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循环流化床脱硫塔直/旋流复合流化下的两相流场试验研究

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摘　要: 循环流化床脱硫装置的文丘里管直流流化速度随锅炉负荷的变化而变化, 这会影响脱硫效率。本文提出了适应锅炉负荷变化的直/旋流复合流化方式, 并用 PDA 测量系统对这种流化方式的气固两相流场进行测试, 得到了循环流化床内旋流风率和假想切圆半径改变时气固切向速度和浓度分布。试验表明, 复合流化循环流化床的切向速度随着半径增大而升高, 气固切向滑移速度比直流流化增大, 脱硫塔内的浓度增加, 内循环增强, 脱硫效率随之提高。

关　键　词: 循环流化床; 复合流化; 切向速度; 内循环
中图分类号: X701.3　　文献标识码: A

1　引　言

半干法烟气脱硫装置中, 采用文丘里管流化的循环流化床是常用的一种, 这种脱硫装置已经成为当今烟气脱硫技术研究的热点之一[1]。该装置的特点之一是中心只有一股用文丘里管流化的直流射流。通常, 为了保证脱硫效率, 都要求塔内较大的颗粒浓度, 这需要文丘里管较大的流化速度来维持, 而流化速度正比于烟气总流量, 因此, 直流流化速度由于锅炉负荷的变化而忽大忽小。负荷低时, 流化速度小, 造成大量颗粒沉降而退出循环, 难以维持较大的颗粒浓度。特别对于燃煤电厂烟气脱硫的情况, 由于大机组经常参加调峰任务, 负荷变化范围很大, 需要脱硫装置锅炉负荷适应性强, 传统的循环流化床脱硫装置难以适应这种要求。

我们在循环流化床脱硫技术的文丘里管直流流化[2~3]基础上抽取一部分直流流化气体作为旋流流化风, 并将其在文丘里管上方切向射入, 将单一的文丘里管直流流化改造成直/旋流复合流化。根据锅炉负荷变化调整旋流流化的烟气量, 保持直流流化速度不变, 可以提高脱硫系统在锅炉负荷变化时的适应性。用三维相位多谱勒颗粒动态分析仪(3D－PDA)对复合流化的流场进行测试, 得到了流化床内两相流动的一些规律, 为中试以及工程应用提供依据。

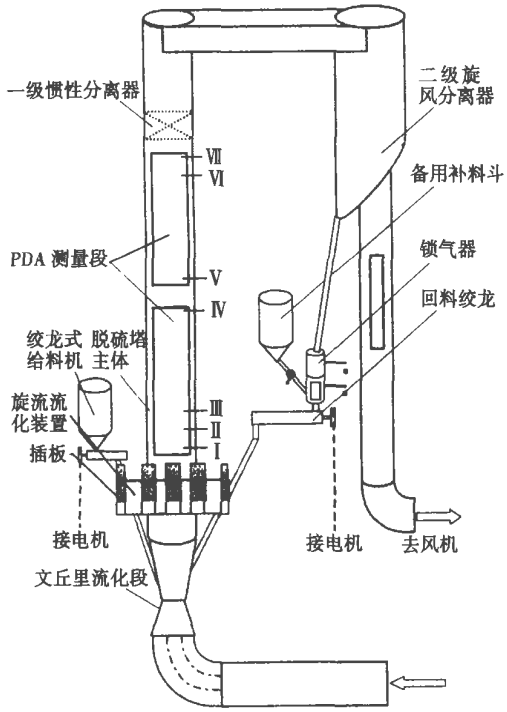

图 1　直/旋流复合流化试验系统图

2　试验装置与测量方法

试验系统如图 1 所示。它主要由入口段文丘里流化段、旋流流化段, 测量段, 测量段上方的一级惯性分离器、塔体出口的二级下排气旋风分离器和给、回料装置等组成; 为了尽量减小入口段气流偏转在转弯处安装了导流板。

