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涡轮叶片多次弯曲冷却通道的换热研究

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多次弯曲冷却通道是燃机高温叶片的一种典型冷却结构。Metzger等人[1]针对叶片冷却问题曾对转角为180°矩形弯曲流道的压力损失进行了研究，但其换热特性目前还没有公开发表的研究资料。本文用实验方法研究了不同高宽比、不同曲率半径比和顶端有排气孔的多次弯曲180°矩形流道内的流动特性与换热规律。

一、实 验 简 介

实验系统介绍见文献〔2〕。用不锈钢制作的实验件是根据某高温涡轮叶片中部内通道冷却结构设计的，冷却通道包括一个扩张形流道、四个直流道和四个180°弯头。在实验件顶端开有两个排气孔，用以调节和控制排气量。1～5流道截面积依次为A＝129，150，117，136，136mm²；当量直径依次为d_e＝13.2，11.8，8.4，9.9，9.9mm。实验件热功率由紧贴在实验件A、B两表面的电加热器提供。为测出各流道和弯头的换热系数分布，在与内通道对应的外壁面上焊有测温热偶（见图1）。测出的外壁温经修正得到内壁温值，再运用平均热通量及流体的温升便可得出流道各部分的换热系数。

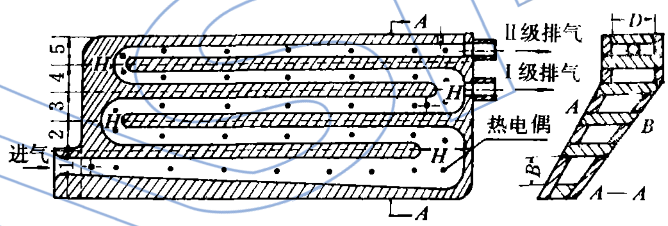

图1 多次弯曲流道实验件热偶布置图

二、多次弯曲流道阻力试验及结果

阻力试验分两种，一种是没有Ⅰ级排气孔的试验，另一种是两级排气孔同时排气的试验。流道内的压降ΔP分三部分测量（见图1）。首先是流道进口至第3流道出口处，在测得空气流量G后，ΔP_{1-3}可由下式表示

$$\Delta P_{1-3}=\frac{G^2}{2g\bar{\gamma}}\xi_{1-3}\left(\frac{L_1}{d_{e1}A_1^2}+\frac{1}{(H_1D_1)^2}+\frac{L_2}{d_{e2}A_2^2}+\frac{1}{(H_2D_2)^2}+\frac{L_3}{d_{e3}A_3^2}\right) \quad (1)$$

式中ξ_{1-3}是1～3流道的当量阻力系数。其次是第3流道出口至第5流道出口处，可由

$$\Delta P_{4-5}=\frac{G^2}{2g\bar{\gamma}}\xi_{4-5}\left(\frac{1}{(H_3D_3)^2}+\frac{L_4}{de_4A_4^2}+\frac{1}{(H_4D_4)^2}+\frac{L_2}{de_5A_5^2}\right) \quad (2)$$

