

循环流化床中贴壁回探流的机理试验研究

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[摘要] 通过在循环流化床模型上 (高度 5.9 m, 内径 0.14 m) 进行的试验研究, 探讨了贴壁回探流的形成机理, 提出了贴壁回探流的物理模型。对工程设计和循环床理论研究都有意义。

关键词 贴壁回探流 循环流化床

中图分类号 TK 229.66

0 引言

循环流化床 (CFB) 内的流动结构早已被许多学者所关注^[1~4], 物料沿床内壁向下流动这一现象 (我们称其为贴壁回探流), 也被一些学者所发现, 但进一步的研究却仍很少。目前描写快速床内气固两相流动规律的模型可归纳为两大类, 一是密集体模型^[5], 颗粒在床中形成密集体, 由于密集体不断生成和解体, 在流化过程中就存在按扩散规律和因重力作用而下沉的运动, 形成强烈反混; 二是环核模型^[6], 认为稀相区床层中径向具有一定的颗粒密度梯度和速度梯度, 在壁面附近存在一个环形密相区, 该区内颗粒向下运动。在密集体模型中, 忽视壁面附近的物料回探下降流动; 在环核模型中, 虽然强调贴壁回探流的存在和作用, 但认为贴壁回探流的形成是由于环、核两区之间质量交换的结果。本文认为在快速床核心区有密集体形成, 在环核两区之间存在质量交换, 还认为 CFB 锅炉内反混强烈的主要原因是贴壁回探流造成的。贴壁回探流是核心区中物料碰到炉顶后, 受到阻碍反过来沿壁面向下流动而形成。本文通过详细的观测试验证明

了这一观点, 并在此基础上提出了一个物理模型。

1 试验设备

图 1 为试验台系统。除旋风分离器外, 其余部件均用有机玻璃制成。主床内径为 140 mm, 从布风板至物料出口中心线高为 5500 mm, 总高为 5900 mm。主床从床顶向下装有标尺, 一侧装有照明装置。空气经转子流量计进入风室, 再经布风板进入主床, 将主床内物料流化。空气携带物料进入旋风分离器, 被分离下来的物料经立管和 U 型回料器重新回到主床; 空气排入大气。在试验台相应部位装有各种测点和测孔。

试验用的物料为河砂, 其物性参数见表

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表 1 试验用物料的物性参数

孔径/mm	1.60	0.8	0.63	0.40	0.315	0.20	0.154
筛余/%	1.10	11.37	26.40	64.30	81.86	96.21	100
平均粒径 \bar{d}_p	0.5133 mm						
视比重 ρ_s	2570 kg/m ³						
堆放比重 ρ'_s	1580 kg/m ³						

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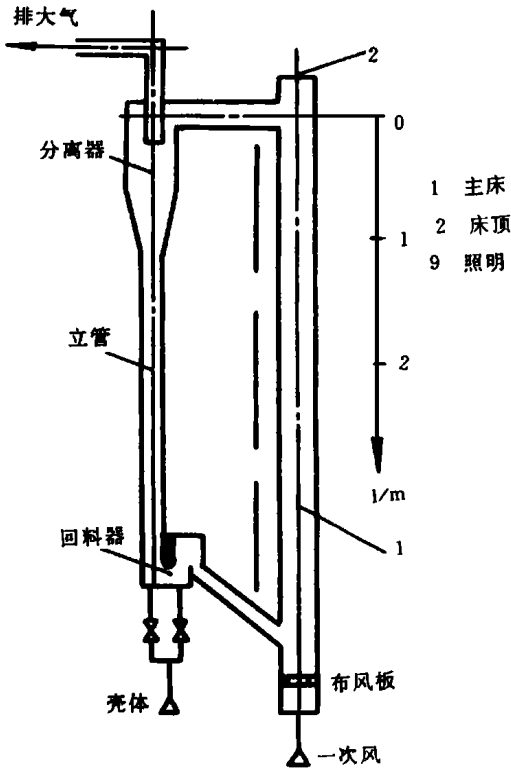


