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串列叶栅流场特性的试验与数值模拟

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摘　要：对某型串列叶栅以及独立后排叶栅进行了多工况下性能和油流显示试验以及数值模拟，分析了串列叶栅的流场特性及前排叶片对后排叶片流场的影响。通过对试验结果分析发现，串列叶栅的攻角特性范围较宽，气流转折角大，损失较单排叶片约增加40%；前排叶片的存在一定程度上使得后排叶片流场受攻角变化的影响减小，并使其吸力面的马赫数峰值降低5%；对比试验与数值模拟结果后发现，压力面马赫数分布吻合较好，吸力面试验值略高于计算值；前排和后排叶片之间相对位置对串列叶栅的性能有着至关重要影响，需要对此进行深入研究。

关　键　词：串列叶栅；流场特性；数值模拟；油流显示；测试点

中图分类号：TK474　　**文献标识码：**A

引　言

串列式轴向压气机是 Beelte 和 Ohashi 在试验过程中通过改变后排叶片轴向和周向位置来优化结构时发现的[1~2]。国外学者通过将串列叶栅与某大弦长参考叶片相比较，明显可见串列叶栅的转折角和部分状态点损失是优于参考叶片[3~5]。国内南京航空航天大学近年来对串列叶栅进行了深入、系统的研究工作，对我国拥有的一些国外航空发动机中应用串列叶栅做过大量的摸底试验工作[6~8]。经过系列研究发现，串列叶栅是提高级负荷、扩大喘振裕度的理想方法之一。

串列叶栅的缺点是结构比较复杂，叶片加工量大，因此有人认为采用串列叶栅将使发动机的质量增加，推重比下降，然而巴默特认为，如果压气机转子由串列叶栅组成，静子由普通单列叶栅组成，级的反力度为100%，当总的压头相同时，它所组成的级的轴向长度可以做到比普通的级小，质量也轻[9]。国外，早已将其应用于多种航空发动机的轴流式压气机的末级静子和末级风扇静子中，例如苏27发动机的串列叶栅静子以及波音360串列叶栅转子等[10~11]。

1　试验情况

试验是在中航工业燃气涡轮研究院 SB301 超跨音速平面叶栅风洞上进行的[12]。串列叶栅的设计是在单排定制叶型造型的基础上，对两个单排叶型按一定规则在轴向和周向布置而形成的，叶型简图以及主要几何参数分别如图1和表1所示。取靠近风洞中间位置的4个叶片作为测压叶片，叶片表面静压测量布点为：前排叶片压力面和吸力面各8点，后排叶片压力面和吸力面各10点，共测取36个叶片表面压力测点。在叶栅出口用楔形三孔探针在叶栅的中间通道后(50%叶高)，沿额线方向每隔一定距离测取一个点移动一个栅距，然后利用探针校准曲线插值求出各点的总压 P_{2t}、静压 P_{2i}、出口气流 β_2、出口马赫数 M_{2t} 和总压损失 ω，具体测试布点如图2所示。由于后排叶片弦长较长弯度较大，试验过程中通过拆除前排叶片后可单独进行后排叶片试验的方法，得到独立后排叶片的流场特性。

表1　串列叶栅叶型几何参数

Tab. 1 Geometric parameters of a tandem cascade blade profile

参数名称	前排	后排
进口马赫数 M_1	0.514	0.375
进口气流角 β_1/(°)	37.73	51.69
出口气流角 β_2/(°)	51.68	90
设计攻角 I/(°)	3.92	-1.0
设计落后角 δ/(°)	6.29	7.98
叶片弦长 b/mm	30.148	47.982
稠度 b/t	0.976	1.552
水平偏移位置 Δx/mm	11.563	
竖直偏移位置 Δy/mm	23.056	

