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旋转圆筒表面对流质交换边界层实验研究

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摘　要: 用微热偶式干湿球温度计, 在稳定对流质交换状态下, 对水平旋转圆筒多孔介质表面边界层的温度场和浓度场进行了测量。实验表明: 对流质交换边界层的厚度随 Re_r 的增大而减小; 浓度边界层的厚度大于温度边界层的厚度; 热质交换边界层的温度梯度小于纯对流热交换边界层的温度梯度; 旋转对于顺向侧和逆向侧对流质交换的影响结果不同, 在顺向侧, 由于旋转受迫对流和自然对流的作用方向一致, 二者相互叠加的结果, 使得边界层浓度梯度加大, 厚度减小, 而在逆向侧, 情况则正好相反。

关　键　词: 旋转圆筒; 边界层; 温度场; 浓度场; 对流质交换
中图分类号: TK124　　　文献标识码: A

符号说明

Re_r—旋转 Reynolds 准则, $n\pi d^2/60\upsilon$; $h_{D,\varphi}$—局部传质系数; Sh_φ—局部谢伍德数; Sh—平均 Sherwood 准则, $h_D d/D$; h_D—平均对流传质系数, m/s; Sc—Schmidt 准则; Gr—Grashof 准则; $Re_{r,cri}$—临界 Reynolds 数; Ra—瑞利(Raylaigh)数, $Gr.Sc$; n—转速, r/min; d—圆筒直径, m; r—测点离圆筒轴线距离, m; y—测点离圆筒壁面距离, m; v—运动粘度, m^2/s; ρ—水蒸气浓度, kg/m^3; D—质扩散系数, m^2/s; t—温度, ℃; t_s—湿球温度, ℃; ψ—湿空气相对湿度; ρ^+—无因次浓度, $(\rho-\rho_f)/(\rho_w-\rho_f)$; y^+—无因次离壁距离, y/r_0; θ—无因次温度, $(t-t_f)/(t_w-t_f)$; m—平均质交换率, $kg/(m^2 \cdot s)$; λ—硅橡胶板的导热系数; $W/(m \cdot ℃)$。

下角标: cri—临界值; sv—饱和; f—环境; w—壁面; φ—圆周角

1　引　言

水平旋转圆筒多孔介质表面的对流热质交换问题, 在化工、建材、轻纺和造纸等工业生产领域经常遇到。文献[1]对水平旋转圆筒表面热交换规律进行了实验研究, 文献[7～8]则分别对小直径垂直圆筒的对流质交换特性进行了研究, 但对水平旋转圆筒多孔介质表面对流质交换边界层温度场和浓度场的专门研究目前尚未见到报道。因此, 本实验通过用自制的微热偶式干湿球温度计, 对水平旋转圆筒多孔介质表面对流质交换边界层的温度场和浓度场分布, 以及旋转对于它们的影响等情况进行了实验测定, 得到了一些实验结果, 发现了一定的分布规律。这些测试结果和规律, 无论是对今后进行同类课题的进一步研究, 还是为工程实际应用中对同类设备采取强化传热传质措施, 都能提供可靠和科学的依据, 具有十分重要的意义。

2　实验方法和数据处理

图 1 所示为实验设备组成示意图, 金属旋转圆筒外径 d=315 mm, 圆筒长 L=800 mm。先在金属圆筒壁上贴上 1 mm 厚的硅橡胶板, 在硅橡胶板外紧缠 7 层脱脂棉纱布, 使棉纱层外径达到 320 mm。在金属圆筒壁表面埋装 0.1 mm 丝径的热电偶 5 对, 用以检测筒壁温度是否均匀。硅橡胶板和棉纱层之间及棉纱层内各装 2 对直径为 0.08 mm 铜－康铜热电偶, 它们处于同一法向直线上, 各热电偶均经校验, 由此可确定硅橡胶板内外表面的温度差及棉纱布层的温度。

