文章编号: 1001－2060(2004)01－0014－04

气液两相流横掠错列圆柱形成旋涡脱落诱发管束振动的试验研究

苏新军, 张修刚, 王　栋, 林宗虎
(西安交通大学 能源与动力工程学院, 陕西　西安　710049)

摘　要: 对相同直径的 3 排错列圆柱表面的旋涡脱落工况进行了试验研究。测试圆柱采用 Φ30 mm 的有机玻璃圆柱。试验时两相隙缝流 *Re* 数范围为 $2.0\times10^4\sim6.0\times10^4$, 含气率的范围在 0～0.3 之间。通过试验分析获得了不同排列形式的错列管束中两相流斯特拉赫数; 试验发现两相流斯特拉赫数 St_{tp} 随含气率的增加而减小; 提出了旋转正三角形排列的错列管束的斯特拉赫数曲线; 指出可以近似应用单相流时的 Weaver 曲线作为两相流中旋转正方形排列和正三角形排列管束旋涡脱落诱发管束振动的判别标准。

关　键　词: 气液两相流; 斯特拉赫数; 错列圆柱

中图分类号: O359　　文献标识码: A

1　前　言

当流体流过一非流线形物体时, 沿物体表面会形成边界层, 在一定的条件下, 边界层将会在物体的两侧分离, 并从物体上脱落, 形成旋涡。旋涡周期性地从物体两侧交替脱落时, 物体两侧会产生一个作用方向周期性更替的力并使物体产生振动[1]。当柱体后的旋涡脱落频率与管子固有频率相一致时, 管子产生共振将诱发柱体发生大幅度振动, 严重时将会导致管子破坏。

在热交换器中经常出现气液两相流动工况。当气液两相流体绕流物体时, 同样也有可能产生旋涡的脱落现象。卢家才[2]等人对气液两相流横向冲刷单根圆柱时旋涡的脱落特性作了研究, 提出了两相流绕流单根圆柱时的斯特拉赫数 St_{tp} 与单相流时的 St_{sp} 关系式。

然而, 在工业的换热设备中, 一般实际情况是流体冲刷管束的工况。因此, 研究管束在气液两相流中旋涡的脱落更有实际意义。在这些设备中, 管束一般成错列和顺列两种排列方式, 谢正武[3]等人对两相流中横向冲刷顺列管束上旋涡的脱落特性作了研究。

错列管束是一种在管壳式热交换器中经常采用的排列形式, 由于其排列形式比顺列更加复杂, 目前, 很少有研究者涉足此领域。本文研究了气液两相流中以正三角形、旋转正方形和旋转正三角形排列的错列管束的旋涡脱落情况及其相应两相斯特拉赫数。本试验中, 含气率的范围为 0～0.3, 气液两相流的流型为细泡状流, *Re* 数的范围在 $2.0\times10^4\sim6.0\times10^4$ 之间。

2　试验装置和数据处理

试验是在西安交通大学的气液两相试验回路[4]试验台上进行的。试验段管束安装在横截面为 185 mm×65 mm 的矩形管内, 矩形管高 0.5 m, 测试管采用 Φ30 mm 的有机玻璃圆柱, 表面经过光洁处理, 试验用的错列圆柱采用上述 3 种标准的排列形式[5]。

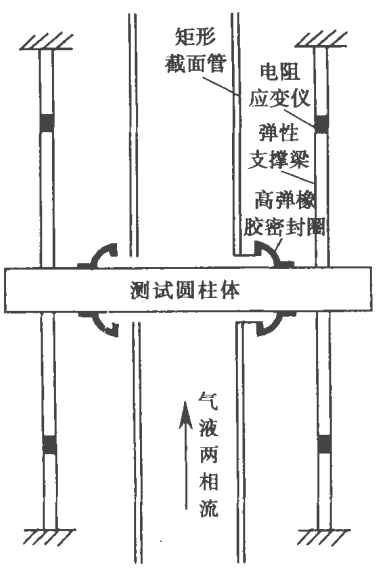

图 1　脉动升力测量结构图

所采用的脉动作用力测量装置如图 1 所示, 试验前对此测力系统进行了静态标定和动态标定, 以满足本试验对所要测定的低频振动的小力值测量的需要。本文所采

收稿日期: 2003－06－30
基金项目: 国家重点基础研究发展规划基金资助项目(G1999022308)
作者简介: 苏新军(1970－), 男, 河北顺平人, 西安交通大学博士研究生。

