# 循环流化床气固两相间传热特性的实验研究

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〔摘要〕在小型实验台上用双热电偶测温法测定床层温度。实验表明:气固间传热主要在循环床下半部进行;同时气体表观流速提高、颗粒循环率增大及颗粒粒径减小有利于气固两相间的传热,获得了相应的无因次方程。

关键词　循环流化床　气相　固相　传热
分类号　TK229.66

## 0 前言

循环流态化技术作为一门基础技术学科已渗透到化工、石油、轻工、能源、冶金、材料、机械和环保等领域。一般认为:由于循环流化床中气固两相间的强烈混合及良好接触,使气体与颗粒、颗粒与颗粒之间的传热在瞬间达到热平衡,因而文献中大量报道了床层与换热表面的传热研究,而忽略了气固两相间的传热。此外,现有文献中提到的流化颗粒大多集中在 Geldart′A类,而对 Geldart′B类等粗颗粒的研究报告很少见。在许多流化床实际工艺操作过程中,如干燥、气固反应生成气相产物或固相产物、造粒、颗粒表面包裹、颗粒直径发生显著变化等都会出现湿颗粒的混合、传热、传质问题。实验结果表明:这时一般性的瞬间热平衡的假定与实际情况就有很大的差异。显然,这种新条件下的气固两相间传热问题的研究就变得极为重要。

本文试图探讨在不同的气体表观流速、固体颗粒循环率及不同粒径的非饱和含湿颗粒的条件下,循环流化床内气固两相间的传热特性。

## 1 实验装置及操作

### 1.1 实验装置

图 1给出了实验设备及系统示意图。循环流化床本体高 3 m,内径 0.1 m,与下降管 3构成了气固两相流的主要回路。由叶氏风机供给的空气分两路进入循环床本体。一路是流化空气的主流,从本体下方直接经气固混合喷射器(7)进入本体;另一路空气经循环喷射器(7′)将经下降管回收的固体颗粒送入气固混合喷射器,然后进入本体。实验中湿物料通过

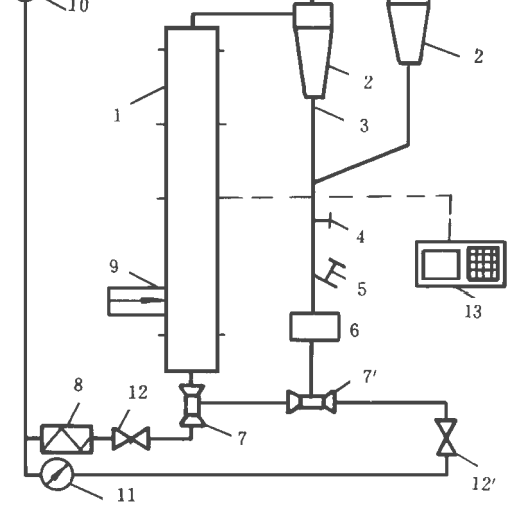


图 1 循环流化床设备和系统

1.循环床本体　2.旋风分离器　3.下降管　4.蝶阀
5.出料口　6.贮料箱　7.混合喷射器　7′循环喷射器
8.电加热器　9.加料器　10.孔板流量计　11.转子流量计
12.阀门　12′阀门　13.数据采集系统

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螺旋加料机(9)连续不断地加入到循环床本体中。

实验中,沿循环床本体高度,每隔 20 cm设有一对左右两侧对称的测试孔,用来埋装热电偶,以测定床层中气固两相温度。所有热电偶均接到 3497A 型数据采集系统上。

**1.2** 床层温度的测定

循环床内气体和固体两相温度测定,是本次实验的关键,为此,本实验采用双热电偶参考标定法[1]测量床层温度。热电偶有两种形式:裸露的和带有网罩的热电偶。网罩式热电偶探头四周覆盖一层金属丝网罩,可以避免颗料与热电偶直接碰撞,该热电偶只能与气体换热。网罩式热电偶输出信号 $t_a$ 可以作为床层中气体温度的参考值,而在同一位置上的另一裸露热电偶输出信号 $t_b$ 则反映了气固两相共同作用,该信号的波峰波谷给出了气相温度与固相温度的极限值。