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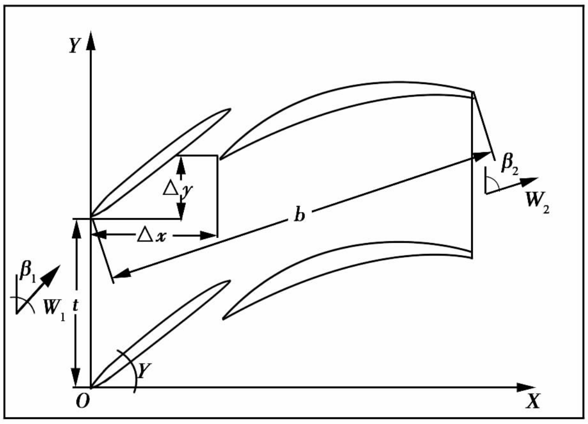


图 1 串列叶型简图

Fig. 1 Sketch of a tandem cascade blade profile

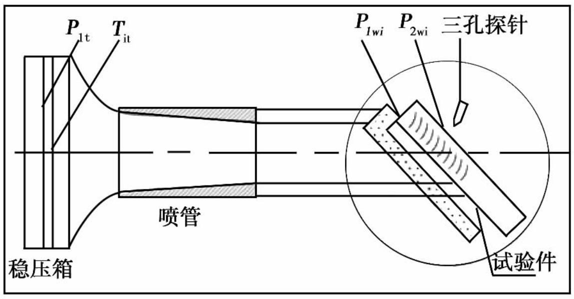


图 2 测试布点简图

Fig. 2 Sketch showing the arrangement layout of the measurement system

2 数值模拟

计算网格采用 NUMECA 软件中专为叶轮机械用户开发的 Autogrid 网格生成模块，自动建立串列叶栅流道拓扑结构，生成结构化网格。为了保证网格质量，单个叶片网格均采用 O－H 型，串列叶栅网格由两个 O－H 型网格自动衔接组合而成。串列叶栅网格数约为 50 万，后排独立叶片为 30 万。计算采用 NUMECA 软件中的 FINE/Turbo 模块，对有限体积形式的三维雷诺平均 $N-S$ 方程进行定常求解。湍流模型采用 $S-A$（Spalart－Allmaras）模型。空间离散采用中心差分格式，时间离散采用四阶显式 Runge－Kutta 法进行时间推进求解。计算采用多重网格法，结合当地时间步长及隐式残差光顺等加速收敛技术。图 3 所示为计算串列叶栅网格。计算边界条件给定为：进口总温、总压（与试验一致）、湍流度及气流角，出口给定平均静压。

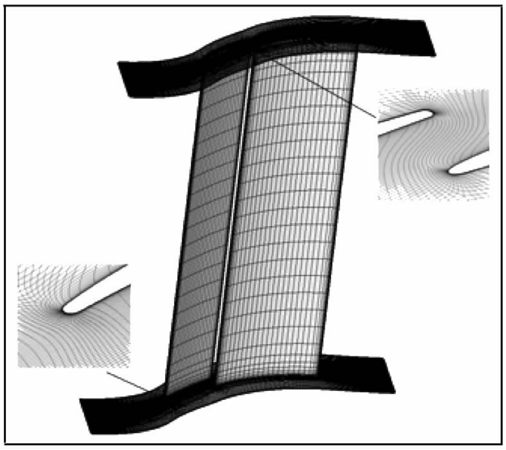


图 3 串列叶栅计算网格

Fig. 3 Mesh for calculating a tandem cascade

3 试验结果及分析

3.1 串列叶栅流场特性试验结果

试验对串列叶栅在各种不同进口工况下进行了叶片表面马赫数分布以及出口尾迹和总体性能等参数进行了测量。图 4 给出了串列叶栅的攻角特性线。由图可知，随着进口马赫数的增加总压损失系数逐渐增大，并且曲线整体向正攻角方向移动，导致负攻角特性范围减小，正攻角特性范围略微增大。整体看，随着进口马赫数的升高，串列叶栅可工作较佳的攻角范围逐渐减小并在设计点时的损失为最小值。设计马赫数下当攻角范围在 $-4° \sim 10°$ 内，叶型损失均处于较低水平（$\omega < 0.06$）。当 $i > 10°$ 后叶栅损失系数急剧增加，原因是此时叶栅可能工作于堵塞状态。在所有试验中叶片表面马赫数均小于 1.0，因而叶栅损失主要为附面层内气流摩擦损失和尾迹损失。

