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一次表面回热器动态特性的数值模拟与实验研究

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摘　要: 对一次表面回热器(Primary Surface Recuperator, PSR)流量阶跃变化时的动态特性进行了数值分析和实验研究。根据能量守恒原理和一次表面回热器(PSR)的结构特点, 导出回热器冷热流体和固体间壁非稳态温度变化的微分方程式, 研究流体流量发生阶跃变化时 PSR 的响应时间。在冷热空气进口参数和换热量相同的条件下, 当冷热侧流量分别增加为原来 3 倍的情况下, PSR 的响应时间只有管壳式换热器的 1/8, 板翅式的 1/3。数值分析结果与实验结果相符。由于 PSR 的固体壁面时间常数远小于板翅式和管壳式回热器, 因此这种轻重量结构的先进回热器响应特性明显优于常规回热器。

关　键　词: 燃气轮机; 一次表面回热器; 动态特性; 数值模拟

中图分类号: TK479; TK124　　　文献标识码: A

引　言

一次表面回热器(Primary Surface Recuperator, 简称 PSR)是当今国际上一种新型换热器, 它的传热元件为厚度 $\delta\approx 0.1$ mm 的不锈钢薄片, 冷热通道的水力直径约为 1 mm, 传热密度能够超过 1 600 m^2/m^3, 紧凑、高效和重量轻等特点使其非常适用于车辆、舰艇及各种小型燃气轮机装置[1~2]。这些装置会遇到非稳态问题, 一次表面回热器在非稳态过程下的响应特性反映了它的灵敏性。研究 PSR 的动态特性, 旨在更加全面地掌握这种先进换热器的工作特点。

1　PSR 通道的传热特性

如图 1 所示, PSR 通道由许多交错排列的不锈钢波纹状薄板组成。其中任一板片上(下)侧和相邻板片下(上)侧构成一排热(或冷)通道, 通道当量直径一般为 1 mm 左右。工作流体从通道中流过时, 若以通道中心假想面为界, 可以看出假想界面上、下侧的工质流动方向并不一致, 而保持某个夹角 θ。PSR 设计独有的这种相互干扰的流态, 必使对流换热系数和摩擦阻力系数比普通管道增大若干, 致使传热强化, 流动损失增大。交错波纹通道内的换热关系式为[3~5]:

$$Nu = 0.0031 M_h Re^{1.18} Pr^{0.4} (H/P)^{0.19} \tag{1}$$

式中: M_h—传热增强因子, 可通过热稳态实验得到: $M_h = 0.2919 Re^{0.25}$[6]; H/P—波纹通道高度宽度之比。

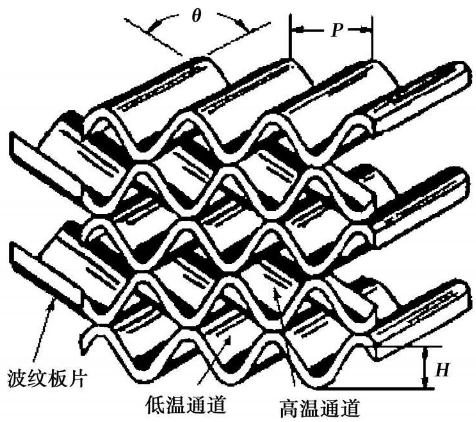

图 1　PSR 通道的构型

2　实验系统和实验样机

表 1　PSR 样机主要几何参数

	数　值
冷通道水力直径 d_{ec}/mm	1.30
热通道水力直径 d_{eh}/mm	1.58
通道长度 L/mm	185.1
波纹板宽度 W/mm	195.0
板片数目 n/片	60
传热面积 A/m^2	1.07
芯体紧凑度 $Comp$/$m^2 \cdot m^{-3}$	1 832

实验样机为 50 kW 燃气轮机 PSR 的缩比件, 结构参数如表 1 所示。实验系统如图 2 所示, 实验介

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质为空气。利用球形阀调节流量, 烟气采用电加热器加热。调节流量的同时需调节电加热器输入功率, 以维持加热器出口热空气温度不变, 流量与加热器输入功率对应关系可通过计算和实验得到。主要测量参数有冷、热空气的流量和进出口温度, 分别使用 LUGB 型涡流流量计、铜－康铜热电偶采集相关信号, 利用自动数据采集器实时监控各热工参数。

