3 实验设备简介

实验设备如图 2 所示,循环流化床上升管为长 900

mm、宽 100 mm、高 5.2 m 的矩形通道。风帽型布风板, 采用三角形排列, 开孔率为 7%, 为观察密相区的颗粒混合, 上升管底部一侧留有长 900 mm、高 500 mm 的观察窗。回料口距布风板 150 mm, 在此高度上水平等距排列 5 根 1 mm× 200 mm 的热电偶, 热电偶与 Ω 多点记录仪连接, 计算机进行在线采集。示踪粒子采用炉外加热, 加热炉位于回料阀上端。床料为实际循环流化床锅炉的循环灰, 床料的初始温度为 20 ℃, 示踪粒子的初温为 100 ℃。床料及示踪粒子的性质如表 1 所示。

表 1　实验工况参数

粒径 $d_p/\mu m$	流化风速 U_g/ m·s^{-1}	最小流化风速 U_{mf}/ m·s^{-1}	静止床高 H/ cm
300	2 ~ 4	0.276	17.5、22.5、25
600	2 ~ 4	0.413	17.5
1000	3 ~ 5	0.557	17.5

4　模型研究

由于循环流化床密相区内气固流动状态处于鼓泡床附近, 颗粒的混合借鉴鼓泡床内颗粒扩散的一维扩散模型:

$$\frac{\partial c}{\partial \tau} = D_{sr}\frac{\partial^2 c}{\partial l^2} \qquad (1)$$

初始条件: $\tau = 0$ 时 $l = 0$, $c = c_0$; $0 < l \leqslant L$, $c = 0$

边界条件: $l = 0$ 及 $l = L$, $\frac{\partial c}{\partial l} = 0$

L 为流化床截面长度; c_0 为初始浓度。通过显式差分格式可得式(1) 的数值解, 一旦横向扩散系数 D_{sr} 被确定, 不同时间不同位置的浓度分布即可确定。

在床内温度的升高正比于示踪粒子浓度的前提下, 对测点 1 ~ 3 的 20 秒内的温升值进行拟和。通过最小二乘法拟和求参数 D_{sr}。即求使 $\sum_{i=1}^{n}(\Delta T_i - kc/c_0)^2$ 最小的 D_{sr}。

由图 2 可看出, 选择适当的横向扩散系数 D_{sr}, 能使示踪粒子浓度的数值解和温升实测值较好地吻合。这说明循环流化床密相区内的颗粒横向扩散可以按扩散模型来描述。在注入热粒子之后 25 秒内, 测点 1 ~ 3 的实测值与数值解较好符合, 而测点 4 由于距离较远, 空气的冷却作用对热粒子的影响加大, 在 15 秒后实测值小于理论解。

5　实验结果及分析

从图 3 可看出不同测点处热电偶温度随时间的变化关系: 随距回料口距离 l 的增加, 各测点的 ΔT 达到峰值的时间 τ 增加, 且峰值依次减小。

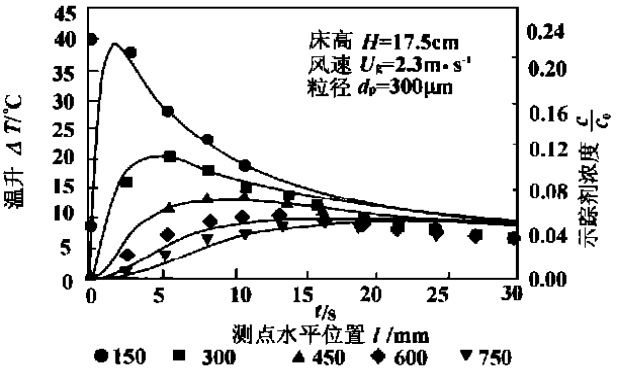


图 3　温度响应曲线与数值计算示踪粒子浓度的比较

5.1　横向扩散系数与流化风速的关系

横向扩散系数 D_{sr} 与流化风速 U_g 的变化关系见图 4。从图中可见, 在静止床高 H 分别为 17.5 cm、22.5 cm、25 cm 的工况下, 扩散系数 D_{sr} 随流化风速 U_g 的增加而增大, 且曲线斜率基本上相同。这是因为, 增加流化风速, 床内含气率变大, 气泡的体积也相应增大, 因此颗粒混合的剧烈程度增加。

