

涡轮叶片内冷却通道的流阻与换热研究

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【摘要】 用实验方法研究了冷却气流在放大 1 倍模型涡轮叶片内通道的压力、冷热态流阻及局部换热系数分布。得出了相应的经验公式。冷却空气径向进入前缘冷却通道,到顶端折而向下在两隔板间流动,大部分空气经隔板 5 个穿孔弦向流入带三排扰流柱的收缩通道,并弦向排出叶片尾部。

主题词: 叶片 流动阻力 换热系数

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采用模拟试验方法,测量 180° 弯曲通道及气流经过穿孔板、扰流柱等复杂通道中局部流阻和换热系数分布,并对这类冷却结构进行评述。

1 实验设备

实验的原则系统为:来自压缩机的空气经净化器去除湿分,并用双重孔板及双管差压计测量流量,然后经过稳定器及厚壁塑料接管进入实验叶片内的复杂流道,空气在冷却叶片壁面后由尾部排出。比原型叶片放大 1 倍的试验件是用 1Cr18Ni9Ti 不锈钢线切割加工而成。图 1 示出了叶片流道及测压点分布。空气自入口管进入径向通道 I,在顶部折而向下进入通道 II,其中一部分经过隔板与端壁的上、下间隙进入通道 III,大部分气流则是经过隔板的 5 个穿孔而进入通道 III,后者是装有三排 $\Phi 3$ 扰流柱的收缩通道。试验叶片的弦向出口为宽度 1 mm、高度 44 mm 的窄缝。

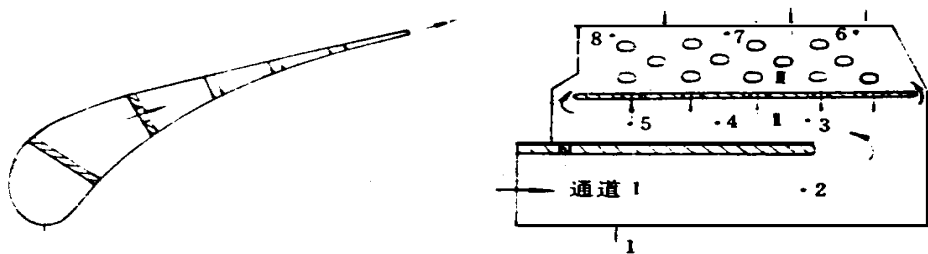


图 1 实验叶片的内冷通道及测压点的分布

在图 2 上示出了在叶盆、叶背外壁面上点焊的 28 对镍铬-镍铝热电偶的位置。在实验件焊接热电偶后,粘贴聚酰亚胺及耐温胶带作为电绝缘,再用耐温胶将自行制作的、与叶片外壁

形状及尺寸一致的电加热片贴于外壁,并用水玻璃固定,最外面再包上厚度足够的硅酸铝作为热绝缘。

由于试验叶片出口窄缝宽度很小,很难测量气流出口温度。因此,出口温度是从叶片加热功率 Q 、空气流量 G 和进口温度 T_1 的热平衡计算得出:

