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复合式气冷涡轮叶片内流动和换热计算

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【摘要】　本文给出了复合式气冷涡轮叶片内冷气流量分配、温增加和换热系数迭代求解方法和计算实例，还讨论了转动效应对冷气流动和换热和影响。并成功地应用于高性能推进系统气冷叶片的设计，同时也可用于气冷涡轮叶片改型和模底分析、验算。

一、计 算 方 法

1.　基本方程

(1)　流量公式

$$G_i = C_D A_c \left(\frac{P_i}{RT_c^*}\right)\left(\frac{P_c^*}{P_i}\right)^{k-1/k}\sqrt{2Rk/(k-1)T_c^*\left(1-(P_i/P_c^*)^{(k-1)/k}\right)} \qquad (1)$$

式中，P_i 和 A_c 分别为孔 (缝) 的反压和面积；流量系数 C_D 取自文献 [1、2]。对于冲击孔和气膜孔，也可以用文献 [3] 的计算公式计算。

(2)　动量方程　考虑摩擦、换热、旋转效应，并有流量流出的变截面管道，一维稳态可压缩气流的动量方程[4] 为

$$\left(1-\left(\frac{G_c}{A_c}\right)^2\frac{RT_c}{P_c^2}\right)\frac{dP_c}{dr}=\frac{P_c}{RT_c}r\omega^2-\frac{RT_c}{2P_c}\frac{d}{dr}\left(\frac{G_c}{A_c}\right)^2-\left(\frac{G_c}{A_c}\right)^2\frac{R}{P_c}\cdot\left(\frac{dT_c}{dr}+f\cdot\frac{T_c}{2D_e}\right) \qquad (2)$$

式中，ω为转速，D_e 为当量直径。针肋通道摩擦系数 f 的计算取自文献 [5]。

(3)　能量方程　考虑叶片复合换热和泵功效应的理想气体一维稳定热平衡方程[6] 为:

$$\frac{dT_c^*}{dr}=\frac{UA_g}{G_cC_p}(\overline{T}_{ge}^*-T_c^*)+\frac{\omega^2}{C_p}r \qquad (3)$$

式中，U 为复合换热系数，是燃气和冷气换热系数的函数；A_g 为叶片燃气边微元侧面积；$\overline{T}_{ge}^*$ 为微元面积上燃气平均恢复温度。利用边界条件，在 Δr 内积分，得到

$$T_{c2}^* = T_{c1}^* e^{-\frac{UA_g}{G_cC_p}(r_2-r_1)}+\left(1-e^{-\frac{UA_g}{G_cC_p}(r_2-r_1)}\right)\cdot\left(\overline{T}_{ge}^*-\left(\frac{G_cC_p}{UA_g}\right)^2\frac{\omega^2}{C_p}\right)$$
$$+\frac{G_c\omega^2}{UA_g}\left(r_2-r_1e^{-\frac{UA_g}{G_cC_p}(r_2-r_1)}\right) \qquad (4)$$

前缘冲击换热系数取自文献 [7] 中的计算公式。无针肋和带针肋通道的换热系数分别取自文献 [8] 和 [6]。必须注意，式 (4) 只适用于通道内气流方向与离心力方向相同的情况。若方向相反时，沿流程计算的公式为

$$T_{c2}^* = T_{c1}^* e^{\frac{UA_g}{G_cC_p}(r_2-r_1)}+\left(1-e^{-\frac{UA_g}{G_cC_p}(r_2-r_1)}\right)\cdot\left(\overline{T}_{ge}^*-\left(\frac{G_cC_p}{UA_g}\right)^2\cdot\frac{\omega^2}{C_p}\right)$$
$$\frac{\omega^2}{C_p}\frac{G_cC_p}{UA_g}-\left(r_2-r_1e^{\frac{UA_g}{G_c\cdot C_p}(r_2-r_1)}\right) \qquad (5)$$

式中，$r_2 < r_1$

2. 适用范围：(1) 纯对流通道；(2) 参流一气膜复合通道；(3) 对流一针肋通道；(4) 对流一冲击一气膜复合通道。

3. 计算思路　(1) 已知叶片几何参数，外边界条件以及 P_c^* (或 G_c)、T_c^*。分别按流路联立迭代求解上列基本方程，获得各腔各计算截面冷气流量、总 (静) 压、总 (静) 温、换热系数以及上列基本 G_c (或 P_c^*)。

