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气膜冷却对涡轮叶片表面压力分布的影响

燃气涡轮研究所　　罗明俊　邓化愚　刘波

一、试验设备及试验件

试验是在燃气涡轮研究所涡轮叶片综合冷却效果试验器上进行的。其试验设备详见文献[1]。试验段由七个叶片组成六通道的扇形叶栅。在试验段中，除中间一个为主试验叶片外，其余六个叶片均为陪衬叶片。在扇形叶栅试验段前、后和叶片冷气进口处，都装有总温、总压和静压测试受感部，用于监视和测量试验状态参数。

鉴于试验器所能提供的参数（压力、温度和流量）均达不到发动机真实状态，故本试验是在保证叶片几何相似，流动相似、热相似和各试验状态折合流量相同的前提下进行的。为了便于各状态试验结果分析比较，始终保持叶栅进口处燃气总压为 297×kPa，然后根据不同的试验目的，调节栅前总温、栅后静压、叶片冷气进口总温和总压，以满足试验中所需叶栅落压比 π_T、冷气流量比 K_G、燃气与冷气的绝对温度比 K_T 的要求。

为了能较真实地反映叶片表面压力分布，在叶片开设了若干条沟槽，分别埋设不锈钢测压管、然后用等离子喷涂将沟槽填平，经抛光后，恢复原叶片型面，最后沿中截面对应各测点位置，垂直型面钻 Φ0.5mm 的静压测孔，与埋设的不锈钢相通。

二、试验结果及分析

图 1 示出了在 $P_3^* = 297\times$kPa，$T_3^* = 1063$K，$K_T = 1.706$，$\pi_T = 2.51$ 状态下，不同 K_G 时，叶片中截面压力分布的对比试验曲线。由图 1 可见，整个叶片表面压力 P 随增加而升高。如将试验数据平均化处理，并整理为叶片表面平均压力系数随冷气流量比变化的曲线。

$$C_p = (\bar{P} - \bar{P}_o)/\bar{P}_o \quad , \quad \bar{P} = (\sum_{i=1}^{n} P_i)/n \quad , \quad \bar{P}_o = (\sum_{i=1}^{n} P_{oi})/n$$

式中 C_p 为压力系数，P_i 和 P_{oi} 分别为有、无气膜冷却的叶面各点压力，n 为叶片表面测点总数。

由图 1 可见，气膜孔开设位置对叶片表面压力分布有很大影响。由于 B 种叶片集中在叶片前驻点附近开设气膜孔，而在叶片中弦区不开设气膜孔，当改变冷气流量比时，对其叶片表面压力分布有一定影响，但影响不大。然而，由于 A 种叶片在中弦区开设了气膜孔，特别是在叶背前部最大叶片厚度处开设了一排气膜孔，对叶片表面压力分布影响相当明显。由此可见，气膜孔开设位置对叶片压力分布影响相当敏感。因此，在气冷叶片研制中，很有必要进行有气膜冷却的叶片表面压力分布试验，为修改设计提供可靠的试验数据。

图 2 示出了气冷叶片在 $P_3^* = 2.97\times10^5$Pa、$T_B^* = 773$k、$\pi_T = 2.51$、$K_G = 3.5\%$ 状态下，燃气与冷气的绝对温度比 K_T 分别为 1.24 和 1.706 时的叶片中截面表面压力分布比较曲线。由

图可见，改变温比对叶片表面压力分布有一定影响。但影响不太明显，当温比从 1.24 变化到 1.706 时，其叶片平均压力最大相对偏差 0.7%。关于温比对叶片表面压力分布影响的规律，有待做进一步的研究。