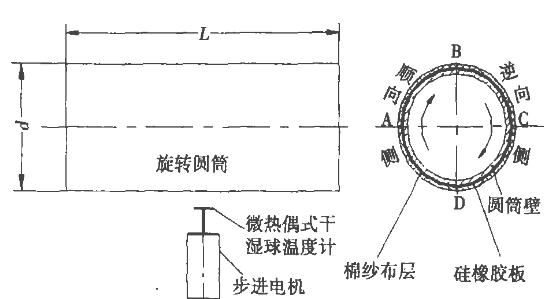

图 1　实验设备示意图

图 2 为圆筒壁、硅橡胶板、棉纱布层及热电偶的配置关系示意图, 各层厚度分别为 5 mm、1 mm 和 15 mm。

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圆筒表面热偶埋深 1 mm, 硅橡胶板上的热电偶靠纱布压紧, 3 层的温差分别以 Δt_1、Δt_2 和 Δt_3 表示, 因硅橡胶板的导热系数最小, Δt_2 将远远大于 Δt_1 和 Δt_3, 温度分布如图 2 所示。例如, 当导热量 $q_\lambda = 2\ 475$ W/m^2 时, 测得的 $\Delta t_2 = 10.4$ ℃, $\Delta t_1 = 0.28$ ℃, $\Delta t_3 = 1.5$ ℃。在本文条件下, 上述方法测定的 Δt_2 误差为 +1%。

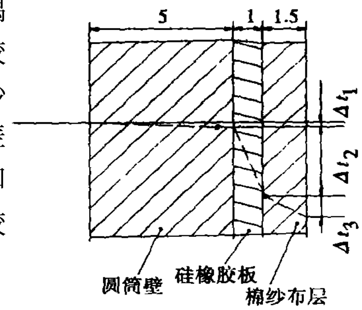

图 2 圆筒上各层厚及温差

为测棉纱层表面对流质交换边界层的干湿球温度, 采用图 3 所示的微型热电偶测量装置。热偶丝直径为 0.05 mm, 对焊焊接, 两对热偶成水平线, 长约 40 mm, 由微机控制热偶的移动和离壁距离, 为使湿球体积尽可能地小, 以减小对边界层的扰动, 热偶丝上仅缠数根棉花丝, 使光滑的热偶丝上保持薄薄的水膜, 外径约 0.2 ~ 0.3 mm, 测量数据中考虑了对辐射的修正。

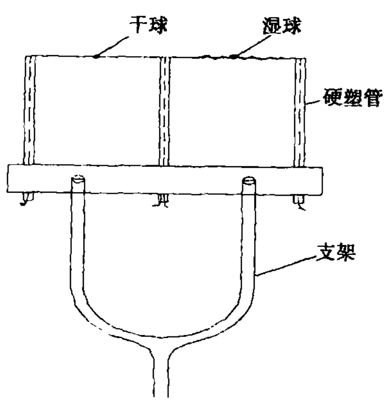

图 3 微型干湿球温度计结构图

本实验采用微型热电偶式干湿球温度计, 测得沿圆周不同位置的干球温度和湿球温度, 计算出局部对流质交换系数 $h_{D,\varphi}$ 和局部 Sh_φ 数, 从而确定旋转对圆筒表面不同位置对流质交换的影响情况。

实验时棉纱层用离子水湿透, 在一定转速下加热时, 先升温, 随后进入等速蒸发阶段, 在本文条件下该阶段能持续 1 h, 足以使各层达到稳态。实测表明, 等速蒸发阶段的温度变化仅 1.25 ℃/h, 而每个工况的测试时间仅数分钟, 在等速蒸发阶段棉纱层的温度与它的初始水含量无关, 故本文的对流质交换过程是在旋转表面具有稳定质量发生源, 并伴有热交换的常壁温边界条件下进行的。本文的实验参数范围为: $t_w = 30 \sim 70$ ℃, $Re_r = 2\ 000 \sim 60\ 000$, $Gr = 5.3 \times 10^8 \sim 1.5 \times 10^9$。

由实验测得的干球温度和湿球温度, 根据文献 [4] 推荐的相对湿度计算公式:

$$\psi = \frac{A_s - 1.005(t - t_s)}{A - [A - A_s + 1.005(t - t_s)]\ P_{sv}(t)/P_a} \quad (1)$$

式中: $A = \frac{P_{sv}(t)}{P_a - P_{sv}(t)}(1\ 556 + 1.156t - 2.604t_s)$

$$A_s = \frac{P_{sv}(t_s)}{P_a - P_{sv}(t_s)}(1\ 556 - 1.448t_s)$$

$$P_{sv}(t) = P_{cv}\exp[7.212\ 75 + 3.981(0.745 - \frac{t + 273.15}{647.3})^2 + 1.05(0.745 - \frac{t + 273.17}{647.3})^3] \times (1 - \frac{647.3}{t + 273.15})$$

