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方柱体与圆柱体气液两相涡街特性的研究

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摘　要: 气液两相流体在垂直上升矩形截面管道内横向冲刷水平布置的柱体时, 一定条件下会在柱体后面产生旋涡交替脱落现象。利用管壁压差法来研究气液两相流横掠圆柱体和方柱体时的旋涡脱落特性, 得到了涡街的脱落频率和斯特罗哈数的变化情况。实验中雷诺数的范围为 $0.9\times10^4\sim2.3\times10^4$, 截面含气率的范围为 0～0.2。实验结果表明: 在一定的含气率范围内, 两种柱体涡街的脱落频率与斯特罗哈数都随着截面含气率的增大而增大; 方柱体斯特罗哈数增大的梯度与雷诺数无关, 圆柱体斯特罗哈数增大的梯度受雷诺数的影响。

关　键　词: 气液两相流; 管壁压差法; 方柱体; 圆柱体; 涡街

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引　言

气液两相流绕流柱体的现象普遍存在于许多具有热交换的设备中, 当流体在一定工况下流过非流线型柱体时, 旋涡会在柱体后面周期性地产生并脱落, 诱使柱体产生振动。随着工业技术的不断发展, 各种工业设备的容量及尺寸越来越趋于大型化, 在电厂凝汽器、核电站轻水反应堆燃料棒子通道间及其它存在相变的换热设备中, 发生流体诱导柱体振动的例子也比较多, 其结果是造成换热器管子破裂、磨损和弯曲变形等。特别是当旋涡的脱落频率同结构的固有频率相接近时, 就会激起结构物的共振导致严重的破坏, 大大缩短了工业设备的使用寿命, 甚至造成难以估计的后果。因此, 掌握气液两相流绕流的特性对工程实际和工业设备的设计非常重要, 这一问题已经引起了人们的极大关注。

在气液两相流中, 由于气泡的存在使得气液两相流体绕流柱体的流动变得更加复杂, 如气泡对柱体的撞击作用、气泡对边界层和旋涡脱落的影响, 以及气泡被吸入旋涡等都会使柱体两侧旋涡的脱落、卡门涡街的形成、涡街的结构及稳定性、两相斯特罗哈数与单相流中的情况有很大的不同。由于气液两相流动与被绕流柱体相互用的复杂性, 只有 Vickery、Hulin、Yokosawa、卢家才、谢正武、林宗虎、周云龙等人开展了对气液两相流绕流的研究[1~8]。为了更清楚地了解两相流绕流柱体的旋涡脱落特性, 本研究选择圆柱体和方柱体作为绕流的对象来对比分析。

1　实验系统及方法

1.1　实验系统装置

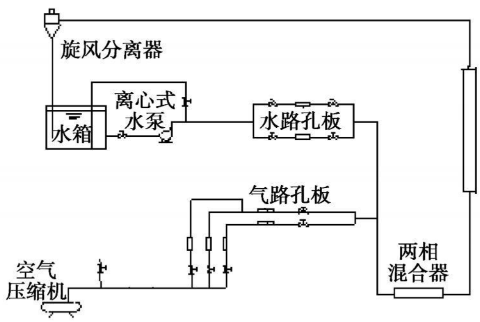

图 1　空气－水两相实验系统图

本实验是在自建的空气—水两相流通用实验台上进行的, 实验系统如图 1 所示。由水和压缩空气组成气液两相实验工质。水经水泵从水箱中抽出, 用旁路调节结合调节阀来调节回路的水流量, 并用电磁流量计测量流量。压缩空气由 SA—22A 螺杆式空气压缩机提供, 其流量测量分两部分, 大流量采用 Rosemount 405P 孔板流量变送器测量, 小流量采用玻璃转子流量计测量。空气和水在混合器中混合后经特制筛板形成细泡状流, 并垂直向上依次流过扩展段、整流格栅、实验段和收缩段后进入气水分离器, 压缩空气直接排入大气, 而水则流回水箱以供循环使用。实验中雷诺数的范围为 $0.9\times10^4\sim2.3$