图 5 为设计进口马赫数（$M_1 = 0.514$）不同攻角下叶片表面马赫数沿轴向分布。由图可知，某些状态下未给出前排叶片压力面马赫数分布，这是由于试验过程中前排测压叶片被吹断，因此无相应试验数据。随着攻角由正到负，后排叶片吸力面马赫数逐渐增大，然而比较 $i = -0.35°$ 和 $i = -2.35°$ 两种攻角下表面马赫数曲线可知，后排叶片表面马赫数分布变化较小，说明当攻角在设计点附近变化时，串列叶栅受攻角变化的影响较小。由表面马赫数分布可知，在试验攻角范围内未出现分离现象。

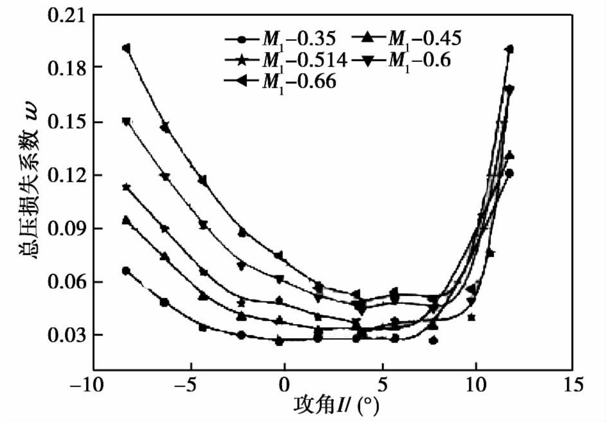


图 4　串列叶栅攻角特性曲线

Fig. 4 Curves showing the attack angle characteristics of a tandem cascade

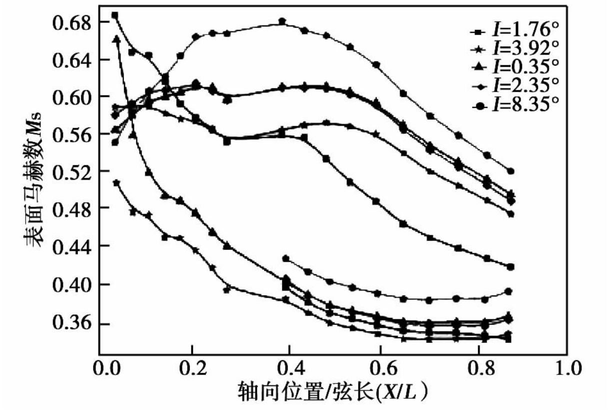


图 5　叶片表面马赫数分布

Fig. 5 Mach number distribution on the blade surface

3.2　串列叶栅与后排独立叶片性能对比

试验过程中拆除前排叶片后在后排叶片设计攻角下进行了后排独立叶片的性能试验测量。表 2 给出了两种叶栅在设计攻角下不同进口马赫数的性能参数。图 6 ~ 图 8 为串列叶片和后排独立叶片的气流转折角、总压损失和静压比随进口马赫数的变化情况。由图可知，在试验进口马赫数范围内，串列叶栅气流转折角和静压比明显大于后排独立叶片，然而损失相对而言较大。这是因为前排叶片后缘与后排叶片前缘之间形成了一条狭缝气流，狭缝气流速度较高一方面可以因减小后排叶片附面层的厚度，防止附面层分离，减小损失；另一方面，狭缝射流与主流间的掺混又可能导致损失增加，特别是在正攻角情况下压力面处狭缝位置压力高，狭缝气流与主流速度差较大时，狭缝气流与主流掺混导致的损失增加，因此导致叶栅总的损失增加较大。