根据测试数据计算出相对湿度 Ψ 后, 即可用下式:

$$\rho = \psi\rho_{sv} \quad (2)$$

其中: t、t_s—测得的干球温度和湿球温度, ℃; P_{cri} 和 P_{sv}—水蒸气的临界压力和饱和压力, P_a—当地大气压。应当注意的是, 在用上式计算时应保证 P_{cri}、P_{sv} 和 P_a 的单位一致; ρ_{sv}—对流质交换边界层中测点温度 t 对应的饱和水蒸气密度; ρ—对流质交换边界层中各测点水蒸气的密度。

局部传质系数 $h_{D,\varphi}$ 和局部谢伍德数 Sh_φ 的计算可根据传质微分方程:

$$h_{D,\varphi} = \frac{D}{\Delta\rho}\left(\frac{\partial\rho}{\partial r}\right)_{r=r_0,\ \varphi} \quad (3)$$

$$Sh_\varphi = \frac{h_\varphi d}{D} = \frac{d}{\Delta\rho}\left(\frac{\partial\rho}{\partial r}\right)_{r=r_0,\ \varphi} = 2\left(\frac{\partial\rho^+}{\partial r^+}\right) \quad (4)$$

式(3)和式(4)中, r 为测点到圆筒轴线的垂直距离; r_0 为圆筒的半径, $\Delta\rho = \rho_w - \rho_f$; D 为质扩散系数; $\rho^+ = (\rho - \rho_f)/(\rho_w - \rho_f)$ 为无因次浓度; $r^+ = r/r_0$ 为无因次距离。

旋转圆筒内部用多个电热丝加热, 保证圆筒沿轴向和周向温度均匀。实验是在稳定对流质交换阶段进行的。当旋转圆筒按顺时针方向旋转时, 在 DAB 侧, 自然对流与受迫对流的作用方向一致, 称为顺向侧; 而在 DCB 侧, 自然对流和受迫对流的作用方向相反, 称为逆向侧, 如图 1 所示。根据圆筒对称的特点, 也为了使问题得到简化, 本实验选择具有代表性的顺向侧的 A 处和逆向侧的 C 处两个特殊位置, 用自制的微热偶式干湿球温度计对其温度场和浓度场的分布情况分别进行了实验测定。

3 实验结果及分析

3.1 旋转对边界层相对湿度的影响

为研究旋转对圆筒表面边界层相对湿度分布的影响，实验选择顺向侧的 A 点，在不同旋转 Re_r 数下对边界层相对湿度 ψ 随无因次变量 y^+ 的变化规律进行了测试，测试结果图 4 所示。

由图 4 可以看出，在等速质交换阶段，随着 Re_r 旋转数(即转速)的增加，曲线的斜率增大，边界层的厚度减小，水蒸气浓度梯度增大。通过实验观察和分析，壁面浓度边界层从里到外可划分为 3 个区间：靠紧圆筒壁面的过饱和湿空气区、稍外侧的饱和湿空气区和最外层的未饱和湿空气区，并逐渐过渡到周围环境状态。随着转速增加，过饱和湿空气区和饱和湿空气区的厚度减小，未饱和湿空气区的厚度增加，当转速增大到一定值后，过饱和湿空气区和饱和湿空气区消失。

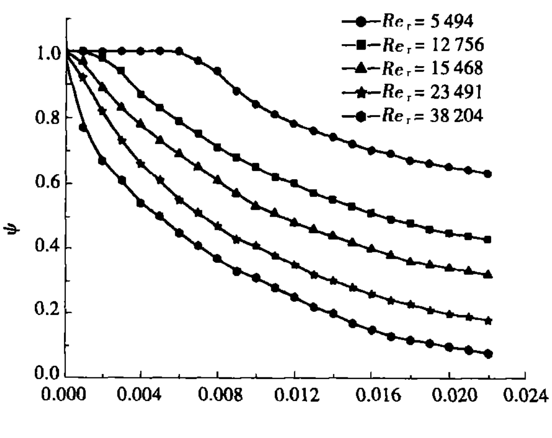

图 4　不同 Re_r 下 A 处边界层相对湿度 ψ 随 y^+ 的变化规律

3.2　旋转对圆筒表面不同位置对流质交换的影响

为研究旋转对圆筒表面不同部位质交换的影响情况，本实验选择了具有代表性的顺向侧的 A 处和逆向侧的 C 处两个位置，分别测定了不同 Re_r 下，ρ^+ 随 y^+ 的变化情况，如图 5 和图 6 所示。

