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气液两相流垂直冲刷错列管束漩涡脱落特性的实验研究

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摘　要: 采用高速摄像仪拍摄的方法, 对垂直上升的气液两相流体在矩形管道内冲刷节距比为 1.0、1.5 和 2.0 三种旋转正方形排列的错列管束漩涡脱落特性进行了研究。给出了在一个漩涡的形成与发展过程中, 对周围气泡进行卷吸并在柱后形成气核的全过程; 通过对漩涡脱落周期的统计, 得出了在本实验范围内随含气率的增大漩涡脱落频率逐渐增大, 漩涡脱落, *St* 逐渐减小的结论; 当含气率 $\alpha=0.147$ 时周期性漩涡脱落现象消失。

关　键　词: 气液两相流; 漩涡脱落; 错列管束

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引　言

流体横向流过物体的绕流现象在日常生活和工程实际中都是比较常见的。当流体流过非流线型物体时, 在物体后部两侧会形成漩涡。在一定条件下, 漩涡交替、周期性的产生并脱落, 并在尾流中产生涡列(或称之为卡门涡街)。卡门涡街的形成促使物体表面压力产生周期性的脉动, 造成流体作用在物体上的力的大小与方向均发生周期性的变化, 诱发物体发生振动, 影响工业设备的可靠性与使用寿命。因此对流体绕流漩涡脱落特性进行研究对工程设备在设计运行时避免发生流体诱发振动具有十分重要的意义。

目前已经有不少学者对气液两相流体横向绕流单圆柱和梯形柱体等工况下的漩涡脱落特性进行了实验研究[1~3]。然而, 就目前的研究而言, 由于测试技术的局限, 其中大部分的实验研究主要集中在对升力系数和阻力系数等直接与压力有关量的测量[4~7], 而对气液两相流体冲刷管束漩涡脱落尾流特性的研究相对较少, 并且一些对尾流瞬态流场显示的新技术(如 PIV 等), 在对气液两相流的应用上还不太成熟, 其尾流特征的表现大多还依赖于数值模拟的结果。正是基于这一点, 本文采用高速摄像仪拍摄了流型为细泡状流的气液两相流体垂直冲刷节距比为 1.0、1.5 和 2.0 三种旋转正方形的错列管束的漩涡脱落的尾流流场, 比较直观地显示了其尾流流场的一些特征。

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1　实验装置及数据处理

1.1　实验装置

实验是在空气－水两相流试验台上进行的, 如图 1 所示。

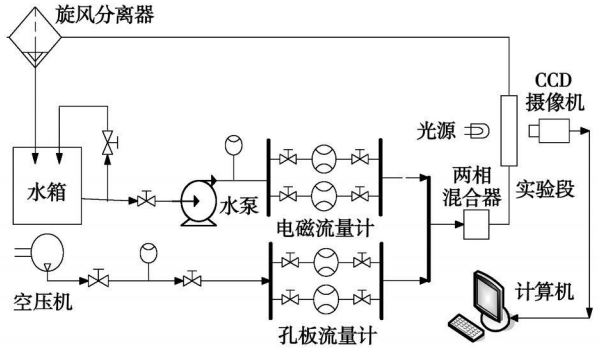


图 1　实验装置示意图

该实验装置主要包括两部分, 即流体控制系统和图像采集系统。流体控制系统主要由空压机、两相混合器、水泵、旋风分离器和水箱组成。实验工质采用空气和水, 空气经空压机升压和孔板流量计计量后进入气液两相混合器。水由水泵抽出, 用电磁流量计计量后到气液两相混合器。从气液两相混合器出来的气水混合物, 流经透明实验段进行图像采集后, 进入旋风分离器, 将空气分离出来并排入大

气，剩下的水流回水箱供循环使用。图像采集系统主要包括照明系统和高速摄像系统。高速摄像仪对光线的亮度有较高的要求，照明系统的光源使用 500 W 的卤素灯进行照明。由于气液两相流横掠错列管束漩涡脱落尾流的流动特征比较复杂，高速摄像仪采用瑞士公司研发的 SpeedCam Visario 系统，其最大分辨率为 1 536×1 024，最大帧频达到 10 000 帧/s，能够清晰的抓拍尾流中的瞬变图像。在图像采集的过程中由于液体和气体均是透明的，可采用逆光照明[8]，拍摄各种尾流特征的阴影。为了使光线分布均匀，在实验段的后侧蒙上两层绘图用的硫酸纸，即可获得满意的拍摄图像。在本实验中，拍摄图像的大小为 768×512，帧频为 1 000 帧/s。