图 1 试验设备

2 试验结果和分析

2.1 观察结果

通过大量试验观察发现,在主床核心区
内气体携带大量物料以很高的速度向上运
动,当达到床顶时突然碰到阻碍,部分物料
被高速气流和物料托住,形成一层料垫,部
分物料则沿料垫表面流向四周,由于流场不
均一,物料以流束的型式流向四周,而且不
时地摆来摆去,碰到床壁面后转弯向下,形
成了贴壁回探流。由于与核心区内气体流动
方向相反,物料流束表面虽然有少量粒子离
开流束进入核心区,但大量的粒子是在流束
头部被上升气流剥离而进入核心区内的,流
束头部变圆变粗。在不同的操作条件下,贴
壁回探流向下流动的距离不同。如在空截面
气体流速一定的条件下,开始回料量较小,
只在床顶附近出现贴壁回探流,随回料量增

大贴壁回探流向下流动的距离增长,直至延
伸到密相区。在这一变化过程中,清楚地观
察到贴壁回探流头部表面存在强烈的传质
过程,流束头部变钝,大量物料被剥离而进
入核心区,当物料束流增大时,头部向下延
伸;当来流减少时,流束被气流削尖,甚至被
气流削掉。通常流束尾部横截面变得扁平,
相邻的流束连成一片。图 2 给出了流束头
部的照片。

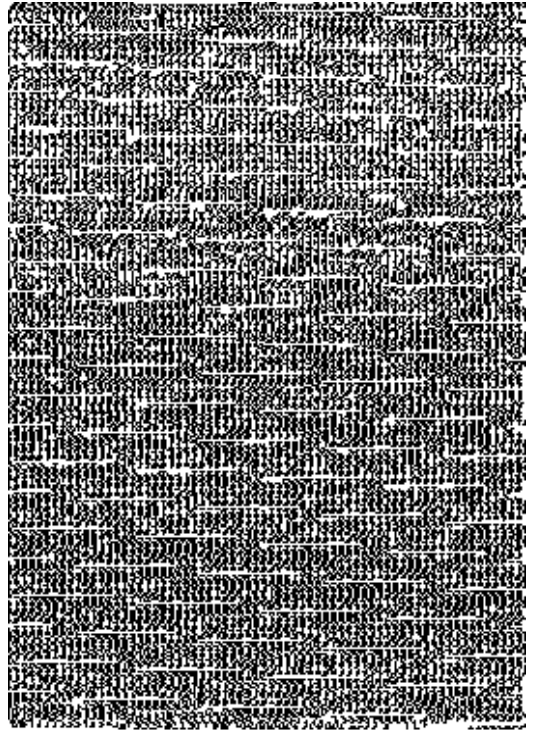


图 2 流束头部照片

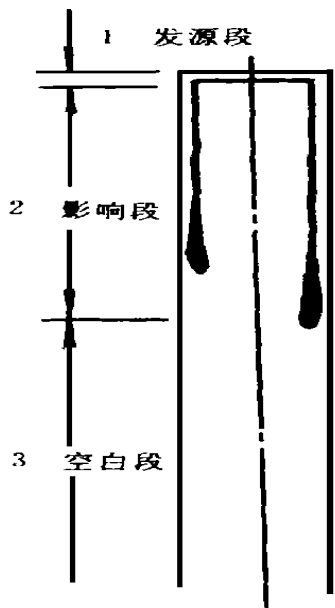
本文着重观察了从贴壁回探流开始出
现到最后延伸到密相区的这一变化过程,并
把主床沿高度分成了三段:

2.1.1 发源段 在这一段中核心区内的
高速气体和物料碰到床顶受阻,改变方向
沿料垫流向四周,达到壁面后转弯向下而形
成贴壁回探流;