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$\times 10^4$，截面含气率的范围为 0～0.2。

实验段为长 0.7 m，截面 180 mm×65 mm 的矩形截面管道，管壁由厚度为 10 mm 的透明有机玻璃板制成，以便于观察两相绕流工况及流场结构情况。本课题研究的圆柱体直径为 35 mm，方柱体截面边长为 20 mm，均以有机玻璃棒制成，表面光洁，水平放置于实验段中。实验中采用管壁压差法来检测尾流中贴近管壁处压差周期变化的频率来检测旋涡脱落频率，为了便于检测，采用管壁两侧取压方式，取压点靠近涡街发生体的迎流面，并且两侧对称布置，这样压差幅值是单侧取压的 2 倍[9]。压差法测量装置如图 2 所示。

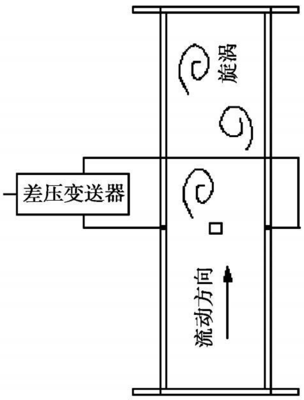


图 2　压差法测量旋涡脱落频率

实验中流量、压力和温度数据由 IMP3595C 数据采集系统采集，采集频率为 1 Hz，采样时间为 20 s。两相流体绕流柱体后的管壁压差波动信号用 ROSEMOUNT3051 压差变送器测量，并由 INV306 型智能信号采集系统采集，动态数据的采集频率为 256 Hz，这大大超过了涡街的发生频率，相邻两个采样点之间的时间间隔是 0.003 9 s，采样时间为 16 s。对得到的压差信号放大后进入 A/D 板采样，转换为数字信号直接利用计算机采集。

1.2　实验数据处理方法

为简化起见，在定义和计算两相流动参数时假设两相流体是均匀混合的。

气液两相流平均流速 u_m 的计算：

$$u_m = (Q_g + Q_l)/A \tag{1}$$

式中：Q_g—气相体积流量，由于气体体积受压力和温度的影响比较大，Q_g 值由流量计测得的流量用状态方程修正后的值；Q_l—液相体积流量；A—矩形截面管的流通面积。

气液两相流 Re 数的计算：

$$Re = u_m D / \nu_l \tag{2}$$

式中：D—涡街发生体的迎流面宽度，对于圆柱体迎流面宽度等于圆柱体直径，方柱体迎流面宽度等于方柱体的截面边长；ν_l—液相的运动粘度，之所以采用 ν_l 是因为覆盖在柱体表面的液体层比边界层厚数倍[3]。

气液两相流斯特罗哈数 St 的计算：

$$St = fD/u_m \tag{3}$$

式中：f—涡街发生频率。

气液两相流截面含气率 α 的计算，采用阿尔曼特(APMAHД)的计算方法[10]：

$$\alpha = C\beta = C \cdot \frac{Q_g}{Q_g + Q_l} \tag{4}$$

式中：$C = 0.883$；β—体积含气率。

2　实验结果及讨论

实验中实际测得的压差波动信号包含多种信号成分，除了旋涡脱落引起的压差波动信号外，还有由于流体本身的紊流脉动和两相流体中气泡的随机运动引起的压差波动成分等，但这些压差波动成分的频率都比较高，可以很容易通过低通滤波器的方法滤掉。滤波后的低频信号成分也存在有各种不同的频率和幅度，管壁两侧的压差波动主要是由涡街从柱体表面交替脱落引起的，其余的压差波动成分可视为干扰信号[11]。图 3 和图 4 分别为圆柱体和方柱体在 $Re = 1.74\times10^4$、$\alpha = 0.07$ 时经过滤波去噪后的管壁压差信号图。