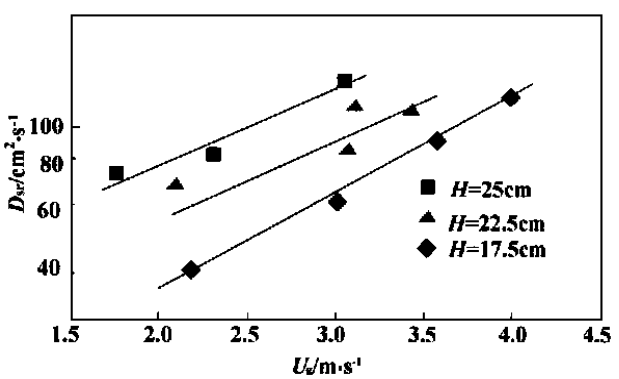


图 4　D_{sr} 与 U_g 的关系

5.2　横向扩散系数与静止床高的关系

D_{sr} 随静止床高 H 的变化关系见图 5。在流化风速 U_g 不变时, D_{sr} 随静止床高 H 的增加而增大。这是因为, 床层高度增加, 使得床层内的气泡体积、上升速度变大, 气泡上升导致更多的颗粒横向移动, 从而增大了横向扩散系数。

5.3　横向扩散系数与颗粒粒径的关系

作者探讨了颗粒粒径对床内颗粒横向扩散的影响。采用同等密度、粒径分别为 $d_p = 600\ \mu m$、1 000 μm 的床料, 在流化风速 2 ~ 4 m·s^{-1} 的条件下, 静止

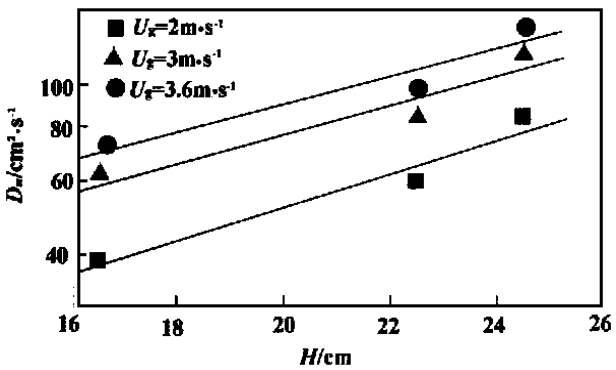


图 5 静止床高对扩散系数的影响

床高为 $H=17.5$ cm 时，进行了对比实验，颗粒粒径大小对横向扩散的影响见图 6。由图可见，在同一风速时，大粒径床料的横向扩散要弱于同一条件下小粒径的扩散。密度相同的颗粒随着粒径的增大，其最小流化风速将增加，因此较大的颗粒在床层中运动时受到的阻力就会增大，从而使颗粒的混合扩散受到抑制。

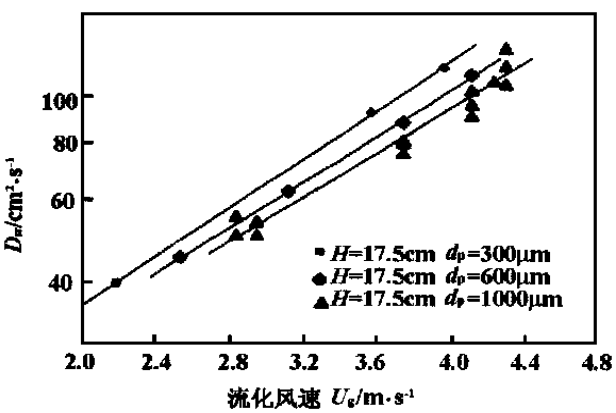


图 6 颗粒粒径对扩散系数的影响

5.4 颗粒横向扩散系数关联式

由上文可知，颗粒的横向扩散系数 D_{sr} 是流化风速 U_g、静止床高 H 和颗粒粒径 d_p 的函数。即 $D_{sr}=f(U_g, H, d_p)$，所以横向扩散系数的无量纲表达形式为：

$$\frac{D_{sr}}{(U_g-U_{mf})H}=2.1\times10^{-4}\left[\frac{(U_g-U_{mf})d_p}{\nu}\right]^{0.376}\cdot\left[\frac{H}{d_p}\right]^{0.429} \quad (2)$$