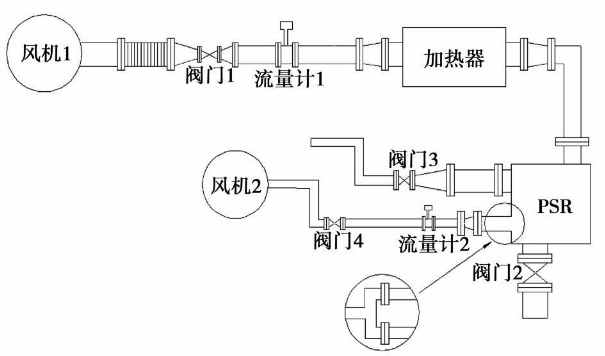


图 2　实验测试系统

3　PSR 动态特性数学模型

推导 PSR 温度响应数学方程的简化假定为[7~8]: (1) 冷、热流体温度及壁温仅随流动方向 x 而变, 为一维温度场; (2) 冷、热流体流量均匀分配, 换热器各流道流速相等; (3) 冷热流体不可压缩, 换热系数沿流动方向保持不变; (4) 不计流体和固体间壁的纵向热传导; (5) 由于金属波纹板片厚度仅为 0.1 mm 量级, 故认为金属固体壁面的导热热阻为零。在上述假设基础上, 根据能量守恒定律, 不难导出逆流式 PSR 3 个瞬态温度分布微分方程为:

$$\frac{\partial T_h(x,t)}{\partial t}=u_h\frac{\partial T_h(x,t)}{\partial x}+\frac{1}{\tau_{hh}}(T_w(x,t)-T_h(x,t)) \tag{2}$$

$$\frac{\partial T_c(x,t)}{\partial t}=-u_c\frac{\partial T_c(x,t)}{\partial x}+\frac{1}{\tau_{cc}}(T_w(x,t)-T_c(x,t)) \tag{3}$$

$$\frac{\partial T_w(x,t)}{\partial t}=\frac{1}{\tau_{wh}}(T_h(x,t)-T_w(x,t))+\frac{1}{\tau_{wc}}\times(T_c(x,t)-T_w(x,t)) \tag{4}$$

边界条件为:

$$T_h(L,t)=T_{h,in},\ T_c(0,t)=T_{c,in} \tag{5}$$

流量阶跃条件:

$$u_{h,c}=\begin{cases}u^0_{h,c} & \text{for} \quad t<0\\ u^\infty_{h,c} & \text{for} \quad t\geqslant 0\end{cases} \tag{6}$$

式中: x(坐标)—冷流体流动方向(热流体流动方向为－x 方向); u_h、u_c—烟气和空气的流速; T_h、T_c—烟气和空气的温度; T_w—固壁温度; τ_{hh}、τ_{cc}—烟气和空气的时间常数; τ_{wh}、τ_{wc}—烟气一侧和空气一侧的壁面时间常数, 其定义分别为:

$$\tau_{hh}=\frac{\rho_h Vol_h C_{ph}}{h_h A_h},\ \tau_{cc}\frac{\rho_c Vol_c C_{pc}}{h_c A_c},\ \tau_{wh}=\frac{\rho_w Vol_w C_{pw}}{h_h A_h},$$

$$\tau_{wc}=\frac{\rho_w Vol_w C_{pw}}{h_c A_c}$$

式中: ρ、Vol、C_p—对应流体和固壁的密度, 体积和比热; h—流体与壁面的对流换热系数, 其值由式(1)计算得到; A—冷热流体侧换热面积。

在初始时刻, 整个方程组是稳态的, 初始稳态的温度分布 $T^0_c(x)$, $T^0_h(x)$和 $T^0_w(x)$可通过求解稳态方程得到:

$$T^0_c(x)=-\frac{T^0_c(0)-T^0_c(\mathrm{L})}{e^{-\varphi^0 L}-1}e^{-\varphi^0 x}+\frac{e^{-\varphi^0 L}T^0_c(0)-T^0_c(L)}{e^{-\varphi^0 L}-1} \tag{7}$$

$$T^0_h(x)=-\frac{u^0_c\tau^0_{cc}\tau^0_{wh}}{u^0_h\tau^0_{hh}\tau^0_{wc}}\frac{T^0_c(0)-T^0_c(L)}{e^{-\varphi^0 L}-1}e^{-\varphi^0 x}+\frac{e^{-\varphi^0 L}T^0_c(0)-T^0_c(L)}{e^{-\varphi^0 L}-1} \tag{8}$$

$$T^0_w(x)=\frac{\tau^0_{wc}}{\tau^0_{wh}+\tau^0_{wc}}T^0_h(x)+\frac{\tau^0_{wh}}{\tau^0_{wh}+\tau^0_{wc}}T^0_c(x) \tag{9}$$

其中, $\varphi^0=\dfrac{u^0_h\tau^0_{hh}\tau^0_{wc}-u^0_c\tau^0_{cc}\tau^0_{wh}}{u^0_c u^0_h\tau^0_{hh}\tau^0_{cc}(\tau^0_{wh}+\tau^0_{wc})}$。

用差分替代微分, 离散式(2)~式(4), 经推导整理后, 得相应差分方程为:

$$T^{i+1}_{h,j}=H_1T^{i+1}_{h,j+1}+H_2T^i_{h,j}+H_3T^i_{w,j} \tag{10}$$

$$T^{i+1}_{c,j}=C_1T^{i+1}_{c,j+1}+C_2T^i_{c,j}+C_3T^i_{w,j} \tag{11}$$

$$T^{i+1}_{w,j}=W_1T^i_{w,j}+W_2(T^i_{h,j}+T^{i+1}_{h,j})+W_3(T^i_{c,j}+T^{i+1}_{c,j}) \tag{12}$$

其中,

$$H_1=\frac{u_h\Delta t}{\Delta x+u_h\Delta t},\ H_2=\frac{\tau_{hh}\Delta x-\Delta t\Delta x}{\Delta x\tau_{hh}+u_h\Delta t\tau_{hh}},$$

$$H_3=\frac{\Delta t\Delta x}{\tau_{hh}(\Delta x+u_h\Delta t)},\ C_1=\frac{u_c\Delta t}{\Delta x-u_c\Delta t},$$

$$C_2=\frac{\tau_{cc}\Delta x-\Delta t\Delta x}{\Delta x\tau_{cc}-u_c\Delta t\tau_{cc}},\ C_3=\frac{\Delta t\Delta x}{\tau_{cc}(\Delta x-u_c\Delta t)},$$

$$W_1=1-\frac{\Delta t}{\tau_{wh}}-\frac{\Delta t}{\tau_{wc}},\ W_2=\frac{\Delta t}{2\tau_{wh}},\ W_3=\frac{\Delta t}{2\tau_{wc}}。$$

隐式格式的计算工作量大, 在每个时间步长需要求解线性方程组, 但它对时间步长和空间步长没有限制, 不会出现解的震荡现象。采用隐式求解方法求解差分式(10)~式(12), 求解步骤大致为:

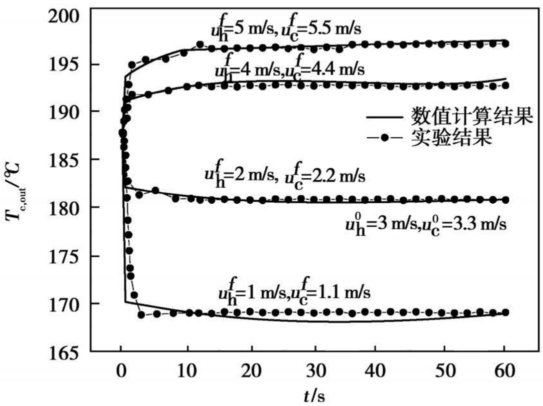
(1) 按照工质初始条件计算稳态温度场，如式(7)～式(9)所示；

(2) 输入阶跃变化后的工质入口条件，然后按照式(11)和式(12)计算 Δt 后各节点温度；

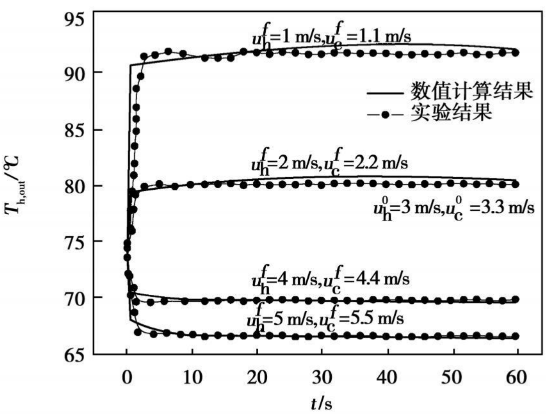
(3) 将求得的各节点温度作为新的初始条件，重复上述计算，直到计算时间达到设定值为止。

4　结果与分析

图 3 给出了一次表面回热器流量阶跃变化时出口温度响应的数值模拟与试验结果，数值模拟结果与实验数据相符。从图 3 中可看出，工质流量阶跃变化对出口温度的影响可分为两个阶段来考察。第一个阶段是工质出口温度在极短时间 $\Delta t_1 = L/u$ ($\ll$ 1 s)内发生了阶跃变化；第二个阶段是工质出口温度相对比较缓慢地达到新的稳定状态。可以发现，对于流量增加工况，PSR 只需要很短的时间就能达到稳定，且与流量变化幅度关系不大，而对于流量减少工况，PSR 需要较长时间才能达到稳定，且响应时间对流量变化比较敏感。

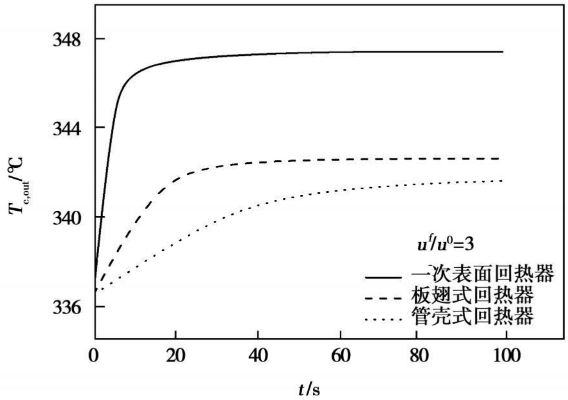


(a) 冷侧出口温度

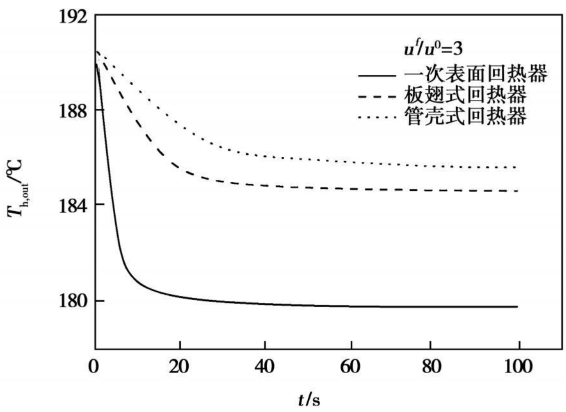


(b) 热侧出口温度

图 3　一次表面回热器出口实验温度与数值模拟结果



(a) 冷侧出口温度



(b) 热侧出口温度

图 4　3 种回热器在不同温度阶跃条件下工质出口温度与时间的关系

从图 4 中可以看出，在冷热空气进口参数和换热量 Q 相同的条件下，如表 2 所示，当冷热侧流量分别增加为原来 3 倍的情况下，管壳式回热器的出口温度大体在 80～100 s 内达到稳定，板翅式回热器的出口温度大体在 30～50 s 内达到稳定[9～10]，而 PSR 只需 10～20 s 温度就已稳定，响应时间只有管壳式换热器的 1/8，板翅式的 1/3。由此可以看出 PSR 在灵敏性上具有明显优势。

