文章编号: 1001－2060(2000)03－0252－04

流化床风帽温度分布及其耐热性的试验研究

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摘　要: 在一热态流化床试验台上, 对热烟气床下点火启动条件下风帽的温度分布进行了试验研究, 并考察了风帽所用材质的耐热性。鉴于目前流化床锅炉逐步采用床下点火启动方式, 该项研究具有很大的实用价值和指导意义。

关　键　词: 温度分布; 风帽; 流化床

中图分类号: TK229.6^{+}6　　文献标识码: A

1　引言

在流化床锅炉能够正常运行之前, 必须进行点火操作。这需要利用辅助加热系统把惰性床料流化加热到足够高的温度, 以使燃料能够开始燃烧。除小型工业流化床锅炉采用固定床燃烧木柴点火启动外, 目前国内外普遍趋于采用热烟气加热床料的方式[1~2]。在热烟气启动过程中, 风帽受高温烟气的冲刷, 承受较大的热负荷, 其温度分布也随传热特性的变化而有较大变化。风帽材质必须保证其在运行过程中的稳定性, 不变形, 不被氧化, 以确保床层的均匀布风和流化。

本文作者首次在所建热态流化床试验台上对风帽温度分布进行了全面的研究, 并利用一马弗炉对所采用的风帽材质进行了锻烧试验, 取得了较为完备的试验数据。

2　试验设备及测量系统

建造了一座热功率可达 2 MW 的水冷布风板流化床热态试验台, 其风帽大小、间距及水冷底板上的水管管径按与常规锅炉相同尺寸设计。流化床层截面积 0.664×0.656 m^2, 有效高度 4 m。布风板采用水冷管排结构, 其上、下侧都敷有耐火混凝土。风帽采用正三角形布置, 三角形边长 99 mm, 每个风帽上开有 8 个直径 5 mm 的小孔, 布风板开孔率为 1.85%, 由膜片连成一片的 9 根管子两端联通到进出口联箱上。

试验台采用螺旋给煤机微正压给煤, 床料采用 0~6 mm 的宽筛分流化床底渣。试验时, 卧式旋流启动燃烧室燃用轻柴油, 产生的热烟气经掺混后降温到 900 ℃以下进入风室, 再经水冷布风板进入床层, 流化并加热床料。

在一个风帽上布置了如图 1 所示的具有代表性的 5 个测温点, 以测量风帽温度分布。在 B 处, 风帽与膜片相连接, 冷却条件最好; C 处最先受气体冲刷; A 处靠近风帽小眼, 因风帽内、外传热状况的差别, 其内外壁温差也值得考虑, 因加工制作的困难, 内、外壁测点分别布置在同一直径两端; 风帽顶部深入在床层中, 受热状况较为恶劣。这些测点在风帽同一垂直截面上布置, 为减小测量误差, 沿风帽周向开槽, 槽内敷设热电偶丝[3]。

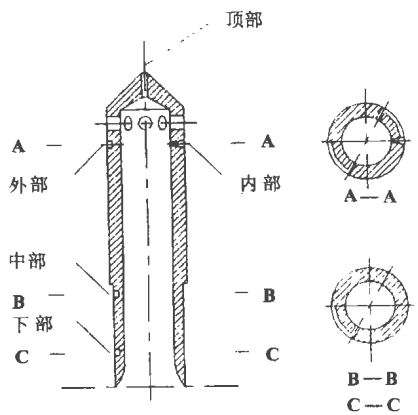

图 1　风帽温度测点布置

在试验前对加工制作、焊接方法等进行了多种尝试, 最后才确定了开槽敷设、铜焊焊接的方法。在马弗炉内进行了煅烧试验, 确保了铜焊在 800 ℃下的可靠性, 所采用的 EU 铠装热电偶能在 800 ℃下长期工作。虽然热电偶在风帽内部受高温热烟气的冲刷, 在长达四个月的试验期中未发因此而破坏的现象, 所有风帽的热电偶均能安全可靠地工作。