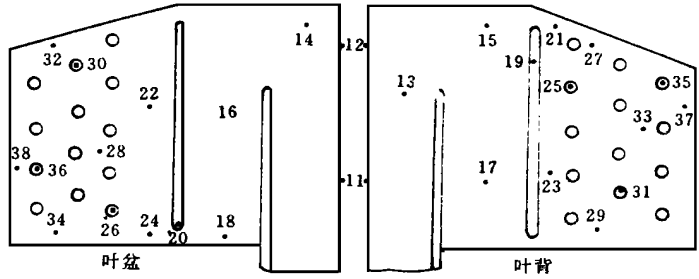


图2 叶片叶盆、叶背壁面的测温点分布

$$T_2 = T_1 + (Q - \Delta Q) / GCp \quad (1)$$

式中 ΔQ 为试验件的环境热损失,试验前进行了电加热片在不同温度下的环境热损失标定。叶片壁温测量截面 i 的气流温度 T_{fi}' 可由式(2)算得,即

$$T_{fi}' = T_1 + (T_2 - T_1) F_i / F \quad (2)$$

这里 F_i 为从气流开始加热至截面 i 所占的加热面积,而 F 是试验叶片的总加热面积。于是,各测点的局部换热系数 α_{ij} 可由下式决定

$$\alpha_{ij} = (Q - \Delta Q) / [F(T_{wij} - T_{fi}')] \quad (3)$$

各测点的内壁温 T_{wij} 从测得的外壁温减去壁厚温差得出, T_{fi}' 为该处的气流恢复温度。

2 通道内的气流压力分布和压力损失

叶片内通道的气流压力分布是在叶片不加热状态下由图1所示的8个测压点用U形管相连而测得。在表1中列出了气流不同出口雷诺数时各测压点的压力或压差分布,其中 p_1 、 p_3 为测点1和3的绝对压力, Δp_{6-0} 、 Δp_{7-0} 、 Δp_{8-0} 分别为测点6、7、8的表压力,而 Δp_{1-2} 、 Δp_{3-5} 则是两个相应测点间的压差(大气压 $p_0 = 104550 \text{ Pa}$ 、环境温度 $T_0 = 300 \text{ K}$)。

表1 空气在试验叶片内通道等温流场中的压力分布

序号	G_{out}^* $\text{kg/m}^2\text{s}$	W_{out} m/s	Re_{out}	p_1 10^5 Pa	p_3 10^5 Pa	Δp_{1-2} Pa	Δp_{3-5} Pa	Δp_{6-0} Pa	Δp_{7-0} Pa	Δp_{8-0} Pa
1	117	95.1	11630	1.149	1.144	10	-147	1127	-3599	1264
2	133	107	13070	1.174	1.170	10	-186	1315	-4359	1599
3	152	119	14570	1.213	1.208	20	-245	1796	-5331	2266
4	157	123	15070	1.225	1.216	20	-265	1881	-5598	2381
5	179	137	16690	1.278	1.269	20	-343	2519	-7197	3332
6	206	151	18500	1.354	1.342	20	-480	3596	-8263	4743
7	223	160	19560	1.410	1.395	20	-539	4136	-10929	5684
8	256	174	21240	1.524	1.507	50	-715	5331	-14261	7418

由表1可看出,在通道I中测点2与1之间的压差很小,最大流量下差别不过50Pa。测点3与测点1之间的压差也不太大,在通道II中,3,4,5这3个测压点相互间的压差很小。令人感兴趣的是在流道II中沿流程的压力竟然是逐渐增大,它在表1中以 Δp_{3-5} 为负值来表示。这可

解释为: 在通道Ⅱ中空气沿流程逐次经隔板 5 个穿孔流出, 气流沿通道减速的结果。试验叶片尾部 3 个测压点中, 6 和 8 两测点靠近叶片上下两端壁, 感受来自隔板与端壁间隙的气流压力, 均为正压, 而中间的测压点 7 正处于两个扰流柱后部的中间位置, 在强烈旋涡作用下形成真空区, 所以 Δp_{7-0} 为负值。在传热试验中能测量的只是空气在叶片进口处的表压 Δp_{1-0} , 即叶片内通道的总阻力, 它包括了气流 180 弯曲、经过穿孔隔板、三排扰流柱的局部损失以及收缩通道的加速损失等。把试验叶片内通道在冷态与加热状态下的气流阻力损失, 考虑不均匀温度场的影响, 用统一的经验公式归纳, 可得到(G^* 为单位面积流量)

$$\Delta p_{1-0} = 0.985 G^{*1.94} (\bar{T}_w / \bar{T}_f)^{0.89} \tag{4}$$

$$\Delta p_{1-0} / p_1 = 0.068 (Re \times 10^{-4})^{1.90} (\bar{T}_w / \bar{T}_f)^{1.23 (Re \times 10^{-4})^{-2.08}} \tag{5}$$

