

气膜出流对叶片各内表面换热系数的影响*

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【摘要】 利用数值计算的方法研究了气膜出流对叶片前腔内各表面冷气对流换热系数的影响。研究的重点是气膜孔间距比和进气雷诺数等因素的影响规律。文章分别就叶片前缘和叶盆区域以及叶背区域的局部和平均换热系数的变化做了讨论,计算表明,在计算所取的参数范围内,随气膜孔间距比和进气雷诺数的增加,叶盆内表面的平均换热系数增加可达一倍以上,但由于气膜出流导致叶背边内表面的平均换热系数有所下降。本文的研究工作只限于不可压层流。

主题词: 数值计算 叶片 换热系数

分类号: V 232. 4

1 前言

涡轮叶片的对流气膜冷却结构,在叶片前缘以及叶盆边分布有较密的小孔排,在叶背边分布较少,并认为当气膜孔足够密时内换热系数的增强不小于两倍,并将此用于实际当中。但应注意的是在有气膜出流的叶盆内表面换热系数显著增加的同时,叶背内表面的换热系数由于气膜出流导致冷气主流流量降低而有所降低。本文利用数值方法对这一问题进行研究,分析孔的分布以及冷气来流雷诺数等因素对内换热系数分布的影响。在本文的研究中,考虑到冷气的流速相对较低,忽略其可压缩性的影响。

2 物理和计算模型

在计算中,所示的冷却腔被简化为一个两维的通道,见图1,气膜孔致密排列的叶片前缘

和叶盆部分作为一边处于通道的 BC 面,叶背视为无孔边处于通道的 AD 面,沿冷气主流横截面上各排气膜孔在该两维通道上体现为 BC 面上单一的气膜条缝。冷却气流由 AB 面进入流道,通道高为 H ,通道长为 L_1 ,冷气由 CD 面和各气膜孔流出,气膜孔孔径为 d ,孔间距为 L_2 。 CD 面的出口条件容易设定,但各气膜孔的出流条件在 BC 面上难于按常规

的一阶导数为零来处理,因为这与气膜孔的实际情况有较大的差距。因此,在计算中除 $ABCD$ 计算域外又引入叶片的壁 $BEFC$ 域。这样在 EF 面上各气膜孔完全可按常规的出流条件处

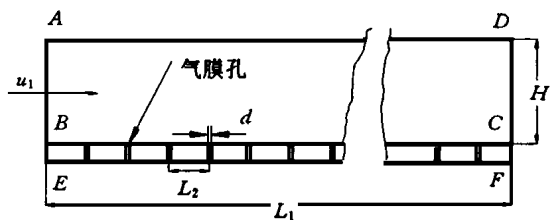


图1 计算区域及几何参数图

理。BEFC 域内气膜孔以外的区域为叶片的金属固壁。计算中,假定冷却空气为不可压粘性流体,流动状态为层流,通道BC和AD面为等温面且二者温度相等。在以上简化的基础上可列出无因次控制方程组(式中符号上的横线代表无因次量):

$$\text{连续方程:} \quad \frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = 0 \quad (1)$$

$$\text{动量方程:} \quad \frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = -\frac{\partial \bar{p}}{\partial \bar{x}} + \frac{1}{Re} \left[\frac{\partial}{\partial \bar{x}} \left(\frac{\partial \bar{u}}{\partial \bar{x}} \right) + \frac{\partial}{\partial \bar{y}} \left(\frac{\partial \bar{u}}{\partial \bar{y}} \right) \right] \quad (2)$$

$$\frac{\partial \bar{v}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = -\frac{\partial \bar{p}}{\partial \bar{y}} + \frac{1}{Re} \left[\frac{\partial}{\partial \bar{x}} \left(\frac{\partial \bar{v}}{\partial \bar{x}} \right) + \frac{\partial}{\partial \bar{y}} \left(\frac{\partial \bar{v}}{\partial \bar{y}} \right) \right] \quad (3)$$

$$\text{能量方程:} \quad \frac{\partial \bar{\theta}}{\partial \bar{x}} + \frac{\partial \bar{\theta}}{\partial \bar{y}} = \frac{1}{RePr} \left[\frac{\partial}{\partial \bar{x}} \left(\frac{\partial \bar{\theta}}{\partial \bar{x}} \right) + \frac{\partial}{\partial \bar{y}} \left(\frac{\partial \bar{\theta}}{\partial \bar{y}} \right) \right] \quad (4)$$