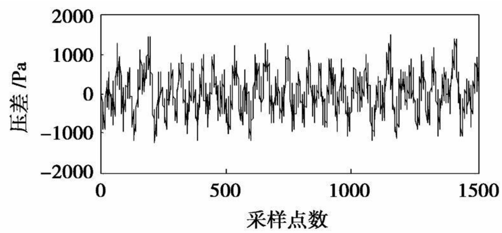


图 3　圆柱体管壁压差信号

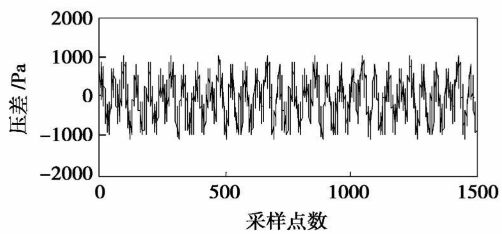
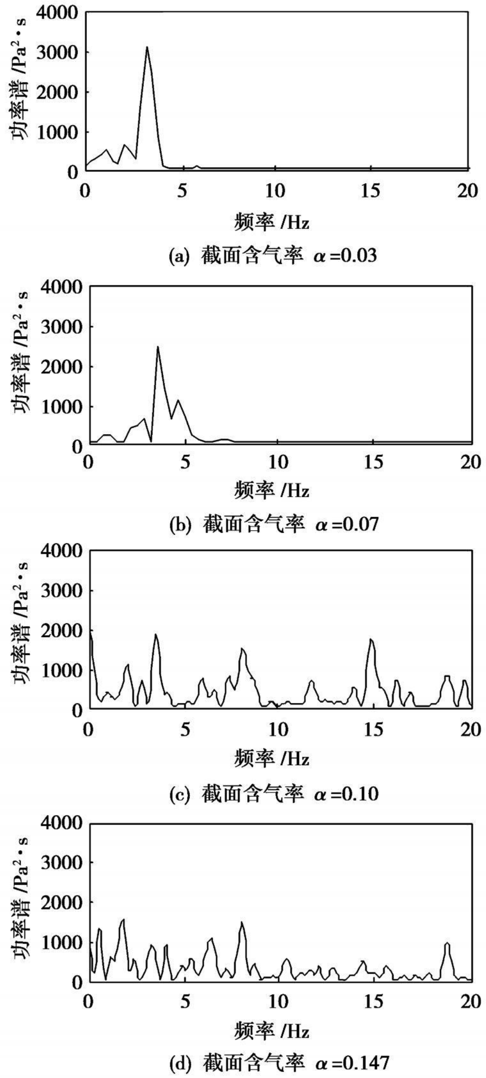


图 4　方柱体管壁压差信号

自功率谱密度函数(简称功率谱)可以通过对动

态数据直接进行快速傅里叶变换得到,对压差信号进行功率谱分析,可以很方便地检验出随机压差信号中包含的周期性波动[12]。由于压差信号主要是由旋涡脱落引起的,其变化的频率与旋涡脱落的频率一致,所以压差功率谱上的尖峰频率就对应于涡街自柱体表面脱落的频率,而峰值则对应涡街能量的强弱[13]。