图 2给出了一个典型的裸露热电偶输出信号。分析该信号可知,温度曲线上的波峰是相应颗粒尚未与探头再次碰撞或撞后颗粒已离开热电偶期间热电偶所显示的温度。此刻,探头主要受空气对流换热的影响,因此,可以认为温度峰值对应着一定时刻热电偶所在位置的气体温度。实验数据表明,各时刻测得的峰值尚有高低,显然这是由于颗粒与热电偶探头的置换频率是随机的及热电偶恢复平衡的差异所

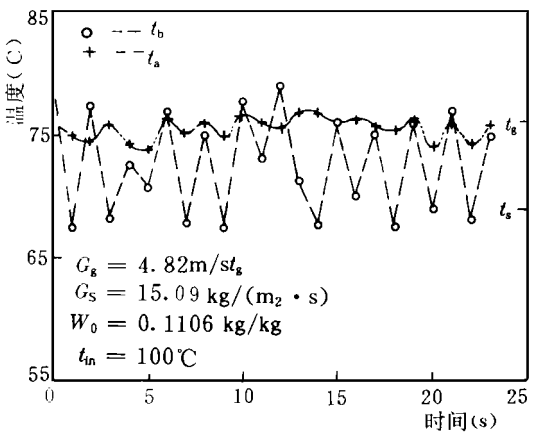


图 2 典型热电偶探头输出信号

引起的。为此利用有金属网罩热电偶信号作参考。对于那些峰值低于网罩热电偶所显示值的波峰,被认为是颗粒离开热电偶之后,热电偶探头尚未与热空气达到平衡时,就有新的颗粒碰撞探头,造成温度下降,所以把这些峰值全部不考虑。然后对所有超过网罩热电偶信号值的波峰进行统计平均,求出局部气流温度 $t_g$。基于同样原因,对高于裸露热电偶全部信号平均得到的温度值的高波谷,可不考虑。然后对所有低于该平均值的波谷再进行平均,求出局部颗料的温度 $t_s$。

**1.3** 实验物料及工况

实验中被流化的砂粒特性见表 1,含湿量均为 0.1 kg/kg

表 1 实验用砂粒的特性

| 粒径 μm | 密度 kg/m$^3$ | Geldart分类 |
|---|---|---|
| 140 | 2625 | B |
| 245 | 2625 | B |
| 387 | 2625 | B |
| 592 | 2625 | B |
| 866 | 2625 | D |

热空气进入床层的温度为 100℃,气体表观流速取五个工况:4.13 m/s 5.22 m/s 6.13 m/s 6.92 m/s 7.62 m/s,颗粒循环率取两个工况:9.01 kg/(m$^2$· s)、14.4 kg/(m$^2$· s)。

实验开始时,先将空气的流速、温度及底料调整到所需的稳定状态。然后湿颗粒由螺旋加料机连续地送入床层;同时干燥后的颗粒以恒定质量流速(与进口质量流速一致)从下降管出口处排出。当系统实验工况进入连续稳定的工况时,可以进行各参数的测定。

## 2 实验结果与分析

**2.1** 气固两相温度的变化规律

2.1.1 气体表观流速对气固两相温度变化的影响

由图 3可见:在颗粒粒径、固相循环率不变化的情况下,随着气体表观流速提高,气相温度曲线整体升高,固相的温度曲线也相应整体提高。随着表观流速的提高,气体单位时间质量流量增大,同时在床层内加强了气固两相的混合与扰动;强化了气固间的对流换热,所以使相应的气体、颗粒温度曲线均上升。