边界条件:进口AB面: $\bar{u}_0 = 1, \bar{v}_0 = 0, \bar{\theta} = 0$ 。AD面: 无滑移条件和 $\bar{\theta} = 1$ 。CD面及各个气膜孔面: 作为出口处理, $\bar{p}$ 设定为 0, 其它因变量取充分发展条件, 其一阶导数为 0, BEFC 的其它区域为金属固壁设定温度为 $\bar{\theta} = 1$ 。

无因次化所取特征长度为通道高 H , 其余特征量皆取进口截面流体的参量。能量方程中无因次焓定义为: $\bar{\theta} = (h - h_0)/(h_1 - h_0)$ 。下标 0 为进口, 1 为通道的上、下表面。

控制方程组通过有限体积法进行离散后求解, 求解的方法见参考文献[1, 2]。计算中, 取通道高 $H = 0.005 \text{ m}$, 通道长 $L_1 = 0.04 \text{ m}$, 气膜孔径 $d = 0.0002 \text{ m}$, 壁厚取为 0.0005 m 。冷却空气的普朗特数 Pr 为常数 0.7, 导热系数 $k = 0.0262 \text{ (W/m}^2 \cdot \text{K)}$ 。

3 计算结果

通过计算可给出速度、压力和温度场。气膜孔附近的一局部放大的典型流场矢量图见图 2。只讨论两个方面问题: (1) 进口雷诺数 Re 一定时, 不同气膜间距比 r 下, 气膜出流面BC换热系数的分布变化特性, 间距比 r 定义为 $r = d/L_2$; (2) 气膜出流对无气膜面AD内换热系数的影响。

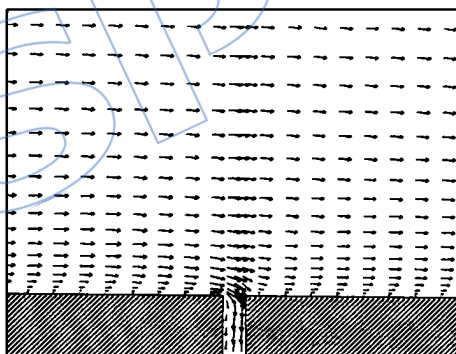


图2 气膜孔附近局部速度矢量图

在计算中, 采用了 6 种不同的间距比: $r = 0, 0.055, 0.105, 0.155, 0.205, 0.255$ 。该 6 个间距比分别对应无气膜孔, 10, 20, 30, 40 和 50 排气膜孔。进口雷诺数 Re 分别确定为: $Re = 500, 1000, 1500, 2000$ 。图 3 给出了雷诺数 $Re = 2000$ 时BC面局部换热系数分布的变化, 在其它各雷诺数下有类似的变化趋势。

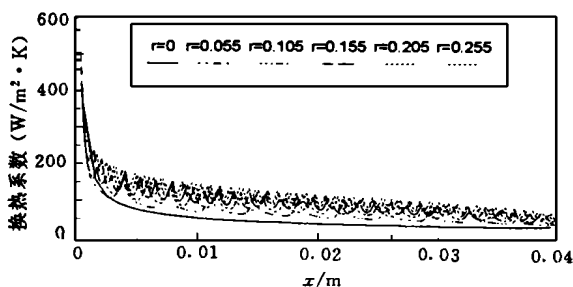


图3 $Re = 2000$ 时各间距比下的换热系数分布

图中实线为无孔通道的换热系数分布, 在进口处最高, 然后随传热边界层的逐渐增厚而下降, 图中虚线为有气膜孔的情况, 可以看出换热系数皆不同程度地有所提高。对于有孔情况, 由于气膜出流割断传热边界层, 在整个通道上传热边界层被分成若干个分段。每个