2.1 截面含气率对脱落频率的影响



(a) 截面含气率 α=0.03

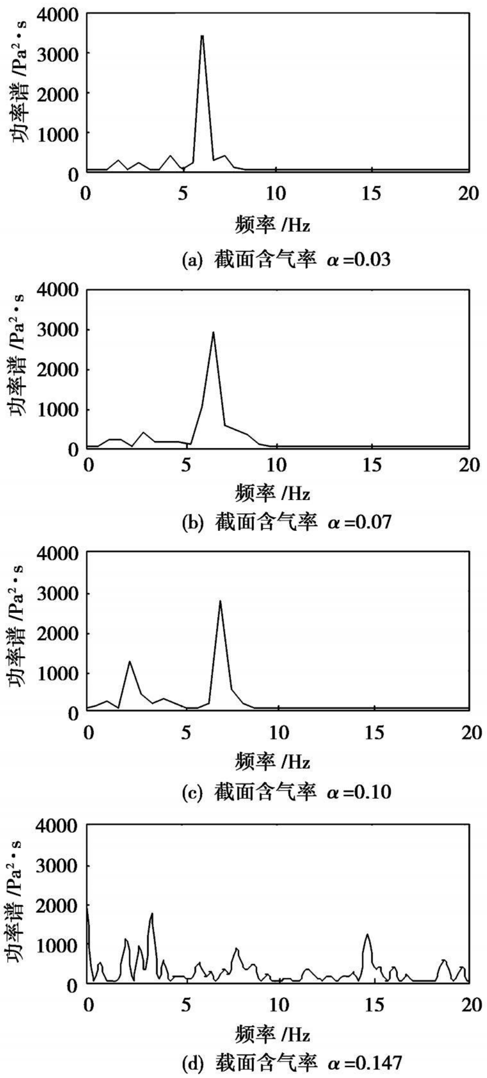
(b) 截面含气率 α=0.07

(c) 截面含气率 α=0.10

(d) 截面含气率 α=0.147

图 5 $Re=1.74\times10^4$ 时各含气率下圆柱体的管壁压差功率谱

图5和图6分别是圆柱体和方柱体在 $Re=1.74\times10^4$,截面含气率为0.03、0.07、0.10和0.147时,由采集的管壁压差数据得到的功率谱图。由图可以看出:当截面含气率为0.03时,两柱体功率谱图上都存在一个明显的尖峰,但方柱体功率谱尖峰所对应的能量值比圆柱体功率谱尖锋所对应的能量值大;截面含气率为0.07时,两柱体功率谱图上峰



(a) 截面含气率 α=0.03

(b) 截面含气率 α=0.07

(c) 截面含气率 α=0.10

(d) 载面含气率 α=0.147

图 6 $Re=1.74\times10^4$ 时各含气率下方柱体的管壁压差功率谱

值所对应的频率有所增大,但峰值能量的绝对值有所降低,而且已经开始出现比较明显的杂峰,此时方柱体功率谱尖峰所对应的能量值仍然比圆柱体功率谱尖峰所对应的能量值大;截面含气率为0.10时,方柱体功率谱峰值所对应的频率继续增大,尖峰能量值继续降低,而圆柱体功率谱图上已经观测不到峰值;截面含气率增加到0.147时,两柱体功率谱图上都不存在明显的峰值,而是由一些峰值点很低的杂峰组成,表现为典型的随机脉动特征,即不存在涡街。这表明:相同工况下,方柱体涡街的强度比圆柱体涡街的强度大;当截面含气率增大时,两柱体涡街的脱落频率也随之而增大,但涡街的强度会有所减弱。当截面含气率增加到一定值时,不能再形成稳定的涡街,在雷诺数 $Re=1.74\times10^4$ 时,对于圆柱体此时截面含气率为0.10,对于方柱体此时截面含气率为0.147。

这主要是因为流体流过非流线型柱体时,旋涡是

引起其能量损失的主要原因。当气液两相流体横向冲刷柱体时，旋涡中心气核的形成和气液两相密度的差异，使旋涡的能量降低；并且随着来流截面含气率的增大，流场的紊流强度增加，同时密度远远小于水的旋涡内的气泡团和旋涡外的气泡在浮力的作用下，也加速了旋涡从柱体表面脱落的频率。当含气率增加到一定值时，气泡对能量比较微弱的旋涡产生了强烈的扰动，涡街稳定性完全遭到破坏，尾流中不再存在周期性的波动，在得到的功率谱上就观测不到峰值。但由于方柱体涡街能量比圆柱体涡街的能量大，延迟了截面含气率增大时对涡街稳定性的破坏，使得方柱体涡街完全破坏时对应的截面含气率比圆柱体涡街完全破坏时所对应的截面含气率大。