图 7 给出了横向扩散系数的实验值与式(2)的计算值的对比图。如图 7 所示，关联式的值与实验值符合得较好，最大相对误差小于 12%。

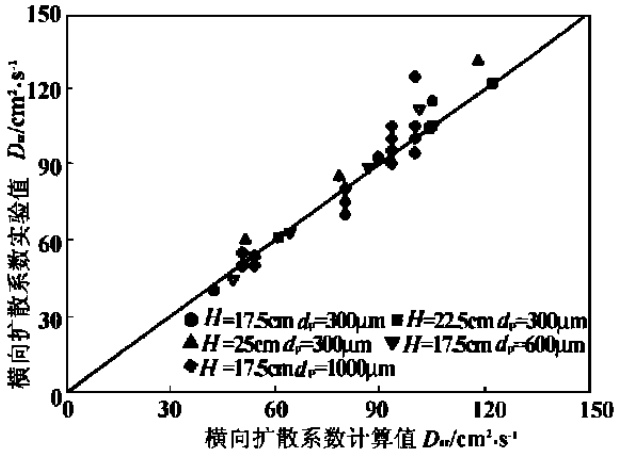


图 7 横向扩散系数的实验值与计算值的比较

6 结论

(1) 循环流化床密相区内颗粒的横向扩散可用一维扩散模型来加以描述。理论值与实验数据吻合较好。

(2) 研究了颗粒粒径、流化风速、静止床高对颗粒混合的影响，随着流化风速的增大和静止床高的增加，颗粒的横向扩散系数 D_{sr} 按一定的规律增大。通过大量的实验，推导出描述密相区内颗粒横向扩散的经验式。

$$\frac{D_{sr}}{(U_g-U_{mf})H}=2.1\times10^{-4}\left[\frac{(U_g-U_{mf})d_p}{\nu}\right]^{0.376}\cdot\left[\frac{H}{d_p}\right]^{0.429}$$

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自由表面摩擦和蒸发对过冷下降液膜传热的影响＝**The effect of Free Surface Friction and Evaporation on the Heat Transfer of Sub-cooled Falling Liquid Film** [刊, 汉] / SHI Jin-sheng, CHEN Yu-zhou (China National Atomic Energy Research Academy, Beijing, China, Post Code: 102413) // Journal of Engineering for Thermal Energy &Power. — 2001, 16(4). —383 ~385, 392

A theoretical analysis was conducted of the heat exchange characteristics of a falling liquid film under the condition of evaporative heat dissipation and of the presence on the free surface of a reverse shearing force. As a result, obtained was a non-dimensional relation of the film thickness and heat exchange factor. Also discussed was the influence of shearing force, liquid film Reynolds number, wall surface heat flux and evaporation rate on the flow and heat transfer. **Key words**: falling liquid film, reverse flow, heat transfer

均衡燃烧控制系统总体设计及关键技术问题研究＝**A Study of the Integrated Design of a Harmonious Combustion Control System and Its Related Technical Issues** [刊, 汉] / LI Yi-guo, SHEN Joing, LU Zhen-zhong (Power Engineering Department, Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy &Power. — 2001, 16(4). —386 ~388

In light of the problems currently existing in the boiler combustion process of a 200 MW power plant in China the authors have designed a harmonious combustion control system. On the basis of the functional requirements of the system and the specific control mode of an inverter proposed is an integrated design scheme of the combustion control system. The communication control of the inverter represents a key issue in implementing the above design scheme. Briefly discussed is a method of the inverter output control realized through the use of a master-slave type of multi-machine communication mode. **Key words**: harmonious combustion, inverter, communication

单元机组运行经济性在线数学模型研究＝**Research on an On-line Mathematical Model for the Evaluation of the Cost-effectiveness of a Monoblock Unit Operation** [刊, 汉] / ZHANG Xiao-tao, WANG Ai-jun (Power Engineering Department, North China Institute of Water Resources and Hydropower, Zhengzhou, Henan Province, China, Post Code: 450045), WANG Pei-hong (Power Engineering Department, Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy &Power. — 2001, 16(4). —389 ~392

On the basis of the real-time information system of a power plant developed is an on-line practical-for-use mathematical model for evaluating the operation cost-effectiveness of a monoblock unit. The model can not only conduct an on-line monitoring of the major economic indexes of the monoblock unit, but also diagnose and analyze its operating cost-effectiveness. Its use at a power plant has been proved to be quite fruitful. **Key words**: on-line monitoring, performance diagnosis, cost-effectiveness, mathematical model

锅筒式锅炉差压式水位计的温度补偿研究＝**Temperature Compensation Study of the Differential-pressure Water Gage Used for a Drum Boiler** [刊, 汉] / YANG Fei, CHEN Guang-hua (Power Engineering Department, Northern Jiaotong University, Beijing, China, Post Code: 100044) // Journal of Engineering for Thermal Energy &Power. — 2001, 16(4). —393 ~394

Due to its location in an atmospheric air environment the reference water column of a differential-pressure water gage is inevitably subjected to the influence of the change in environmental conditions. In the design of the present-day differential-pressure water gage either no temperature compensation or a temperature compensation of only 50 ℃ fixed value has been set for the reference water column. Through a numerical calculation analyzed was the influence of the ambient temperature the reference water column temperature of the differential-pressure water gage of a sub-critical drum boiler is being subjected to. Moreover, a simple calculation formula is given to facilitate the achievement of a higher level of precision for the differential-pressure water gage. **Key words**: drum boiler, water gage, temperature compensation