实验段主要由扩展段、试验段、收敛段和测试管束 4 部分组成，如图 2 所示。从混合器流出的气液两相流体混合物经过稳定后由扩展段进入试验段，最后由收敛段流出经一段管路进入气液分离器。扩展段为倾角 9.6°，长 500 mm 的锥形管。为达到较好的拍摄效果，试验段是由 10 mm 厚的有机玻璃板制成的长度为 700 mm，截面为 180 mm×65 mm 的矩形管道。为了尽可能地贴近工业设备中的实际工况，在扩展段和实验段的连接处安装了筛网和导流栅，使进入实验段的两相流体混合物在矩形截面管道内呈现分布均匀的泡状流，气泡的直径为 3～5 mm。测试管束由直径 20 mm 的表面光滑的有机玻璃圆柱组成。收敛段为倾角 13.3°，长 350 mm 的锥形管。

图 2　实验段示意图

1.2　数据处理方法

气—液两相流中 Re 的计算公式：

$$Re=\frac{u_m D}{\nu_1}=\frac{(q_{VQ}+q_{VL})D}{A\nu_1} \tag{1}$$

式中：u_m—气—液两相流的平均流速；q_{VQ}—气相体积流量；q_{VL}—液相体积流量；A—矩形管道截面流通面积；ν_1—液相的运动粘度；D—当量直径。

截面含气率的计算公式采用阿尔曼特（APMAH 公）的计算方法[9]：

$$\alpha=C\beta=C\frac{q_{VQ}}{q_{VQ}+q_{VL}} \tag{2}$$

式中：$C=0.883$，β 为体积含气率。

在本实验范围内雷诺数的范围为 1.26×10^4～3.15×10^4，含气率的范围为 0.01～0.15 之间。

2　实验结果及分析

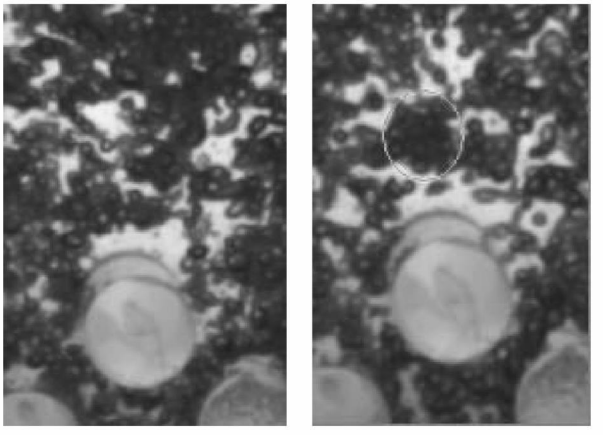
2.1　圆柱尾迹漩涡脱落过程分析

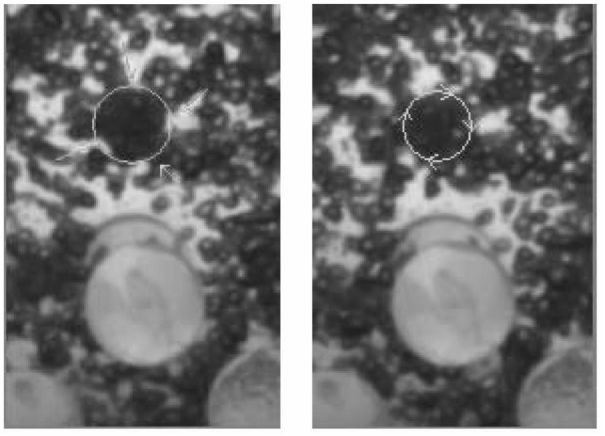
根据对单相流体的研究，当流体绕流过非流线型物体时会在物体的后面形成漩涡，其主要的能量损失是由漩涡引起的，在靠近漩涡的地方贮存着许多能量，漩涡的中心是一个低压区，漩涡内外就有较大的压力梯度[10]。在两相流中，由于加入了气泡，质量较轻的气泡在漩涡的形成与运动过程中就会不断地被吸入到漩涡的中心，并在漩涡的中心进行聚集和融合形成小气核。本文通过实验，十分清晰地记录下了节距比 1.0 的错列管束在雷诺数为 2.82×10^4、含气率为 0.074 时，在一个漩涡形成过程中，圆柱后面的气核从无到有，不断增大，同时根据两幅图像间的时间间隔和所截取图像在连续视频中的位置，给出了每幅图像对应的漩涡脱落周期时间。

