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LDV 实验测量气冷环形涡轮叶栅内部流场

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摘　要: 采用 LDV 对气冷环形涡轮叶栅流场三维平均速度进行实验测量, 研究孔射流对环形涡轮叶栅流场的影响。实验结果表明, 由于孔射流的影响, 在孔下游靠近叶片表面处形成回流区, 回流区速度随着下游距离的增加逐渐减弱, 同时射流在与主流的掺混过程中产生反向涡对。在涡轮叶片的吸力面和压力面, 由于壁面曲率、来流附面层状态和压力梯度的差异, 射流与主流的掺混以及流场结构也有所不同。在压力面侧, 射流与主流掺混形成的反向涡对比较明显, 射流尾迹的影响范围也较吸力面大。

关　键　词: LDV 测量; 环形涡轮叶栅; 孔射流; 三维平均速度

中图分类号: O358　　文献标识码: A

引　言

随着涡轮入口温度的提高, 涡轮叶片气膜冷却越来越重要。由于喷射冷气的引入, 涡轮内部流场结构变得更加复杂。尤其是采用离散孔形式喷射冷气时, 导致了一种极为复杂的三维流场结构。射流与主流掺混的流动结构对涡轮气膜冷却效率、气动性能等影响较大, 了解射流与主流的掺混机理有助于在气膜冷却中抑制射流对主流的穿透, 减弱高温主流对叶片的直接冲刷, 提高冷却效率。

采用离散孔喷射冷气时影响冷却效率的参数很多, 包括喷射角度、孔间距、来流附面层状态、压力梯度和壁面曲率等。在叶栅中, 由于射流出口受到上述几种参数的共同作用, 因此国内外学者的研究大部分都在平板流动这一简化条件下展开。Y. J. Perry 研究了射流与主流掺混的反向涡(Counter-rotating Vortex)的形成[1], Khan 采用流场可视化方法证明反向涡模型与平板射流的实验结果符合较好[2], Dieter E. Bohn 采用数值计算的方法研究了叶片前缘冷气射流对其下游流场结构和温度场的影响[3]。国内的学者对平板和平面叶栅内冷气射流的流场结构也做了大量的计算和实验工作[4~9]。由于叶片压力面和吸力面在壁面曲率、来流附面层状态和压力梯度均有所不同, 射流对于涡轮压力面和吸力面的流场影响也会不一样, 特别是对于环形叶栅, 以前的文献关于射流对吸力面和压力面侧流场影响的异同比较相对较少。本文采用三维激光多普勒测速仪(Laser-Doppler Velocimetry, 简称 LDV)对气冷环形涡轮叶栅流场三维速度进行实验测量, 研究孔射流对环形叶栅压力面和吸力面侧流场的影响。

1　实验装置与测量系统

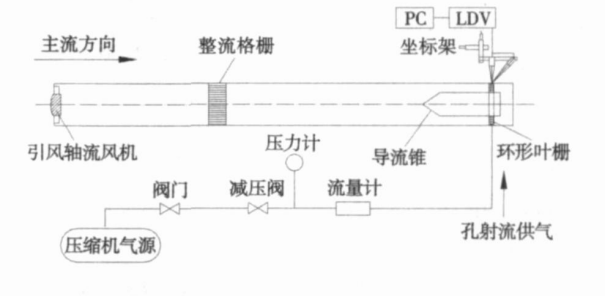

图 1　实验装置示意图

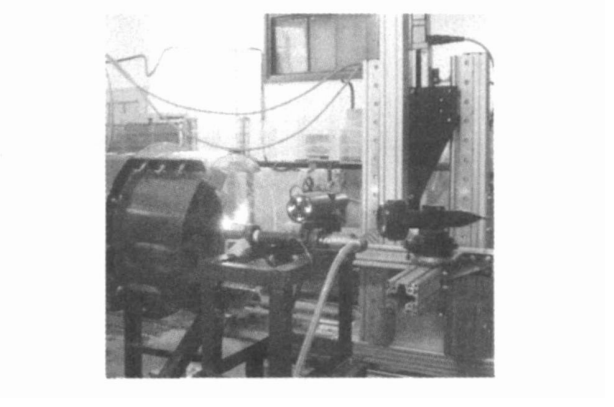

图 2　LDV 测量系统

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图 1 是实验测量装置示意图。实验设备主要由低速直流式风洞、LDV 系统、环形涡轮叶栅和孔射流供气系统等几部分组成。实验所用的低速风洞中部加有整流格栅，用来减少来流紊流度。利用全数字变频调速器（变频范围为 0.00 ~ 50.0 Hz）调节轴流风机的转速来达到所需的主流速度，该风洞的稳定风速范围为 0.5 ~ 15 m/s。实验测量采用的 LDV 系统由丹麦 Dantec 公司生产，如图 2 所示。