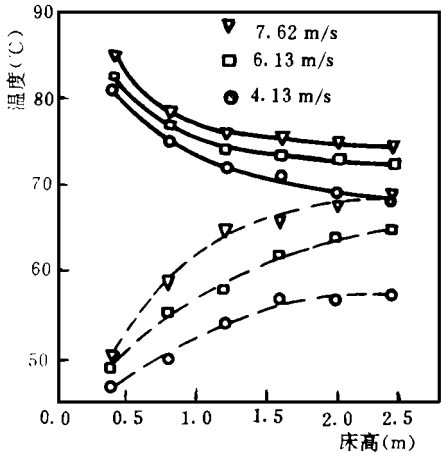


图 3　不同气体表观流速下气、固两相温度的轴向分布

颗粒粒径　141μm　颗粒循环率　9.01kg/(m²° s)
实线— 气相温度　虚线— 固相温度

2.1.2　颗粒循环率对气固两相温度变化的影响

由图 4可见: 在其它条件不变情况下,颗粒循环率提高,对应的气相温度降低,固相温度降低。这是因为随着颗粒循环率的提高,空隙率随之减小,增强了气相向固相的传热,造成气相温度下降;同时单位质量颗粒的吸热减少,所以固相温度也下降。

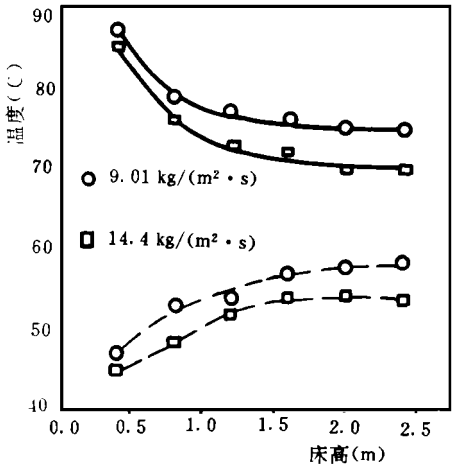


图 4　不同颗粒循环率下气固两相温度轴向分布

颗粒粒径　387μm　气体表观流速　6.13 m/s
实线— 气相温度　虚线— 固相温度

2.13　颗粒粒径对气固两相温度变化影响

由图 5可见: 随着颗粒粒径增大,对应的气相温度提高,固相温度下降。这是因为粒径增大,床层内单位体积内的颗粒表面积减少,此外,粒径变大,不利于颗粒聚集,减少了返混程度,这些都不利于气、固间热量交换,这样,随着颗粒粒径增大,使相应的气相与固相间的温差越来越大。

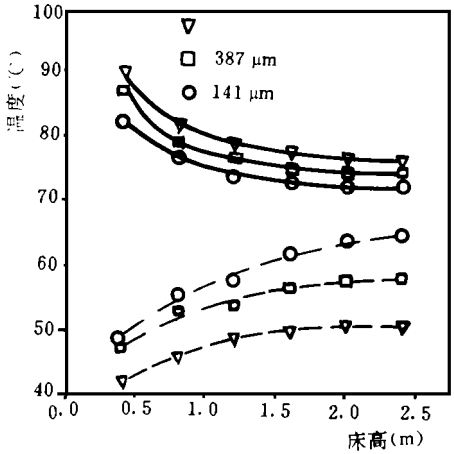


图 5　不同颗粒粒径情况下气、固两相温度的轴向分布

气体表观流速　6.13 m/s　颗粒循环率
9.01 kg/(m²° s)　实线— 气相温度　虚线— 固相温度

**2.2**　气、固间换热系数变化规律

2.2.1　气体表观流速的影响

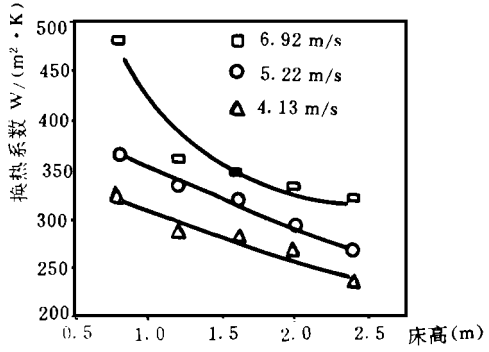


图 6　不同气体表观流速下换热系数轴向分布

颗粒粒径 378μm
固体颗粒循环率 9.01 kg/(m²° s)