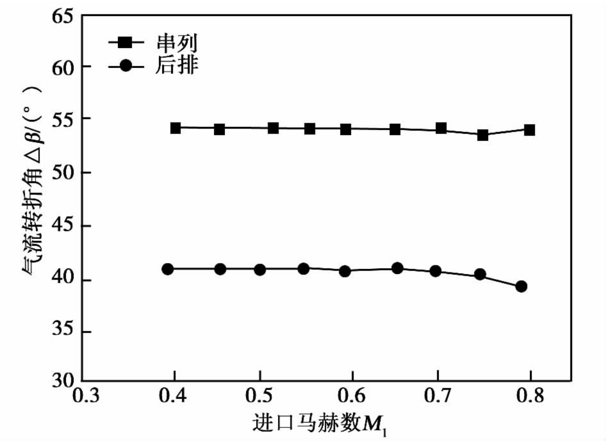


图 6　气流转折角对比图

Fig. 6 Mach number distribution on the blade surface

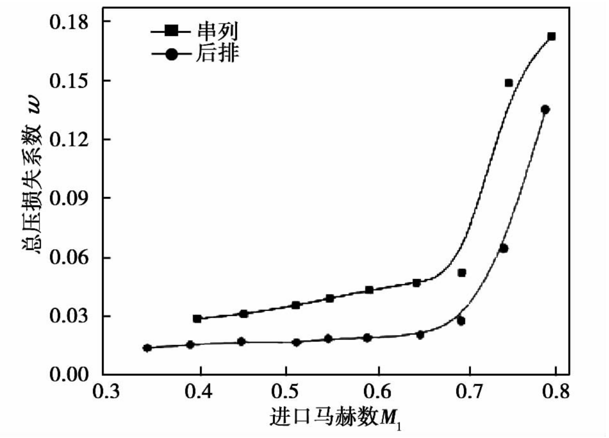


图 7　总压损失系数对比图

Fig. 7 Chart showing a contrast of the turning angles of the gas flow

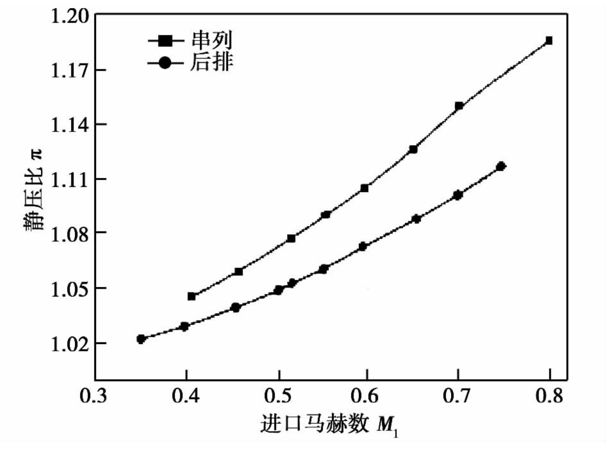


图 8　静压比对比图

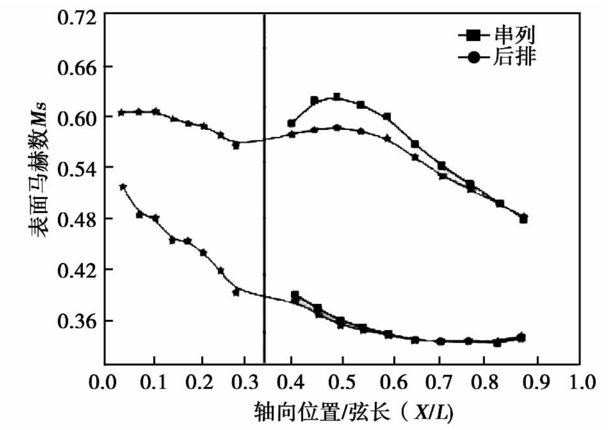
Fig. 8 Chart showing a contrast of the loss coefficients