2　涡轮模型及实验测量位置

实验叶片采用某型号涡轮叶片，如图 3 所示。叶片压力面和吸力面各开一排（3 个）孔，孔喷射角度 α 取 90°。具体实验参数见表 1。射流的吹风比 M 定义为：

$$M = \rho_j V_j / \rho_0 V_0 \tag{1}$$

式中：ρ_j、ρ_0—孔射流气体和涡轮叶片入口的平均密度；V_j、V_0—孔射流气体和涡轮叶栅入口的平均速度。

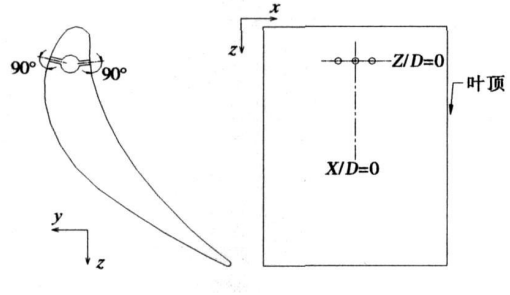

图 3　实验叶片和测量坐标系统

表 1　实验参数

	数值
涡轮入口风速/ $m \cdot s^{-1}$	7
涡轮出口静压/ Pa	101 300
孔直径 D/ mm	2
孔间距/ mm	6
孔射流角度/（°）	90
吹风比 M	2
主流气体温度/ K	290
射流气体温度/ K	290

分别以叶片压力面和吸力面上中间孔的圆心为起点，沿孔下游取 5 个测量面（L/D = 0、1、3、5、8），测量面垂直轴向方向（Z 轴），具体测量点位置如图 4 所示（L 表示沿轴向方向距离孔中心的距离，S 表示测量面上任意点距离叶片表面的距离）。

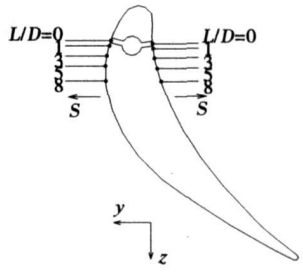

图 4　测量点位置示意图

3　LDV 测量三维速度方法

图 5 给出了 LDV 测量光束和速度分量的示意图。蓝色光和绿色光由于从同一光学探头中发出，在硬件上严格保证汇聚在同一点上。为保证紫色光也通过同一点，将一个 0.2 mm 的小孔放置在该交点上，然后调节紫光光束对通过该小孔，即保证测量在同一点上；另外还要符合信号处理的采样要求，三色信号必须在限定的时间窗内同时出现，否则数据采集无效。

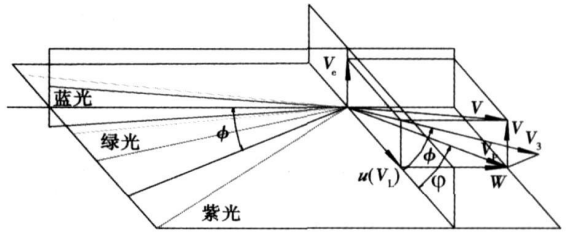

图 5　LDV 系统测量速度分量示意图

根据图 5 中 LDV 测量系统的布置，速度 u 和 v 可以被绿光和蓝光光束对直接测量获得，而速度 w 可以通过绿光和紫光光束测量得到的速度分量计算得到，下面给出速度的转换公式：

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1/\tan\phi & 0 & 1/\sin\phi \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{2}$$

式中：u、v、w—沿坐标轴 Z、Y 和 X 方向的速度分量；V_1、V_2、V_3—绿光、蓝光和紫光光束对所测量得到的速度分量；ϕ—绿光光束对角平分线和紫光光束对角平分线的夹角。

4 实验结果与分析

测量的三维平均速度值(u、v、w)都由孔射流平均速度(V_j)进行无量纲化。在数据处理过程中,认为叶栅内部的流动是定常的,而且每个流道内部的流动情况相似。

图6给出了吸力面侧沿中间小孔中心下游3个不同位置(L/D=1、3、8)的三维平均速度分量的等值线图。从图可以看出流场结构在叶片吸力面不同位置的变化情况(图中 V_j 表示孔射流平均速度,u、v、w 分别表示沿坐标轴 Z、Y 和 X 方向的平均速度)。