式中 G^* 和 Re 都是基于叶片出口面积, $\bar{T}_w$ 和 $\bar{T}_f$ 分别是叶片内壁及气流的平均绝对温度。

3 叶片的传热试验

如图 1 所示, 叶片内冷通道是由通道Ⅰ、Ⅱ、Ⅲ三部分构成。对于无扰流柱部分, 通道的特性尺寸可用常规的水力直径 $D_h = 4A/U$ 来决定, 但在通道Ⅱ中经过的空气流量沿流动方向是逐渐减少的, 因此对通道Ⅱ的气流温度及平均雷诺数都是近似地按气体总流量的一半来计算。通道Ⅲ是带扰流柱的收缩通道, 沿流动方向的通道截面积、湿周及扰流柱长度各不相同, 而且窄缝流道的端壁影响也必须考虑。因此, 对于有扰流柱部分采用 F. E. Faulkner^[1] 提出的通道当量直径 $D_{hi} = 4A_{min} / \left(\sum F_i / L_i \right)$ 。其中 A_{min} 为区 i 中的最小流动截面积, $\sum F_i / L_i$ 为区 i 有扰流柱部分的平均湿周长度, 其中 L_i 为沿流向长度, 等于扰流柱直径 3mm, $\sum F_i$ 是该测量区内为气流冲刷的固体面积, 包括通道侧壁、顶壁和扰流柱表面积。

在图 3 中示出了各测点在不同 Re 数下的 Nu 值, 它们都可归纳为

$$Nu = C Re^n \tag{6}$$

不同测点的系数 C 和指数 n 列于表 2 中。

表 2 式(6)中不同测点的 C 与 n 值

测点	11, 14	12, 13, 31	15, 16, 23	17	18, 20	19, 22	21	24
C	0.113	0.19	0.34	0.43	0.60	0.23	0.134	0.43
n	0.66	0.60	0.62	0.62	0.65	0.73	0.81	0.673
测点	25, 26, 28	27	29	30	32	33	34	
C	0.305	0.035	0.235	0.0477	0.00098	0.021	0.020	
n	0.637	0.91	0.64	0.80	1.25	0.87	0.86	

在表 2 和图 3 中没有列入测点 35~38 实验资料, 因为这些测量截面上的气流速度高达 267~294m/s, 由此算得的气流恢复温度很接近, 甚至高于壁温, 所以得出的换热系数值很不合理。这可能是复杂通道壁面气流温度恢复系数的合理选择问题(数据处理中取 $y = Pr^{1/3} = 0.89$), 也可能是由于叶片尾部很高排气速度卷吸环境冷空气, 增强了叶片尾部的冷却。必须说明, 按照上述特性尺寸定义 Nu 和 Re 准则是为了便于从模化试验资料换算成涡轮工作条件下的换热系数, 不同测点的 Nu 值内由于包含了不同的 D_h 值, 因此高的 Nu 值可能是由大的 D_h 值引起, 未必表明该处的换热系数也很高。