2.2　截面含气率对斯特罗哈数的影响

实验中保持气液两相流的雷诺数不变，逐渐增加截面含气率。由功率谱得到的涡街频率求出两相流绕流方柱体和圆柱体时旋涡脱落的斯特罗哈数 St，得到斯特罗哈数 St 与截面含气率 α 的关系，如图 7 和图 8 所示。由两图可以看出，在有涡街生成的范围内，方柱体和圆柱体涡街的斯特罗哈数都是随着截面含气率的增大而不断增大的；方柱体斯特罗哈数增大的梯度基本上与雷诺数无关，而圆柱体斯特罗哈数增大的梯度受到雷诺数的影响，且雷诺数越大，其增大的梯度也就越大。

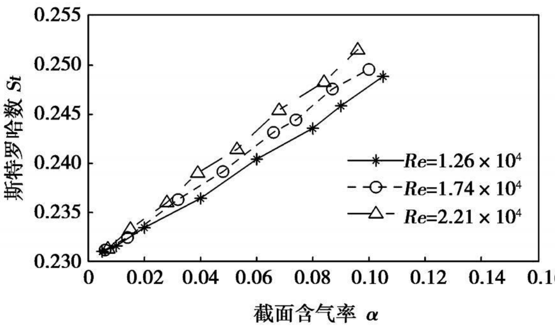


图 7　圆柱体斯特罗哈数与截面含气率的关系

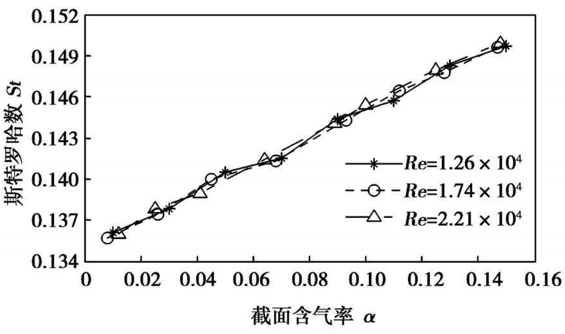


图 8　方柱体斯特罗哈数与截面含气率的关系

这是因为方柱体表面存在锐边，其边界层的分离点是固定的，与来流的雷诺数没有关系，斯特罗哈数主要取决于截面含气率；圆柱体迎流面为曲面，气泡对边界层的干扰使边界层更易于分离，其分离点是随雷诺数而变化的，在大雷诺数时这种效果更加明显[14]。所以，圆柱体的斯特罗哈数在随截面含气率增大的同时，其增大的梯度受到雷诺数的影响。

3　结　论

（1）在本实验范围内，气液两相流体绕圆柱体和方柱体流动发生涡街时，随着截面含气率的增大，两柱体的涡街脱落频率不断增大，但涡街的能量和稳定性不断减弱。当截面含气率增加到一定值时，就不再有稳定的涡街存在，对于圆柱体此时的截面含气率为 0.10，对于方柱体此时的截面含气率为 0.147。

（2）圆柱体和方柱体涡街脱落的斯特罗哈数都随着截面含气率的增大而增大。方柱体斯特罗哈数增加的梯度基本与雷诺数无关，圆柱体斯特罗哈数随截面含气率增大的梯度受到雷诺数的影响，雷诺数越大，其增加的梯度也就越大。