用的试验装置及试验仪器的详细资料请参阅文献[6]。

当流体横向冲刷管束时, 根据对单相流和两相流的研究, 若在管束的表面发生周期性的旋涡脱落和紊流随机脉动[7~8], 则会诱发管束在流动的法线方向(即升力方向)的振动。通过对升力方向振动信号的功率谱分析, 可以检测出随机振动中的周期性振动, 也就是振动的主频。即圆柱上的旋涡发生周期性脱落时, 在功率谱图上对旋涡脱落处会出现一个功率谱的尖峰, 一般认为此功率谱尖峰值对应的频率即为旋涡脱落频率[9] (如图2(a)所示)。

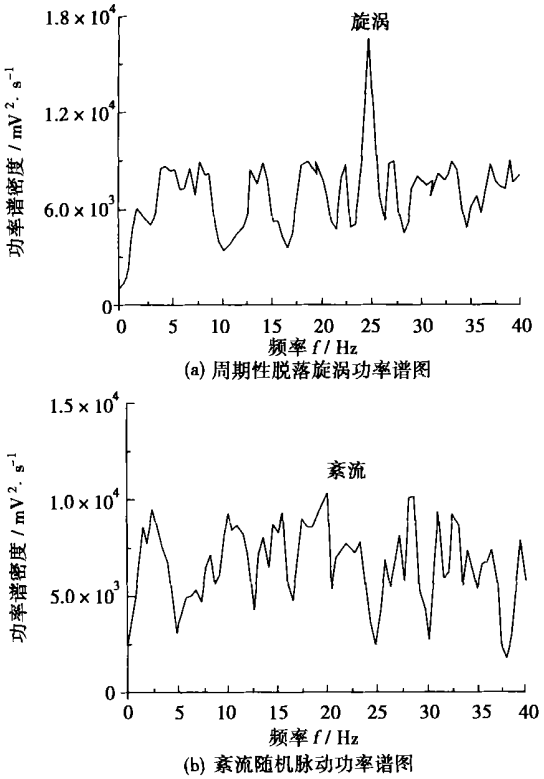

图 2　周期性旋涡脱落的功率谱图和紊流随机脉动功率谱图

根据单相流中错列圆柱表面发生周期性旋涡脱落时的斯特拉赫数 St_{sp} 的定义[10], 在气液两相流中采用类似的两相斯特拉赫数 St_{tp} 表达式:

$$St_{tp} = \frac{fd}{v} \tag{1}$$

式中: f — 气液两相旋涡周期性脱落频率, Hz;

d — 圆柱直径, m;

v — 气液两相流来流的平均流速, m/s。

来流的截面含气率的计算根据 Армand[11] 研究, 采用下式:

$$\alpha = C\beta = \frac{cq_g}{q_g + q_l} \tag{2}$$

式中: $C = 0.833$, β — 体积含气率;

q_g — 气相体积流量, m^3/s;

q_l — 液相体积流量, m^3/s。

3　试验结果和分析

3.1　旋转正方形排列错列管束的两相斯特拉赫数

由实验获得的两相脉动升力功率谱图, 可得出两相旋涡的脱落频率, 再由式(1) 求出此时相应的两相斯特拉赫数。图 3 是当气液两相流横向冲刷旋转正方形排列的错列圆柱时, 两相斯特拉赫数 St_{tp} 和管子节距与直径比 p/d 的关系曲线。其中的实心符号是作者等在不同的含气率时得到的实验值, 其它空心符号为已发表的其他研究工作者的单相流体实验值, 图中曲线为Weaver[12] 在单相流中得出的曲线。从图上可以看出: 在两相流中, 旋转正方形排列的错列管束上的斯特拉赫数随含气率的增大而减小; 两相旋涡发生周期性脱落时的两相斯特拉赫数小于Weaver 曲线上相应点的值。