(2) 已知叶片外边界条件、P_c^*，T_c^* 以及 G_c。可通过改变叶片几何参数，按 (1) 同样的计算思路，得到不同内冷结构方案，经温度场计算，择优选取所需方案。

二、算　　例

对图 1 所示的叶片进行了计算。冷气由叶根分三路进气，共 8 个内冷通道。图 2 给出了有流量从孔 (缝) 中流出时部分通道各截面流量换热系数和温度沿径向的变化。显然，随着 r 增加，冷气流量减少，温度增加，导致冷气雷诺数降低，换热系数下降。上述曲线是对冷气流动和离心力同向而言。下面讨论它们反向时转动效应对压力和温度的影响。图 3 的 (a) 示出了叶片第 4 通道在不同转速 (Nr/min：1–10000；2–15000；3–19000；4–23000) 下冷气压力沿流程的变化 (由于迭求解，进口处气流状态有差别)，3 (b) 示出了在同一进口气流状态下转动效应的影响。(Nr/min：1–10000；2–16000；3–19230；4–21000；5–24000) 可以看到，由于转动效，使冷气压力沿流向降低，随着转速增加，压力下降的梯度越大。图 4 的 (a) 给出了叶片第 4 通道在不同转速下 (Nr/min：1–10000；2–15000；3–17800；4–19000；5–23000) 冷气总温沿流程的变化 (进口处气流状态有差别)。(b) 给出了在同一进口气流状态下转动效应的影响 (与图 3b 的 N 相同)。由图中可以看到，当转速降低时，冷气沿流程的温度递增，表明加热项大于泵功效应项。当转速增加到某一临界值时，在流程中冷气温度不变，这时加热项和泵功效应项相等。当转速再进一步增加，冷气温度沿流程降低，表明泵功效应项大于加热项。