2.1.2 影响段 发源段生成的贴壁回
探流沿壁面自上而下流动,操作条件不同,
贴壁回探流向下回探的距离也不同。有贴壁

回探流存在的区段称作影响段；

2.1.3 空白段 没有贴壁回探流的区段称作空白段。



这一流动模型示于图 3 根据上述观察,可以认为贴壁回探流的生成条件,除了要有足够大的回料量和流化速度,以保证具有足够高的动能外,壁面附近气体的低流速区的存在是形成贴壁回

图 3 贴壁回探流流动模型

探流的重要条件。

2.2 操作条件对贴壁回探流的影响

试验表明,贴壁回探流流过的路程(称作延伸长度 l),与主床操作速度、回料量有关。空截面流化速度越低,回料量越大,延伸长度就越长。由于实验中流束很明显,下探位置也很清楚,所以延伸长度可用主床边的标尺准确读出。回料量可根据稳定运行时立管中移动床移动速度(可在立管某处塞入示踪物测得)以及立管横截面尺寸和其中物料密度测得。同样,还观测了回料量不变时,延伸长度与主床流化速度的关系,在主床流化速度低于 7 m/s 时,延伸长度变化较大,而超过 7 m/s 时,流化速度的影响较小。

图 4 给出了延伸长度与流化速度和回料量的关系。可见 CFB 锅炉应保证一定的流化速度和与之相应的回料量。

2.3 核心区与贴壁回探流之间的传质

观察发现,在贴壁回探流向下流动过程中,除贴壁回探流头部外,流束表面被气体剥离进入核心区的粒子和从核心区进入贴壁回探流中的粒子都很少,而贴壁回探流头部粒子被剥离进入核心区的传质过程则十分强烈,受气流的作用流束头部变钝变粗,当发源地物料来流减弱时,流束立即缩回而消失,在消亡的过程中头部被削尖。当来流增大时,流束向下延伸。可见贴壁回探流不是核心区与贴壁回探流之间传质过程平衡的产物。

核心区与贴壁回探流之间的传质过程主要是头部粒子被剥离的过程。被剥离的粒子进入核心区后随气流上升,直至床顶又进入贴壁回探流。这样,就构成了 CFB 锅炉一种特有的内循环流动结构。如图 5 所示,在循环过程中,特别是在贴壁回探流头部表面,两相之间具有很大的相对速度,使燃烧过程强化;物料反复循环增大了物料在炉内的停留时间,有利于燃尽和提高燃烧效率。