表 2　试验结果

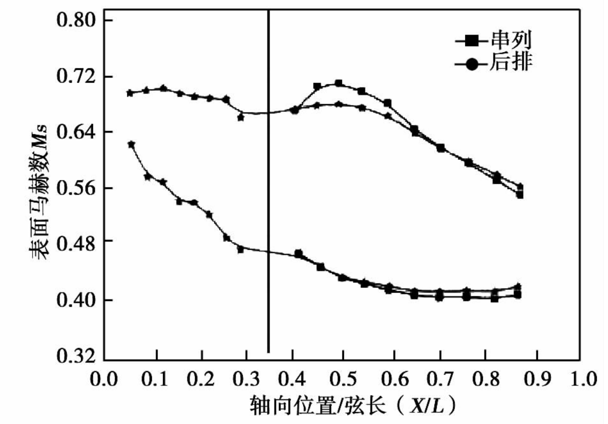
Tab. 2 Test results

进口马赫数	总压损失系数 ω		气流转折角 Δβ/(°)		静压比 π	
	串列	后排	串列	后排	串列	后排
0.405	0.029	0.015	54.27	40.595	1.046	1.030
0.457	0.031	0.017	54.25	40.656	1.060	1.040
0.515	0.036	0.016	54.15	40.718	1.078	1.049
0.553	0.040	0.019	54.18	40.863	1.091	1.061
0.597	0.044	0.019	54.08	40.563	1.105	1.073
0.650	0.048	0.021	54.07	40.789	1.126	1.088
0.701	0.053	0.028	54.1	40.501	1.150	1.101
0.753	0.151	0.065	53.53	40.011	1.142	1.117
0.801	0.175	0.137	54.18	39.088	1.185	1.110

图 9 为设计攻角下串列叶栅进口马赫数分别为 0.514 和 0.6，独立后排叶栅进口条件与串列时进口马赫数一致的情况进行试验所得的叶片表面马赫数分布。分析两图可知前排叶片的存在对后排叶片的压力面影响较小，然而对吸力面的峰值点影响较大，由于前排叶片的存在后排叶片的峰值点有所降低。