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On a CFB (Circulating Fluidized Bed) cold-state test rig with a riser section having a net height of 4.0 meters and an inner diameter of 0.19 meters, an experimental study has been performed of the radial gas mixing in the following two flow patterns: i.e. fast bed and pneumatic conveyance. The bed material used in the test was river sand, $d_p = 120\ \mu m$ and the real density $\rho_s = 2400\ kg/m^3$. The particle cyclic flow rate (G_s) and fluidized air speed (U_g) can be controlled independently on the test rig. The variation relationship of the pressure gradient between the upper and lower bed layers with the fluidization air speed can be used to ascertain the zone where a fast fluidization is present. By using a plunger flow model and with CO_2 serving as a tracer gas, the radial gas mixing was tested at three air speeds. The tendency of *Dr* changing with the particle concentration was obtained in the following two flow patterns, the fast bed and pneumatic conveyance. It has been found that in the pneumatic conveyance flow pattern, *Dr* will decrease with an increase of the particle concentration while in the fast bed flow pattern, *Dr* will increase with a particle concentration increase. In conjunction with the existence status of solid particles in various flow patterns, the different influence of the flow patterns on *Dr* can be reasonably explained. **Key words**: circulating fluidized bed, gas-solid flow pattern, radial gas mixing

600 MW 超临界 CFB 垂直并联内螺纹管两相流压力降不稳定试验研究= **Experimental Study of the Two-phase Flow Pressure Drop Instability in Vertical Parallel Inner Threaded Tubes of a 600 MW Supercritical CFB (Circulating Fluidized Bed)**[刊,汉]/DENG Zhi-an, LUO Yu-shan, CHEN Ting-kuan, et al (National Key Laboratory on Multi-phase Flow in Power Engineering, Xi' an Jiaotong University, Xi' an, China, Post Code: 710049)//Journal of Engineering for Thermal Energy & Power. — 2009, 24(6). —741 ~ 745

Under the practical load-variation operating condition of a 600 MW supercritical CFB (Circulating Fluidized Bed) water wall and with the actually-used Φ28.6×5.8 4-head inner threaded tubes in the water wall serving as an object of study, experimentally studied was the pressure drop instability of the gas-liquid two-phase flow in vertical parallel tubes of HP steam-water two-phase flow loops. Determined was the influence of pressure, mass flow speed, inlet supercooling degree and upstream compressible volume on the pressure drop pulsation of the above tubes. The research results show that with an increase of the pressure, the critical heat load at which a pulsation occurs will increase, the limit dryness will gradually go up, and the system stability will be improved. The pulsation period will be first extended and then shortened with the amplitude of the pulsation being gradually diminished. In the present experiment, when the pressure is greater than 6 MPa, no pressure drop pulsation will occur. With an increase of the mass flow speed, the limit heat load at which a pulsation occurs will increase while the pulsation period will diminish. The inlet supercooling degree will exercise a monodromy influence over the density wave pulsation. With an increase of the inlet supercooling degree, the limit heat load will monotonically increase and the change of the limit dryness will exhibit different tendencies. At a relatively low mass flow speed, with an increase of the supercooling degree, the limit dryness will diminish monotonically. At a relatively high mass flow speed, with an increase of the supercooling degree, the limit dryness will rise monotonically. The upstream compressible volume will have a relatively small influence on the limit heat load. With an increase of the gas-filling ratio, the pulsation period and amplitude will also gradually increase. **Key words**: supercritical, circulating fluidized bed, low-mass flow speed, vertical parallel inner threaded tube, gas-liquid two-phase flow, pressure-drop pulsation

方柱体与圆柱体气液两相涡街特性的研究= **Study of Gas-liquid Two-phase Vortex Street Characteristics of a Square Cylinder and a Circular One**[刊,汉]/ZHOU Yun-long, DIAO Cheng-dong, CAO Ru (College of Energy Source and Mechanical Engineering, Northeast University of Electric Power, Jilin, China, Post Code: 132012)//Journal of Engineering for Thermal Energy & Power. — 2009, 24(6). —746 ~749