3　结果与分析

3.1　风室烟温和烟速一定时, 床温的影响

保持风室烟温 T_c = 700 ℃, 风室烟速 U_c = 0.829 m/s*, 维持此加热条件不变, 使床温从 432 ℃

收稿日期: 1999－03－23; 修订日期: 1999－06－07

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注: 文中 m/s*为标准米每秒

到 800 ℃变化时, 风帽温度分布如图 2。

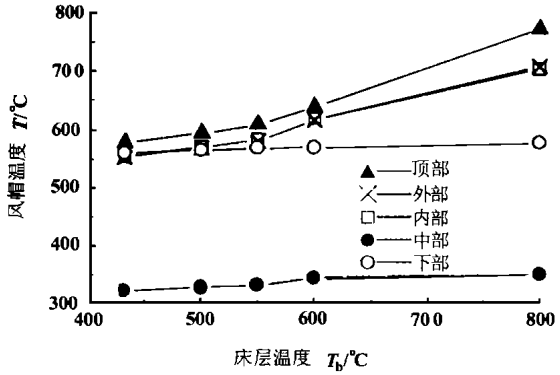

图 2　床温对风帽温度分布的影响

从图中可以看出, 当床温较低时(432 ℃), "风帽下部"温度高于"风帽内、外部"温度, 其原因一方面是因为风室烟温、烟速都大为增大, 热烟气对风帽下部入口处的冲刷加强, 对流传热系统增大提高了该部分温度。另一方面, 风帽上半部浸没在沸腾层中, 床内流速较大而温度较低, 则上部的外表受冷却作用较强; 这就使得"风帽下部"温度有可能稍高于"风帽内、外部"温度。当床层温度继续升高, 则对风帽的冷却作用减小, 在床温约为 480 ℃时, "风帽内、外部"温度高出"风帽下部"温度, 呈现出以下风帽温度分布规律: 风帽下部温度不受床温影响, 中部温度随床温升高略有升高, 其它三点温度升高显著。

"风帽内、外部"温度曲线因为其数值接近而近乎重叠, 根据原始数据及图 2, 依旧可以发现, 发生传热机理转换的温度点约为 625 ℃, 超过该温度后, 风帽外部温度就大于内部温度, 在该处床层对风帽传热。另外, 风帽顶部温度与风室烟温、床层温度在 700 ℃趋于一致。低于此温度, 则风帽顶部温度高于床层温度; 超出此温度, 则风帽顶部温度低于床层温度。

试验了保持热烟气回热而使床层温度达到 800 ℃时的工况。此时布风板与风帽处于整个热态试验中的最恶劣受热工况。因为在实际启动过程中, 当床层温度在 700 ℃～750 ℃时就可停止供油, 直接供给冷空气用以燃烧。作者有意安排了该种工况, 以考察风帽在正常启动过程中可能达到的最高温度分布, 并考验风帽的使用性能, 进而对风帽的选材提供依据。这时候的最高温度出现在风帽顶部, 为 772 ℃, 低于中硅球墨铸铁 RQTSi5.5 的最高使用温度[4], 说明在采用水冷布风板的条件下, 该风帽的选材是合适的。

3.2　床温和风室烟速一定时, 风室烟温的影响

在 T_b=450 ℃, U_c=0.638 m/s* 的综合条件下, 考察了风室烟温对风帽温度分布的影响, 如图 3 所示。

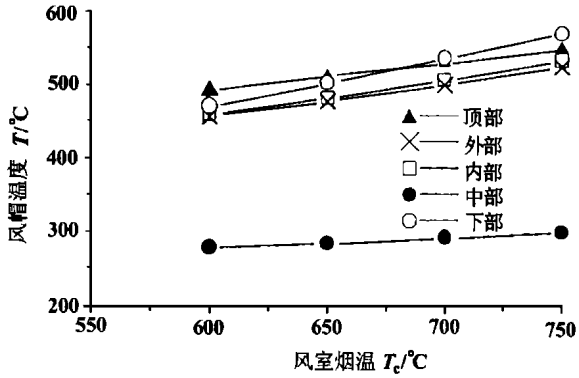

图 3　风室烟温对风帽温度分布的影响

当风室烟温由 600 ℃到 700 ℃变化, 风帽各测点温度也升高, 其中"风帽下部"温度又高于"风帽内、外部"温度。其原因前已述及, 即在 450 ℃的床层温度下, 床层对风帽主要起冷却作用。各点温度近乎线性升高, 其增值以"风帽下部"温度为最高, 风帽中部为最低。这表明, 在不同风室温度下同样存在"风帽中部"的升温隋性, 这恰恰体现了水冷布风板对风帽的保护作用。在 700 ℃、750 ℃的风室烟温下风帽下部温度高于"风帽顶部"温度, 成为风帽上温度最高点。