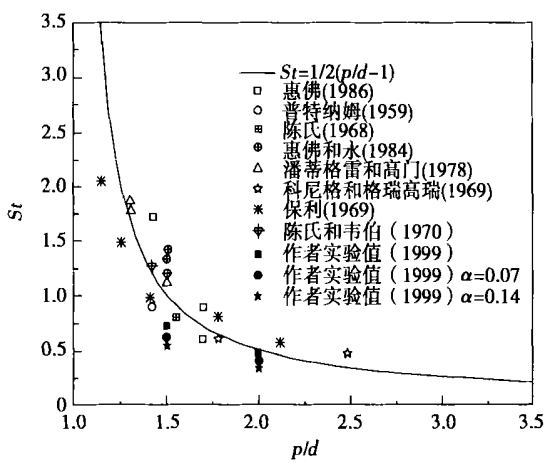

图 3　旋转正方形排列的错列管束的斯特拉赫数 St 与 p/d 的关系曲线

因此, 在两相流的工程设计中, 可以近似用单相流中的旋转正方形排列的错列管束的斯特拉赫数公式:

$$St = \frac{1}{2(\frac{p}{d} - 1)} \tag{3}$$

来计算两相斯特拉赫数 St_{tp}。按照图 3, 只要使管子的固有频率大于按式(3) 计算所得斯特拉数 St_{tp} 所确定的频率值, 即可避免由于管束上脱落的两相旋

涡的主频和管子的固有频率相耦合，从而引发共振而造成危害。

同时由图 3 可见，随着含气率的增加，两相斯特拉赫数减小。

3.2 正三角形排列的错列管束的两相斯特拉赫数

图 4 是正三角形错列管束的斯特拉赫数和管子 p/d 的关系曲线，此曲线由 Weaver 根据单相流得出可按式(4)计算。其中的实心符号是作者等在不同的含气率时得到两相流的实验值。从图上可以看出：随着含气率的增加，斯特拉赫数减小；管束的两相斯特拉赫数大于按式：

$$St = \frac{1}{1.73(\frac{p}{d}-1)} \tag{4}$$

得出的单相流时 Weaver 曲线上的相应值。

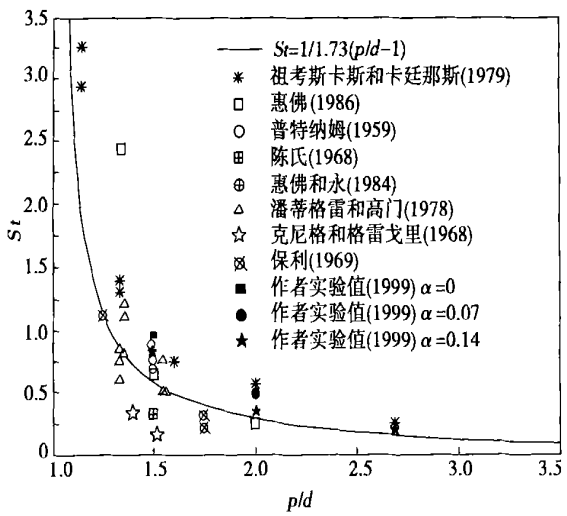

图 4 正三角形排列的错列管束的斯特拉赫数 St 与 p/d 的关系曲线

在两相流的工程设计中，为了避免由于两相旋涡周期性的脱落引起的管束的振动，就要在设计中使管束的固有频率远离这一区域，从图 4 来看，在相同的来流流速时，应该使管束的固有频率小于按式(4)计算得出的斯特拉赫数所确定的频率值。