试验装置中单管文丘里的喉口直径 120 mm; 文

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丘里结构上方为旋流流化装置，该装置由 6 个旋流流化进气口组成；塔主体高 2 000 mm，水平截面 220 mm×220 mm 的长方体；测量段分为上下两部分，每部分高度均为 500 mm(见图 1)。旋流流化装置的烟气量通过插板调节，试验中选取的旋流流化风量 q 占总风量 Q 的比例：q/Q = 0、11%、21%、35%、47%，旋流流化角度通过导流片调节，旋流流化角所对应的假想切圆半径 r 与以水平截面内切圆半径 R 的比值 r/R = 0.5、0.7、0.8(见图 2)。试验中用激光相多谱勒颗粒分析仪(3D—PDA)无接触的测量循环流化床脱流塔的二维流场。为了 PDA 测量需要，测量段三面为平面玻璃，这样设置有利于 PDA 的前向接收[4]。PDA 的速度测量精度：±0.5%；浓度测量精度：30%。

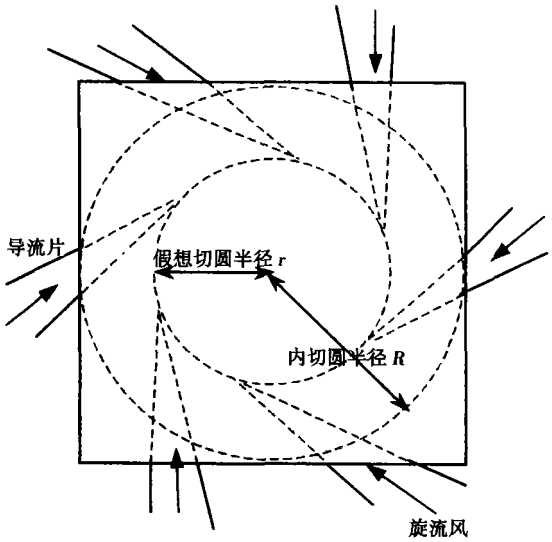

图 2 旋流流化装置

试验中采用的颗粒为玻璃微珠，其给料粒度 325 目，密度 2 300 kg/m^3，平均粒径 45 μm，折射率 1.5～1.55，球形度大于 90%。高度方向上的两个测量区域：靠近文丘里管流化段的下部测量区和靠近一级分离器的上部测量区。每个测量区沿高度方向设置 11 个测点，相邻测点相距 50 mm；沿内切圆半径方向设置 11 个测点，测点之间距离为 10 mm，每个测量工况的测点数为 242 个点。因为 PDA 激光交点汇聚在壁面时，会导致 PDA 系统阳极电流异常升高，系统停止工作，所以径向无因次半径(r/R)的范围：0～0.91。试验中，每个测试点采样 2 000 个，限时 25 s。数据分析时取 0～8 μm 的玻璃微珠作为气相，8 μm 以上的玻璃微珠作为颗粒相。试验中循环流化床的颗粒浓度控制在 70 g/m^3 左右，脱流塔操作气速 3 m/s 左右。

3 试验结果及分析

3.1 气固切向平均速度分布

分析切向速度时，取下部测量区的最下 3 个截面和最上 1 个截面，上部测量区的最下 1 个截面和最上 2 个截面(见图 1)，7 个最有代表性的截面进行分析。

文丘里管直流流化时(见图 3(a))，随着半径的增加切向速度的变化小，随着高度的增加切向速度的变化趋势不明显，而且各个截面的气固切向滑移速度比较小，这与文献[5]对循环流化床文丘里直流流化的 PDA 试验的结果类似。

3.1.1 相同假想切圆半径，不同旋流流化风量的气固切向平均速度分布

随着切向风的引入，在旋转动量的作用下，气固切向速度表现出与文丘里管直流流化不同的规律(见图 3(b)～(e))。对于同一个 q/Q 切向速度分布图，由于气流入射时的刚性，直/旋流流化的切向速度最大值发生在近壁处，而不是旋流流化的假想切圆半径处。旋转及扰动传播到床轴心区域，并使该区域的气流具有一定的旋转强度。接近旋流流化段的截面(截面Ⅰ～Ⅲ)受旋流流化的影响最大，具体表现在近壁区与中心区的较高的速度差值。随着高度的增加(截面Ⅳ～Ⅶ)，气流阻力减小了旋流强度，同时由于一级分离器分离下来颗粒回流返混，所以轴向各层切向速度沿着半径增大方向的增加程度逐渐变小。