When a gas-liquid two-phase fluid in a vertically ascending tube with a rectangular section transversely scours a horizontally arranged cylinder, under certain conditions, an alternating vortex shedding phenomenon will occur at the back of the cylinder. By adopting a tube-wall pressure-difference method to study the vortex shedding characteristics of the above flow

transversely sweeping across a circular cylinder and a square one, the authors have identified the vortex street shedding frequency and the variation of Strouhal number. During the test, the Reynolds number ranges from 0.9×10^4 to 2.3×10^4 and the sectional gas content has a variation range of 0 to 0.2. The test results indicate that in a certain range of gas content, the vortex-street shedding frequency and Strouhal numbers of the two types of cylinders will increase with an increase of the sectional gas content. The increment gradient of the square cylinder Strouhal number is independent of the Reynolds number while that of the circular one is susceptible to the influence of the Reynolds number. **Key words**: gas-liquid two-phase flow, tube-wall pressure-difference method, square cylinder, circular cylinder, vortex street

气固两相 Y 型分支管网流量分配特性的试验研究与数值模拟= **Experimental Study and Numerical Simulation of the Flow Distribution Characteristics of a Gas-solid Two-phase Y-shaped Branch Pipe Network**[刊, 汉] /DUAN Guang-bin, HU Shou-gen, ZHAO Jun, et al (College of Energy Source and Power Engineering, Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093)//Journal of Engineering for Thermal Energy & Power. —2009, 24(6). —750 ~755

By using compressed air as conveyance power and millet as a transport medium in horizontal Y-shaped branch pipes, the solid flow distribution characteristics of the above pipes were studied. The test results show that the change of the included angle between the central axial lines of the branch and main pipes as well as the superficial gas velocity have a relatively big influence on the solid-phase flow distribution characteristics. In the meantime, by adopting Euler-Lagrange two-phase flow research method and a discrete phase model (DPM) for the solid phase, the authors have employed Fluent software to numerically simulate the gas-solid two-phase flow in the Y-shaped branch pipes having three different included angles. The simulation results have predicted relatively well the flow pattern of particles at the branch points, the movement trajectory of the particles inside the branch pipes and the distance required for resuming a uniform distribution of the particle phase flow field. By comparing the numerical simulation results with the test ones of the solid particle mass distribution in the branch pipes, the authors have found that there exists a relatively small error between the two results. **Key words**: gas-solid two-phase flow, Y-shaped branch pipe, flow distribution characteristics, numerical simulation, included angle

热电联供系统中烟气冷凝传热性能试验研究= **Experimental Study of the Condensation Heat Transfer Performance of Flue Gases in a Heating-and-power Cogeneration System**[刊, 汉] /ZHAO Xi-ling, FU Lin, ZHANG Shi-gang, et al (Building Technology and Science Department, Tsinghua University, Beijing, China, Post Code: 100084)//Journal of Engineering for Thermal Energy & Power. —2009, 24(6). —756 ~758

Concerning the problem of the inability to fully recover the waste heat in flue gases, experimentally studied was a flue gas condensation heat recovery device of an innovative heating-and-power cogeneration system that could fully recover the waste heat in flue gases. In this connection, the research emphasis was laid on the heat transfer performance of a smooth tube flue-gas condensing equipment item under the relevant operating condition. The research results indicate that under the test operating condition, the heat transfer coefficient of the dry type condensing section can be as high as 60 W/(m^2·K) with that of the condensing section being 90 to 100 W/(m^2·K). The heat transfer coefficient of the condensing section is about 1.5 to 1.7 times that of the dry type one. The authors have also worked out a heat transfer criterion-based relational expression under the operating condition, thus providing an underlying basis for popularizing the design and operation of the system in question. **Key words**: heating-and-power cogeneration, flue gas, condensation heat, latent heat, heat transfer performance

平行流蒸发器内气液两相流分配均匀性实验研究= **Experimental Study of the Distribution Uniformity of the Gas-liquid Two-phase Flow in a Parallel Flow Evaporator**[刊, 汉] /LI Kui-ning, WU Xiao-bo, YIN Ya-ling (College of Power Engineering, Chongqing University, Chongqing, China, Post Code: 400030)//Journal of Engineering for Thermal Energy & Power. — 2009, 24(6). —759 ~765