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# 半圆腔壁表面二维冲击流动和换热的模拟计算

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【摘要】　本文用有限元素法对半圆形腔壁表面的冲击流动和对流换热作了数值计算，由于引射作用在腔内会出现回流，使得流动结构和换热系数的分布与大空间的冲击流动存在明显的区别。计算结果表明，除在冲击缝两侧壁面附近有第一回流区外，在一定流动条件下还可能在下游产生第二回流区。本文根据计算结果整理了流函数、等温线和局部努赛尔数的分布曲线，并作了物理说明。

## 一、前　　言

表面冲击流动具有良好的传热传质性质，因而在工程技术中常被用来作为增强传热和传质的一种手段。例如在纸张和纺织品的干燥过程中，金属材料和玻璃等的热处理工艺中都已得到实际应用。目前航空发动机的高温涡轮叶片，也往往采用叶片前缘内壁冲击冷却，它近似于腔内圆弧表面的冲击流动和冲击换热。

现有的冲击流动计算多是以平壁作为冲击靶面的。例如Scholtz 和Trass[1]以圆孔射流冲击平靶面为研究对象；Miyazki 等[2]和Sparrow 等[3]以二维缝槽射流冲击平靶面为计算对象。对于圆柱形冲击靶面，而且射流在有限空间的腔道内作 180 转折的流动结构和换热情况，其数值求解还未见诸报导。本文是对腔内半圆靶面的二维层流冲击流动和换热的计算，目的在于了解流动结构的特点，以及摩擦系数、换热系数的分布情况。

## 二、计 算 模 型

由两个不同半径的同心半圆筒柱构成的半圆环形空腔，其后部与足够长的平直槽道相接（图 1)，整个通道在 $z$ 轴方向是无限延伸的。气流自内圆弧壁上的窄缝轴向（负 $x$ 方向）流入，对外圆弧壁面冲击并转折，最后由两侧的平直槽道轴向（正 $x$ 方向）流出。考虑流动是层流，流体的物性量均为常数。进气窄缝的宽为 $B$，进口处的流速为均匀分布或抛物线型分布，即　$u = -u_o$

或者　　$u = -(3/2)u_o\{1 - y^2/(B/2)^2\}$

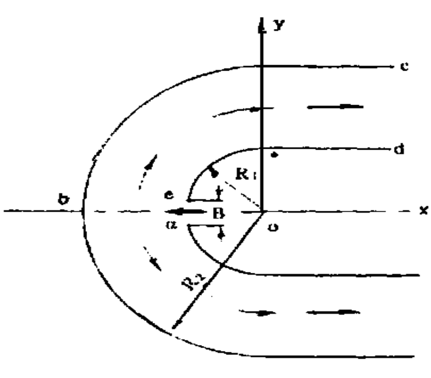


图 1　圆弧靶面冲击流动的通道图

在温度计算中，取内壁和外壁温度分别为 $T_{w1}$和 $T_{w2}$，它们都是常数。

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用流函数 $\Psi$ 和涡函数 $\omega$ 表示的方程组 $\quad \nabla^2\Psi = -\omega$ (1)

$$\frac{\partial\omega}{\partial\tau} + \frac{\partial\Psi}{\partial Y}\frac{\partial\omega}{\partial X} - \frac{\partial\Psi}{\partial X}\frac{\partial\omega}{\partial Y} = \frac{1}{Re}\nabla^2\omega \tag{2}$$

$$\frac{\partial\theta}{\partial\tau} + \frac{\partial\Psi}{\partial Y}\frac{\partial\theta}{\partial X} - \frac{\partial\Psi}{\partial X}\frac{\partial\theta}{\partial Y} = \frac{1}{Pe}\nabla^2\theta \tag{3}$$

式中

$\partial\Psi/\partial Y = U = u/u_0$, $\partial\Psi/\partial X = -V = -v/u_0$, $\omega = \partial V/\partial X - \partial U/\partial Y$, $\theta = (T - T_{w1})/(T_{w2} - T_{w1})$