q/Q 增大，旋转动量也随之增大。对于低截面(截面Ⅰ～Ⅲ)，q/Q 增加时气相切向速度有更大的增量；而固相惯性大其切向速度增量较小，所以低截面直/旋流流化的气固滑移切向速度比文丘里管直流流化大；q/Q 越大，气固滑移切向速度越高。高度增加(截面Ⅳ～Ⅶ)，q/Q 增加对切向速度的影响不如低截面明显，截面Ⅳ～Ⅶ的气固切向速度沿着半径方向变化较小，但是受到一级分离器分离下的颗粒影响，气相切向速度分布曲线上下振荡，固相的惯性较大，其切向速度分布曲线变化较小，所以截面Ⅳ～Ⅶ气固切向滑移速度也比文丘里管直流流化大。

3.1.2 相同旋流流化风量，不同假想切圆半径的气固切向平均速度分布

本文取 q/Q = 35%为例进行分析。对于低截面

(截面Ⅰ ~ Ⅲ), 随着 r/R 的增加气相切向速度沿着半径方向增量较大; 而固相切向速度并没有明显增加, 所以气固切向滑移速度较大。截面Ⅳ ~ Ⅶ随着 r 增大气固切向速度沿着半径增大方向的增量较小; 但是颗粒惯性比气体大, 沿半径方向波动较小, 所以气固切向滑移速度仍比文丘里直流流化大。