图 3(a)是 $t=0.039$ s 时最后排圆柱后面的尾流状况，此时圆柱后面的气泡分布比较均匀，还没有明显的小气核的存在；图(b)是 $t=0.078$ s 时的状况，此时已经明显地看出气核的存在，如图中标注所示；图(c)～(e)显示的是伴随着漩涡的发展，漩涡的旋转特性已经明显起来，漩涡中心的小气核也跟着漩涡旋转。由于旋转，漩涡周围的气泡呈“辐射”状被继续吸入到小气核所在的漩涡中心；图(f)显示的是圆柱后面的气核已经达到最大并开始向后运动，说明一个漩涡已经形成，并从圆柱上脱落。整个过程经历了 234 幅图片，用时 0.234 s。

由漩涡脱落的机理可知，在漩涡脱落的一个周期内会有两个漩涡从圆柱的两侧先后形成并脱落，所以上述圆柱后面的小气核从无到有，再增大到一定程度并开始向后运动的过程经历两次就可以认定为一个漩涡脱落的周期。以上述工况为例，漩涡脱落的周期应该为 0.468 s。本文对每个工况下的漩涡脱落周期均统计了 5 次，相对误差不超过 2%。

基于此，通过对周期的统计，研究了含气率对漩涡脱落特性的影响。





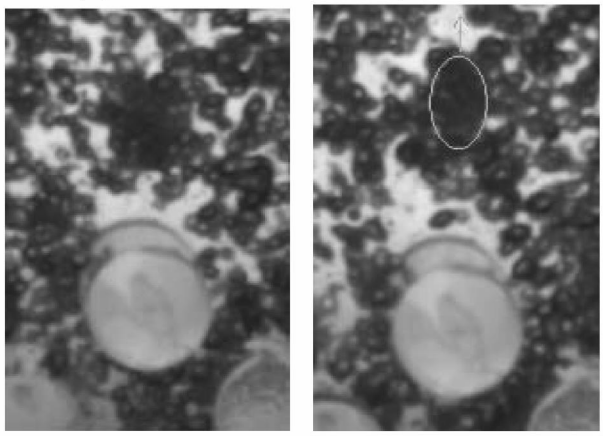


图 3 气泡卷吸过程

2.2 含气率对漩涡脱落特性的影响

在气液两相绕流的研究中，含气率是一个重要的参数。由于两相流中气泡的存在，使得流动的状态变的非常复杂。此时，柱体两侧漩涡的形成、涡街的结构及稳定性，两相斯特罗哈数等都与单相流中的情况有很大的不同。本文通过对两种固定液相流量分别为 11.42 和 7.53 m^3/h、含气率在 0.01～0.15 之间的多个工况下的尾流特征进行拍摄和对漩涡脱落的周期进行统计，得出了含气率对漩涡脱落频率和斯特罗哈数的影响。