$Re = u_0(B/2)/\upsilon$ , $Pe = u_0(B/2)/a$ , $X = x/(B/2)$ , $Y = y/(B/2)$

对应的边界条件

进口 $ae$ 上, $\Psi = 1 - Y$ 或者 $\Psi = 1 - 3(Y - Y^3/3)/2$; $\omega = 0$ 或者 $\omega = -3Y$; $\theta = 0$。

内壁 $ed$ 上, $\Psi = 0$; $\omega = -[(3\Psi_N/\Delta N^2) + (\omega_N/2)]$; $\theta = 0$。

对称面 $ab$ 上, $\Psi = 1$; $\omega = 0$; $\partial\theta/\partial Y = 0$。

外壁 $bc$ 上, $\Psi = 1$; $\omega = 3(1 - \Psi_N)/\Delta N^2 - \omega_N/2$; $\theta = 1$。

出口 $cd$ 上, $\partial\Psi'/\partial X = 0$; $\partial\omega/\partial X = 0$; $\partial\theta/\partial X = 0$。

方程 (2) 和 (3) 中的 $\tau$ 是无量纲时间坐标, 加上时间项是为了用逼近法求解。符号 $\Delta N$ 是距壁面的一个无量纲法向距离 ($\Delta N = 2\Delta n/B$), $\Psi_N$ 和 $\omega_N$ 是该处的流函数和涡函数, 这种边界条件的导出可参阅文献 [4]。

## 三、求 解 过 程

方程 (1)、(2) 和 (3) 的求解可转化为下述泛函的变分计算[5]

$$I_\Psi = \frac{1}{2}\iint_\Omega \left\{\left(\frac{\partial\Psi'_{n+1}}{\partial X}\right)^2 + \left(\frac{\partial\Psi_{n+1}}{\partial Y}\right)^2 - 2\omega_n\Psi_{n+1}\right\} d\Omega \tag{4}$$

$$I_\omega = \frac{1}{2}\iint_\Omega \left\{\frac{1}{Re}\left[\left(\frac{\partial\omega_{n+1}}{\partial X}\right)^2 + \left(\frac{\partial\omega_{n+1}}{\partial Y}\right)^2\right] + 2\left[\left(-\frac{\partial\Psi_{n+1}}{\partial X}\right)\left(\frac{\partial\omega_n}{\partial Y}\right) + \left(\frac{\partial\Psi_{n+1}}{\partial Y}\right)\left(\frac{\partial\omega_n}{\partial X}\right) + \left(\frac{\partial\omega_n}{\partial\tau}\right)\right]\omega_{n+1}\right\} d\Omega \tag{5}$$

$$I_\theta = \frac{1}{2}\iint_\Omega \left\{\frac{1}{Pe}\left[\left(\frac{\partial\theta_{n+1}}{\partial X}\right)^2 + \left(\frac{\partial\theta_{n+1}}{\partial Y}\right)^2\right] + 2\left[\left(-\frac{\partial\Psi}{\partial X}\right)\left(\frac{\partial\theta_n}{\partial Y}\right) + \left(\frac{\partial\Psi}{\partial Y}\right)\left(\frac{\partial\theta_n}{\partial X}\right) + \left(\frac{\partial\theta_n}{\partial\tau}\right)\right]\theta_{n+1}\right\} d\Omega \tag{6}$$

把计算域分割成一系列元素后, 元素体的变量由节点值的插值函数表示, 于是取 $\delta I_\Psi = 0$, 可写出元素方程

$$[K_\Psi]^e\{\Psi\}^e_{n+1} + \{R_\Psi\}^e_n = \{O\} \tag{7}$$

其中

$$k_{\Psi,ij} = \iint_\Omega \left[\left(\frac{\partial N_i}{\partial X}\right)\left(\frac{\partial N_j}{\partial X}\right) + \left(\frac{\partial N_i}{\partial Y}\right)\left(\frac{\partial N_j}{\partial Y}\right)\right] d\Omega^e$$

$$r_{\Psi,i} = -\iint_\Omega \omega_n N_i \, d\Omega^e$$

取 $\delta I_\omega = 0$ 可得元素方程

$$[K_\omega]^e\{\omega\}^e_{n+1} + [K_{\mathring{\omega}}]^e\{\mathring{\omega}\}^e_{n+1} + \{R_\omega\}^e_n = \{O\} \tag{8}$$