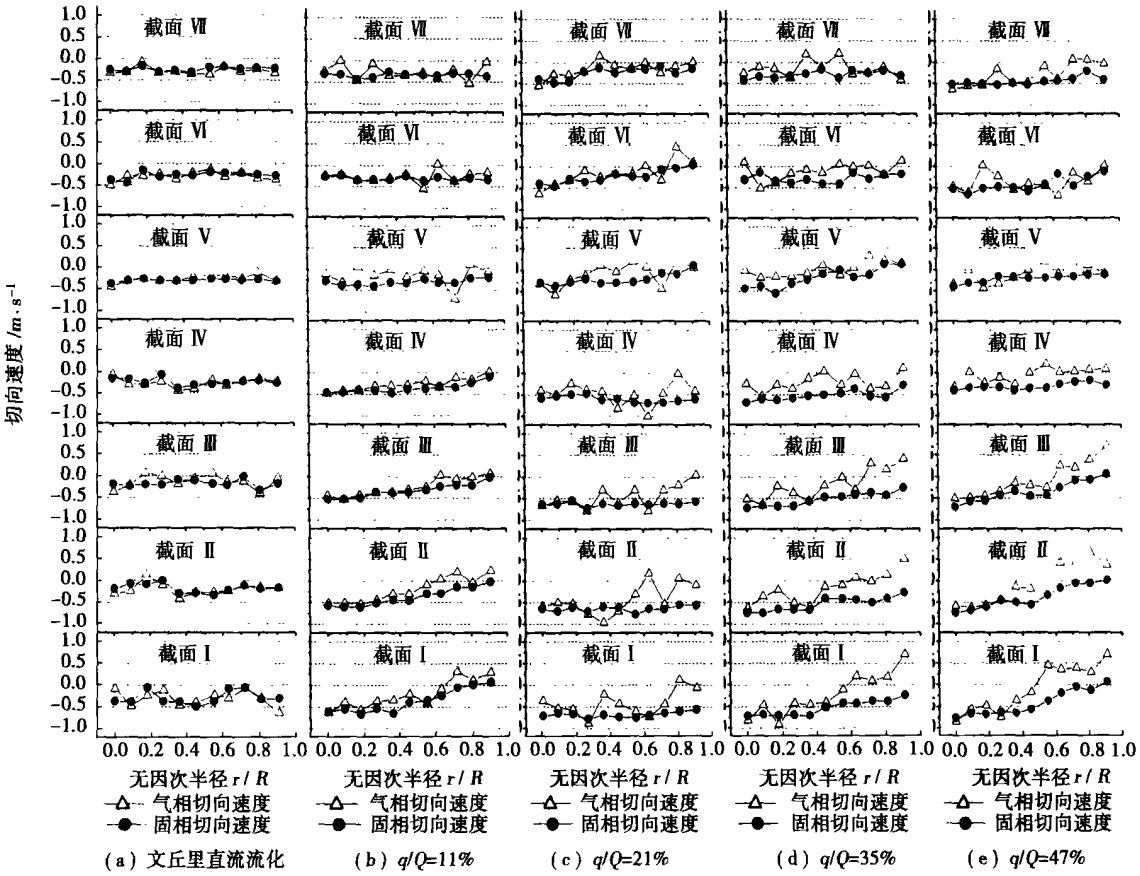

图 3　$r/R=0.7$ 的切向速度分布图

由直/旋流复合流化的切向速度分布图可以看出, 靠近文丘里流化段和一级分离器区域的气固滑移速度与文丘里管直流流化相比增大最明显。循环流化床半干法脱硫工艺中, 靠近文丘里流化段的区域, 是脱硫反应进行的主要场所之一, 此处颗粒被涂抹上石灰浆液, 气固滑移速度增大, 气固接触效率提高, 传热传质效率提高, SO_2 更易于扩散至浆液表面, 使脱硫反应以快速的液相离子反应进行。烟气上升到靠近一级分离器的区域, 大部分的液体蒸发, 气固滑移速度增大, 有利于磨掉颗粒的外壳, 露出内部未反应的石灰。所以直/旋流流化时, 气固切向滑移速度的增加, 对半干法脱硫效率的提高是十分有益的。

3.2　颗粒平均浓度分布

试验中数据量非常大, 在简化数据量的同时为了能比较准确的反映循环流化床内颗粒浓度分布规律, 所以选择如图 5 所示的 4 组数据。

当流化床处于文丘里管直流流化方式下, 如图 5(a), 近壁处的浓度高于中心区域的浓度; 随着高度的增加, 浓度的差别很小, 没有出现普通流化床的稀相区, 这主要是因为上部区域存在一级分离器, 使得上部的颗粒浓度增大, 同时床内颗粒浓度跟实际烟气流化床脱硫过程存在差别的原因。

将文丘里流化风的一部分作为旋流流化风加入以后, 气流能够携带更多的颗粒, 强旋转动量的作用使得颗粒的悬浮能力增强, 颗粒在脱硫塔内的停留时间延长, 同时扬析损失降低, 从一级分离器分离下来的颗粒量增加, 因此塔内更容易维持高的颗粒浓度, 增强了颗粒的内循环, 脱硫效率随之提高。

直/旋流复合流化的循环流化床浓度场与普通流化床的差别很大(见图 5(b)、(c)、(d)): 塔内依旧

没有浓、稀相区的分界, 床层上部的浓度有时甚至比下部高; 浓度曲线上下振荡, 浓度的最大、最小值随机出现。这都说明脱硫塔内颗粒有强烈的湍动, 强烈湍动对脱硫效率的提高是有利的。

研究表明[6~8], 脱硫塔颗粒粘壁是液滴在未干燥前黏附在壁面上造成的。直/旋流复合流化时脱硫塔近壁处的浓度增加, 但是近壁处增大的切向速度和更高的气固滑移速度增强传热传质效率, 促进液滴干燥; 同时, 增大的切向速度对壁面有更强的冲刷作用, 所以直/旋流复合流化方式可以减轻甚至防止脱硫塔粘壁现象。