由图 5 和图 6 可以看出：

(1)在相同旋转 Re_r 数下，顺向侧 A 处边界层浓度要比逆向侧 C 处边界层浓度梯度大，边界层厚度相对较薄；

(2)在顺向侧的 A 处，边界层浓度梯度随 Re_r 数的增加一直增大；而在逆向侧的 C 处，边界层浓度梯度随 Re_r 数的增加先减小，在临界点达到最小，然后才随 Re_r 数的增加而增加；

(3)实验结果表明，旋转对 A 和 C 两位置边界层浓度分布的影响规律与文献[5]所报道的旋转对边界层温度场的影响规律一致。

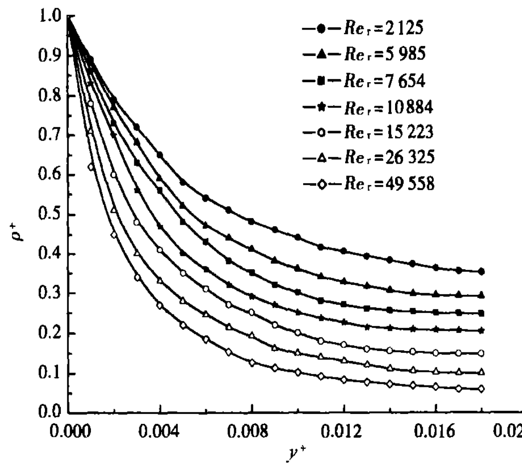

图 5　旋转对顺向侧 A 处边界层浓度分布的影响

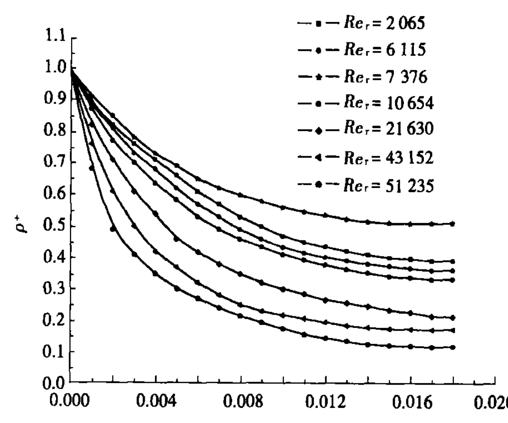

图 6　旋转对逆向侧 C 处边界层浓度分布的影响

分析出现以上现象的原因，主要是：在顺向侧，由于旋转圆筒壁面剪切力的作用方向和自然对流质交换的作用方向一致，两者叠加的结果，加剧了边界层的扰动，紊流度加大，从而增大了顺向侧的对流质交换强度和传质系数，而且，转速越高，旋转的作用就越明显；在逆向侧，由于旋转壁面剪切力的作用方向和自然对流方向相反，二者相互叠加的结果，使得边界层厚度增大，质交换强度减弱，传质系数减小，而且随着 Re_r 数的增大旋转的副作用越明显，当 Re_r 数增大到超过临界值(约 11 000)时，旋转对于质交换的强化作用才表现出来，且随着 Re_r 数的增加，旋转受迫对流的作用超过自然对流的作用，逐渐占据主导作用。由于上述原因，导致在相同旋转 Re_r 数

下顺向侧的边界层厚度要比逆向侧薄, 浓度梯度较大, 传质效果比较明显。

3.3　质交换边界层浓度场、温度场及纯对流热交换边界层温度场之间分布规律的比较

为比较旋转圆筒质交换情况下边界层浓度场、温度场以及与纯热交换工况下温度场的分布规律之间的关系, 本试验在相同加热功率、相同转速、相同圆筒直径和相同表面状况下, 对质交换时边界层的浓度场和温度场, 以及纯对流热交换时的温度场分布情况进行了实验测定, 测试结果经整理后示于图 7。