3.3 旋转正三角形排列错列管束的两相斯特拉赫数

图 5 是旋转正三角形排列的错列管束的斯特拉赫数和管子节距与直径比的关系曲线。其中的实心符号是作者等在不同的含气率时得到的两相流实验值。实线是 Weaver 根据单相流得出的曲线，可按式(5)计算。从图 5 上可以看出：随着含气率的增加，两相斯特拉赫数减小；两相流时的斯特拉赫数远小于 Weaver 曲线上的相应点处的值。

从图上可以看出，Weaver 提出按下式：

$$St = \frac{1}{1.16(\frac{p}{d}-1)} \tag{5}$$

计算单相流中旋转正三角形排列的错列管束的斯特拉赫数，和多数研究者实验得到的单相研究结果并不一致。通过单相流的实验，作者等拟合了 1 条更好反应单相流斯特拉赫数的曲线(图 5 上的虚线)，其计算式如下：

$$St = \frac{1}{1.50(\frac{p}{d}-1)} \tag{6}$$

而从图 4 中，我们可以看出，在两相流中，在相同的流速时，只要旋转正三角形排列的错列管束的固有频率大于按式(6)计算得出的两相斯特拉赫数所确定的频率，即可以避免由于两相旋涡周期性脱落频率和错列管束的固有频率相耦合而引起的共振。

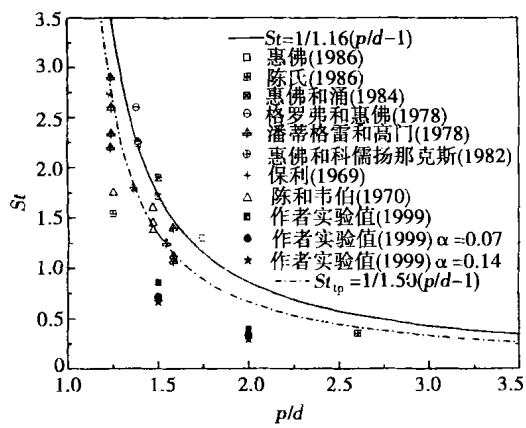

图 5 旋转正三角形错列管束的斯特拉赫数 St 与 p/d 的关系曲线

4 结 论

(1) 获得了气液两相流横向冲刷错列管束时的两相流斯特拉赫数；研究发现，两相流中两相斯特拉赫数 St_{tp} 数随含气率的增加而减小。

(2) 对于旋转正三角形排列的错列管束本文提出了一个新的斯特拉赫数计算公式。

(3) 在当前气液两相流横掠错列管束诱发两相旋涡脱落的实验研究数据不足时，可近似用本文提出的方法，应用单相流斯特拉赫数曲线作为两相流旋涡脱落诱发管束脉动发生的判别标准。

(下转第 51 页)

图4 和图 5 分别给出了管内壁等温时管出口表面当量定向发射率 ε(θ) 随管内壁发射率 ε、管长与半径比(xl/Rc) 的变化曲线。由图中的曲线可发现:

(1) 管出口当量定向发射率 ε(θ) 出现极大值;

(2) 随管长与半径比的增加, 最大当量定向发射率 ε(θ) 所对应的天顶角 θ 向较小角度方向移动; 该极值随 xl/Rc 增大而增大。但是 xl/Rc 大于 20 以后, xl/Rc 的增大对 ε(θ) 影响较小。

由图4和图5比较可看出: 管长与半径比(xl/Rc = 4) 较小时, 管内壁发射率 ε 对管口当量定向发射率的影响不显著(xl/Rc = 4, ε = 0.8、0.2时最大当量定向发射率分别为 1.53、1.57); 随 xl/Rc 增加(xl/Rc 大于 10), ε 小时, 管内壁发射率 ε 对管口当量定向发射率的影响非常明显(xl/Rc = 10, ε = 0.8、0.2时最大当量定向发射率分别为 1.80 和 2.04; xl/Rc = 20, ε = 0.8、0.2时最大当量定向发射率分别为1.91 和 2.37)。