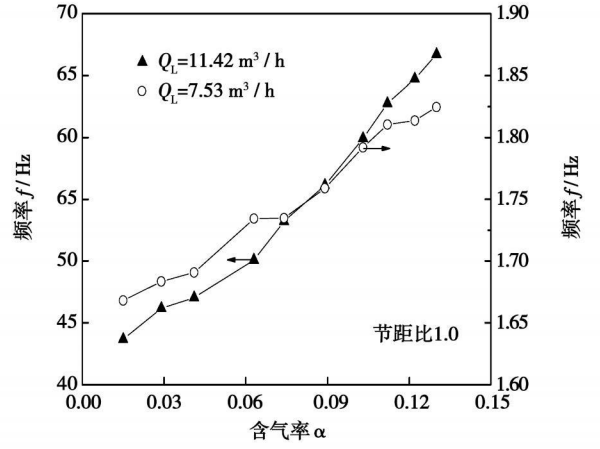


图 4 节距比 1.0 频率变化

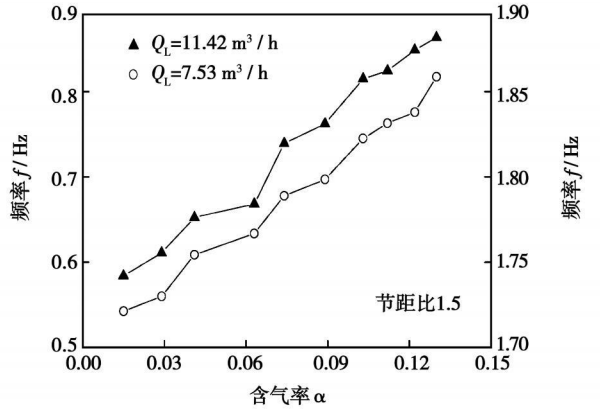


图 5 节距比 1.5 频率变化

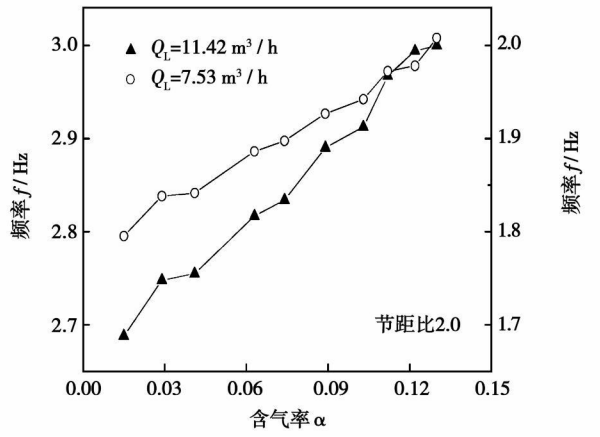


图 6 节距比 2.0 频率变化

图 4 ~ 图 6 是 3 种不同节距比的错列管束在两种固定的液相流量下, 漩涡脱落频率随含气率变化的曲线图。由图可以看出, 两种固定液相流量下的漩涡脱落频率都是随着含气率的增大而增大的。这是因为由于漩涡中心气核的形成和气液两相密度的差异, 使得漩涡的能量降低; 随着来流含气率的增大, 使流场的紊流强度增加, 这样漩涡更容易在柱体上脱落。同时密度远远小于水的漩涡内的气核和漩涡外的气泡在浮力的作用下也使得漩涡脱落频率随着含气率的增大而增大。上述基于周期所得的频率的相对误差在 3%以内。

图 7 ~ 图 9 是 3 种不同节距比的错列管束在两种固定的液相流量下, 其斯特罗哈数随含气率变化的曲线图。由图中我们可以得出在本实验范围内, 漩涡脱落斯特罗哈数虽然有一些浮动, 但总体是随含气率的增大呈逐渐下降的趋势, 这同漩涡脱落的频率变化趋势是相反的。