其中

$$k_{\omega,ij} = \frac{k_{\Psi,ij}}{Re}, \quad k_{\mathring{\omega},ij} = \iint_\Omega N_i N_j \, d\Omega^e$$

取 $\delta I_\theta = 0$

$$r_{\omega,i} = \iint_\Omega N_i\left[\left(\frac{\partial\Psi_{n+1}}{\partial Y}\right)\left(\frac{\partial\omega_n}{\partial X}\right) - \left(\frac{\partial\Psi_{n+1}}{\partial X}\right)\left(\frac{\partial\omega_n}{\partial Y}\right)\right] d\Omega^e$$

$\{\mathring{\omega}\}^e$ 和 $\{\mathring{\theta}\}^e$ 均采用时间的线性差分计算。

选用三角形三节点元素作元素分析, 然后组集成代数方程组, 最后用 Choleski 法求解。若时间步长不改变，系数矩阵也不改变，迭代过程每次只改变常数项。从腔内气体静止开始，$\omega_i = 0$，算出流函数 $\Psi_{n+1}$，再由 $\Psi_{n+1}$ 计算 $\omega_{i+1}$，直到求得 $\Psi$ 和 $\omega$ 的收敛解。应用 $\Psi$ 和 $\omega$ 的解和假设的初温 $\theta_i$ 计算 $\theta_{i+1}$，重复该过程逼近温度的稳定解。

## 四、计算结果与分析

图 2 是速度矢量图，符号 $Z=(R_2-R_1)$。图中表明在射流进口的侧面存在回流区，这是由于在腔内，射流只能靠本身下游的气流来补充气体，这和大空间中可由环境气体来补充是不同的。该回流区 (也称第一回流区) 的强度随 $Re$ 和 $Z$ 增大而加强。图 3 是流线图, 自缝口到靶面之间流层不断扩张, 压力不断提高, 压差为气流提供转折所需的向心力。当气流由外壁向内转折过于强烈时 (如 $Re$ 和 $Z/B$ 较大)，又可能诱导出靠近外壁的第二回流区 (图 4)，使气流折转回到沿外壁流动。两个回流区的回流方向相反, 第二回流的强度较弱。

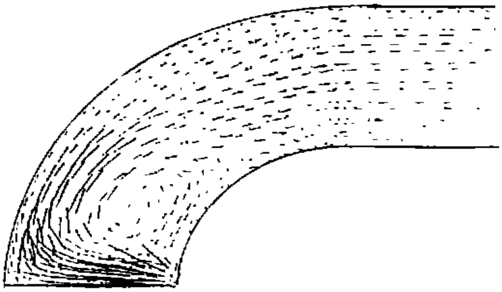

图 2　速度矢量图

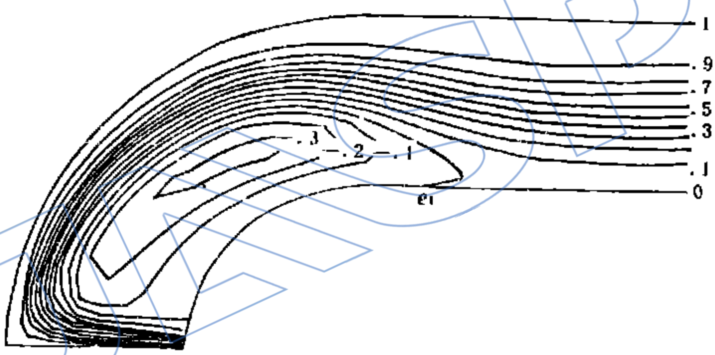


图 3　流线图 ($Re=115$, $z/B=5$)