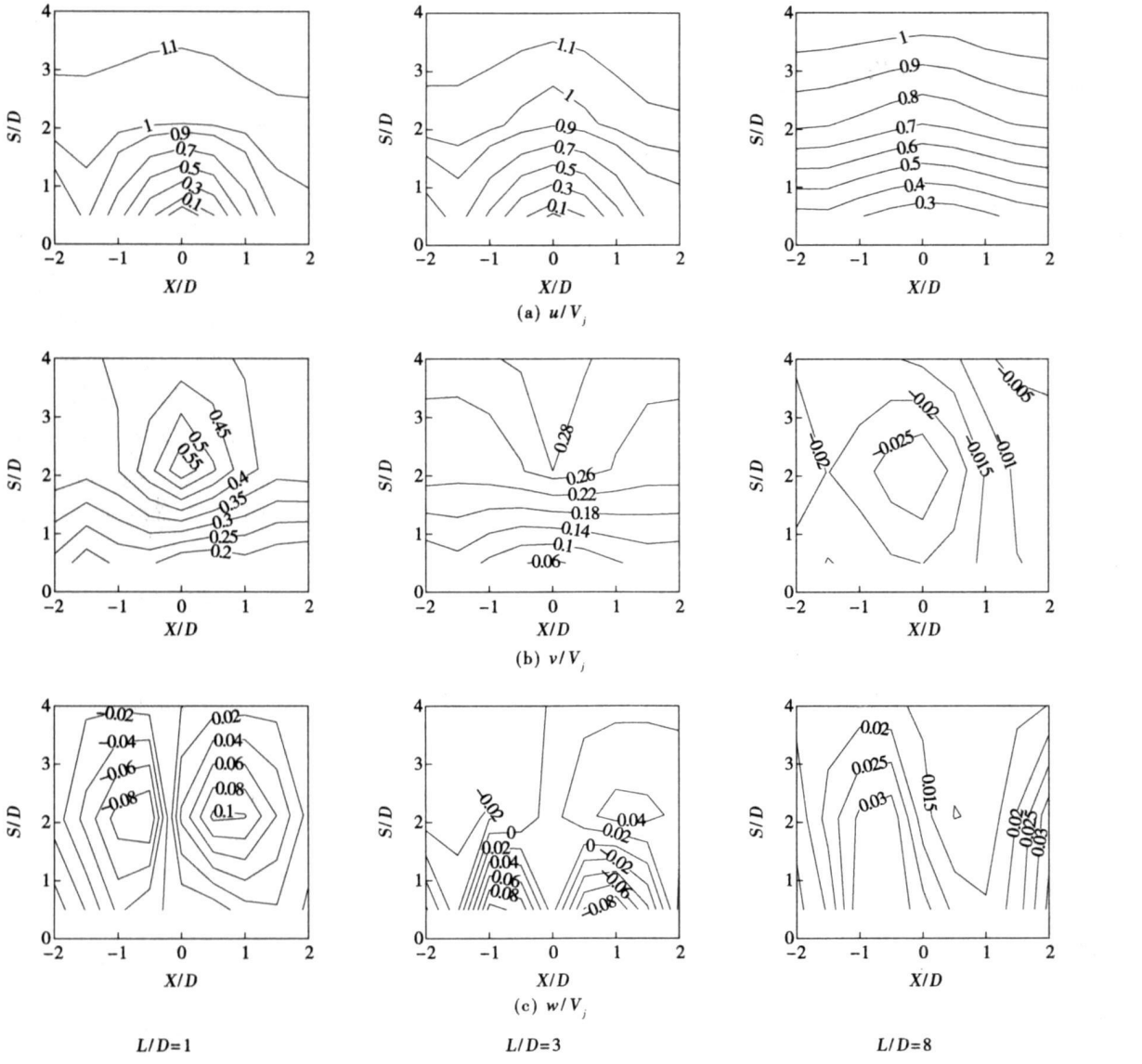

图6 吸力面中心孔下游三维平均速度等值线

吸力面侧轴向速度(u/V_j)沿孔下游不同位置的变化如图6(a)所示。由于射流的影响,在孔下游附近位置(L/D=1和 L/D=3),主流和射流的掺混使掺混区域的轴向速度增大,在 L/D=8 处掺混基本完成。由于 L/D=1 和 L/D=3 处于孔射流下游的尾迹区,靠近叶片壁面处的流体轴向速度较小。在 L/D=8 处,射流尾迹区的影响逐渐消失,射流对主流的影响减弱,叶片近壁面处的轴向速度有所增大。