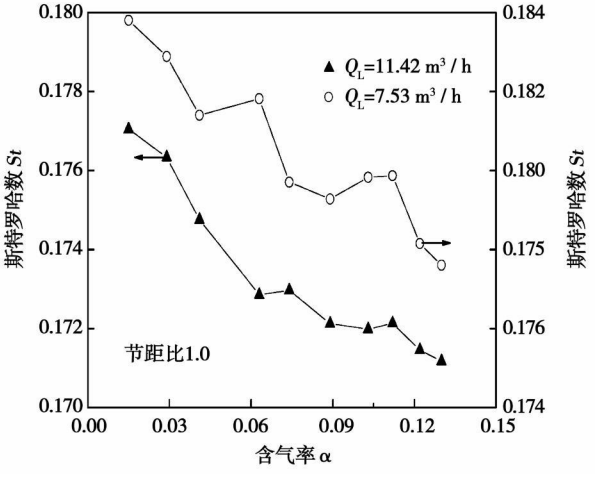


图 7　节距比 1.0 *St* 数变化

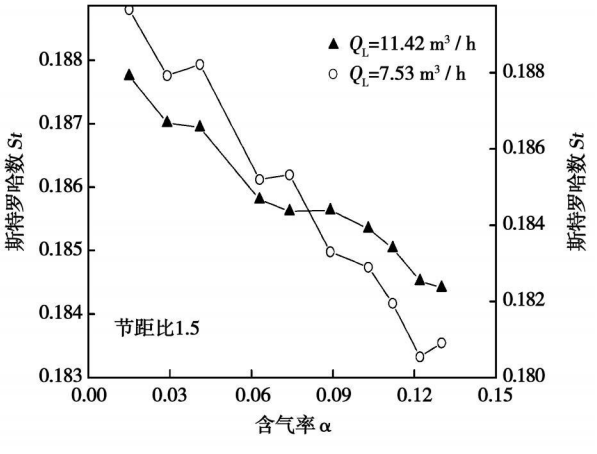


图 8　节距比 1.5 *St* 数变化

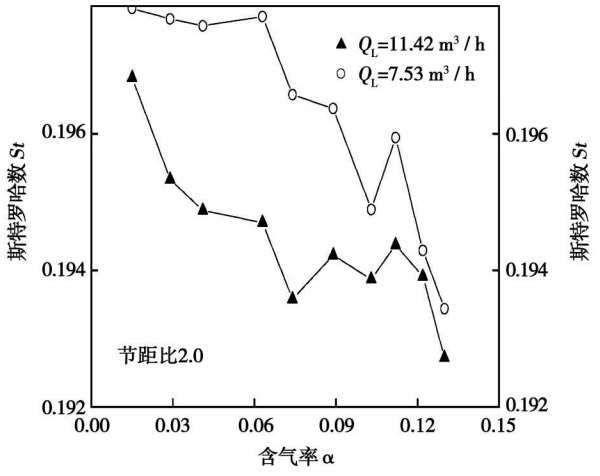


图 9　节距比 2.0 *St* 数变化

随着含气率的继续增大, 主流中的紊流脉动强度继续增强, 对水平能量较低、处于不稳定状态的漩涡产生强烈的扰动, 影响旋涡的形成, 从而破坏了涡街的稳定性, 表现在尾流图像上就是含气率大时在圆柱的后部形成长长的气袋, 如图 10 所示。此时由拍摄的视频可以发现, 小气核随漩涡的旋转而旋转的特性和在圆柱两侧交替产生的摆动特性已经消失了。这和文献[11 ~ 12] 上提出的在含气率大于 0.14 时不再产生周期性漩涡脱落的结论是相符的。

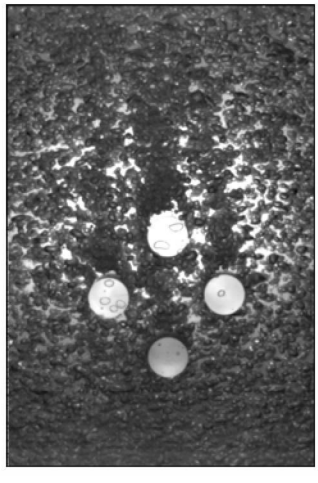


图 10　节距比 1.5, α= 0.147 时尾流特征

3　结　论

(1) 通过对漩涡脱落尾流特征的拍摄, 给出了一个漩涡在形成与发展过程中对周围气泡卷吸的过程。

(2) 通过对 3 种节距比的错列管束在相同液相

流量、不同含气率下的漩涡脱落周期的统计分析得出，在本实验的范围内随含气率的增大，漩涡脱落的频率是逐渐增大的。

(3) 在本实验范围内，在固定液相流量的情况下，3 种节距比的错列管束的斯特罗哈数都随含气率的增大而减小；当 $\alpha=0.147$ 时，圆柱后面的周期性漩涡脱落现象消失。

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(编辑 韩 锋)

联合循环装置

核动力与燃蒸联合装置

据《Энергетика》2007 年 11～12 月号报道，白俄罗斯国立技术大学博昆И А博士、教授分析了核动力和燃蒸联合装置火电站的特点，并对它们的生态和经济指标做了比较。

在 2001 年，世界生产的电力为 154 760 亿 kW·h，其中燃煤火电站生产 38.7%，燃液体燃料火电站生产 7.5%，燃天然气火电站生产 18.3%。核电站在世界电力生产中的份额为 17.1%，水电站为 16.6%，非传统能再生的能源为 1.8%。

按照科学家的意见，世界电力需求增加的速度为每年 3%。

20 世纪产生的两次大事故(美国三厘岛核电站，1979 年；前苏联切尔诺贝利核电站，1986 年)并未动摇某些工程技术人员关于核电站效果和生态性方面的观点。

当前，在核动力工程领域面临下述一些问题：造价、安全性、核废料的储存等，这些问题与生态和经济限制紧密相关。

燃蒸联合装置火电站的单位投资是核电站单位投资的一半。现在，俄罗斯火电站的电力生产成本不超过 0.6 卢布/(kW·h)，而装有 ВВЭР—1000 水水动力反应堆的核电站的电力生产成本为 1 卢布/(kW·h)。