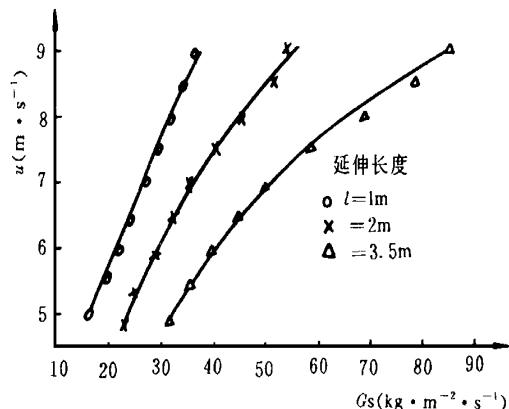


图 4 延伸长度与流化速度、回料量的关系

2.4 床顶结构对贴壁回探流的影响

既然床顶是贴壁回探流的发源地,床顶结构对贴壁回探流就应具有一定的影响。本文讨论了斜床顶和不同高度平床顶的试验结果,试验用的炉顶结构示于图 6。

试验表明,床顶结构对贴壁回探流有明显的影响。图 7 给出了平床顶和斜床顶

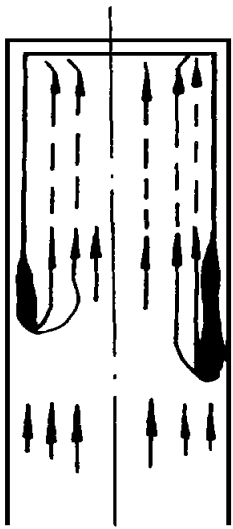


图 5 CFB 锅炉的内循环流动结构

(平均高度均为 0.16 m)对贴壁回探流延伸长度的影响比较,因斜床顶对流化介质和物料具有导向作用,所以较多的物料就随流化气体进入了分离器,因而延伸长度比平床顶短得多。图 7 还给出了不同高度平床顶的试验结果。如图所示,当回料流率均为 $25 \text{ kg}/(\text{m}^2 \cdot \text{s})$ 时,贴壁回探流的延伸长度分别为 0.9 1.85 和 4.35 m,床顶高度越高,延伸长度越长,要实现同样的延伸长度,床顶越高时所需回料量就越小。这就进一步证明了前述关于贴壁回探流的生成机理是正确的。床顶结构对贴壁回探流的影响,对 CFB 锅炉具有重要的工程应用价值。

3 结论

- (1)贴壁回探流发源于主床顶部;
- (2)贴壁回探流生成条件,除要求流化介质具有足够高的流化速度以使气体和固体物料具有足够的动能外,壁面附近气体低流速区的存在是一个重要条件;
- (3)核心区与贴壁回探流之间的传质过程,主要是贴壁回探流头部表面粒子被剥离进入核心区的过程;

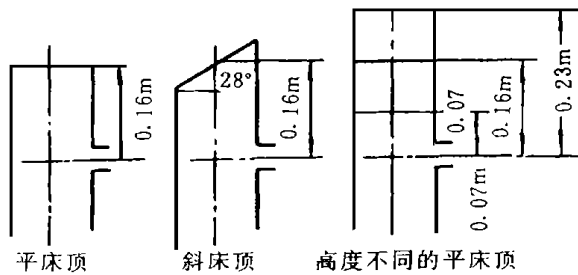


图 6 床顶结构

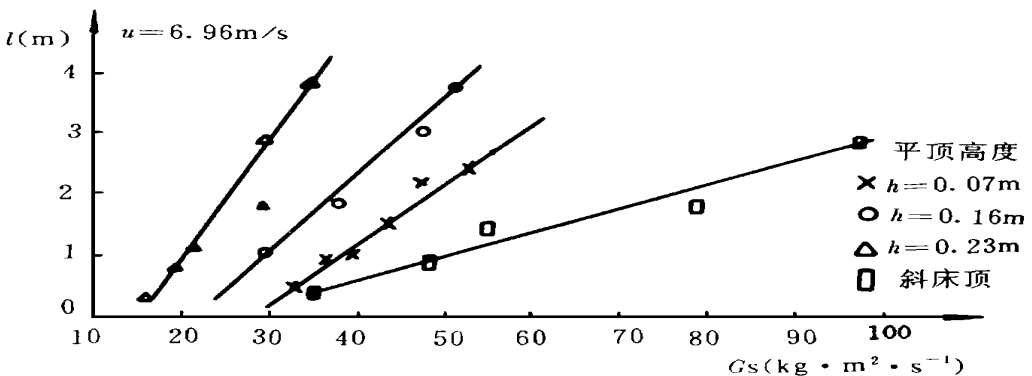


图 7 斜床顶和不同高度的平床顶对延伸长度的影响

(4)贴壁回探流沿壁面向下流动,直抵密相区,然后被流化介质携带向上流动,经核心区直抵床顶又进入了贴壁回探流,是CFB锅炉特有的物料内循环流动结构;

(5)CFB锅炉反混强烈主要是物料内循环流动的结果;

(6)CFB锅炉顶部结构对内循环流动有重要影响

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(渠源 编辑)

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(1)与低温供冷相结合 VAV系统降低新风负荷及显热换热器回收排风冷量使制冷系统运行费用降低

从上述分析可以看到,制冷系统负荷降低了 57 kW,考虑到系统低温制冷能效比 EER(将所有耗电设备折合在一起作为系统耗电,考虑到蓄冷器的冷损失后实际冷量作为产冷量)取为 2.0;每天相当于全负荷运行 13小时,节省运行电费: 74元/天。