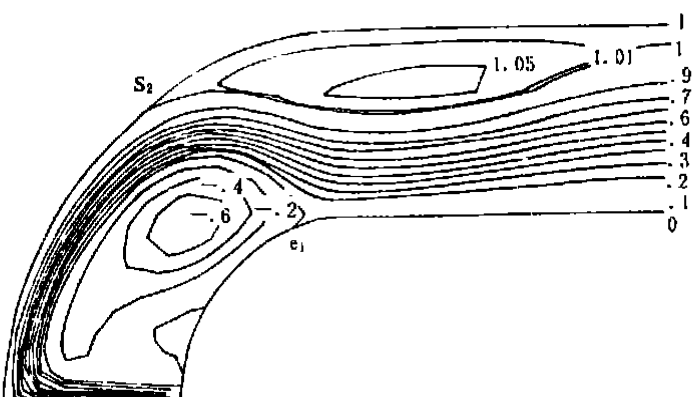


图 4　两个回流区的流线图 ($Re=131$, $z/B=8.8$)

图 5 是等温线图，沿外壁的等温层有过度扩张然后收缩的变化。这是由于在第二回流区中、下游加热了的气体逆流而上造成的，当地的外壁法向温度梯度和局部换热系数也会减小。沿外壁局部努赛尔数 $Nu_s = h_s B/\lambda = 2\cdot\Delta Q/\Delta N$ 的分布表示在图 6 上，图线表明 $Nu_s$ 并非由驻点开始单调地下降，而是先急剧下降到最低点而后有所回升，最后趋于定值。这种变化规律在进口速度为抛物线型时比较

明显，对于相同流量而进口速度均匀分布的情况，则在较高的 $Re$ 和 $Z/B$ 下才出现。

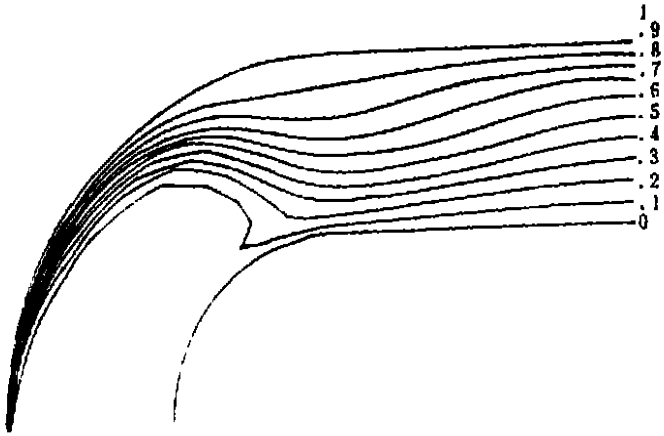


图5 等温线图（$Re=131$，$z/B=8.8$）

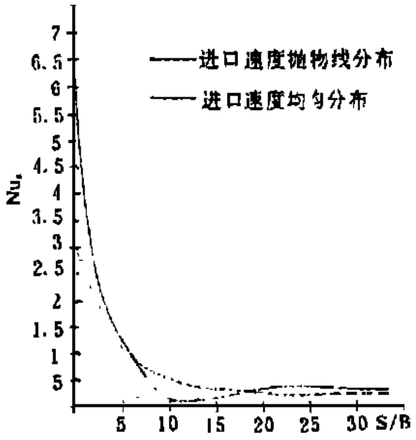


图 6 局部努赛尔数分布（$Re=96$，$z/B=5$）

## 五、结 论

腔内冲击靶面的流动结构与大空间情况有明显差别，除了在缝口两侧有靠近内壁的回流区外，在高 $Re$ 和 $Z/B$ 下，下游靠近外壁面处还可能出现第二个回流区。两个回流区的流向相反，第二回流区的回流强度较弱。