以上分布特点表明, 风帽上部温度因主要受床温控制, 所以随风室烟温的变化较小; 而风帽下部温度则主要受风室烟温影响。

3.3　风室烟温、床温一定时, 风室烟速的影响

比较了风室烟温为 700 ℃、床温为 450 ℃, 风室烟速分别为 0.57 m/s*、0.64 m/s*、0.77 m/s* 时的风帽温度分布, 如图 4 所示。图中"风帽下部"温度均高于"风帽顶部"温度, 为风帽上最高温度, 表明在 450 ℃床温下, 风室烟温的加热作用和床层的冷却作用都很强烈。

随着风室烟速的提高, 风帽上各点温度升值极小, 当 U_c 增加了近 1/2 倍时, 温度升高的最大值不超过 10 ℃。

3.4　风帽的耐热性

流化床锅炉在运行过程中床温一般控制在 900

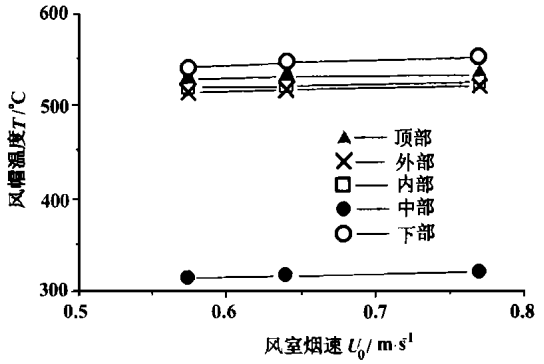

图 4 风室烟速对风帽温度分布的影响

℃左右,正常运行时,空气通过风帽送入床层,对风帽有一定的冷却作用,特别是在采用水冷布风板的情况下,能使风帽的温度进一步降低。在 900 ℃床温正常运行工况下风帽上最高温度不超过 700 ℃,由于床内的传热强烈,特别是在压火、结焦等情况下,风帽的工作条件更为恶劣。这就要求风帽材料必须有良好的耐高温性能。目前,流化床锅炉中风帽一般用灰口铸铁,或高硅球墨铸铁 RQTSi5.5 铸造加工而成。灰口铸铁来源广,价格低,所以在早期多采用该材料来制造风帽,但其耐热性较差,在高温下除了会发生表面氧化外还会发生"热生长"现象,即其体积会产生不可逆的胀大,严重时可胀大 10%左右。

在球墨铸铁中,由于 Si 的含量较高,使铸铁的临界点提高,这样在使用温度范围内铸铁不发生固态相变,减少了由此而引起的体积胀大及显微裂纹。同时,由于 Si 的含量较高,铸铁在高温下会在表面形成一层致密的 SiO_2 膜,使内层不被继续氧化。高硅球墨铸铁的基体组织为铁素体,它不象渗碳体那样在受热时会发生分解石墨化。而原有的石墨在铸铁内部呈孤立分布,互不相连,不会构成氧化性气体渗入铸铁内部的通道,这样就进一步提高了高硅球墨铸铁在高温时的抗氧化性[5]。由于上述原因,现在都倾向于用 RQTSi5.5 作为风帽材料,可在 950 ℃以下可靠使用。硅在铸铁中的含量越高,其耐高温性能越好,但机械性能则有所下降。由于采用水冷布风板,其对风帽的保护作用较之常规布风板要理想。考虑选用中硅球墨铸铁 RQTSi5.0 作为风帽材料;与 RQTSi5.5 相比,其使用温度略有所下降,但机械性能得到提高,便于加工制造,且价格较低。

试验装置中风帽的材料选用中硅球墨铸铁 RQTSi5.0,铸件由东南大学机械系提供,材料实测的硅、锰、磷含量分别为 4.74%、0.52%、和 0.032%。为了解其耐高温性能,与 1Cr18Ni9Ti 及普通碳钢一起在马弗炉中进行了对比煅烧试验。