经过比较分析，在影响回热器响应特性的 4 个时间常数 τ_{hh}、τ_{cc}、τ_{wh}和 τ_{wc}中，流体时间常数 τ_{hh}和 τ_{cc}与固体壁面时间常数 τ_{wh}和 τ_{wc}相比非常小，影响回热器动态特性的主要参数是壁面时间常数 τ_{wh}和 τ_{wc}。PSR 能够具有很好的灵敏响应特性，其自身的重量轻结构是最主要的原因：PSR 传热板片为厚度只有 0.1 mm 的不锈钢薄板，没有重质隔板和其它杆件，固壁质量远小于传统换热器，加上 PSR 的换热系数较大，导致 PSR 的固体壁面时间常数显著减小。板片厚度 δ增加导致固壁质量增加，壁面时间常数相应成正比增加，厚度 δ对 PSR 动态特性影响

如图 5 所示。

表 2 3 种回热器的参数比较

	PSR	Plate-fin	Shell tube
换热量 Q/kW	22.5	22.5	22.5
空气进口温度 $T_{c,in}$/℃	120	120	120
烟气进口温度 $T_{h,in}$/℃	400	400	400
空气质量流量 m_c/kg·s^{-1}	0.1	0.1	0.1
烟气质量流量 m_h/kg·s^{-1}	0.103	0.103	0.103
传热面积 A/m^2	3.1	6.0	10.0
质量 G/kg	3.76	15.42	71.8
对流换热系数 h_c, h_h/W·m^{-2}℃$^{-1}$	229.0/201.1	91.6/122.6	348.1/36.2
传热系数 k/W·m^{-2}℃$^{-1}$	103.9	52.3	32.5
壁面时间常数 τ_{wc}, τ_{wh}/s	2.4/2.8	12.1/10.4	9.5/91.7

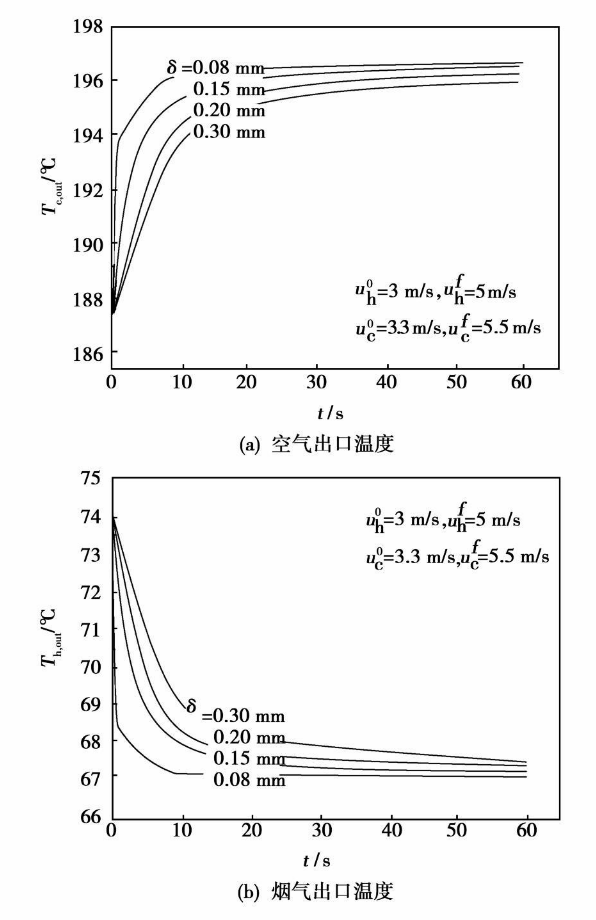


图 5 板片厚度 δ 对 PSR 响应特性的影响

5 结 论

对流量阶跃变化时, PSR 的动态特性进行了数值模拟和实验的研究, 发现相对常规的板翅式和管壳式换热器, 先进的 PSR 之所以能有灵敏的响应特性, 根本原因是它的固体壁面时间常数远小于板翅式和管壳式换热器。流量阶跃变化时, PSR 响应灵敏的优点更加明显, 原因是 PSR 流道短且换热系数大, 并且在流量增加时达到稳定需要的时间小于流量减小时所需时间。PSR 灵敏的动态变化特性, 使其适用于那些要求多变、反应灵敏的舰船燃气轮机动力装置。