（a）M_1=0.514,I=3.92°（设计点）



（b）M_1=0.6,I=3.92°

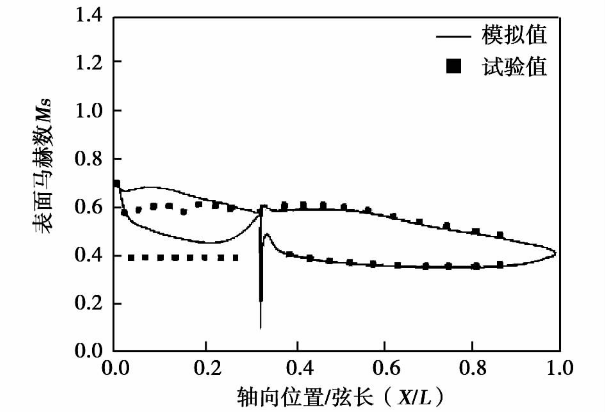
图 9　串列叶栅与后排叶栅表面马赫数分布

Fig.9 Chart showing a contrast of the static pressure ratios

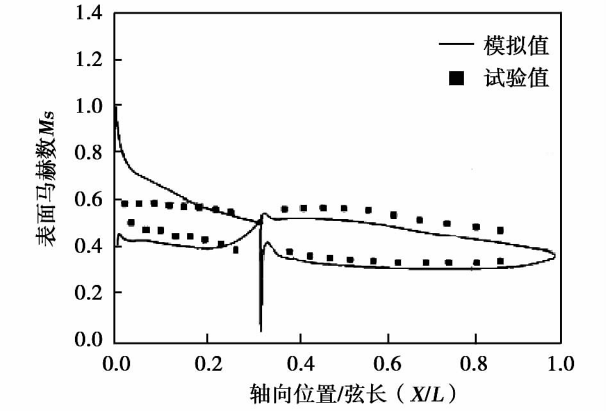
4　试验与数值模拟结果对比

4.1　叶片表面马赫数分布

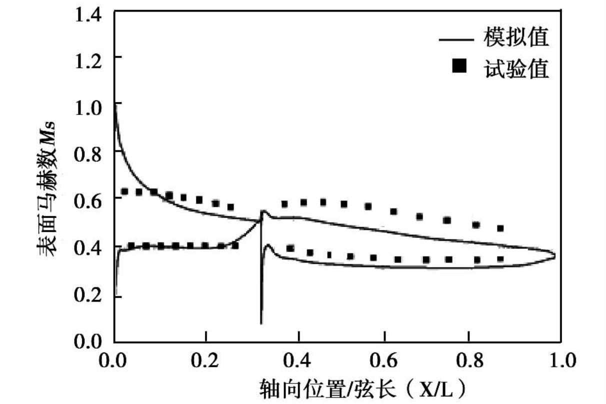
图 10 为各工况下试验与计算所得叶片表面马赫数分布。



（a）M_1=0.514, I=−2.35°



（b）M_1=0.514, I=−3.92°（设计点）



（c）M_1=0.514, I=7.65°

图 10　叶片表面马赫数分布

Fig. 10 Mach number distribution on the surface of the tandem cascade and the cascade in the following row

由图可知，试验值整体略高于模拟值，前排叶片的表面马赫数分布两者吻合较差特别是吸力面，然而后排叶片吻合情况相对较好，特别是压力面的马赫数分布试验值与模拟值基本吻合。由马赫数分布情况可知，在试验攻角范围内叶栅流场特性较好，叶片表面不存在明显的分离现象。

4.2　流场显示

由图 11 叶片表面油流图谱也可再次看出，进口攻角的变化对后排叶片的流场分布影响较小，并且在试验攻角范围内后排叶片流场较好，无分离，二次流区域较小。在较大的正攻角（$I = 11.65°$）时，前排叶片流场变得较为恶劣，在靠近尾缘处出现了大面积的回流区，试验所得的回流区基本覆盖整个叶高。分析端壁油流图谱可知，在正攻角工况下，端壁叶片通道中出现涂料堆积，即存在速度较低的区域，并且该区域主要集中于后排叶片吸力面靠近尾缘处，而大的负攻角工况下（$I = -8.35°$），端壁流场情况较好，无旋涡和分离，并且后排叶片尾迹区域面积较小。不同攻角下端壁流场拓扑结构有所不同主要表现在两排叶片进口马蹄涡的压力面分支的不同，在较大正攻角下，前排叶片进口马蹄涡压力面分支与相邻前排叶片尾迹相交汇；在较大负攻角下，前排叶片通道中不存在气流的横向流动，后排叶片的进口马蹄涡压力面分支与相邻叶片的吸力面相交汇。随着攻角由正到负，端壁流场中叶片尾迹区逐渐减小，叶片通道中，气流的横向流动逐渐后移。相比较而言，模拟所得的马赫数分布和极限流线图与试验所得的油流图谱基本吻合，只是计算所得的角涡区域面积较小于试验。