气体表观流速增大,相同高度的换热系数随之增大,其增幅在床层下部比较明显(见图 6)。这是因为:对粗湿颗粒来说,气流速度增大对床层下部颗粒浓度减少程度较弱;而同时对湿颗粒之间的粘附有抑制作用,使湿颗粒在碰撞之后易于被吹散,同时气固对流换热增强。因此传热系数明显增大。在床层上部,当气速增大时,气固间对流作用增强,但同时由于颗粒浓度减小,又使气固接触减弱,因此,传热系数增幅变化不大,并趋于均匀。

2.2.2 颗粒循环率的影响

在其它条件不变的情况下,颗粒循环率提高,其对应的换热系数也提高(见图 7)。由于循环率提高,床层内颗粒浓度增大,加强了气固混合和接触;增强了气固间对流换热。

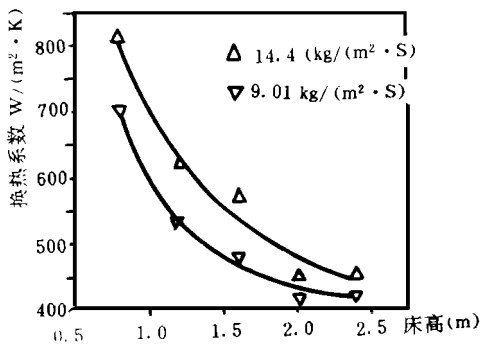


图 7 不同固体颗粒循环率下换热系数轴向分布

颗粒粒径 141μm

气体表观流速 4.13 m/s

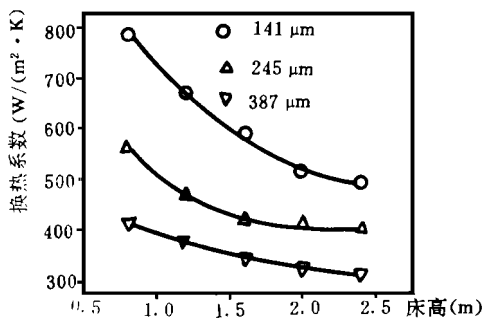


图 8 不同固体颗粒粒径情况下换热系数轴向分布

气体表观流速 5.22 m/s;

颗粒循环率 14.4 kg/(m²·s)

2.2.3 颗粒粒径的影响

当颗粒粒径减小时,同一床层高度对应的换热系数增大(见图 8)。这是因为粒径减小时,床层单位体积内气固换热表面积增大;有利于床层内颗粒聚集,增强了返混程度;同时颗粒浓度相应增大,强化了气固间换热。

**2.3** 气固两相间传热准则关系式

循环床区别于普通流化床的主要特点在于固体颗粒的循环运动和颗粒在不同高度的返混作用[2]。因此,在传热关联式中除了通常的流动参数外,还需要反映该两个重要因素的影响。为此引入两个新的无因次参数:$G_{gs}$为气体质量流率和颗粒循环率的比值;$H_L(1-L/h)$为床层某一截面高度 $L$ 和床层总高度 $h$ 的比值。

最终气固两相间传热准则关系式为:

$$Nu_P = 5.5\times 10^{-6} Re_P^{1.428} h_L^{-1.19} G_{gs}^{-0.392} D_0^{-1.266} \quad (1)$$

式中 $Nu_P = h\cdot d_P/\lambda_g$ 努塞尔数

$Re_P = u_g\cdot d_P/\nu_g$ 雷诺数

$D_0 = d_P/D$ 颗粒粒径与床层直径比

经验证,式(1)与实验值平均偏差在 15% 内。适用范围:热空气进口温度 100℃、颗粒含湿量 0.1 kg/kg,4.13≤ $u_g$ ≤7.62 m/s,9.01≤ $G_s$ ≤14.4 kg/(m²·s),0.14 mm≤ $d_P$ ≤0.87 mm。