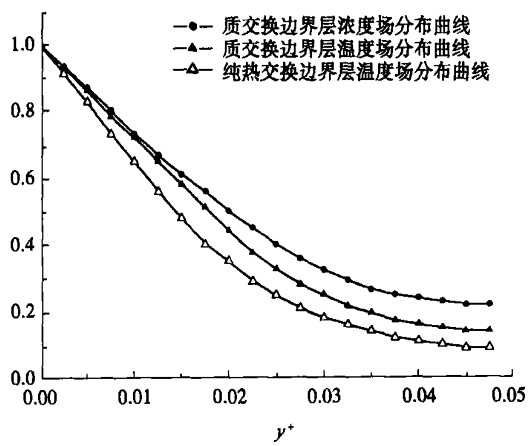

图 7　对流质交换边界层浓度场、温度场和纯对流热交换边界层温度场之间的分布比较

由图 7 可以看出: (1) 质交换边界层浓度场的厚度大于温度场的厚度; (2) 在相同实验工况下, 质交换边界层温度场的厚度大于纯热交换边界层温度场厚度。

这是由于在对流质交换边界层中有水蒸气存在, 由里向外随着温度降低, 有部分水蒸气凝结放出热量, 使得温度降低速度变缓, 温度梯度较小, 因此, 对流质交换温度边界层厚度要比纯对流热交换边界层的厚度更厚。

4　结　论

根据对旋转圆筒稳定质交换工况下边界层浓度场和温度场的测定和分析, 以及对纯对流热交换工况下边界层温度场的测定和分析, 可以得出以下几个结论:

(1) 在稳定质交换状态下, 旋转圆筒表面对流质交换边界层的厚度随着旋转 Re_r 数的增大而逐渐减薄, 浓度梯度则逐渐增大;

(2) 旋转对于顺向侧和逆向侧的影响结果不同。在顺向侧, 由于旋转壁面剪切力的作用方向和自然对流的作用方向一致, 二者相互叠加的结果, 使得边界层浓度梯度加大, 厚度相对减小; 而在逆向侧情况则正好相反; 这一结论为工程设计和实际应用中, 对旋转圆筒多孔介质表面采取喷射等强化传热和传质措施提供了依据;

(3) 在顺向侧的 A 处, 边界层浓度梯度随 Re_r 数的增加一直增加; 而在逆向侧的 C 处, 边界层浓度梯度随 Re_r 数的增加先减小, 在临界点达到最小, 然后才随 Re_r 数的增加而增加;

(4) 旋转对 A 和 C 两处浓度边界层分布的影响规律与文献[5] 所介绍的旋转对温度边界层分布的影响规律一致;

(5) 实验结果表明, 旋转圆筒表面质交换情况下的临界雷诺数 $Re_{r,cri}$ = 7 000 ~ 11 000, 要比纯热交换情况下的临界 $Re_{r,cri}$ = 17 000 小; 同时测定的对流质交换边界层浓度场的厚度要大于温度场的厚度;

(6) 在相同实验工况下, 对流质交换边界层温度梯度要比纯热交换情况下的边界层温度梯度小。

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utilized to set up a unitary-module refined model of high versatility. Second, with the help of a general correction formula featuring the impact of key factors on component performance a refined revision was conducted for a model of unitary modules. Finally, by using the general means of network connection among modules the logic relationship of system connection is described with a pipe duct equation being used to effect a refined quantification of correlation relationship of variables among modules. A huge amount of engineering cases has demonstrated the validity and feasibility of the measures adopted for the enhancement of the versatility and precision. **Key words**: steam system, modeling, versatility, precision

振荡热管传热性能的试验设计与多因素分析＝**Experimental Design and Multifactor Analysis of the Heat Transfer Performance of an Oscillating Heat Pipe**[刊,汉] /MA Yong-xi, ZHANG Hong (College of Mechanical and Power Engineering under the Nanjing Polytechnic University, Nanjing, China, Post Code: 210009) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(6). —571～574

A multitude of factors can affect the heat transfer in an oscillating heat pipe. The relationship between the heat-pipe heat transfer performance and the various factors is complicated and assumes a nonlinear character. By applying statistical techniques analyzed was the relationship between the heat-transfer performance of the oscillating heat pipe of a copper-water closed loop on the one hand and liquid filling rate, inclination angle and heat input on the other. First, tests were arranged by employing a central composite design method. Then, a fitting of the relationship between test variables and a response was achieved by using a least square method. Finally, through a variance analysis studied were three factors and the degree of their interacting influence. The results of the study indicate that the model of a second order equation can remarkably well reflect the relation between the heat transfer rate and the influencing factors. The three factors have a significant impact on the heat transfer rate with the inclination angle showing the most conspicuous impact. However, their interacting influence is not significant. Within the range of the study the optimum liquid-filling rate and the optimum inclination angle will be somewhat greater when the heating water flow rate undergoes an increase. **Key words**: oscillating heat pipe, central composite design, variance analysis