图6(b)给出了速度 v 沿孔下游不同位置的等值线。在 L/D=1 位置,射流进入主流后,使得 X 方向距离孔中心1倍孔径范围内的流体加速,速度 v 的值明显增大。随着孔下游距离的增大(L/D=3),射流气体与主流逐渐掺混,流体也逐渐贴附壁面

流动，速度 v 减小。在 $L/D=8$ 位置处，叶片表面曲率较小，该处曲面的切线方向与 Z 轴基本平行，且 Y 轴的分量指向 Y 轴负方向，因此速度 v 很小，方向也与前面相反。

图 6(c)给出了叶片吸力面侧，径向速度(w/V_j)沿孔下游不同位置的等值线。在距离孔下游一倍孔距的位置($L/D=1$)，射流对径向速度的影响较大，在孔中心线($X/D=0$)两侧，径向速度方向相反且较为对称。沿孔中心下游 $L/D=3$ 处，有很明显的反向涡对出现，涡心位置在 $S/D=2$ 左右。随着孔下游距离的不断增大，尾迹影响的强度减弱，反向涡对在 $L/D=8$ 处基本消失。

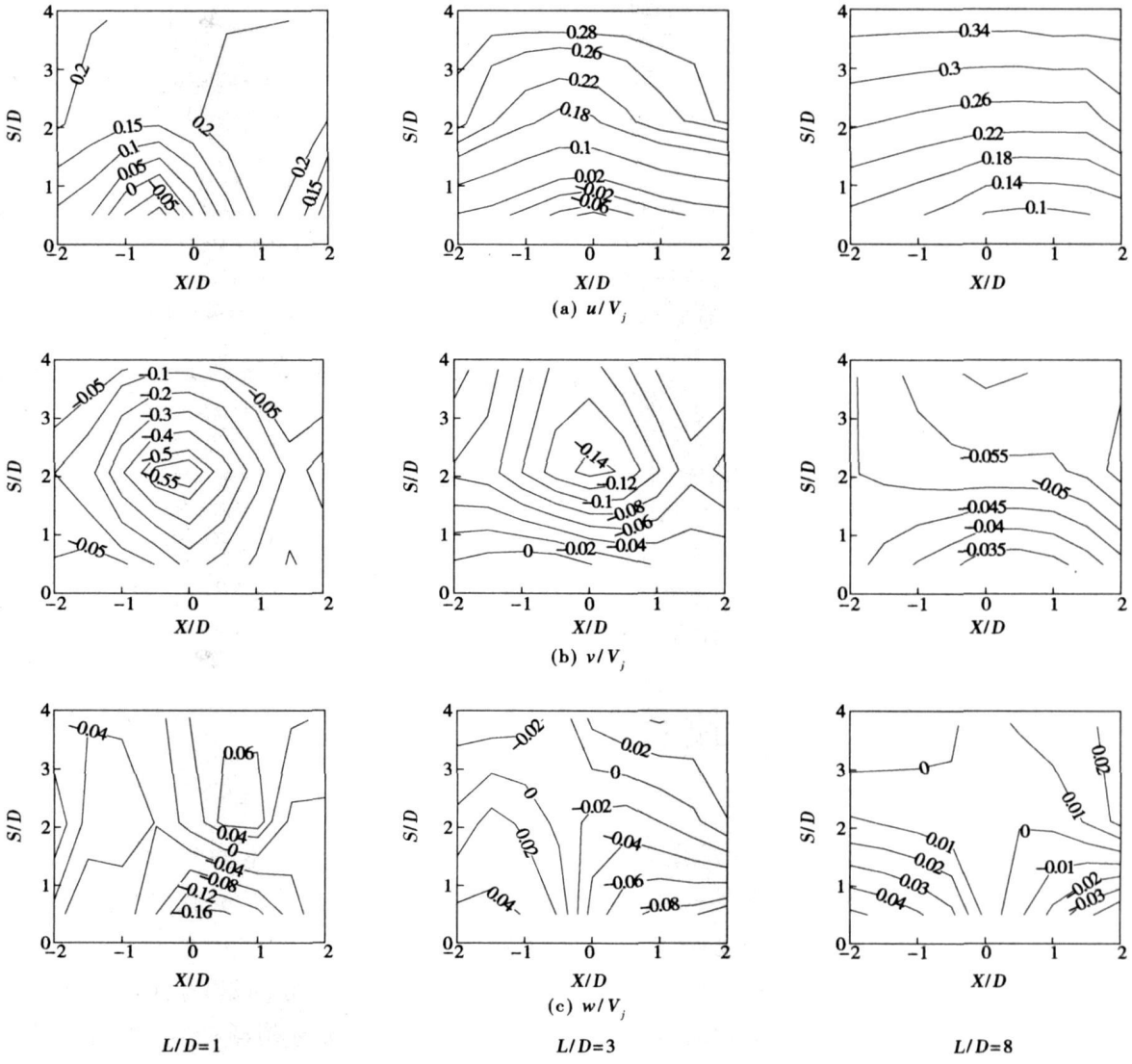

图 7　压力面中心孔下游三维平均速度等值线

图 7 分别给出了压力面侧沿中间孔中心下游不同位置($L/D=1$、3、8)的三维平均速度分量的等值线图。从图 7(a)可以看出，在压力面孔下游 $L/D=1$ 和 $L/D=3$ 位置，靠近壁面的轴向速度与主流速度方向相反，这是由于孔射流对主流的阻挡作用形成尾迹区，产生了回流。在 $L/D=8$ 处，射流产生的回流区域基本消失，叶片近壁面的轴向速度有所恢复，速度值增大。

图 7(b)是速度 v 沿孔下游不同位置的速度等值线。与吸力面相似，随着孔下游距离的增大，射流气体与主流逐渐掺混，在孔下游附近($L/D=1$ 和 $L/D=3$)，射流与主流的掺混较为明显，速度 v 的最大值出现在距离叶片表面 $S/D=2$ 处。在 $L/D=8$ 位置，射流与主流基本完全掺混。

图7(c)是径向速度(w/V_j)沿孔下游不同位置的等值线。在 $L/D=1$ 处,射流与主流的掺混过程中形成反向涡对,涡心在 $S/D=2$ 附近,该处的反向涡对比较明显,叶片近壁面回流区的径向速度也较吸力面大。反向涡对的影响范围在 $L/D=3$ 处达到最大,涡心位置上升到 $S/D=3$ 附近。在 $L/D=8$ 处,反向涡对呈现减弱趋势,涡心位置有所降低,速度也相应降低。在压力面,射流对径向速度 w 的影响区域比吸力面大。