4　结　论

(1) 管出口当量定向发射率不管 xl/Rc 多大, 都存在极大值, 但其最大值随 xl/Rc 增大而增大;

(2) 最大当量定向发射率对应天顶角 θ 随着 xl/Rc 的增大向小角度天顶角方向移动, 但当 xl/Rc 大于20 以后, 增加的数值较小。

(3) 在管长与半径比大于 4 时, 管内壁发射率 ε 对管口当量定向发射率的影响显著, 随着 xl/Rc 的增大ε 减小, 从管口逸出的辐射能集中在天顶角较小的空间范围, 其定向性越好。

参考文献:

[1] 李艳红, 徐吉浣, 张鹤声. 多孔陶瓷板中城市煤气预混燃烧的实验研究与数值模拟[J]. 工程热物理学报, 1997, **18**(3): 385—388.

[2] 王承炜. 径向浓淡旋流燃烧器扩锥温度场数值模拟[D]. 哈尔滨: 哈尔滨工业大学, 1999.

[3] YANG W J, HIROSHI TANIGUCHI, KAZUHIKO KUDO. Radiative heat transfer by the monte carlo method [M]. California: Academic Press Inc, 1995.

[4] HOWELL J R. The monte carlo method in radiative heat transfer [J]. **Journal of Heat Transfer**, 1998, **120**(3): 547—560.

[5] MODEST M F. Radiative heat transfer [M]. New York: McGraw—Hill Inc, 1993.

[6] SIEGEL R, HOWELL J R. Thermal radiation heat transfer[M]. New York: Taylor &Francis, 2002.

[7] 谈和平, 崔国民, 阮立明, 等. 用区域分解算法结合蒙特卡罗法求坦克温度场和红外辐射出射度[J]. 工程热物理学报, 1998, **19**(3): 340—344.

(何静芳　编辑)

(上接第 16 页)

参考文献:

[1] 钱颂文, 岑汉钊, 曾文明. 换热器流体诱导振动[M]. 北京: 烃加工出版社, 1989.

[2] 卢家才, 谢正武, 林宗虎, 等. 气液两相流中旋涡诱发圆柱振动时的脉动升力研究[J]. 应用力学学报, 1999, **16**(3): 20—25.

[3] 谢正武, 苏新军, 林宗虎, 等. 气液两相流诱发顺列双圆柱升力功率谱特性研究[J]. 西安交通大学学报, 1999, **33**(8): 28—31.

[4] 苏新军, 张修刚, 林宗虎. 错列圆柱表面周向压力分布的试验研究[J]. 西安交通大学学报, 2001, **35**(1): 1—4.

[5] 苏新军, 牛冬梅, 林宗虎. 气液两相流中错列管束上脉动升力的试验研究[J]. 西安交通大学学报, 2000, **34**(11): 9—12.

[6] 苏新军. 气液两相旋涡脱落时错列管束受力的实验研究[D]. 西安: 西安交通大学能源与动力工程学院, 1999.

[7] GUNTER S. On the force fluctuations acting on a circular cylinder in crossflow from subcritical up to transcritical reynolds numbers[J]. **J Fluid Mech**, 1983, **133**(8): 265—285.

[8] RICHTER A, NAUDASCHER E. Fluctuating forces on rigid circular cylinder in confined flow[J]. **J Fluid Mech**, 1976, **78**(3): 561—576.

[9] WEAVER D S, FITZPATRICK J A. A review of cross-flow induced vibrations in heat exchanger tube arrays[J]. **Journal of Fluids and Structures**, 1988, **10**(2): 73—93.

[10] 白莱文斯 R D. 流体诱导振动[M]. 北京: 机械工业出版社, 1983.

[11] 林宗虎. 气液两相流和沸腾传热[M]. 西安: 西安交通大学出版社, 1987.

[12] WEAVER D S, FITZPATRICK J A, ELKASHL H. Strouhal numbers for heat exchanger tube arrays in cross flow[J]. **Flow Induced Vibration**, 1986, **104**: 193—200.