(2)风机和泵降低的运行费用

风机和泵降低的运行功率为 22 kW,合计降低运行费用为: 330元/天。

(3)泵和风机本身的动力功耗转化热的降低

泵和风机本身的动力功耗最终转化为冷媒或风机冷风的热负荷,使冷媒温度或风机冷风温度升高,泵和风机总功率降低 22 kW,转化为运行电费为: 92元/天。

以上三项合计每天可节省 492元,大约占整个系统的运行费用的 20%。对工程技术方案我们详细地分析了上述设计方案的经济性:常规送风系统的增加投资回收期为 3~ 5年,而采用 VAV系统的蓄冰空调系统回收期为 2.5年左右,回收期明显降低^[5]。

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(渠源 编辑)

超临界直流锅炉启动过程汽水膨胀的研究 = **A Study of the Water Swell in Supercritical Once-through Boilers During Start-up** [刊, 中] / Yang Dong, Chen Tingkuan, Hou Shuhai, Bi Qingcheng (Xi'an Jiaotong University), Yang Zhongmin, Li Yongxing (Harbin Boiler Works) // Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -161~ 164

A mathematical model is set up for calculating the water swell in a supercritical pressure once-through boiler during its start-up. The model has been verified through tests and was used to calculate the water swell during a cold-state and hot-state start-up process in a 600 MW supercritical pressure once-through boiler designed and developed by Harbin Boiler Works. All the above has provided a basis for the design of boiler start-up systems and the drawing-up of start-up curves. **Key words** supercritical pressure, once-through boiler, water swell

三通型汽轮机电-压力转换器的研究 = **A Study of Three-way Electro-pressure Converter for a Steam Turbine Regulating System** [刊, 中] / Wei Jianhua (Zhejiang University) // Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -165~ 167

Described in this paper is the principle of an imported electro-pressure converter for use in a steam turbine regulating system. The electrical control principle and mechanical structure features of a home-made three-way electro-pressure converter are also discussed with its experimental curves presented. **Key words** steam turbine regulation, electro-hydraulic converter

汽轮发电机转子扭振模型修改 = **Modification of a Turbogenerator Rotor Torsional Vibration Model** [刊, 中] / Guo Li, Sheng Xiaomin (Hunan University), Cheng H S (American Northwestern University) // Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -168~ 170

In connection with the establishment of a precise turbogenerator rotor torsional vibration model this paper discusses the modification with the help of test-obtained incomplete modalities of a concentrated parametric model set up by a finite element method, making it within the required frequency range to coincide with the measured dynamic characteristics. Given in this paper are the results of calculation for a home-made 200 MW turbogenerator unit. **Key words** turbogenerator, rotor, torsional vibration

大港电厂 328 MW 汽轮机凝汽器数值模拟与特性分析 = **Numerical Simulation and Characteristics Analysis of 328 MW Turbine Condenser of Dagang Power Plant** [刊, 中] / Zhu Guangyu, Li Hongmei (Xi'an Jiaotong University), Tang Ming (Harbin No. 703 Research Institute) // Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -170~ 174

By the use of a numerical method calculated was the flow and heat transfer process on the condenser shell side of a 328 MW steam turbine condenser imported from Italy. An analysis is given of the rationality of the condenser design. The results of the analysis show that the layout of the condenser tube bank features rationality in certain aspects but there is room for improvement. Hence, the operating pressure may be slightly higher than the design pressure. **Key words** condenser, numerical simulation, analysis

蓄冰空调变风量系统工程可行性分析 = **The Analysis of Engineering Feasibility of VAV in an Ice Storage-assisted Air Conditioning System** [刊, 中] / Liu Zhenyan, Yu Guangbao, Ding Yihong (China National University of Science & Technology) // Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -175~ 177

Proposed in this paper is a new concept concerning the use of variable air flow rate air feeding system in the ice storage assisted air-conditioning system. An analytical study is performed of its engineering feasibility. The results of the study have shown that the setting-up of the variable air flow rate air feeding system in the above-cited air conditioning system will not only reduce the cold load but also lower operation cost. In addition, it can eliminate the major defect in the ice storage-assisted air conditioning system, namely the serious mismatching of loads. The authors have also through specific engineering cases analyzed engineering economics. **Key words** ice storage-assisted air conditioning, variable air flow, system feasibility