循环流化床锅炉密相区内颗粒的横向扩散研究＝**A Study of the Transverse Dispersion of Solid Particles in the Dense-phase Zone of a Circulating Fluidized Bed Boiler** [刊, 汉] / YANG Hai-rui, LU Jun-fu, LIU Qing, et al (Thermal Energy Engineering Department, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy &Power. — 2001, 16(4). —395 ~398

With hot particles serving as tracer ones the radial variation of the latter was measured by the use of thermocouples. A study of the particle transverse dispersion has been conducted in the dense-phase zone of a circulating fluidized bed,

which has the following dimensions: length 900 mm, width 100 mm and height 5200 mm. The particle transverse dispersion in the above-cited zone can be described with the help of a one-dimensional dispersion model. The model calculation results are in very good agreement with experimental data. Through the experimental data fitting one can obtain the particle transverse dispersion factor Dsr. The tests show that with the increase in fluidizing air speed and stationary bed height there will be an increase in the transverse dispersion factor. The transverse dispersion factor will decrease with the increase in particle diameter. Finally, an empiric formula was given for the transverse dispersion factor with the fluidizing air speed, stationary bed height and particle diameter serving as influencing factors. **Key words**: circulating fluidized bed, transverse dispersion factor, hot tracer particle

大容量锅炉锅筒两侧水位测量偏差问题的研究=**An Investigation of the Deviation in Water Level Indication at the Two Ends of the Boiler Drum of a Large-sized Boiler** [刊, 汉] / LIU Fu-guo (Thermal Energy Institute under the Shandong Provincial Electric Power Research Academy, Jinan, China, Post Code: 250002), MOU Chun-hua (Shandong Rizhao Power Plant, Rizhao, Shandong Province, China, Post Code: 276826), TAN Zhe-ling (Shangdong No. 3 Electric Power Construction Co., Rizhao, Shandong Province, China, Post Code: 276826) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(4). —399 ~ 402

A recurrent problem in recent years is the measurement discrepancy in water level indication at the two ends of the drum of a large-sized boiler. This can affect the safe operation of a power plant. After an analysis of the root cause of this deviation the authors present their successful experience in employing uniform-pressure tubes for coping with the issue and recommend some effective measures both in design and operation aimed at reducing the discrepancy of water level measurement. **Key words**: boiler, boiler drum water level, liquid level measurement, correction of calculation

适用于无烟煤燃烧的新型涡流拱特性的研究=**A Study of the Features of a Novel Vortex Arch Suited for the Combustion of Anthracite Coal** [刊, 汉] / ZHUANG Zheng-ning, ZHU Chang-xin, TANG Gui-hua (Energy Engineering Institute under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(4). —403 ~ 405, 430

Presented is a kind of new technology incorporating a vortex arch suited for the burning of anthracite coal in a traveling-grate boiler. Through modeling tests an experimental investigation was conducted of the features of the vortex arch along with an analysis of its working mechanism. As a result, identified are the key conditions to be met for achieving the optimum structural dimensions of a vortex arch. The results of study indicate that the vortex arch can effectively increase the suction and transport quantity of gas flow from a rear arch to a front one, contributing to an increase in the front arch temperature. During its practical use for the first time it has been found that the vortex arch is conducive to the timely ignition of a furnace firing flaxseed coal of category III accompanied by an intensified combustion. **Key words**: stoker boiler, anthracite coal, vortex arch, intensified combustion

中小煤粉炉运行优化新方法研究=**An Investigation of New Methods for Attaining an Optimized Operation of Small and Medium-sized Pulverized Coal-fired Boilers** [刊, 汉] / WANG Xin-xin, XU Xiang-dong (Thermal Energy Engineering Department, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(4). —406 ~ 408, 382

On the air feed control loop of a computer-based control system for present-day small and medium-sized pulverized coal-fired boilers there usually lack suitable economic indexes to evaluate the boiler operating efficiency. In this regard some new methods are proposed to optimize the control of the above-cited boilers. Based on the counterbalance calculating method of boiler thermal efficiency and the energy balance of boiler furnace the authors have come up with a set of discriminating criteria through a detailed deductive process. The above-mentioned criteria can be employed to evaluate the boiler thermal efficiency and reflect the variation trend of the latter in case of a change in air feed rate. All the above has been accomplished by taking into account the practical operating data of boilers and neglecting some secondary unimportant factors. With the above discriminating criteria serving as a basis a continuous optimization was conducted with respect to the target of the air feed control loop, i.e. the oxygen content in flue gas, thereby achieving the aim of an optimized combustion process through the proper adjustment of air-coal ratio. **Key words**: pulverized coal-fired boiler, optimized operation, discriminating criteria for evaluation of thermal efficiency