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端壁造型在叶轮机械中的应用与发展= **Application and Development of End-wall Profiling in Turbomachinery** [刊, 汉] / LU Jia-ling, CHU Wu-li, LIU Zhi-wei (College of Power and Energy Source, Northwest China Polytechnic University, Xi'an, China, Post Code: 710072), ZHU Jun-qiang (Engineering Thermophysics Research Institute, Chinese Academy of Sciences, Beijing, China, Post Code: 100190)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(6). —687~691

Reviewed was the evolution of a new design technology-end-wall profiling technology, which can reduce secondary flow losses in the zones around end-walls. The technology may enhance the thermal efficiency of a turbine, and has been widely verified with relevant conclusions being adopted directly in engineering projects. Although the research for applying the above technology in compressors is somehow delayed in comparison with that in turbines, the latest research findings show that the technology has played a definite role in such efforts as changing the shock wave structure of a transonic compressor, improving its stable operating margin and reducing the separation of flows in the corners of stationary blades. The technology in question reflects the research tendency of utilizing complex profiles to enhance turbomachine performance, and merits further study and investigation in the future by researchers. **Key words**: end-wall modeling, turbomachinery, turbine, compressor

CC 型一次表面传热与阻力特性试验研究= **Experimental Study of Heat Transfer and Flow Resistance Characteristics of CC (Cross Corrugated) Type Primary Surfaces** [刊, 汉] / MA Hu-gen (College of Power Engineering, Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093), DUAN Rui (College of Energy Source and Environment Engineering, Shanghai University of Electric Power, Shanghai, China, Post Code: 200090)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(6). —692~695

Described were the development of primary surface heat transfer and the current status of its research both at home and abroad. By adopting a single-blow transient method, the heat transfer and flow resistance characteristics of three kinds of CC (cross corrugated) type primary surfaces were experimentally studied. A mathematical model was established, and the functional relationship among the fluid outlet temperature, time and *NTU* (number of transfer units), obtained from numerical solutions. Through a proportioned matching, the *NTU* value of the heat exchange surface under the relevant measurement conditions was determined with the test correlation of j and f for the three kinds of CC surface being obtained for the first time. Both j and f factor decrease gradually with an increase of Re number, conforming with the general law featuring the heat transfer and flow resistance performance of compact surfaces. After an error analysis, the fit error obtained from the test correlation being provided was assessed as not greater than 15%, offering sufficient engineering precision. The conditions for using the correlation are given as follows: $Re = 120 \sim 800$, the equivalent diameter of the heat exchange surface equals to 1.2~1.4 mm and the staggered angle ranges from 45 degrees to 75 degrees. By using the comprehensive evaluation factor of j/f, the performance of the three kinds of surface was analyzed. The research results show that the profile with a comparatively great width/height ratio can secure a relatively good comprehensive performance. The data thus obtained were also compared with the numerical simulation results of other academics both at home and abroad. The test data are basically in agreement with the numerical simulation results. **Key words**: CC (Cross Corrugated) type primary surface, single-blowing transient change method, heat transfer and flow resistance characteristics, heat exchanger

一次表面回热器动态特性的数值模拟与实验研究= **Numerical Simulation and Experimental Study of the Dynamic Characteristics of a Primary Surface Recuperator** [刊, 汉] / LIU Zhen-yu, SU Yong-kang, CHENG Hui-er (College of Mechanical and Power Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200240)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(6). —696~699