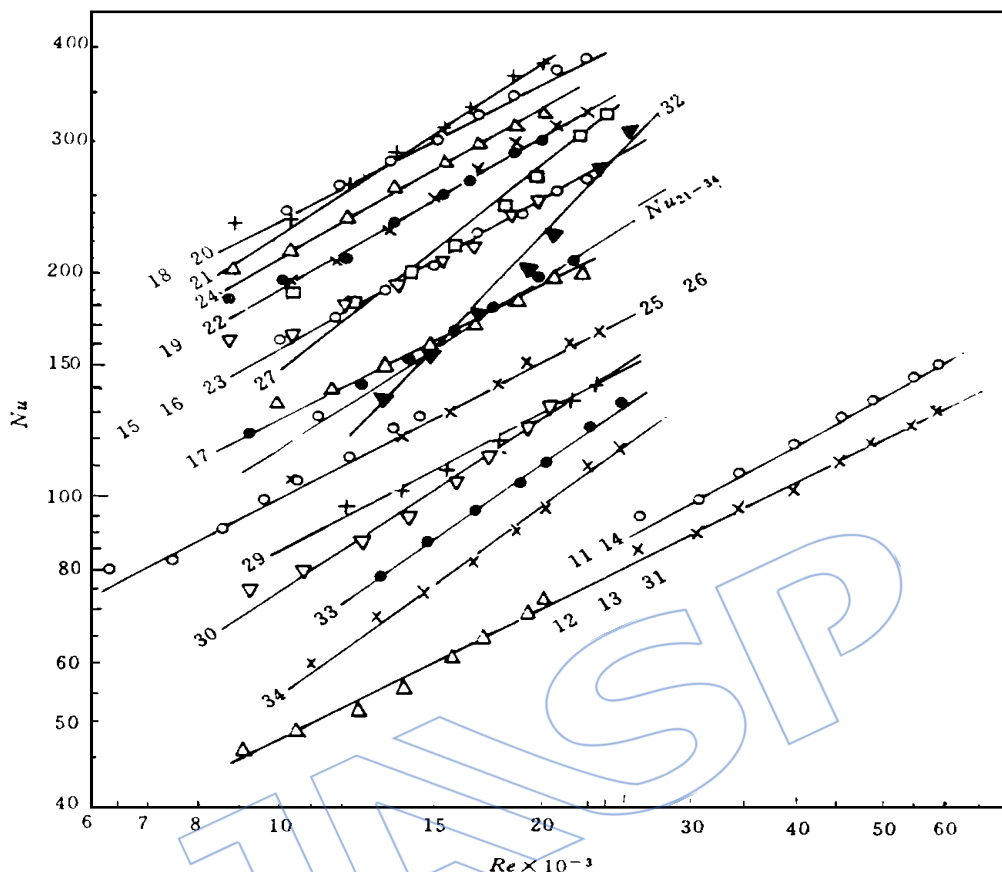


图3 叶片内壁面各测点的 Nu 与 Re 的关系

测量区 I 是直流通, 它的通道长度与水力直径之比只有 4 左右, 进口段的影响使该区的换热系数比用 Dittus-Boelter 公式算出的高出 50% 左右。在通道 II 中既有上下两端隙的绕流, 又有通过隔板的抽吸流, 因此经过这部分直流通道的 Nu 值也比一般圆管的高出很多。在叶片后部扰流柱通道中的 Nu_i 值差别很大, 其平均值可用 $Nu = 0.114 Re^{0.788}$ 表示。就换热系数 α 值而言, 通道 I 的 α 值最低, 通道 II 的要高一些, 通道 III 的 α 值比前面两径向流道要高的多。

结论 (1) 得出气流在实验叶片内部复杂冷却通道中的流阻分布和冷热态下的阻力计算公式; (2) 得出等热流下的内通道换热系数分布和各测点的换热经验公式; (3) 本实验叶片前部的内冷换热系数较低, 应采用诸如冲击冷却或各类粗糙肋、气膜孔等强化冷却措施^[2]; (4) 叶片尾部出口处应有导流槽道, 以防止尾部高速气流卷吸环境燃气, 导致叶片尾部冷却性能恶化。

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flow on the stall flutter has been investigated experimentally. The results of experiments show that the small radial distortion of the inlet flow at blade tip can eliminate the stall flutter. This phenomenon is verified by computation with three-dimensional actuator disk method. The computed results conform with the experimental data.