5 结 论

本文采用 LDV 系统对气冷环形涡轮叶栅内部流场进行实验测量,结果表明:

(1) 采用 LDV 测量环形涡轮叶栅内部流场,对流场干扰小,可成功捕捉到叶片孔下游受射流影响的流场结构及其变化;

(2) 在孔射流与主流的掺混过程中,孔下游附近会产生反向涡对。随着下游距离的增大,反向涡对强度逐渐减弱。同时,由于射流尾迹的影响,在孔下游附近靠近叶片表面会产生回流,其随着下游距离的增大逐渐减弱;

(3) 在叶片吸力面和压力面,由于壁面曲率、来流附面层状态和压力梯度均有所不同,射流与主流的掺混范围以及流场结构的变化也有所不同。在压力面侧,射流与主流掺混形成的反向涡对比较明显,射流尾迹的影响范围也较吸力面更大。在吸力面孔下游,射流对主流的影响范围较小,相比压力面,射流在吸力面孔下游不远处较易贴附叶片表面流动。

参考文献:

[1] PERRY Y J, KOH S R. Counter-rotation streamwise vortex formation in the turbine cascade with endwall fence[J]. Computers & Fluids, 2001, 30(4): 473-490.

[2] KHAN Z U. On the dominant vortex created by a pitched and skewed jet in crossflow[D]. Stanford University, 1999.

[3] BOHN DIETER E, KUSTERER KARSTEN A. Aerothermal investigations of mixing flow phenomena in case of radially inclined ejection holes at the leading edge[J]. Journal of Turbomachinery, 2000, 122: 334-339.

[4] 王松涛, 冯国泰, 王仲奇. 叶栅内冷气射流场结构的数值模拟[J]. 航空动力学报, 2000, 15(3): 274-277.