## 3 结论

(1)循环流化床中气固两相温差沿床层高度逐渐减小,且两相温度变化主要在床层下半部。

(2)在同一床层高度,气体表观流速提高、颗粒粒径减小及颗粒循环率减小有利于固相温度提高。

(3)循环流化床中,气固两相间的传热系数沿轴向高度逐渐减小。

(4)在同一床层高度,气体表观流速提高,颗粒循环率增大,粒径减小将导致气固间换热系数变大。

(5)获得了适用于本实验工况的气固两相传热的准则方程。

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2 白西荣,金 涌等.化学反应工程与工艺,1991(9)

(乡复 编辑)

count. By employing a finite-element flexibility matrix method the authors have drawn up a set of rigidity calculation procedures, providing the relationship between the momentary meshing rigidity variation rate and axial congruence during the axial gear meshing process. On the basis of the rigidity calculation and by utilizing the optimization concept of inner point penalty function method a full set of calculation procedures for gear shape modification was prepared and an in-depth study of the tooth profile modification of helical gears conducted. **Key words**: momentary meshing rigidity, tooth profile modification, flexibility matrix, inner point penalty function

管内在线防垢及强化传热的实验研究= **An Experimental Study of On-line Fouling Prevention Inside Tubes and the Intensification of Heat Transfer**〔刊,中〕/Xiao Hongliang, Zhu Dongsheng, Tan Yingke(South China University of Science & Technology) //Journal of Engineering for Thermal Energy & Power. – 1997, 12(4), – 275~ 277

With saturated $CaCO_3$ serving as a material a study is conducted of the fouling prevention, heat transfer augmentation and structural parameters of a moving spring coil in a heater tube as well as the interrelated effects of operating variables. The paper discusses and presents the experimental study results of anti-fouling and heat transfer intensification mechanism with a theoretical basis for the said results being given. **Key words**: heater, inserted object, scale-formation, intensified heat transfer

碳酸钙分解的试验研究= **An Experimental Study on the Decomposition of Calcium Carbonate**〔刊,中〕/Yu Zhaonan(Zhejiang University) //Journal of Engineering for Thermal Energy & Power. – 1997, 12(4). – 278~ 280

By the use of a high-precision thermobalance an experimental study was performed of the decomposition of small particles of $CaCO_3$, resulting in a clarification of the effect of particle size, heating rate and impurities on the decomposition of $CaCO_3$. The mechanism of the above-cited decomposition was studied with an interpretation given for such phenomena. **Key words**: calcium carbonate, decomposition, test

青山烟煤及其燃后飞灰中有机污染物分布的研究= **An Investigation of the Distribution of Organic Pollutants from Qingshan Bituminous Coal and its Post-combustion Fly Ash**〔刊,中〕/Xu Minghou, Yan Rong, Long Yuxuan, Hao Liang(Huazhong University of Science & Technology) //Journal of Engineering for Thermal Energy & Power, – 1997, 12(4), – 281~ 284

With the help of a GC/MDS system determined from the extractive solutions of 7 hours, 16 hours and 24 hours the sort and content of such a variety of organic pollutants as aliphatic chains, benzene families and polycyclic aromatic hydrocarbons(PAHs), and obtained are the distribution characteristics of the organic pollutants of Qingshan bituminous coal and its fly ash products. The test results show that there are several kinds of organic pollutants, especially PAHs, in the raw coal itself. The different sorts and content of benzene families in the fly ash will increase while those of the PAHs decrease following the combustion of the raw coal. The rational organization of the combustion process can play a significant role in achieving a decrease in organic pollutants. **Key words**: bituminous coal, combustion product, organic pollutants, measurement, distribution characteristics, fly ash

循环流化床气固两相间传热特性的实验研究= **An Experimental Study of Gas/Solid Interphase Heat Transfer Characteristics of a Circulating Fluidized Bed**〔刊,中〕/Zheng Shouzhong, Lu Feng, et al(Southeastern University) //Journal of Engineering for Thermal Energy & Power. –1997, 12(4). –285~ 288