(何静芳　编辑)

新型热管技术开发及应用=**Development and Application of Innovative Heat Pipe Technology**[刊,汉]/ CHEN Yan-ze, DING Xin-wei, YU Jian-liang, et al (Institute of Chemical Engineering under the Dalian University of Science &Technology, Dalian, China, Post Code: 116012)//Journal of Engineering for Thermal Energy &Power. — 2004, 19(1). —1~3

The theory of innovative heat pipe technology, such as refrigeration heat pipes (RHP) and thermosyphon Rankine (TSR) engines, as well as current study results are described with an emphasis on the TSR technology, which integrates the technology of heat pipes with that of turbines. The TSR technology represents a new approach to energy utilization and recovery, and offers wide prospects for engineering applications. The refinement and in-depth research of the TSR technology can be conducive to enhancing the conversion efficiency of heat energy to mechanical power. **Key words**: heat pipe, thermosyphon, Rankine engine, refrigerating heat-pipe

微小通道内流动沸腾压降特性实验研究=**Experimental Investigation of Pressure Drop Characteristics of Flow Boiling in Mini-channels**[刊,汉]/ WANG Xu, CHEN Hong, KUANG Bo, et al (Institute of Mechanical and Power Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030)//Journal of Engineering for Thermal Energy &Power. — 2004, 19(1). —4~9

In the wake of experimental tests of flow boiling in rectangular mini-channels discussions are held concerning the steady and dynamic characteristics of pressure drop in the channels and a method for stable domain discrimination. After a frequency domain analysis of pressure-drop time series under various experimental operating conditions it is found that the emergence of pressure-drop oscillations in mini-channels can mainly be attributed to vapor generation, transmission and the coupling of mini-channels with inlet compressible or flexible space. Moreover, based on an autoregression model of time-series analysis a model for testing pressure drop oscillations along a test section has been set up. The test results indicate that during a relatively great flow rate the pressure-drop oscillations in the presence of a restricted and deformed steam-bubble flow and an annular flow was found to be relatively stable. However, in the case of a small flow rate the unstable condition of the pressure drop is rather complicated, tending to set up an unstable zone. **Key words**: mini-channel, flow boiling, pressure drop, pressure drop oscillation

射流泵内部流动的实验研究=**Experimental Study of Flows in a Jet Pump**[刊,汉]/ HE Pei-jie, LONG Xin-ping, LIANG Ai-guo (Institute of Power &Mechanical Engineering under the Wuhan University, Wuhan, China, Post Code: 430072), LIU Hou-lin (Research Institute of Fluid Machinery under the Jiangsu University, Zhenjiang, Jiangsu Province, China, Post Code: 212014)//Journal of Engineering for Thermal Energy &Power. — 2004, 19(1). —10~13

For carrying out the experimental study of the turbulent mixing between water jets in a jet-pump confined space and its surrounding low-velocity water-flow streams, static pressure taps were arranged at 11 axial locations. The pressure taps assume the following layout: one tap at the inlet of a converging conical throat, 6 taps in the throat, and the remaining 4 in a diffuser pipe. Wall-surface static pressure was measured at 11 pressure measuring points by using a U-type tube. Measurements were taken of the water jets in a confined space at the jet pump throat inlet and inside the throat by using a particle image velocimetry device. As a result, the distribution of velocity vector and axial velocity on the symmetrical flow field was obtained under four flow-rate ratios. The measurement results may provide a reliable basis for the analysis of internal flows of a jet pump. **Key words**: particle image velocimetry, jet pump, flow velocity measurement

气液两相流横掠错列圆柱形成旋涡脱落诱发管束振动的试验研究=**Experimental Investigation of Tube Bundle Vibrations Induced by a Vortex Shedding Generated by Gas-liquid Two-phase Flows Sweeping Across Staggered Tube Arrays**[刊,汉]/ SU Xin-jun, ZHANG Xiu-gang, WANG Dong, et al (Institute of Energy and Power Engineering under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049)//Journal of Engineering for Thermal Energy &Power. — 2004, 19(1). —14~16, 51