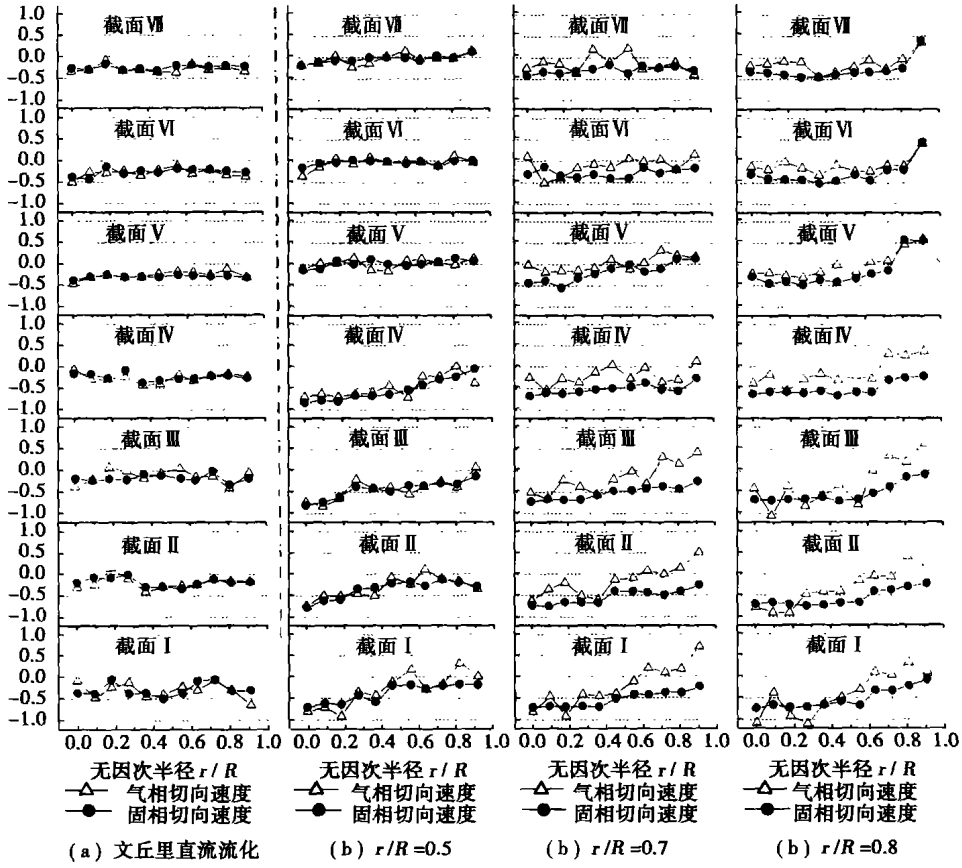

图 4 $q/Q=35\%$的切向速度分布图

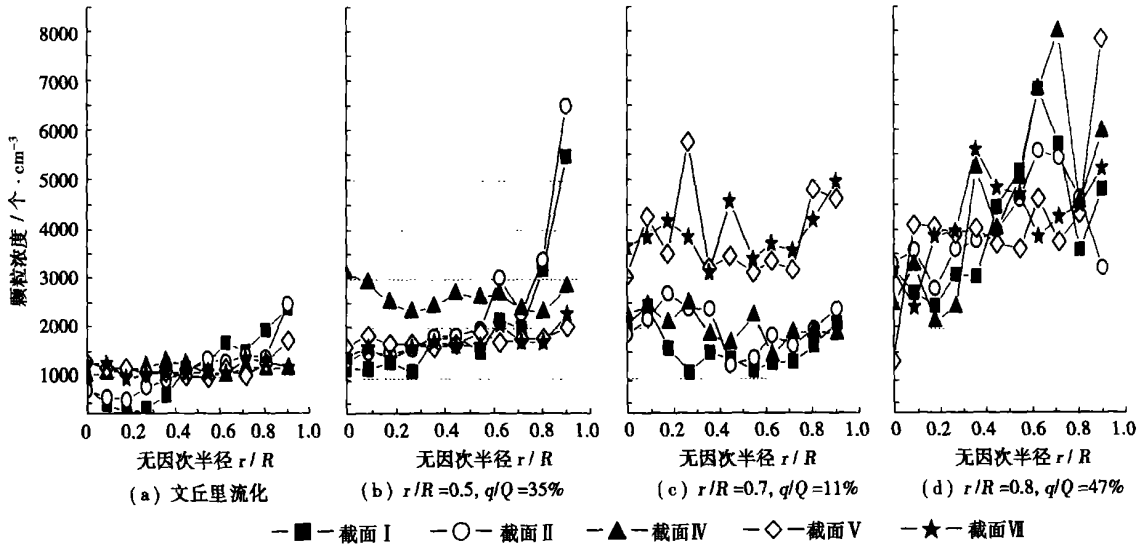

图 5 颗粒平均浓度分布图

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一个气流速度极低的滞止区;

(2) 通过对一、二次风量大小调整的比较, 发现为了保证旋流区的形成, 一、二次风风量比有一个最低值, 低于这个值就难以在燃烧器内部形成有效的旋流区, 将无法保证煤粉的稳定和完全燃烧。