On a small-sized test stand and by using a dual thermocouple temperature measuring method determined is the temperature of a fluidized-bed layer. The test results show that the gas/solid interphase heat transfer mainly takes place in the lower half portion of the circulating bed. The increase in gas apparent flow speed, the

enhanced circulating rate of particles and the decrease in particle diameter will be beneficial to the gas/solid interphase heat transfer. Also obtained is a corresponding dimensionless equation. **Key words**: circulating fluidized bed, gas phase, solid phase, heat transfer

隔膜式气压给水设备的节能研究= **A Study on the Energy-saving of Diaphragm Air-pressure Water Supply Installation**〔刊,中〕/Wu Xifu(Zhejiang Industrial University)//Journal of Engineering for Thermal Energy & Power.- 1997,12(4).- 289~291

On the basis of energy consumption test of a diaphragm variable-pressure and constant-pressure water supply installation energy-saving analyses are performed with respect to the air feeding of air compressors, the utilization of exhaust gas, the selection of water pumps and the number of times of water pump startups. Energy-saving measures are proposed. All the above can serve as a guide for design and operation management. **Key words**: diaphragm type, water supply installation, energy-saving

复杂换热器系统的动态特性计算= **Calculation of the Dynamic Characteristics of a Complex Heat Exchanger System**〔刊,中〕/Li Zheng, Sun Xin, Ni Weidou(Tsinghua University)//Journal of Engineering for Thermal Energy & Power.- 1997,12(4).- 292~296

This paper deals with a method for calculating the dynamic characteristics of a complex heat exchanger system, which was developed during the modelling and simulation of a 220 t/h home-made CFB boiler. Based on an approximate analytical solution the said method significantly enhances the calculation speed and solves the problem of non-convergence during calculations. A decoupling method has been adopted, Which separates the balance calculation of cold and hot working mediums, making it possible to completely avoid iterative computations. By combining the approximate analytical solutions and the decoupling calculation method established is a set of generalized method for calculating the dynamic behavior of heat exchanger systems, thereby providing a general-purpose, high-efficient and simple calculation method for complex heat exchangers. **Key words**: natural circulation boiler, heat exchanger, dynamic characteristics, calculation

再热抽汽式汽轮机中压缸末级叶片压差保护控制= **Differential-pressure Security Control of the Last-stage Blades of a Reheat Extraction Steam Turbine Intermediate-pressure Cylinder**〔刊,中〕/Yu Daren, Wang Xitian, et al(Harbin Institute of Technology)//Journal of Engineering for Thermal Energy & Power.- 1997,12(4).- 297~299

Discussed in this paper is the differential-pressure security control of the last-stage blades of a reheat extraction steam turbine intermediate-pressure cylinder. Through an analysis of the simulation results of a mathematical model basic measures for the blade differential-pressure security control have been summed up. **Key words**: reheat extraction steam turbine, blade, differential-pressure security control

螺旋板稳定性分析和计算= **The Analysis and Calculation of a Spiral Plate Stability**〔刊,中〕/Zhou Chuanyue, et al.(Harbin No. 703 Research Institute)//Journal of Engineering for Thermal Energy & Power.- 1997,12(4)-300~303

Based on a classical linear elastic stability theory the authors have set up a mechanics model for stability analysis of a spacing column-supported spiral plate. A theoretical formula for calculating the theoretical pressure of a critical pressure has been derived with some engineering calculation examples being presented. Some conclusions helpful for performing engineering design are also proposed. **Key words**: spiral plate, stability, critical pressure

综合似然率(GLR)试验在传感器故障检测中的应用= Application of a Generalized Likelihood Ratio(GLR) Test in Sensor Failure Detection〔刊,中〕/Huang Shanheng, Zhu Qiaobin, et al(Shanghai Jiaotong University)//Journal of Engineering for Thermal Energy & Power.- 1997,12(4).- 304~306