在选择供电源—核电站或利用有机燃料的火电站时，必须与具有现代燃蒸联合装置的火电站进行比较。研究表明，核电站在技术—经济指标方面不如燃蒸联合装置火电站。

(吉桂明 供稿)

off-design condition under the mode of "determining power generation on the basis of heating (cooling) demand", thus revealing the off-design operating performance of the system under various regulating methods. It has been found that a recuperation adjustment can accommodate a relatively wide range of cooling and heating load regulation. Therefore, the micro gas turbine-based cogeneration system is particularly suitable for the occasion when the cooling and heating load undergoes a great change while the electric power load in the system is relatively stable. To keep a comparatively high performance of the system when operating at off-design conditions, in case of an increase of the cooling and heating load, the electric power regulation should be adopted as a first priority, followed by the recuperation regulation as a second choice and supplementary firing regulation as a last resort. When the cooling and heating load decreases, a reverse regulation order should be chosen. The research results can well provide useful reference and guidance for the design and operation of micro gas turbine-based CCHP cogeneration systems. **Key words**: micro gas turbine, cooling, heating and power cogeneration system, off-design performance

循环流化床旋直复合流化下的两相流动试验研究= **Experimental Study of Two-phase Flows in a Circulating Fluidized Bed under a Rotating and Straight Compound Fluidization**[刊, 汉] / HAO Xiao-wen, (College of Automobile Engineering, Harbin Institute of Technology, Weihai, China, Post Code: 264209), MA Chun-yuan, ZHANG Li-qiang (College of Energy Source and Power Engineering, Shandong University, Jinan, China, Post Code: 250061), WANG Chun-bing (ZHONG-guang Nuclear Engineering Design Co. Ltd., Shenzhen, China, Post Code: 518124) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(6). — 620 ~ 624

To increase in-tower blending and material concentration represents an approach for raising the flue gas desulfuration efficiency of a circulating fluidized bed. The authors have proposed a rotating and straight compound fluidization mode and measured gas-solid two-phase in-tower flow field by using a PDA (Phase Doppler Anemometer) measurement system. Obtained was a law governing the gas-solid two-phase flows in a desulfuration tower before and after axial rotating blades were installed in a Venturi throat. It has been found that the non-uniform air distribution as characterized by the rotating and straight compound fluidization mode can help increase the tangential speed in the tower, leading to an in-tower strong pulsation, good mixing and resulting in a higher in-tower particulate concentration and an increased inner circulation. In addition, a higher superficial speed can bring about a better comprehensive effectiveness of the compound fluidization. The experimental results can provide an underlying basis for the structural design and optimization of new technologies for flue gas desulfuration. **Key words**: circulating fluidized bed, compound fluidization, impulsive speed, inner cycle

串联型化工动力多联产系统主导因素与变工况特性= **Leading Factors and Off-design Operating Characteristics of a Tandem Type Chemical-industry Power Polygeneration System**[刊, 汉] / FENG Jing, NI Wei-dou, LI Zheng (Thermal Energy Engineering Department, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(6). — 625 ~ 629

A polygeneration system having electric power as one of its main products, will, as a result, unavoidably face load variation problems during its operation. From the viewpoint of load variations to design a polygeneration system capable of meeting the requirement of an electric grid, the authors have through a detailed simulation analysis, come to emphasize two leading factors influencing the load variation capacity of a tandem type polygeneration system, namely, designed power-chemical production ratio and synthetic unit capacity surplus degree. In the form of a four-quadrant chart, shown was a relationship between the system design parameters and system product output on the one hand and the load variation capacity on the other. In addition, the characteristics of the system in question during a load variation were further analyzed, especially concerning the case when the fuel gas H_2/CO of the gas turbine increases with a decrease of the electric power load. **Key words**: polygeneration system, load variation, methanol synthesis, four-quadrant chart, leading factor