对于有孔情况, 由于气膜出流割断传热边界层, 在整个通道上传热边界层被分成若干个分段。每个

分段的传热边界层一开始逐渐增加, 然后由于气膜出流而迅速衰减为零, 体现在换热系数图上是对应每个气膜孔出现峰值。沿通道的平均换热系数由表 1 列出。可以看出, 在 Re 一定的条件下, 孔间距比的增加导致平均换热系数显著增加, 在 $Re=2000$ 时, 平均换热系数与无孔时相比增加了 104.8%。在孔间距比一定的条件下, 平均换热系数增加的百分比随雷诺数的增加而增加, 如 $r=0.255$ 时, $Re=500$ 的平均换热系数增加量为 82.6%, 而 $Re=2000$ 却增加了 104.8%。若孔的分布更为致密时, 平均换热系数还将有所提高。

表 1 平均换热系数

r	0	0.055	0.105	0.155	0.205	0.255
$Re=500$	29.88	36.76	42.28	46.98	50.92	54.56
$Re=1000$	40.68	53.12	61.93	68.88	74.88	80.17
$Re=1500$	48.89	65.80	76.79	85.34	92.74	99.23
$Re=2000$	55.78	76.37	88.91	98.63	107.02	114.23

但应注意的是, 尽管平均换热系数显著增加, 设计计算上简单地采用平均换热系数值是不妥当的, 通道出口端的局部换热系数远低于平均换热系数, 因而采用平均值是危险的, 必须使用当地换热系数。

气膜出流导致通道 BC 面的换热系数有大幅度的增加, 但同时对其对面 AD 面的对流换热有不利的影响, 换热系数与无气膜孔通道相比有所下降。下降的原因可能有两个: 1) 气膜出流导致冷气量降低; 2) 气膜出流导致纵向压力梯度, 致使 AD 面的换热边界层增厚。图 4 给出了在 $Re=2000$ 时不同孔间距比下 AD 面的换热系数分布, 可见换热系数相对于无孔通道有一定的降低, 且随孔间距比的增加而下降。因而在工程设计上, 在考虑叶盆和叶片前缘换热系数由于气膜出流而加强的同时要考虑到叶背的换热系数要有一定程度的下降, 否则叶背的热状态将是很危险的。

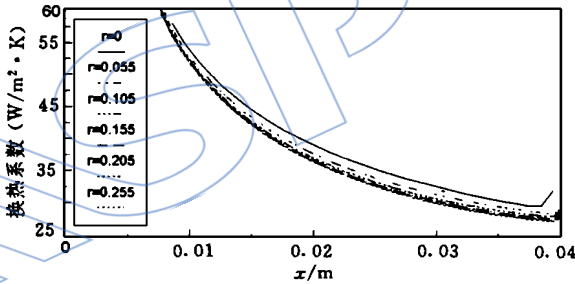


图 4 AD 面换热系数受气膜出流的影响

图 4 给出了在 $Re=2000$ 时不同孔间距比下 AD 面的换热系数分布, 可见换热系数相对于无孔通道有一定的降低, 且随孔间距比的增加而下降。因而在工程设计上, 在考虑叶盆和叶片前缘换热系数由于气膜出流而加强的同时要考虑到叶背的换热系数要有一定程度的下降, 否则叶背的热状态将是很危险的。

结论 本文就气膜出流对叶片腔内各面的冷气对流换热系数的影响进行了数值研究, 研究的重点是气膜孔间距比以及冷气进气雷诺数的影响。从计算结果可给出以下几点结论: (1) 孔间距比 r 的增加致使气膜孔边的换热系数显著增加, 计算结果显示, 在 $Re=2000$ 和 $r=0.255$ 时平均换热系数比 $r=0$ 增加一倍以上。(2) 气膜出流导致其对边的换热系数有所下降。

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surfaces in our method. The results of digital simulation for the spiral bevel gears used in a Chinese aeroengine show that the presented method describes the tooth shape and tooth contact characteristics more conveniently and efficiently, and can determine optimal cutting adjustment parameters for obtaining spiral bevel gears with good contact quality.