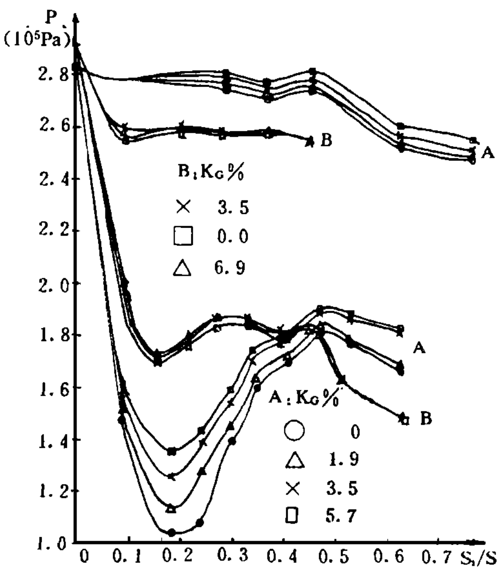

图 1　A 种和 B 种叶片 P 分布随 K_G 的变化

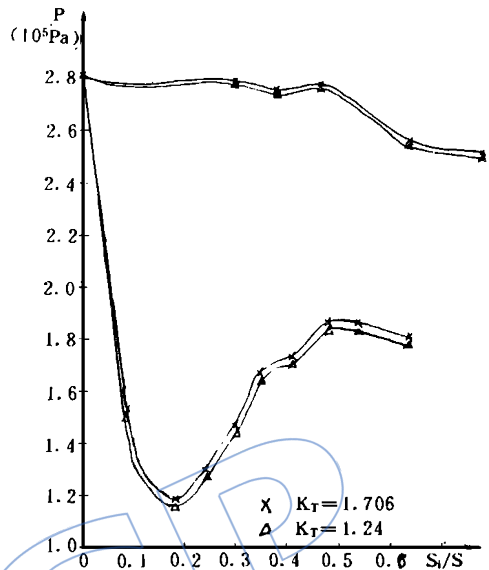

图 2　叶片表面压力随温比变化的曲线

如图 3 所示，对于 A 种气冷叶片，K_G 每增加 1.0%，其对应的叶片表面平均压力系数提高 1.0%。特别是叶背那排气膜孔影响相当明显，当 K_G 从 0 变化到 5.7% 时，在该气膜孔下游，其局部压力比无气膜冷却情况高 325×kPa，压力升高约 31.8%。分析图 1 曲线可见，对于这种跨音速大弯转角涡轮叶片，在其叶片前缘最大厚度处开设气膜孔，可降低前缘冲波强度，对涡轮气动性能可能有一定好处，但应合理选择冷气流量比，如冷气流量比过大，叶片后半部压力也随之增高，从而影响涡轮膨胀比，降低涡轮作功能力。

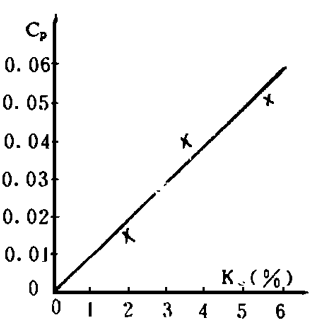

图 3　A 种叶片 C_p 随 K_G 的变化

试验研究表明，气膜冷却对叶片表面压力分布确有影响，其影响的大小程度，与气膜孔开设位置、冷却流量比、燃气与冷气的绝对温比均有密切关系。特别值得注意的是，对于将来设计先进的高温涡轮气冷叶片来说，正确选择气膜孔开设位置、合理使用冷气流量是至关重要的。需综合考虑冷却性能与气动性能，以求找出一组对涡轮气动性能影响最小，而又满足冷却性能要求的冷却参数。

参加本项研究的还有孙德行、陈瑞华等同志。

参　考　文　献

[1]　刘存禄、罗明俊、邓化愚、刘玉芳，《高负荷跨音速复合式气冷涡轮叶片试验研究》，航空动力学报，Vol. 4，No. 4，1989。

EFFECTS OF FILM COOLING ON SURFACE PRESSURE DISTRIBUTION ON TURBINE BLADES

Luo Mingjun, Deng Huayu, Liu Bo (*Gas Turbine Establishment*)

ABSTRACT Effects of film cooling on the surface pressure distribution on composite air-cooled blades has been investigated experimentlly at medium temperatures and pressures. The effects of the ratio of cooling mass flow to gas mass flow K_G, the ratio of gas temperature to coolant temperature K_T, and the location of film cooling holes on the surface pressure distribution are discussed. It is found from the experimental results that the K_G and the location of the film cooling holes have considerable effects on the surface pressure distribution.

HEAT TRANSFER IN A WEDGED PIN-FINNED PASSAGE WITH PRESET PERFORATED PLATE

Gu Weizao, Zhang Yuming, Liu Changchun (*Institute of Engineering Thermophysics*)

ABSTRACT An experimental research on enhanced cooling of gas turbine blades are presented, based on scaled up model heat transfer tests. The air from the radial inlet channel passes through the perforated plate and is forced into the pin-finned wedged passage with a dip angle of $3°52'$ and initial width 18.6mm. At a distance 9mm from the plate is located a guide pillar row with the oval cross section and then 8 pin-fin rows. 5 test runs have been conducted with varying air flow rates and 5 sets of experimental data for 6 measuring sections have been obtained. When Nu_{ij} and Re_i are based on the hydraulic diameter D_{hi} at the measuring sections, the correlation of Nu_{ij}-Re_i can be expressed by the formula $Nu_{ij} = C_{ij} Re_i^n$. The exponent n is 0.59 or 0.50 and coefficient C_{ij} equals 0.36 to 1.31 for the various measuring points. Due to different values of D_{hi} the signifficant difference between Nu_{ij} values for the different sections does not mean the actual difference of the heat transfer coefficients. When the Nu_{ij} and Re_i number are based on the pin diameter d, the average heat transfer coefficient in the test passage can be expressed as $\overline{Nu}_d = 0.53\, \overline{Re}_d^{0.57}$ and the flow friction factor ζ can be correlated as $\zeta = 54.6\, \overline{Re}_d^{-0.16}$. Both $\overline{Nu}_d$ and ζ are higher than those in the passages without perforated plate.

FLOW PATTERNS AND HEAT TRANSFER OF IMPINGEMENT FLOW

Oiu Xuguang and Kang Ying (*Beijing University of Aeronautics and Astronautics*)

ABSTRACT The various flow patterns and corresponding various characteristics of local heat transfer of impingement flow are considered for the short distance between nozzle exit and target surface. In the case of the two-dimensional slot jet, the flow patterns and characteristics of local heat transfer are remarkably influenced by these factors such as the degree of turbulance development in jet, the reaction of target surface on the jets and the compressibility of jet at high velocity. The types of multi-peak distribution of local heat transfer on the target surface depend on variation of these factors. For the row of circular jets, besides the above-mentioed factors, the effect of the three-dimensional flow of jets at short distance between nozle exits and target surface, leads to makes the local heat transfer from both sides of the stagnant line drop sharper than that of the two-dimensional slot jet.