Key words Axial-flow compressors Radial distortion Flutter

NUMERICAL SIMULATION OF INTERNAL FLOW IN 2- D NOZZLES WITH THRUST VECTORING

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ABSTRACT Numerical simulation of internal flow with thrust vectoring in two-dimensional convergent nozzles is described, which utilizes multigrid technique in conjunction with MacCormack's explicit scheme. In computations, the Reynolds averaged Navier-Stokes equations are adopted for the five grids with $k-\epsilon$ turbulence model; and on the other hand, Euler equations are solved on the coarse grids. Numerical results provide good resolution to the flow fields, and the computed pressure distributions are found in good agreement with the experimental data. The influences of geometric parameters upon the flow quality and thrust coefficient are also analyzed. It is demonstrated that the multigrid technique adopted here is reliable and suitable for parametric study.

Key words Jet nozzles Thrust vector control Numerical simulation

COMPUTATION OF 2- D TRANSONIC AND SUPERSONIC FLOW FIELDS USING TVD SCHEME AND FOUR- STAGE RUNGE- KUTTA TECHNIQUE

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ABSTRACT Harten's TVD scheme is extended to 2- D general curvilinear coordinates by local rotation matrix translation. A new fully explicit solving method based on Four- Stage Runge- Kutta technique is developed to predict 2- D supersonic and transonic flow field. Comparison between computation and experiment is presented for both supersonic and transonic flow. The numerical results show that this scheme is not only convenient to solve the supersonic flow, but also capable of predicting the transonic flow.

Key words Euler motion equation Supersonic flow Transonic flow

INVESTIGATION ON FLOW RESISTANCE AND HEAT TRANSFER IN COOLING PASSAGES OF GAS TURBINE BLADE

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ABSTRACT An enlarged test blade of gas turbine has been investigated experimentally for flow resistance and heat transfer in its cooling passages. Air entered the radial cooling channel inside the leading part of the blade and contrary flowed downward into the passage between two plates while the air flow reached to the top. The bulk of the air stream

flowed through five holes on the plate into the chordwise wedged passage with three pin-fins and exhausted to the atmosphere. The experimental results of the pressure distribution, the flow resistance under heating and without heating, and the distribution of the local heat transfer coefficient in the cooling passages of a gas turbine blade are presented. Therefrom an empirical formula is obtained.

Key words Blades Cooling Flow resistance Thermal-convection coefficient

AN INVESTIGATION ON LOCAL HEAT TRANSFER PERFORMANCE FOR RM HEATED ROTATING DISK WITH CENTRAL AIR INFLOW

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ABSTRACT An actual Gas-Turbine disk was simplified to a rim heated rotating disk with central air inflow. The effects of rotational Reynolds number, Re , Mass flow coefficient C_w , gap ratio G and shrouded clearance ratio G_s upon local heat transfer were experimentally studied. The disk diameter was 360mm and the maximum rotational speed was 3600 r/min. It was found that the distribution of the local heat flux on the disk surface was U-shaped. The heat transfer could be enhanced by increasing mass flow coefficient and rotational Reynolds number. The effects of gap ratio and shrouded clearance ratio were small.

Key words Discs Cooling Convective heat transfer

A METHOD FOR CALCULATION OF CONTACT HEAT RESISTANCE BETWEEN TWO CONTACTING SURFACES

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ABSTRACT A method is provided for calculation of contact heat resistance between two contacting surfaces. The contact heat conductance was derived for a single contact spot of a simplified disk contact model. The distribution function of contact spots can be solved by using the method of counting functionals. As a result, an empirical formula of the contact heat resistance with the fluctuations of extruding stress is derived.

Key words Thermal contact resistance Bearing stress Computational methods

A PSEUDOTHERMAL-LOAD ANALYTICAL METHOD FOR CONTROLLING CRACK GROWTH IN AN INTELLIGENT COMPOSITE COMPONENT

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ABSTRACT A new method to analyze the stress fields of the intelligent composite components, namely the pseudothermal-load method, is proposed for active control of crack growth according to their structural characteristics. This method has been applied to computing and analyzing several intelligent composite components. The results are in good agreement with experimental data. So this is the theoretical basis for research and application of the intelligent composite material with the aim of the crack growth active control.