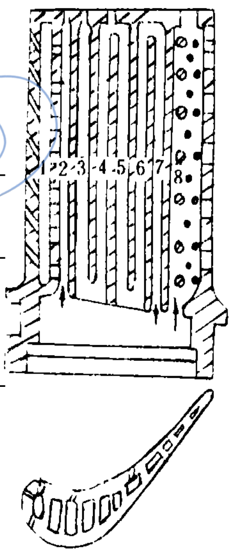

图 1　叶片示意图

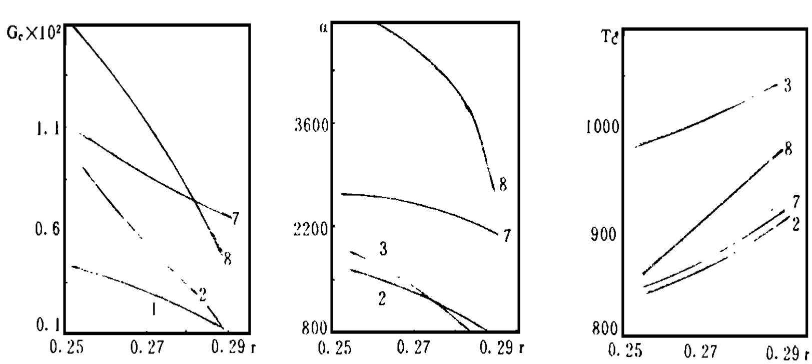

图 2　部分通道各截面 G_c、α 和 T_c^* 沿径向的变化

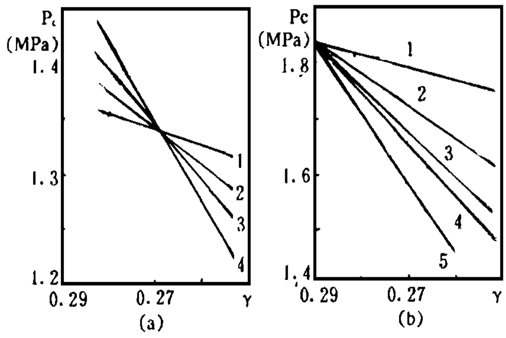

图 3 转速 N (r/min) 对冷气压力沿流程变化的影响

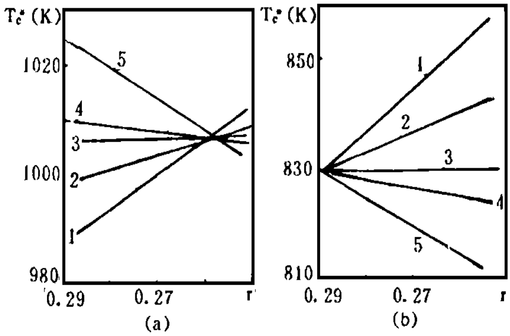

图 4 转速 N (r/min) 对冷气总温沿流程变化的影响

综上所述，气冷叶片设计，一定要考虑转动效应对气流流动和换热的影响。

参 考 文 献

[1] Hippenstede, Steven A. "Pressure-Loss and Flow Cofficients inside a Chordwise-Finned, Impingement. Convection and Film Air-Cooled Turbine Vane", NASA TMX-3028, 1974.

[2] Meitnor, Peter L. and Hippenstede, steven A., "Experimental Flow Coefficients of a Full-Coverage Film-Cooledvane Chamber", NASA TP-1036, 1977.

[3] Tay Chu etc., "Disharge Coefficients of Impingement and Film Cooling Holes", ASME 85-GT-81, 1985.

[4] Eckert, E. R. G., Livingood, J. N. B, prass, E. I., "One-Dimensional Calculation of Flow in a Rotating Passage with Ejction through a Porous Wall", NASA TN-3408, 1955.

[5] Damerow, W. P., "Experimental and Analytical Investigation of the Coolant Flow Characteristics in Cooled Turbine Airfoils", NASA CR-120883, 1972.

[6] Faulknor F. E., "Analytical Investigation of Chord Size and Cooling Methods on Turbine Blade Cooling Requirements", NASA CR-120882, 1977.

[7] chupp, R. E. and helms, H. E. etal., "Evaluation of Internal Heat Transfer Coefficients for Impingement Cooled Turbine Airfoils", AIAA paper No. 68-564, 1968.

[8] Л. И. Одиванов, А. С. Лиманский "Исследование пропускной способности продольных охлаждающих каналов лопатки газовой турбины", ИВУЗ 《Авиационная Техника》 No. 4, 1972.

DESIGN AND CALCULATION OF COMPOSITE AIR-COOLED BLADES IN A HIGHLY-LOADED TRANSONIC TURBINE

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ABSTRACT A set of calculation methods is presented for predicting coolant mass flow distribution, temperature rise、heat transfer coefficients (internal and external) and temperature field of transonic turbine blades with impingement-convection-film cooling. Various air-cooled schemes has been calculated, in result four internal air-cooling structures in turbine blades have been chosen accordingly and designed elaborately. The results of calculation according to actual parameters are compared with the measured wall temperature distributions over turbine blades. Maximum and minimum deviations of the local wall temperature over the turbine vanes and blades are 9.8% and 2%, 6.4% and 1.3% respectively. The methods are verified to be credible and accurate.

CALCULATION OF COOLANT FLOW AND HEAT TRANSFER INSIDE COMPOSITE AIR-COOLED TURBINE

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ABSTRACT A calculation method is presented for iterative solution of the coolant mass flow distribution, temperature rise and internal heat transfer coefficient inside composite air-cooled turbine blade. An numerical example is given. The effects of rotation on coolant flow and heat transfer are discussed. The method has been successfully applied to the design of air-cooled turbine blades for HPPSARP project, and it can also be used in model modification and calculation check.

NUMERICAL STUDY OF CONDUCTIVE TEMPERATURE DISTRIBUTION AND RECURRENCE RELATION IN TRANSIENT COMPUTATION

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ABSTRACT The numerical analysis of steady and unsteady conductive temperature distributions of turbine disk and blade is presented as part of HPPSARP project. It consists of two-dimensional (plane and axisymmetric) and three-dimensional problems. This paper gives a summary illustration of its feactures and emphasis on the stability of time recurrence relations in transient computation. A variable weighted coefficient to summarize the different time schemes is proposed in the developed computing program. It is favourable to improve the accuracy and restrain the oscillation in calculation. Some numerical examples are given to verify the characters of different schemes.