局部努赛尔数 $Nu_s$ 在靶心区最大，然后沿靶壁下降，在第二回流区中达到最低点，最后又略有回升趋于定值。

缝口的速度分布对局部努赛尔数 $Nu_s$ 的大小和分布有明显影响，在平均速度相同的条件下，抛物线型分布具有更高的靶心区换热系数，但它沿壁面的下降也更快。

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## AN INVESTIGATION ON FILM-COOLING FROM TWO-STAGGERED ROWS OF HOLES — (1) HEAT TRANSFER COEFFICLENTS

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**ABSTRACT**　The film-cooling performance downstream of injection from two-staggered rows of holes were investigated in a Ludwieg tube wind tunnel. For the first time, heat transfer measurements were conducted in both streamwise and spanwise directions in a short duration flow facility. The details of wall temperature and heat transfer coefficient in region close to injection holes have been were obtained.

## AN INVESTIGATION ON FILM-COOLING FROM TWO-STAGGERED ROWS OF HOLES — (2) EFFECTIVENESS

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**ABSTRACT**　The experimental results and numerical computation of film-cooling effectiveness downstream of injection from two-staggered rows of holes are presented in this paper. On the basis of measured effectiveness in both streamwise and spanwise directions, especially in the region close to injection holes, the different heat transfer behaviors of the jets from upstream and downstream rows are analyzed. In the computation, a three-dimensional calculation procedure is used to solve the related elliptic equations and the results agree well with present measurements far downstream. The discrepancies are increased in the near-injection region.

## PREDICTION FOR FLOW AND HEAT TRANSFER OF IMPINGEMENT IN A SEMICIRCULAR CLOSURE

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**ABSTRACT**　Calculation for two dimensional flow and heat transfer of impingement in a semicircular closure has been completed with a Finite Element Method. It is found that the impinging flow in closure is much different from the impingement in free space. Except the circulations on the two sides of inlet nearby the inner wall, it is possible to induce two contrary circulations nearby the out wall in down stream. The effects of the currents on isotherm and heat transfer are given graphically.

## EXPERIMENTAL STUDY OF FLAME EXTINCTION CHARACTERISTICS FOR A GAS TURBINE COMBUSTOR BURNING LOW BTU GAS

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**ABSTRACT** For developing the Integral Gasification Combined Cycle in China, Gas turbine combustors would have to burn a variety of coal-derived low Btu gases. A worse flame extinction characteristic is one of weakness of these gases, especially used in the case of gas turbine. In this paper, a series of experimental studies of flame extinction characteristics have been completed for a gas turbine combustor from a Aero-gas-turbine modifier with two different kinds of air swirlers, fuel gas injectors and flame liners. the effects of such geometrical factors on flame stability have been obtained obviously, which are useful in designing gas turbine combustors burning such low Btu gases.

## PREDICTION OF HEAT TRANSFER COEFFICIENT ON TURBINE BLADE PROFILES

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**ABSTRACT** Several problems involved in the prediction of heat transfer coefficient on the turbine blade profiles without film cooling are studied in this paper for the purpose of improving the accuracy. These problems are: heat transfer in the vicinity of stagnation point, the location of boundary layer transition, heat transfer of transitional boundary layer and the influence of free stream turbulence intensity. Cebeci-Smith method is used to solve the boundary layer equations obtaining the similar solution in the vicinity of stagnation point. It is assumed that the free stream velocities near the leading edge of a blade can approximately be expressed as that for a cylinder, the radius of which equals to that of leading edge circle or to the radius of a "equivalent cylinder", the solution obtained by this method in the vicinity of stagnation point is used as a initial profiles of velocity and enthalpy for the computation of boundary layer along the blade surface. STANS[9] with some modifications is used to calculate heat transfer coefficient on the rest part of the blade surface. Transition origin and transition length are predicted by using the models suggested by Seyb[5] and Dhawn at el. [12] respectively. In order to take the free stream turbulence intensities into account, a turbulence viscosity is introdued as a part of effective viscosity of the fluid. Several numerical examples obtained by the proposed method in this paper indicate better agreement with the experimental data than by original STAN 5.