Numerically analyzed and experimentally studied were the dynamic characteristics of a primary surface recuperator (PSR) when it undergoes a step change of flow rates. In the light of the energy conservation theory and structural features of the PSR, a differential equation was derived, indicating a temperature change of the recuperator in an unsteady state between the cold and hot fluid as well as solid walls. Studied was the response time of PSR during the period of the fluid flow rate undergoing a step change. Under the condition that the inlet parameters and heat quantity exchanged between the cold and hot air are identical and the flow rates at the cold and hot side have increased to three times of the original ones respectively, the response time of the PSR is only 1/8 of a shell-and-tube heat exchanger and 1/3 of a plate-fin type one. The numerical analytic results fully correspond to the test ones. As the time constant of the solid walls in the PSR is far less than that in a plate-fin type or a shell-and-tube recuperator, the response characteristics of the advanced recuperator with such a light weight structure are conspicuously superior to those of a conventional recuperator. **Key words**: gas turbine, primary surface recuperator, dynamic characteristics, numerical simulation

采用弯叶片控制高负荷涡轮叶栅内附面层迁移的机理分析＝**Analysis of the Mechanism Governing the Migration of Boundary Layers in a Highly-loaded Turbine Cascade Controlled By Using Bowed Blades**[刊，汉]/TAN Chun-qing, ZHANG Hua-liang (Engineering Thermophysics Research Institute, Chinese Academy of Sciences, Beijing, China, Post Code: 100190), HAN Wan-jin, WANG Zhong-qi (College of Energy Science and Power Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001)//Journal of Engineering for Thermal Energy & Power. —2009, 24(6). —700～704

Numerically simulated was the inner flow field in a highly-loaded plane turbine cascade with a turning angle of 128.5 degrees. In combination with the previous test results and by utilizing topological theory, the influence of bowed blades on the evolution of boundary layers and movement of vortices in the above-mentioned cascade was analyzed in detail. It has been found that the concentrated vortex system predominated by the passage vortices was drastically mixed and diluted in the middle portion of the highly-loaded turbine cascade and its energy loss coefficient (0.56) is conspicuously higher than that at both ends (0.07). This constitutes the underlying cause that negatively-bowed blades can improve the overall aerodynamic performance of a cascade. After a further discussion of boundary layer migration theory, it is noted that when the bowed blades are used in highly-loaded turbine cascades to reduce the secondary flow losses, the migration of free vortex layers should be investigated with focused attention. **Key words**: bowed blade, high load, flow separation, boundary layer migration, secondary flow, topology

单缸低参数汽轮机末级排汽湿度的热力分析＝**Thermodynamic Analysis of the Last-stage Exhaust Steam Wetness of a Single-cylinder Low-parameter Steam Turbine**[刊，汉]/TIAN Rui-feng (College of Nuclear Science and Technology, Harbin Engineering University, Harbin, China, Post Code: 150001)//Journal of Engineering for Thermal Energy &Power. —2009, 24(6). —705～709

By adopting VB language and using a dynamic-link data base, designed was a thermodynamic calculation program for low-parameter single-cylinder steam turbines. By employing this program, the change of the last-stage wetness of the turbine unit for the following three versions of wetness removal was studied at various design parameters: namely, (1) without any steam extraction, (2) by extracting steam between stages and (3) by adopting a wetness removal stage. It has been found that the inlet steam pressure and temperature as well as the exhaust steam pressure can affect the last-stage wetness in different ways, and the inlet steam temperature exercises a maximal influence on the last-stage outlet wetness with consecutively less influence being exerted by the inlet steam pressure and the exhaust steam pressure. Under the given parameter condition of the present study, it is difficult for a full-load operation to meet the requirement for the last-stage outlet wetness, making it necessary to take effective inner wetness removal measures. The research results also indicate that the wetness removal by extracting steam at different locations, and by using a wetness removal stage exercises a relatively big influence over the last-stage wetness of the unit. At the same design parameters, the wetness removal by extracting steam after the fourth stage of the unit can maximally affect the last-stage wetness of the unit. At an identical wetness removal efficiency, when the location of the wetness removal stage shifts one stage backwards each time, it will lower the last-stage wetness by about 1%. With the location of the wetness removal stage moving backward, the influence of the wetness removal efficiency on the last-stage wetness will increase. **Key words**: single-cylinder steam turbine, thermodynamic design,