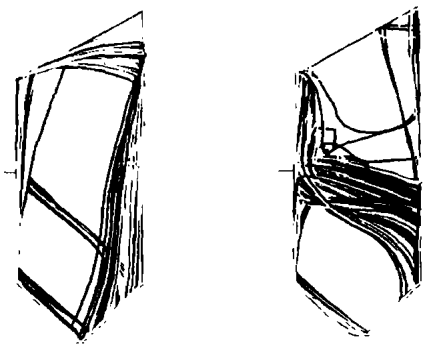

图 11　改进前和改进后的颗粒运动轨迹(d=0.2 mm)

(3) 基于STAR—CD 软件, 采用 RNGk—ε 模型对燃烧器内部流场进行了模拟, 计算结果基本反映了燃烧器内的流体动力学特性和变化规律。

(4) 通过改变一次风粉的单管进口方式为均布进风, 可以增加小颗粒在旋涡区内的停留时间, 提高燃烧器对不同粒径煤粉燃料的适应性。

参考文献:

[1] HARTMUT SPLIETHOFF, ULRICH GREUL, HELMUT RUDIGER, *et al*. Basic effects on NO_x emissions in air staging and reburning at a bench-scale test facility[J]. **Fuel**, 1996, **75**(5): 560—564.

[2] 周力行, 李荣先. 喷腾旋风固排渣煤燃烧方法及装置[P]. 中国专利: 92101967.X, 1992.

[3] WANG D X, MA Z H, WANG X L, *et al*. Experimental studies on gas-particle flow and coal combustion in new generation spouting-cyclone combustor[J]. **J of Thermal Science**, 1995, **5**(2): 132—137.

[4] 聂　森. 沸腾式涡旋燃烧方法及装置[P]. 中国专利: 93106089.3, 1993.

[5] NISHIMURA M, SUZUKI T, NAKANISHI, *et al*. Low-NO_x combustion under high preheated temperature condition in an industry furnace[J]. **Energy conversion**, 1997, **38**(10—13): 1353—1363.

[6] 钟北京, 徐旭常. 低 NO_x 煤粉燃烧器的设计原理[J]. 动力工程, 1995, **15**(5): 18—23.

[7] 金志刚. 燃气测试技术[M]. 天津: 天津大学出版社, 1994.

[8] 徐明厚, 胡平凡, 韩才元. 受限空间中两相交叉射流穿透及混合特性研究[J]. 华中科技大学学报, 1996, **24**: 85—87.

[9] YAKHOT VICTOR, ORSZAG S A. Renormalization group analysis of turbulence: I. Basic theory[J]. **J of Scientific Computing**, 1986, **1**(1): 1—51.

[10] CD ADAPCO GROUP. STAR-CD version 3.15 user guide[M]. Tokgo: Computational Dynamics Limited, 2001.

[11] 陶文铨. 数值传热学[M]. 西安: 西安交通大学出版社, 1995.

[12] WANG X, CHENG L. Three-dimensional simulation of a side discharge into a cross channel flow[J]. **Computers & Fluids**, 2000, **29**(4): 415—433.

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4　结　论

(1) 循环流化床脱硫技术采用直/旋流复合流化方式时, 脱硫系统的锅炉负荷适应性提高。

(2) 直/旋流复合流化时, 近壁处的切向速度最高。气固滑移切向速度比文丘里管直流流化有明显的提高。

(3) 直/旋流复合流化的循环流化床脱硫塔的湍动强烈, 脱硫塔内颗粒浓度比文丘里管直流流化时高, 流化床内循环有了较大的增强, 这都有利于脱硫效率的提高。

参考文献:

[1] 赵旭东, 高继慧, 吴少华, 等. 干法、半干法(钙基)烟气脱硫技术研究进展及趋势[J]. 化学工程, 2003, **31**(4): 64—67.

[2] 张凤兰, 程　岩. 小龙潭电厂引进烟气循环流化床一悬浮吸收脱工艺[J]. 云南电力技术, 2001(1): 23—25.

[3] 董　勇. 双循环流化床烟气悬浮脱硫工艺[J]. 电站系统工程, 2002, **18**(6): 9—10.

[4] MOORTEL VAN DEN T, AZARIO E, SANTINI R, *et al*. Experimental analysis of the gas-particle flow in a circulating fluidized bed using a phase doppler particle analyzer[J]. **Chemical Engineering Science**, 1998, **53**(10): 1883—1899.