旋转圆筒表面对流质交换边界层实验研究＝**Experimental Study of the Convective Mass-exchange Boundary Layer of a Rotating Cylindrical Surface** [刊,汉] /MA Hong-ting, ZHANG Yu-feng (Institute of Environmental Science and Engineering under the Tianjin University, Tianjin, China., Post Code: 300072), LUO Wan-jun (China National Air-to-air Missile Research Institute, Luoyang, China, Post Code: 471000) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(6). —575～578

Under the status of a stable convective mass-exchange the temperature field and concentration field of the porous-medium surface boundary layer of a horizontal rotating cylinder were measured by using a dry-wet bulb thermometer of micro thermocouple type. The results of the measurements indicate that the thickness of the boundary layer of the convective mass exchange will decrease with an increase in Re_r and the thickness of the concentration boundary layer is greater than that of the temperature boundary layer. The temperature gradient of the heating mass-exchange boundary layer is smaller than that of the pure convective heat-exchange boundary layer. Rotation can produce a different impact on the convective mass-exchange at the consequent side and the inverse side. At the consequent side, due to the coincidence of the action direction of both the rotation-enforced convection and the natural convection, the result of this overlap has led to an increase in the boundary layer concentration gradient and a decrease in boundary layer thickness. However, at the inverse side, an exactly opposite situation will prevail. **Key words**: rotating cylinder, boundary layer, temperature field, concentration field, convective mass exchange

纵流壳程换热器新型抗振折流元件的数值研究＝**Numerical Investigation of an Innovative Vibration-proof Baffle Element for a Heat Exchanger with Longitudinal Flows at the Shell Side** [刊, 汉] / LI Jing, LIU Ming-shan, DONG Qi-wu (Research Center of Thermal Energy Engineering under the Zhengzhou University, Zhengzhou, China, Post Code: 450002) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(6). —579～583

Proposed is the construction of an innovative vibration-proof baffle rod element along with a simplified model for the unitary flow duct of this construction. By employing a numerical method the flow and heat transfer condition was simulated in a unitary flow duct supported by a clamp-type baffle rod. The results of the simulation were compared with those of the unitary flow duct of a straight baffle rod from the standpoint of fluid flow configuration, pressure and temperature distribution, etc. It has been found that with the exception of resistance drop the recommended construction has its heat transfer rate and heat transfer factor somewhat improved. **Key words**: heat exchanger, baffle rod, flow field, numerical simulation

回热器对 HAT 循环影响的分析＝**An Analysis of the Influence of a Recuperator on a Humid Air Turbine (HAT) Cycle** [刊, 汉] / QIU Chao, SONG Hua-fen (Institute of Mechanical & Power Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(6). —584～586

Nowadays two methods are generally adopted for the theoretical analysis of recuperators in a HAT cycle, namely, heat-transfer temperature difference method and thermal-ratio analysis method featuring the characteristics of a recuperator. Calculations were conducted using respectively the above-mentioned two methods of analysis and their impact on the HAT cycle was compared and analyzed. It has been found that the heat-transfer temperature difference method is more suited for the theoretical analysis of the HAT cycle. However, due attention should be paid during the selection of the heat-transfer temperature difference. On the other hand, the thermal ratio method has found more applications for the design of recuperators. **Key words**: humid air turbine cycle, recuperator, thermal ratio, heat-transfer temperature difference

波槽管管外珠状凝结换热的实验探讨＝**Experimental Investigation of Tube-outside Dropwise Condensation Heat Exchange of a Corrugated Tube** [刊, 汉] / HUANG Wei-tang, LIU Feng, ZHAO RI Getu (Institute of Power & Nuclear Engineering under the Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(6). —587～590

Under the condition of steam condensation outside a horizontal and vertical tube a comparative experimental investigation was conducted for the heat transfer performance of four kinds of experimental tubes. Within the range of tests for a horizontal tube with a condensation condition slightly higher than one atmospheric pressure the total heat transfer factor of tube BGT is about 1.38 - 1.60 times of that of a bare tube, while the total heat transfer factor of tube BGT-1 is about 2.05 -