马弗炉温分别控制在 800 ℃、850 ℃、900 ℃和 950 ℃,四组试件在上述四个温度下各保温 4 小时。试验发现,800 ℃温度下的 RQTSi5.0 试件表面平整、致密,与试验前相比,无明显变化;在 850 ℃温度下的试件局部表面可见到少量直径 1 mm 左右的因氧化而形成的白斑,白斑有轻微的鼓起,但整个加工表面的其它部分仍十分平整、致密,试件颜色加深呈墨绿色;在 900 ℃温度下保温的试件,其表面白斑的数量略有增加,白斑直径在 1.5 mm 左右,颜色稍加深,其它基本与 850 ℃温度下的试件相同。在 950 ℃温度下保温试件,表面有一明显的氧化层;加工表面变得比较粗糙,颜色呈浅墨绿色;与前三个试件明显不同,并且试件体积略有增加。这显然是因"热胀大"所致。与上述试件相对比的普通碳素钢试件,均发生了严重的氧化,并且有氧化皮脱落,而 1Cr18Ni9Ti 试件在 950 ℃的高温下其表面情况仍与试验前无明显差别,其耐高温性能明显高于 RQTSi5.0,但其价格也较昂贵。

从上述试验看,RQTSi5.0 在 900 ℃以下有优良的抗氧化性和抗热生长性,能够长期使用。

3.5 床内稳定燃烧及结焦时对风帽的考验

流化床锅炉在正常运行时床温一般控制在 950 ℃左右,这时进入风室的空气温度在 250 ℃左右。在我们的试验中,当床层温度为 955 ℃,风室温度为 249 ℃时,测到的风帽最高温度即顶部温度为 675 ℃,中部温度为 400 ℃。在上一节所述的对比煅烧试验中可知,在 900 ℃以下,RQTSi5.0 有很好的抗氧化性及抗"热生长"性。这样就能断定,用 RQTSi5.0 制成的风帽能经受长期运行的考验。

在试验中曾因加煤速率过大先后发生过三次结焦,床温记录均超过仪表量程 1 100 ℃。在清炉时发现,床内呈玻璃状结焦,说明结焦时床温已超过试验煤种的溶化温度,但观察床内风帽,发现所有风帽均完好无损,无变形、无氧化等现象,表明用 RQTSi5.0 制成的风帽在短时间内承受住了 1 100 ℃以上床内高温的考验。

4 结论

本文首次对热烟气床下点火条件下流化床风帽温度分布进行了试验研究,结果表明,风帽测点布置

及其方法是行之有效的。

风帽中部受水冷布风板冷却程度较强, 其温度基本不受其它因素影响; 风帽上部温度主要受床温影响, 下部温度由风室烟温所控制; 风室烟速对风帽温度影响较小。

风帽材料 RQTSi5.0 在 900 ℃以下有优良的抗氧化性和抗热生长性, 能够长期使用; 用该种材料制成的风帽在短时间内承受住了 1 100 ℃以上床内高温的考验。

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3.3　实例计算

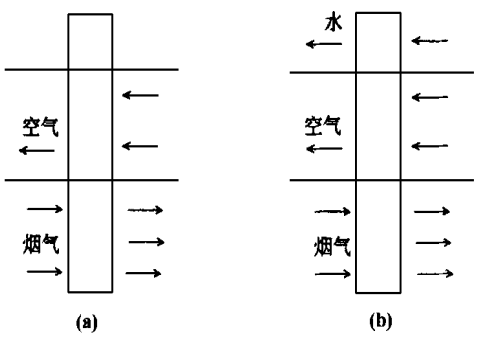

图 4　热管换热器的工作示意图

对于图 4(a) 所示热管, 当排烟温度瞬时剧烈上升至 800 ℃时, 换热器立即启用第二种冷却流体(常压水), 如图 4(b) 所示。排烟温度最高可达 1 100 ℃, 冷却空气的温度 t_2 为 150 ℃, 设计时认为水很快达到沸腾, 取 $t_3 = 100$ ℃。热管(碳钢－水) 的许可工作温度 300 ℃。加热段的传热系数 $U_1 = 30$ W/(m·℃), 两个冷却段的传热系数分别为 $U_2 = 35$ W/(m·℃) 和 $U_3 = 300$ W/(m·℃)。

3.3.1　冷却段 1 与加热段长度比的计算

(a) 经济长度比的计算

由 $L^*_{经} = \sqrt{\dfrac{U_1}{U_2}}$, 可得 $L_2^* = 0.926$

(b) 安全长度比校核

$$[L_2^*] = \frac{U_1}{U_2} \cdot \frac{t_1 - [t_v]}{[t_v] - t_2} = 1.714 > L_2^*$$