The vortex shedding condition of three rows of staggered circular cylinder with a same diameter was experimentally investigated. The cylinders being tested were made of acrylic glass cylinders with a diameter of 30mm. During the tests the two-phase gap-flow Reynolds number ranges from 2.0×10^4 ~ 6.0×10^4 and the range of void fraction, from 0 - 0.3. By way of experimental analyses the Strouhal number of two-phase flows was determined in staggered tube bundles with different layout modes. The test results indicate that the Strouhal number of the two-phase flows decreases with an increase in the void fraction. The characteristic curves of Strouhal numbers are presented for the staggered tube bundles with a rotating regular-triangle layout. It is noted that Weaver curves of single-phase flows can be approximately used as discrimination criteria for the tube bundle vibrations induced by the vortex shedding in rotating-square arranged and regular-triangle arranged tube bundles in two-phase flows. **Key words**: gas-liquid two-phase flow, Strouhal number, staggered cylinder

汽—液相变过程的热力学分析＝**Thermodynamic Analysis of a Vapor-liquid Phase Transition Process** [刊, 汉] / ZENG Dan-ling, HUANG Shuang, WANG De-ming, et al (Power Engineering Institute under the Chongqing University, Chongqing, China, Post Code: 400044) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —17 ~ 19

By applying a thermodynamic theory a thermodynamic analysis was conducted of the actual vapor-liquid phase transition process commonly encountered in engineering practice. The necessary thermodynamic conditions for realizing the above-mentioned process are discussed along with the laws governing the progress of the process and relevant influencing factors. The authors have focused on the study of boiling phase-transition process, and especially analyzed from a thermodynamic perspective the enhancement of convection heat-transfer factor due to the phase transition and also the related influencing factors. It is stressed that in a phase-transition process the chemical potential difference $\Delta\mu$ between the two coexisting phases serves as a major generalized thermodynamic driving force of the process. The heat exchange process has been realized under the joint action of $\Delta\mu$ and ΔT and in tandem with the convection movement of fluids. The introduction of the driving force $\Delta\mu$ makes the above process different from a single-phase convection heat exchange and this also constitutes a main cause leading to an intensification of the phase-transition heat exchange process. **Key words**: phase transition, superheated liquid, subcooled vapor, metastable state, chemical potential

冷却水流程数对凝汽器热力性能的影响＝**The Impact of the Number of Cooling-water Passes on the Thermodynamic Performance of a Steam Condenser** [刊, 汉] / WANG Guo-shan (Institute of Power & Mechanical Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030), JIN Chun-nan, CHEN Yu-xiang (No. 703 Research Institute, Harbin, China Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —20 ~ 24

Power plant steam condensers can be designed as single-pass or two-pass ones. By using a self-developed computer program PPOC3.0, a software for the numerical simulation of condenser operation characteristics, the authors have simulated and analyzed the impact of the number of cooling water passes on the thermodynamic performance of power-plant steam condensers. The results of simulation and analysis indicate that a single-pass condenser offers a higher thermal load and smaller steam-side resistance. **Key words**: steam condenser, thermodynamic performance, flow pass, steam resistance, degree of subcooling

压水堆核电机组二回路热力系统计算的研究＝**A Study of the Thermodynamic System Calculations for the Secondary Circuit of a Pressurized Water Reactor** [刊, 汉] / YANG Yu-sen, YAN Jun-jie, LIU Li-cheng (National Key Lab of Power Engineering Multi-phase Flows under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049), SHEN Gou-sheng (Shenzhen Daya Bay Nuclear Power Station, Shenzhen, China, Post Code: 518124) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —25 ~ 28

In the light of the specific features of the secondary circuit of a PWR (pressurized water reactor) nuclear power plant a conception is proposed of the most simplified thermodynamic system of a PWR secondary circuit. Through a method based