[5] 董　勇. 烟气脱硫循环流化床内物料分离循环的研究[D]. 哈尔滨: 哈尔滨工业大学, 2004.

[6] 张　凡, 王军方, 王　凡, 等. 半干法钙基烟气脱硫技术[J]. 能源环境保护, 2004, **18**(1): 44—47.

[7] 赵　卷, 张少峰, 张占锋. 半干法烟气脱硫技术研究新进展[J]. 河北工业大学学报, 2003, **32**(5): 81—86.

[8] 赵旭东, 吴少华, 马春元, 等. 循环流化床烟气脱硫中过湿现象的实验研究与分析[J]. 动力工程, 2002, **22**(3): 1815—1818.

transition system is different from that of a simple compressible single-phase system. The phase transition force-stable marginal curves constitute a limit or boundary which cannot be overstepped during a phase transition. **Key words**: non-equilibrium thermodynamics, liquid-vapor phase transition system, available energy, equilibrium stability

并联蒸发管内两相流密度波型脉动线性分相模型= **Linear Phase-separation Model for the Two-phase Flow Density-wave Type Pulsations in Parallel-connected Evaporating Tubes** [刊, 汉] /ZHOU Yun-long, HONG Wen-peng, ZHAO Xue-feng, et al (Energy &Mechanical Engineering College under the Northeast China Electric Power Institute, Jilin, China, Post Code: 132012) //Journal of Engineering for Thermal Energy &Power. —2005, 20(5). —489 ~491, 496

Methods for the theoretical analysis of two-phase flow density-wave type pulsations can be divided into two categories: 1. numerical analysis method and 2. approximate analysis method. Many academics have conducted a huge amount of research on the first method, while relatively little research has been undertaken on the second method. In particular, even less research by using the method of system control theory has been conducted to analyze the two-phase flow density-wave type pulsations. In view of this, the authors have employed the method of system control theory to study the above-mentioned pulsations, proposing a linear phase-separation model for describing the two-phase flow density-wave type pulsations in parallel-connected boiling tubes. A status-space expression for describing system stability has been derived. Calculations were performed to determine the impact of the variation of mass flow velocity, thermal load and system pressure on the characteristic root of a system characteristic equation. The results of the calculation indicate that the law governing the impact of various parameters on the density-wave type pulsation limit values is in agreement with that of the experimental values. **Key words**: parallel-connected evaporating tubes, two-phase flow, density wave, phase-separation model

烟气脱硫循环流化床内的温度分布与干燥特性= **Temperature Distribution and Drying Characteristics in a Flue Gas Desulfurization-based Circulating Fluidized Bed** [刊, 汉] /DONG Yong, MA Chun-yuan, WANG Wen-long, et al (Institute of Energy &Power Engineering under the Shandong University, Jinan, China, Post Code: 250061) //Journal of Engineering for Thermal Energy &Power. —2005, 20(5). —492 ~496

The adiabatic saturation temperature in a flue-gas circulating fluidized bed was analyzed. A device was designed for measuring the temperature in a flue gas desulfurization-based circulating fluidized bed. With the help of this device and on the flue-gas desulfurization pilot test rig measurements were taken of the temperature distribution of the flue gas and wet ball temperature distribution in the fluidized bed. The results of the measurements indicate that after the injection of humidifying water there exist in the circulating fluidized bed two different temperature fields, i.e., one being characterized by a gradual lowering of flue gas temperature and another one featuring a gradual rise of the humidifying water temperature. The flue gas temperature underwent two stages, namely, a rapid reduction and a slow reduction of temperature. However, the humidifying water experienced a rapid rise in temperature and then evaporated. Upon completion of the liquid-droplet drying process the flue gas temperature and the humidifying water temperature tend to coincide. Test results also indicate that the drying time of the atomized liquid droplet in the flue gas circulating fluidized bed is approximately 1.5 ~2.0 seconds. **Key words**: flue gas desulfurization, circulating fluidized bed, temperature distribution, drying time

循环流化床脱硫塔直/旋流复合流化下的两相流场试验研究= **Experimental Study of Two-phase Flows under the Composite Fluidization of Desulfurizer Straight/rotating Flows in a Circulating Fluidized Bed** [刊, 汉] /HAO Xiao-wen, MA Chun-yuan, ZHANG Li-qiang (Institute of Energy &Power Engineering under the Shandong University, Jinan, China, Post Code: 250061), HUANG Sheng-zhu (The School of Energy Science &Engineering under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy &Power. —2005, 20(5). —497 ~500, 505