故不能选用 L_2^*, 即在正常运行的情况下单纯考虑经济性是不安全的。考虑一定的裕度, 取

$$[L_2^*] = 2.0$$

热管工作温度 t_v 为:

$$t_v = \frac{U_1 L_1 t_1 + U_2 L_2 t_2}{U_1 L_1 + U_2 L_2} = 285 \text{ ℃}$$

3.3.2　冷却段 2 与加热段长度比的计算

由式(5) $[L_3^*] = \dfrac{((t_1)_{\max} - [t_v])}{([t_v] - t_3)} \cdot \dfrac{U_1}{U_3} + \dfrac{(t_2 - [t_v])}{([t_v] - t_3)} \cdot \dfrac{U_2}{U_3}[L_2^*] = 0.435$

因此本例提到的超温应急冷却用的复合型热管, 其冷却段长度比为 1: 2: 0.435。

4　结论

(1)　对于同时加热两种冷流体的复合型热管, 其经济长度比由方程组式(3)确定, 用式(4)或式(5)计算其安全长度比用以校核。

(2)　对于超温应急冷却用的复合型热管, 其长度比可分两个步骤加以确定, 其中冷却段 2 与加热段的长度比由式(5)计算。

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(渠　源　编　辑)

Meanwhile, an investigation was conducted of the effect of blade curving on the location of horseshoe vortex and passage vortex formation. A positive curving of the blades has been found to be conducive to a decrease in the transverse pressure gradient at the end wall and a weakening of the end wall secondary flows. Moreover, the blade positive curving will lead to a shift of the initial separation point of the horseshoe vortex to the middle of the flow passage, bringing about a generation of the passage vortex ahead of the anticipated time. The differential scheme selected in this paper is a Godunov one of the third-order precision with TVD properties. The turbulent flow model is a B-L algebraic one after a correction. **Key words**: positive-curved blade, flow field parameter, numerical simulation

中心扩口对径向浓淡旋流煤粉燃烧器出口气固流动特性的影响＝**The Effect of a Central Flared Angle on the Gas-solid Flow Characteristics at the Outlet of a Radial Bias and Pulverized-coal Swirl Burner** [刊, 汉] / Wang Le, Wu Shaohua, Hao Jinbo, *et al* (College of Energy Science and Engineering under the Harbin Institute of Technology, Harbin, China, Post Code 150001) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —243 ~246, 263

Under the condition of different central flared angles and through the cold-state particle dynamic analyzer (PDA) testing of a radial bias and swirl burner a study was conducted of the burner outlet velocity, pulverized coal particle diameter and concentration distribution. As a result, obtained was the mechanism of the effect of the central flared angle on the gas-solid flow characteristics at the burner outlet. Also analyzed was the influence on the burner performance of the central flared angle. All the above work can provide some reference data and serve as a basis for the engineering application and optimized design of the above-mentioned burners. **Key words**: pulverized-coal swirl burner, pulverized-coal combustion, gas-solid dual-phase flow, particle dynamic analyzer (PDA)

复合型热管长度比的优化计算＝**Optimization Calculation of Length Ratios for a Composite Heat Pipe** [刊, 汉] / Adel M, Hu Yacai, Yuan Hai, *et al* (Energy Source Engineering Department, Zhejiang University, Hangzhou, Zhejiang, China, Post Code 310027) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —247 ~ 248, 255

A heat exchanger composed of gravity heat pipes with two kinds of cooling fluids has some specific features and merits in engineering applications. This paper presents a brief description of the method for determining the length ratios between the heating and cooling sections. In addition, several calculation examples are also given. **Key words**: composite heat pipe, heat pipe, length ratio

燃煤循环流化床模型与试验研究＝**Experimental Study and Simulation of a Coal-fired Circulating Fluidized Bed** [刊, 汉] / Shen Laihong (Thermal Energy Engineering Research Institute under the Southeastern University, Nanjing, Jiangsu, China, Post code 210096) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —249 ~251, 259

Based on the basic research results concerning the gas-solid dual-phase flow of a circulating fluidized-bed and an in-bed gas-solid bias flow model the author has set up a circulating fluidized-bed combustion model suited for different construction parameters. The model has taken into account the return mixing and the circulation process of gas and solid particles in the bed. Also considered are such a variety of factors as coal burning, the generation and dissolution of nitrogen oxides and particle wear action, etc. The results of the experimental study and model simulation on a circulating fluidized-bed combustion test rig are in good agreement with the experimental data. This fully demonstrates that the circulating fluidized-bed combustion system set up on the basis of the gas-solid dense-lean flow model can accurately simulate the combustion process of a circulating fluidized bed. **Key words**: coal, circulating fluidized bed combustion, mathematical model, experimental study