来表示，ξ_{4-5}是4～5流道的当量阻力系数。最后一部分是排气口的局部损失，即

$$\Delta P_{排}=8\zeta G^2/(\pi^2 g\bar{\gamma}d^4) \quad (3)$$

式（3）中ζ、d分别为排气孔的局部阻力系数和排气孔直径。式（1～3）中的空气比重$\bar{\gamma}$

按流道中的平均压力和平均温度计算，L为流道长度。当有Ⅰ级排气时，(2,3)两式中空气流量为$G_2 = G - G_1$。此处G_1为Ⅰ级排气量。

8个工况的压力损失试验结果列于表1中。由表1可见，射孔Ⅰ排气与否，对1～3流道压力损失有明显影响。另外排气口惊人的局部损失应引起设计者的注意。

表1　　实验参数及各部分压力损失

序号	P_{in} (kg/cm²)	G(kg/h)			Re×10⁻⁴						ΔP(kg/m²)		
		进口	Ⅰ	Ⅱ	1	2	3	4	5	出口	1～3	4～5	出口
1	1.312	23.3	13.7	9.6	3.75	2.89	2.62	1.09	1.09	12.04	195	106	1782
2	1.372	26.7	15.7	11	4.29	3.31	3.01	1.25	1.25	13.78	234	126	2203
3	2.185	26.8	0	26.8	4.31	3.32	3.02	3.07	3.07	33.73	140	254	8935
4	1.492	30.6	17.1	13.5	4.93	3.80	3.46	1.55	1.55	17.06	279	170	3237
5	1.562	36.0	21.2	15.4	5.89	4.53	4.12	1.77	1.77	19.42	351	191	3740
6	1.752	41.0	22.9	18.7	6.69	5.15	4.68	2.14	2.14	23.49	395	244	5154
7	1.912	47.6	26.8	20.8	7.66	5.90	5.36	2.38	2.38	26.13	461	283	6338
8	2.122	55.4	31.2	24.2	8.91	6.86	6.24	2.77	2.77	30.39	522	342	7820

三、多次弯曲流道换热试验及结果

换热实验数据按流道分为5个换热区处理，每个区的换热系数h_i是由区平均热功率$\overline{q}_i = Q/(F_{Ai}+F_{Bi})$来确定的，换热系数

$$h_i = \overline{q}_i/(T_{wik} - \overline{T}_{fi}) \qquad (4)$$

式（4）中T_{wik}为i区第K测点壁温，$\overline{T}_{fi}$为i区流体平均温度（也是计算流体物性的定性温度）。F_{Ai}、F_{Bi}分别为A、B两加热面第i区换热面积，Q为实验件总热功率。

1. **扩张形流道（第1区）的换热**　由于流道截面积沿轴向渐增，所以换热系数逐渐降低。在流道出口处由于气流受到通道隔板扰动和转弯加速影响，该处换热系数有所增加。沿轴向不同截面的换热系数可用下式计算

$$Nu_x = CRe^{0.68}Pr^{0.4}(T_w/T_f)^{-0.19} \quad (10^4 < Re < 10^5,\ 1 \leqslant T_w/T_f \leqslant 2.95) \qquad (5)$$

式（5）中的C值给出在图2中。

2. **四个直流道（第2～5区）的换热**　尽管四个直流道流通截面积各不相同，但每个流道本身则是等截面的，所以换热仅存在强弱之差而无规律之异，平均换热公式可写成

$$\overline{Nu} = 0.515Re^{0.52}Pr^{0.4}(T_w/T_f)^{-0.19} \quad (1.5\times10^4 \leqslant Re \leqslant 5\times10^4,\ 1 \leqslant T_w/T_f \leqslant 2.95) \qquad (6)$$

图3给出了四个直流道的平均换热结果。公式（6）与实验点的最大偏差在±12%以内。

3. **四个180°弯头的换热**　弯头的湍流换热与流动状态、离心力及曲率半径R等因素有关。实验数据可用下面的经验公式关联

$$\overline{Nu} = 0.194Re^{0.375}De^{0.25}Pr^{0.4}(T_w/T_f)^{-0.19}$$

$$(1.5\times10^4\leqslant Re\leqslant5\times10^4,\quad 1\leqslant T_w/T_f\leqslant2.95)\qquad(7)$$