Key Words Digital Simulation Spiral bevel gears Curved surface

FRETTING FATIGUE OF DOVETAIL JOINT UNDER COMBINED CYCLIC LOADING

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ABSTRACT The state-of-art in research on fretting fatigue of dovetail joint in aircraft engine at home and abroad was sized up. Stress analysis of dovetail joint part was carried out. Experimental equipment was designed and set up. A number of tentative experiments was conducted. It is confirmed that the experimental technique and equipment can offer a great deal of data for designing.

Key Words Tenon Cyclic Loads Fatigue

PRESSURE AND AVERAGED THRUST OF A PULSED DETONATION ENGINE MODEL

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ABSTRACT A mode of Pulsed Detonation Engine (PDE) has been made. Its pressure and averaged thrust were analysed and calculated according to detonation wave theory, and then were measured with two sensors in testing of the PDE model. The comparison of the calculated results with the measured data shows that the PDE model can produce the pulsed detonation wave and thrust.

Key Words Impulsive burst Engines Pressures Thrust

EFFECTS OF FILM COOLING ON INTERNAL HEAT TRANSFER COEFFICIENTS OF BLADES

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ABSTRACT Effects of film cooling on the internal heat transfer coefficients of turbine blades were investigated numerically and the key factors have been found out as the film cooling hole distance ratio and the inlet Reynolds number. The local heat transfer coefficient variations were discussed both for the pressure and the suction sides of blades. Numerical results showed that, for the pressure side the internal heat transfer coefficient was much enhanced and could be doubled, as compared with the no-hole passages at the same range.

Heat transfer coefficient for the suction side, however, was decreased due to film cooling

Key Words Numerical computation Bladw s Thermo- convection coefficient

TECHNICAL NOTES

DEVELOPMENT OF FAILURE DIAGNOSIS TECHNIQUES IN ENGINE DIGITAL CONTROL SYSTEMS

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ABSTRACT This paper surveys the development of sensor failure diagnosis in engine digital control systems. First, the early research works on techniques of sensor failure detection and isolation are reviewed. The main disadvantage of model-based methods is high sensitivity to modeling errors which are inevitable because of the complexity of the aircraft engine. Then, the paper considers the necessity of robust failure diagnosis and its development. In view of the fact that the neural networks have been successively applied to control realm and possess themselves of tremendous potentials, the neural-network-based failure diagnosis is recommended as a promising approach in the engine digital control systems.

Key Words Aircraft engines Digital control system Fault diagnosis

INFLUENCE OF TEMPERATURE RATIO ON PENETRATION DEPTH OF 2D CONFINED CROSS FLOW

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ABSTRACT The influence of temperature ratio on the penetration depth of two-dimensional confined cross flow is investigated numerically. It is found that the temperature ratio of jet to main flow was an important parameter independent of momentum ratio. This phenomena can be explained in terms of the concept of "thermal drag". A cold jet injected perpendicularly into a confined hot air flow is heated and accelerated as the momentum ratio is given. The thermally induced pressure drop is converted into the momentum increase and consequently increases the penetration depth. On the contrary, a hot jet injected perpendicularly into a confined cold air flow for the given momentum ratio decreases its own momentum due to cooling by the mainflow. As a consequence, its penetration depth also is cut down.

Key Words Temperature distribution Jet penetration Numerical computation

FINITE ELEMENT STRESS ANALYSIS OF POWDERMETALLURGY TURBINE DISC

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