流化床风帽温度分布及其耐热性的试验研究＝**Experimental Study of the Temperature Distribution of a Nozzle Button in a Fluidized Bed and Heat Resistance of the Nozzle Button** [刊, 汉] / Wu Xin, Zhao Changsui, Duan Yufeng, *et al* (Thermal Energy Engineering Research Institute under the Southeastern University, Nanjing, Jiangsu,

China, Post Code 210096)//Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —252~255

An experimental study was conducted of the nozzle button temperature distribution on a fluidized bed test facility under start-up conditions with the under-bed ignition being carried out with the help of high-temperature gases. The heat resistance of the material used for the nozzle button is also assessed. In view of the increasing use of under-bed ignition mode for the start-up of fluidized bed boilers the above study is of great significance in providing guidance for practical engineering applications. **Key words**: temperature distribution, nozzle button, fluidized bed

压气机进气用雾化式蒸发冷却器实验研究=**Experimental Study of a Fog-atomizing Evaporative Cooler for Compressor Inlet Air** [刊, 汉] / Lin Feng, Li Weishun, Xiao Dongmin, Wen Xueyou (Harbin No. 703 Research Institute, Harbin, China, Post Code 150036)//Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —256~259

From an experimental viewpoint a study has been performed of evaporative coolers for the cooling of compressor air. Discussed are some methods for measuring the wetness of water drop-containing air. With respect to different schemes of wetness addition by way of evaporation at a constant temperature the authors have investigated the effect produced by different water spray quantity on the evaporative cooling effectiveness. An experimental analysis is also conducted of the evaporative cooling effectiveness resulting from the different types of atomizing nozzles under different spray directions. **Key words**: compressor, inlet air cooling, heat transfer, mass transfer, evaporative cooler

中心进气旋转盘的冷却效果实验研究=**Experimental Study of the Cooling Effectiveness of a Rotating Disc with a Central Cooling-air Feed** [刊, 汉] / Xu Guoqiang, Ding Shuiting, Tao Zhi, *et al* (Power Engineering Department under the Beijing University of Aeronautics and Astronautics, Beijing, China, Post Code 100083)//Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —260~263

With regard to the cooling of turbine engine high-temperature components it is essential to meet the following main requirements: a minimal overall temperature of the hot components and a minimal temperature difference within the various parts of the hot components. In view of the foregoing one has to address the above-cited main requirements in addition to the study of convection heat transfer factor of the disc surface. In the present paper an engine turbine disc has been simplified to a rotating disc model with a central cooling-air feed. Under this simplification an experimental study is conducted of the effect of rotating Reynolds number, air inlet Reynolds Number, disc cowl clearance ratio and outlet air clearance ratio on the non-dimensional excessive body average temperature and non-dimensional radial temperature difference. In addition, a relevant criterion relation has also been given in the paper. **Key words**: rotating disc, heat exchange, non-dimensional excessive body average temperature, non-dimensional radial temperature difference

新型双流化床锅炉运行煤种变换仿真试验研究=**Experimental Study of the Simulation of Fired-coal Rank Variation for a New Type of Double Fluidized-bed Boilers** [刊, 汉] / Zhao Jian, Suo Yisheng, Jiang Zikang, *et al* (Department of Thermal Engineering, Qinghua University, Beijing, China, Post Code 100084)//Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —264~266, 271

A general mathematical model has been set up for a circulating double fluidized-bed boiler. On this basis a simulation test of the fired-coal rank variation was performed as a new pioneering attempt in the area of fluidized-bed boiler simulation. The results obtained can serve as useful information and data for the design and operation of fluidized beds, providing guidance for their further advancement. **Key words**: simulation, test, fluidized bed, coal

工业汽轮机增容改造技术研究=**Technical Study of a Power Output Uprating-oriented Modification of Industrial Steam Turbines** [刊, 汉] / Qin Xiaocheng, Gao Lei, Qiu Zufa (Harbin No. 703 Research Institute, Harbin, China, Post Code 150036)//Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —267~268

Described in this paper is the technical modification of a Model EC-301T steam turbine for enhancing its rated power output by 15%. The power uprating of the steam turbine has been achieved through a technical modification of such components as nozzle box, diaphragms and couplings, etc. However, the steam turbine rotor has been kept unchanged. **Key**