[5] 陈 浮, 宋彦萍, 王仲奇. 吸力面上气膜冷却对涡轮叶栅流场影响的实验研究[J]. 航空动力学报, 1999, 14(2): 161-165.

[6] 杨 科, 王松涛, 王仲奇, 等. 平面叶栅中冷气射流三维分离的数值模拟[J]. 推进技术, 2003, 24(1): 43-46.

(编辑 伟)

致作者、读者

世界能源储量逐渐减少,全球能源危机日益加重。因此,新能源技术的研究和开发越来越受到人们的关注。在我国新能源种类较多,如太阳能、生物能、地能、风能和燃料电池等这些新能源技术的发展给我国的能源领域发展带来新的生命力。

为此,本刊在2007年设立了一个新栏目“新能源动力技术”,其目的就是将国内外的新能源动力领域的最新科研成果及时加以报道。本刊欢迎从事能源动力领域研究、教学的院校师生、科研人员和工程技术人员为《热能动力工程》期刊撰写新能源动力领域研究成果论文、各国新能源研究最新进展的综述性文章。

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《热能动力工程》编辑部

水煤浆锅炉的发展及现状＝**Development and Status Quo of Coal-water-mixture (CWM)-fired Boilers**[刊, 汉] /LI Yi, YANG Gong-xun, GAO Song (College of Electromechanical and Information Engineering, China University of Mining and Technology, Beijing, China, Post Code: 100083)// Journal of Engineering for Thermal Energy & Power. —2007, 22(6). —583 ~ 585

The concept of coal-water-mixture (CWM)-fired boilers and the features that set them apart from other boilers are briefly described along with a detailed account of the evolution and status quo of CWM-fired boilers both at home and abroad, i.e. the evolutionary process of various oil and coal-fired boilers being converted to burn CWM. The authors have noted the problems existing in the retrofitted CWM-fired boilers and the emergence of special purpose ones. The main technologies used in such boilers are depicted in detail with an analysis of their new technologies and related existing problems. Finally, the future development of CWM-fired boilers was forecasted and the authors conclude that the boilers in question will play a positive role in promoting energy-savings and environment protection. **Key words**: boiler, development, status quo, coal-water-mixture

零压力梯度平板边界层转捩的数值模拟＝**A Numerical Simulation of the Boundary Layer Transition on a Plate with Zero Pressure Gradient**[刊, 汉] /DONG Ping, HUANG Hong-yan, FENG Guo-tai (College of Energy Sciences and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001)// Journal of Engineering for Thermal Energy & Power. —2007, 22(6). —586 ~ 590

A numerical simulation of the boundary layer transition tests T3A and T3B on a plate was performed and the calculated values were in relatively good agreement with the test ones. Through a study of the phenomenon of boundary layer transition on a plate at zero pressure gradient, the authors have concluded that the influence of the complexity of the transition flows on the boundary layer of a flow field should not be neglected. The M-L transition model can somewhat accurately predict the generation and development process of the transition. At a high turbulence, the use of a total turbulence model to simulate a transition flow will result in a relatively small error. **Key words**: boundary layer transition on a plate, transition model, zero pressure gradient, numerical simulation

影响系数法平衡中的病态方程研究＝**A Study of Ill-conditioned Equations Involved in a Dynamic Balancing Process When Influence Coefficient Method is Used**[刊, 汉] /WANG Xiu-feng, NIU Zhen (National Key Laboratory on Machine Building Systematic Engineering, Diagnosis and Control Theory Research Institute, Xi' an Jiaotong University, Xi' an, China, Post Code: 710049)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(6). —591 ~ 595

Dynamic balancing technology provides the most important means for the elimination of unbalance faults of rotors while influence coefficient method (ICM) represents a major approach in dynamic balancing techniques. However, in practical operations the balancing efficiency may be lowered due to the influence of ill-conditioned equations. To cope with the problem of possible emergence of ill-conditioned equations, a single-span rotor model was established and by using rotor vibration mode theory the mechanism governing the appearance in the ICM of ill-conditioned equations analyzed. On this basis, an experimental study was conducted. The research results show that the ICM can be used for the dynamic balancing of flexible rotors. However, the rotors may be influenced by the ill-conditioned equations at a special rotating speed and a special counterweight plane while the selection of a rational balancing speed and balanced counterweight plane constitutes a main measure for avoiding the ill-conditioned equations. **Key words**: influence coefficient method, dynamic balancing, ill-conditioned equation