式（7）中De数是反映弯曲流道中离心力和惯性力的准则数，对矩形弯曲流道其定义为

$$De=Re\sqrt{H/R}=\frac{ud_e}{\nu}\sqrt{H/R}$$

$$=\frac{2uBD}{\nu(B+D)}\sqrt{H/R}\qquad(8)$$

式（8）中 $d_e=2BD/(B+D)$ 为矩形流道当量直径，u、ν分别为空气的流速和运动粘度。图 4 给出了四个180°弯头的平均换热系数分布。

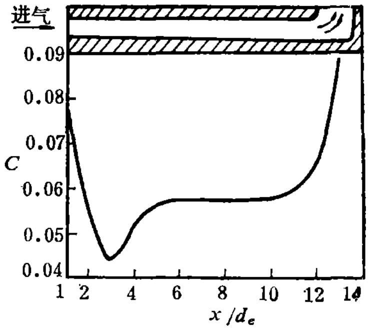

图 2　公式（5）中的C值

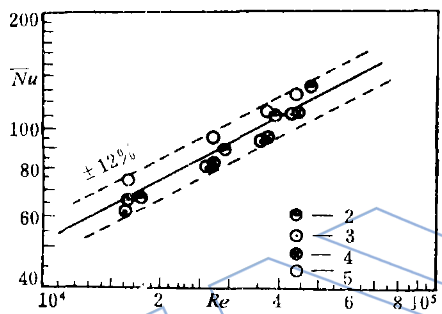

图 3　四个直流道平均换热系数分布

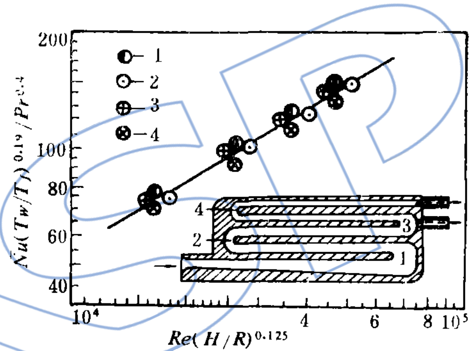

图 4　弯头平均换热系数分布

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EXPERIMENTAL INVESTIGATION ON COOLING EFFECTIVENESS OF A TURBINE BLADE UNDER VARIOUS DESIGN CONDITIONS

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Abstract

Blade cooling characteristics under various design conditions were obtained from the turbine blade cooling effectiveness experiments of a given aeroengine and its two modifications. The results obtained provide useful data for air-cooled blade design. Structure and testing approach of the blades are also described.

Experimental results are also analysed. The analysis demonstrates that the testing technique is aviable, the experimental data are amenable and satisfactory for air-cooled blade design.

COOLING FLOW TECHNIQUE FOR DESIGNING AFTERBURNER HEAT SHIELDS

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Abstract

By employing the air flow cooling technique, an afterburner heat shield was designed semi-empirically. It exhibited the desired advantages of long service life, low wall temperature and good performance. The cooling air flow accounted for 10% of the total airflow. The distribution of the cooling air was designed in reference to successful designs. The practice of the aeroengine with the designed afterburner verifies that the presented technique is reliable.

HEAT TRANSFER THROUGH MULTI-TURNS OF COOLING PASSAGES IN A TURBINE BLADE

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Abstract

With the aim of cooling high-temperature turbine blade, the heat transfer characteristics and flow drag of turbulent air flow through 180 degree multi-turns of rectangular passages were investigated experimentally. The experimental data of the heat transfer coefficients both through a 180 degree turn and in a straight passage were correlated. The test results may be useful to cooling designing gas turbine blades.

A CALCULATION METHOD OF DETERMINING BLADE SECTION DRAG IN A ROTOR BASED ON WAKE MEASUREMENTS

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Abstract

A calculation method is proposed to determine the blade section drag instead of sophisticated experimental measurement of it. Since it is possible to obtain the detailed distributions of velocity and pressure on the boundary line from the wake measurements behind a compressor rotor. By using these distributions, the blade section drag is determined by means of the momentum equation of integral representation and appropriate mathematical manipulation.

THERMAL EFFECTS ON TRANSIENT PROCESS OF A TURBOJET ENGINE

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Abstract

The mathematical models commonly used for dynamic process of turbojet or turbofan engine consider only the rotor inertia and gas path volume dynamics. Usually the gas path volume of an aeroengine is not great, so the effect of volume dynamics on normal transient process is negligibly small. The thermal effects include transient heat transfer and the component efficiency changes caused by clearance variation with temperature in the components of compressor and turbine. A single-shaft turbojet engine has been tested for cold and hot transient processes. The comparison between the cold and hot transient test results shows that the thermal effects have significant influence on the acceleration time, the changing rate of aerothermodynamic parameters with engine speed, etc. The experimental investigation demonstrates that the thermal effects must be taken into account so as to establish an accurate mathematical model for the transient process of turbine engines.

CORRESPONDENCE

APPLICATION OF MEDIATE COMBUSTION CYCLE TO INDUSTRIAL MODIFICATION OF AEROENGINES

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