5　结　论

对一前小后大的串列叶栅进行了多工况下的性能与油流显示试验和数值模拟，通过对其结果的对比分析针对该叶栅得出以下结论：

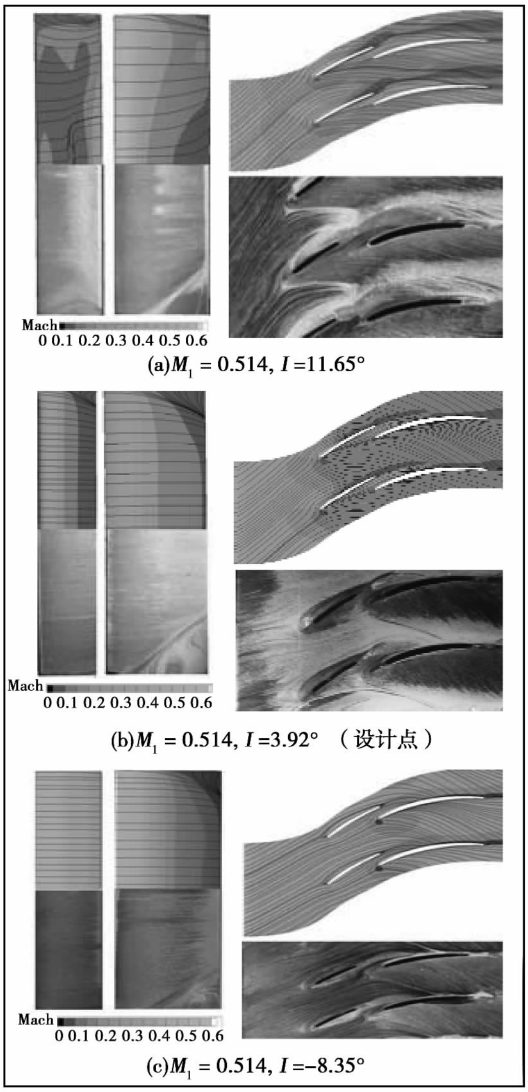
（1）串列叶栅可得到较大的气流转折角，并且可工作的攻角范围较大，属于一种被动流动控制；

（2）由于叶型损失增加以及前后两排叶片掺混损失，导致串列叶栅与独立后排相比损失约增加 40%；

（3）前排叶片转折角小，弦长小，主要起整流作用，因此进口攻角的变化对后排叶片表面流场分布影响较小，然而前排叶片的存在使得后排叶片吸力面马赫数峰值约降低 5%；

（4）随着攻角由正到负，端壁流场中叶片尾迹区逐渐减小，叶片通道中，气流的横向流动逐渐后移；

（5）双排叶型狭缝气流具有减小叶型损失，防止和推迟附面层分离的作用。建议开展前后叶片相对位置对气动性能影响的试验研究。



(a)$M_1 = 0.514$, $I = 11.65°$

(b)$M_1 = 0.514$, $I = 3.92°$ （设计点）

(c)$M_1 = 0.514$, $I = -8.35°$

图 11　吸力面与端壁油流图谱

Fig. 11 Oil flow spectrums on the suction surface and end walls

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(辉　编辑)

新技术、新工艺

GE和东芝公司将联合开发世界最高热效率的燃气轮机联合循环装置

据《Gas Turbine World》2013年3－4月刊报道,GE和东芝公司最近签订了一个共同开发50和60 Hz联合循环电力生产项目。

此外,两个公司将探索形成战略上的合资企业,用来开发下一代更高效率的联合循环电力项目。

GE和东芝公司在2012年获得一个合同,给中部电力公司在日本的2 200 MW的名古屋西区火电站供应GE的新的Flex Efficiency联合循环装置,共同形成Flex Efficiency联合循环装置设计,以便达到世界上最高的62%热效率(在现场条件下)。

目前,GE的最大的1×1(1台燃气轮机加一台汽轮机)50 Hz,9F 7系列联合循环具有512 MW额定净装置输出功率和61.0%净效率(5 622 kJ/(kWh)热耗率)。

用于60 Hz运行的最大的Flex联合循环装置是1×1的7F－5系列装置,装置的净性能为额定输出功率为323 MW,效率为58.2%(5 892 kJ/(kWh))。

(吉桂明　摘译)

IGCC **关键技术及其热力学与经济性评价** = **IGCC Key Technologies and Their Thermodynamic and Economic Evaluation** [刊,汉] ZHANG Yong, YAN Yuan－yuan(College of Electromechanical Engineering, Shanxi University of Science and Technology, Xi'an, China, Post Code: 710021) //Journal of Engineering for Thermal Energy & Power. －2013, 28(5). －443～448

Introduced were the process flow path of the IGCC power generation technology and its recent development, gasification technologies and coal gas purification systems etc. key technologies with an emphasis being put on an analysis of the core equipment item-gasifier, which had been considered as one of the key technologies. Its working principle, process and structure were described with some existing problems and corresponding remedies being discussed. Through a contrast with supercritical and natural gas combined cycle power generation technologies, the cost-effectiveness of the system in question was evaluated with its thermodynamic performance being assessed. Finally, the future development demands of the IGCC technology were put forward from the viewpoint of IGCC systems, gasification technologies and coal gas purification systems etc., further enhancing the performance of various subsystems and the overall integration degree, and diversifying the development directions so as to pursue a lower energy consumption rate and better environmental protection. **Key words**: IGCC(integrated gasification combined cycle), gasifier, thermodynamic evaluation, economic analysis