LDV 实验测量气冷环形涡轮叶栅内部流场＝**Experimental Measurement of the Flow Field in an Air-cooled Annular Turbine Cascade by Using LDV (laser-Doppler velocimetry)**[刊, 汉] /YUAN Feng, WU Ya-dong, ZHU Xiao-cheng, et al (School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200030)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(6). —596 ~ 600

An experimental measurement was performed of the three-dimensional average speed in the flow field of an air-cooled an-

nular turbine cascade by using LDV method to study the impact of hole jet flow on the flow field in an annular turbine cascade. The test results show that due to the influence of hole jet flow a return flow zone will be formed downstream of the hole near the blade surface. The speed in the return flow zone will be gradually lowered with an increase of the distance away from the hole at the downstream. Meanwhile the jet flow will produce a reverse vortex pair during its mingling and dilution with the main flow. At the blade suction and pressure surface due to the difference in wall surface curvature, incoming-flow boundary layer status and pressure gradient, the mingling and dilution of the jet flow with the main flow as well as the structure of flow field will also be somehow different. At the pressure side, the reverse vortex pair formed by the mingling and dilution of the jet flow and the main flow is relatively evident and the range of area influenced by the wake of the jet flow is also much larger than that at the suction side. **Key words**: LDV (laser-Doppler velocimetry)-based measurement, annular turbine cascade, hole jet flow, three-dimensional average velocity

涡轮叶片用渗 Al 涂层高温氧化行为=**High-temperature Oxidation Behavior of Aluminized Coatings on Turbine Blades**[刊, 汉] / WANG Yong-gui, QIU Er-ni, YANG Li-fa (Gas Turbine Design Department, CSIC No. 703 Research Institute, Harbin, China, Post Code: 150036), DING Ming-hui (College of Material Science and Chemical Engineering, Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(6). —601 ~ 604

By adopting a slurry process an aluminized coating is formed on the high-temperature nickel-base alloy surface of blade material K4104. By making use of static-state high-temperature oxidation and various physical testing methods, studied was the protective performance of the aluminized coating. An in-depth analysis was performed of the oxidation dynamic characteristics and the morphological change of an oxide film during the test process. The test results show that the aluminized coating has improved the oxidation-resistance performance of the alloy. A long-duration high-temperature oxidation can lead to the emergence of cavities between the aluminized coating and basal body, resulting in the peeling-off of the oxide film and the weakening of the oxidation-resistance performance of the coating to a certain extent. **Key words**: turbine blade, aluminized coating, oxidation dynamics, oxide film morphology, short-circuit passage

基于叶片弯掠技术的优化设计=**Optimized Design Based on Skewed and Swept Blade Technology**[刊, 汉] / LI Yang (College of Electromechanical Engineering, Qingdao University of Science and Technology, Qingdao, China, Post Code: 266061), OUANG Hua, DU Zhao-hui (School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(6). —605 ~ 609

By utilizing a BP (back propagation) neural network and genetic algorithm on a program platform for the numerical calculation of three-dimensional viscous flow fields, the circumferential bending angle of rotor blades in an axial compressor was optimized through the use of skewed and swept blade technology to further improve the aerodynamic performance of the fan. It has been found through a comparison of the blade wheels before and after the optimization that the blades thus optimized exhibit obvious characteristics of being circumferentially forward-skewed. The testing results show that the total pressure and aerodynamic efficiency have increased by 3.56% and 1.27% respectively with the stall margin being significantly extended by over 36% and the losses at both the upper and lower end further reduced. **Key words**: circumferential forward-skewed blade, artificial neural network (ANN), genetic algorithm (GA), optimized design

单级轴流氦气压气机空气模拟气动性能数值分析=**Numerical Simulation Analysis of the Aerodynamic Performance of a Single-stage Axial Helium Compressor with Air Serving as the Working Medium**[刊, 汉] / ZHU Rong-kai, ZHENG Qun (College of Material Science and Chemical Engineering, Harbin Engineering University, Harbin, China, Post Code: 150001), JI Guang (Naval Representative Office Resident at CSIC No. 703 Research Institute, Harbin, China, Post Code: 150036), ZOU Ji-guo (CSIC No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(6). —610 ~ 614

Being the fourth generation of an advanced reactor type, HTGR-10 (modular high-temperature gas cooled reactor) features a simple system, safe and reliable operation as well as high cost-effectiveness etc. Furthermore, the performance of the he-