The Venturi straight-flow fluidization speed of a circulating fluidized bed desulfurizer will change with a change in boiler load. This has a negative influence on desulfurization efficiency. The authors have come up with a straight/rotating flow

composite fluidization mode, which can adapt to boiler load variation. Moreover, a PDA (Phase Doppler Anemometer) measurement system was employed to test the gas-solid two-phase flow field under this kind of fluidization mode. As a result, the gas-solid tangential speed and concentration distribution were obtained under the condition of a change in swirl airflow and an imaginary tangential radius in the circulating fluidized bed. Test results indicate that the tangential velocity in the composite-fluidization circulating fluidized bed will increase with an increase in radius and the gas-solid tangential slip speed is higher than that of the straight flow fluidization. There will also be an increase in concentration in the desulfurizer and a higher intensity in internal circulation, resulting in a corresponding increase in desulfurizaion efficiency. **Key words**: circulating fluidized bed, composite fluidization, tangential velocity, internal circulation

旋涡式低温煤粉燃烧器的实验及其数值研究＝**Experimental and Numerical Study of a Swirl-type Low-temperature Pulverized-coal Burner** [刊, 汉] /ZHU Bo, WANG Xiao-han, YAN Chang-feng, et al (Guangzhou Institute of Energy Conversion under the Chinese Academy of Sciences, Guangzhou, China, Post Code: 510640) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —501 ~505

Based on the principle and flow field organization of air staged combustion aimed at reducing NO_x emissions the authors have designed a swirl-type low-temperature pulverized-coal burner featuring low NO_x emissions. By employing an experimental and numerical method a study was conducted of its flow field characteristics. The results of the study indicate that there is at the lower portion of the burner an intensive swirl flow zone, which can contribute to the formation of a reduction and burn-out zone required by the grading of air. As regards the primary and secondary air feeding location and mode there exists for the flow field organization an optimized proportioning option. The numerical simulation of a two-phase flow motion in the burner based on a RNG $k-\varepsilon$ model has reproduced the experimental results of the flow field, reflecting the motion law of particulates of various sizes in a zoned gas-flow field. **Key words**: swirl-type burner, coal combustion, air staged combustion, low NOx emissions

基于小波变换的气化燃烧状态诊断试验研究＝**Experimental Investigation of the Diagnosis of Gasified Combustion Status of a Wavelet-based Transformation** [刊, 汉] / LIANG Qin-feng, YU Guang-suo, NIU Miao-ren, et al (Research Institute of Clean Coal Technology under the East China University of Science &Technology, Shanghai, Post Code: 200237) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —506 ~508, 516

An effective method is proposed for analyzing through pressure signals the flame gasified combustion condition of an entrained flow gasifier. Under this method a scalar decomposition approach has been utilized to analyze furnace pressure time-domain signals. A study has revealed that in a cold state prior to ignition there exists no characteristics frequency. Under the condition of ignition and flame-extinction the pressure signals experience a step change with the signals at 0 Hz being subjected to a relatively great shock. In time of flame intensive fluctuations there exists a characteristic frequency of about 2 Hz. With the flame in a stable combustion state there will be a characteristic frequency of about 40 Hz. The above phenomenon indicates that within a certain range of frequencies the pressure signal distribution is closely related to the flame combustion condition in the gasified furnace. With the strengthening of flame combustion stability the pressure signals will shift in the direction of higher frequencies. **Key words**: wavelet transformation, entrained flow gasifier, flame, combustion diagnosis

中温下热解对半焦燃烧反应性的影响＝**The Impact of Medium-level Temperature Pyrolysis on Semicoke Combustion Reactivity** [刊, 汉] /LIU Yan-xia, LU Jun-fu, LI Yong, et al (Department of Thermal Energy Engineering under the Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —509 ~512

By employing the method of thermogravimetric analysis and powder X-ray diffraction measured respectively were the combustion reactivity and structural changes of the semicoke of two low-rank bituminous coals and one type of anthracite during the process of pyrolysis at 400 ~1400 ℃. The cause of the variation in reactivity of the low-rank coals was also dis-