气液两相流垂直冲刷错列管束漩涡脱落特性的实验研究= **Experimental Study of Vortex Shedding Characteristics of a Gas-liquid Two-phase Flow Vertically Sweeping Across a Staggered Tube Bundle**[刊, 汉] / ZHOU Yun-

long, DIAO Cheng-dong, WU Mao-song, et al(College of Energy Source and Mechanical Engineering, Northeast University of Electric Power, Jilin, China, Post Code: 132012)//Journal of Engineering for Thermal Energy &Power. — 2008, 23(6). —630 ~ 634

By adopting a method of high-speed video camera shooting, a study has been conducted of the vortex shedding characteristics of a staggered tube bundle, which is swept across by a vertically rising gas-liquid two-phase flow in a rectangular duct. The tube bundle has been arranged in three kinds of rotating square with a pitch ratio of 1.0, 1.5 and 2.0 respectively. Shown are the whole process of entrainment of surrounding bubbles and the formation of a gas nucleus after a gas column during a vortex formation and development course. It has been concluded through a statistics survey of the vortex shedding cycles that with an increase of the void fraction within the range of the present experiment, the shedding frequency will gradually increase, leading to a shedding of the vortex, and the Strouha number assumes a gradual decrease. When the void fraction $\alpha = 0.147$, the phenomenon of a periodical vortex shedding will eventually disappear. **Key words**: gas-liquid two phase flow, vortex shedding, staggered tube bundle

C 型混沌结构中传热强化的数值分析= **Numerical Analysis of the Heat Transfer Intensification in a C Type Chaotic Structure**[刊, 汉]/WANG Yong-qing, DONG Qi-wu (College of Mechanical and Power Enmgineering, East China University of Science and Technology, Shanghai, China, Post Code: 200237), LIU Min-shan (Henan Provincial Key Laboratory on Process Heat Transfer and Energy Savings, Zhengzhou University, Zhengzhou, Post Code: 450002)//Journal of Engineering for Thermal Energy &Power. — 2008, 23(6). —635 ~ 639

With more and more academics giving priority to and engaging in the research on intensified heat transfer, the new technology of utilizing a chaotic convection to intensify heat transfer has attracted ever increasing attention. The authors have conducted a numerical simulation of the fluid flow and heat transfer in a C-type chaotic structure by using CFD (Computational Fluid Dynamics) software Fluent, and compared the detailed information depicting the difference between the structure in question and ordinary straight structures in respect of fluid flow field distribution, temperature profile and heat transfer characteristics. Also analyzed were the intensified heat transfer performance and specific features of the C-type chaotic structure. The analytic results show that the latter enables the fluid to produce a chaotic convection at a relatively low speed. This fluid state will intensify the turbulence and perturbation of the fluid, enhance the mixing of flows in the main flow zone or at places near walls, intensify the heat transfer in flow passages, and impart a uniform temperature distribution on flow channel cross section. Moreover, the Nusselt and Poiseuille number (i.e. fRe value) for the heat transfer in a chaotic convection is no longer a constant like that of an ordinary laminar flow, but will increase with an increase of Reynolds number. **Key words**: chaotic convection, heat transfer intensification, laminar flow, computational fluid dynamics (CFD)

非圆形微通道热沉的流动换热特性数值模拟= **Numerical Simulation of the Heat Exchange Characteristics of the Flow in a Noncircular Microchannel Heat Sink**[刊, 汉]/XIAO Chun-mei, CHEN Yong-ping, SHI Ming-heng, et al (College of Energy Source and Environment, Southeast University, Nanjing, China, Post Code: 210096)//Journal of Engineering for Thermal Energy &Power. — 2008, 23(6). —640 ~ 644

Established was a three-dimensional model for a single-phase flow and heat exchange process in a noncircular silicon microchannel, and numerically simulated was the heat exchange of flows in a triangular, rectangular and trapezoidal microchannel respectively. It has been found that cross-sectional averaged Nusselt number attains a maximum value at the inlet of the channel, and then will drastically decrease along a fluid flow direction. It tends to be constant when the flow has been fully developed. Both solid and fluid temperatures grow in an approximately linear way along the flow direction. The wall temperatures on the heat exchange surfaces increase only along the flow direction and those along the direction perpendicular to the flow, however, basically maintain an equilibrium state. Reynolds number exercises a relatively big influence on the flow and heat exchange characteristics of the microchannel. The higher the Reynolds number, the greater the corresponding Nusselt number. It has been found through the analysis and comparison of the thermodynamic cost-effective-