串列叶栅流场特性的试验与数值模拟 = **Experimental and Numerical Study of the Flow Field Characteristics of a Tandem Cascade** [刊,汉] LIU Zhi-gang(College of Power and Energy Source, Northwest Polytechnic University, Xi'an, China, Post Code: 710072), LIANG Jun, LING Dai-jun, MA Chang-you(China Gas Turbine Research Institute, Chengdu, China, Post Code: 610500) //Journal of Engineering for Thermal Energy & Power. －2013, 28(5). －449～454

The performance and oil flow display test and numerical simulation of a tandem cascade and an independent rear row cascade were conducted under multiple operating conditions. The flow field characteristics of the tandem cascade and the influence of the front row cascade blades on the flow field of the rear row cascade blades were analyzed. An analysis of the test results shows that the tandem cascade can accommodate to a relatively wide attack angle variation range and a large gas flow turning angle but its loss increases by about 40% when compared with that of a single row cascade blade. The presence of the front row cascade blades makes the influence on the flow field in the rear row cascade blades by the attack angle variations decreased to a certain extent and the Mach number peak value on the suction surface lowered by 5%. It has been found through a comparison of the test results with the nu-

merical simulation ones that their Mach number distributions on the pressure surface are in relatively good agreement and the test value on the suction surface is slightly higher than the calculated ones. The relative position between the front and rear row cascade blades has a most important influence on the tandem cascade and it deserves an in-depth investigation. **Key words:** tandem cascade, flow field characteristics, numerical simulation, oil flow display

基于激光扫描的轴流压缩机叶片反求技术探讨 = Exploratory Study of the Reverse Solution-seeking Technology for Axial Flow Compressor Blades Based on the Laser Scanning [刊，汉] SONG Wei, LAI Xi-de, LI Guang-fu, et al (College of Energy Source and Environment, West China University, Chengdu, China, Post Code: 610039) //Journal of Engineering for Thermal Energy & Power. -2013, 28(5). -455 ~460

To solve the problems relating to numerical models for blade modification design, aerodynamic optimization and repairing based on a real object in actual engineering projects during operation of an axial flow compressor, the portable type laser scanning technology was used to develop a high precision and efficiency flow path for reverse design of axial flow compressor blades. In compliance with the geometrical characteristics of and aerodynamic optimization design requirements for axial flow compressor blades, the laser triangular method was adopted with auxiliary planes and marking points being added to the blade leading edges, trailing edges and tips, enhancing the point cloud data acquisition efficiency of the blade. In the light of the problem that the curved surface in the blade body zone had a low fitting precision and the curved surface pieces around the tenon area were of self-intersection, an interactive method for dividing the curved surface pieces of the blade based on the flow streamlines, meridian lines, contour lines and their extension lines was proposed to express the tenon end surface area of non-four-edges but N-edges by using several curved surface pieces of four edges according to the flow path "detect the contour and its extension lines-subdivide and extend the contour lines-structure the curved surface pieces-repair them" with the method for man-machine interactively adding auxiliary contour lines being employed and obtain a model for the curved surface meeting the requirements for engineering projects. A high efficiency reverse solution-seeking technology for axial flow compressor blades was studied and developed, including point cloud data acquisition, processing, curved surface restructuring and precision evaluation of a blade. The technology in question can be applied in an actual engineering project when repairing a large-sized axial flow compressor. **Key words:** axial flow compressor blade, reverse solution-seeking technology, point cloud data acquisition, curved surface restructuring

微小流量喷嘴雾化特性实验方法 = Method for Testing the Atomization Characteristics of a Micro Flow