循环流化床中贴壁回探流的机理试验研究 = **An Experimental Study of Wall-adhered Return Flow Mechanism in a Circulating Fluidized Bed** [刊, 中] / Guang Xin, Niu Changshan, Gu Yaping, et al (Xi'an Jiaotong

University) // Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -178~ 182

Through an experimental study conducted on a circulating fluidized bed model (height 5.9 m, inner diameter 0.14 m) the formation mechanism of a wall-adhered return flow was explored and discussed with a physical model of the wall-adhered return flow proposed. The above work is meaningful for both engineering design and theoretical research of circulating fluidized beds. **Key words** wall-adhered return flow, circulating fluidized bed

《热能动力工程》引文分析和研究 = **Analysis and Study of the Engineering Literature Citations of "Journal of Engineering for Thermal Energy & Power"** [刊, 中] / Huang Mao Lin (Harbin Institute of Technology)

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逆算法对涡轮特性柯特略尔估算的改进 = **An Improvement on Kotliar Prediction of Turbine Performance by the Use of an Inverse Computation Method** [刊, 中] / Xie Zhiwu, Wang Yonghong, Hong Bo, Chen Delai

(Shanghai Jiaotong University) // Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -185~ 188

Taking Kotliar method as an example, this paper discusses the applicability of an inverse computation method for the calculation of stage superimposed type turbine performance. It has been proved that the last stage first stagnation hypothesis can be naturally fulfilled under the condition of identical design pressure ratio for each corrected stage. In case of the design pressure ratio for each corrected stage not identical given are ascertainment criteria for finding the first stagnant stage. In addition, the use of a combined sequential-inverse computation method is proposed for the treatment of critical issues, thus making a breakthrough regarding the last stage first stage hypothesis. Computation procedures have been optimized, resulting in an enhancement in evaluation precision. **Key words** turbine, inverse computation method, Kotliar method

弯曲叶片涡轮叶栅二次流损失计算经验模型 = **An Empirical Model for Calculating Secondary Flow Losses of Curved Blade Turbine Cascades** [刊, 中] / Yu Qing (Beijing University of Aeronautics and Astronautics)

// Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -189~ 192

On the basis of the experimental data analysis of inclined and composite curved plane cascades the author has come up with a secondary flow loss calculation model applicable for turbine cascades of curve-twist aerodynamically formed design. This model reflects the effect of such factors as blade inclination angle, aspect ratio, cascade solidity on the magnitude and distribution mechanism of secondary losses. With the help of this model evaluated in advance are the losses of a small aspect ratio gas turbine guide vane device under two forms of blades, i. e. straight and curved. The model-calculated values are in good agreement with those of the test and measuring results. **Key words** curved blades, turbine cascade, secondary loss model

恒热流竖壁降膜发展段流动换热分析 = **Flow Heat Exchange Analysis of Constant Heat Flow Vertical Wall Downcoming Liquid Film Development Section** [刊, 中] / Shi Jinsheng, Shi Mingheng (Southeastern University)

// Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -193~ 195

With the help of a boundary layer analogous solution an analysis is conducted of the laminar flow and heat exchange characteristics in the constant heat flow vertical wall downcoming liquid film development section. Obtained is the calculation expression of the development section length, liquid film thickness and non-dimensional heat exchange factor. **Key words** downcoming film, development section, speed boundary layer, temperature boundary layer

NG-130/39-M₂型锅炉的节能技术改造与运行 = **Energy Saving-oriented Technical Modification and Operation of a Model NG-130/39-M₂ Boiler** [刊, 中] / Cheng Qingang, Bao Yanjun, Zhang Guojun, et al (Harbin Power Equipment Design Institute)

// Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -196~ 199

Through the tests of a NG-130/39-M₂ boiler installed at a thermal power plant and its pulverized coal system, analyzed are some causes leading to the excessively high fly ash and slag combustible content and ex-