

用 N-S 方程计算三维叶栅流

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【摘要】 发展了基于微元中心有限体积方法,采用雷诺平均 N-S 方程求解三维叶栅流动的程序,特别注意了格式中人工粘性的加法;程序采用 Baldwin-Lomax 模型。格式经过平板层流及湍流流动的校验,层流与 Blasius 解、湍流与实验经验公式及 Wilcox 的计算值符合很好,最后以 Goldman 涡轮导向器为例进行了叶栅流动计算校核,结果符合于实验以及 Chima 等人的计算。

主题词: 叶栅流动 三维流动 数值计算

分类号: TB115

1 数值方法

控制方程为直角坐标系下参数表达、曲线坐标、守恒形式 N-S 方程:

$$\partial Q / \partial \alpha + \alpha F / \alpha \xi + \alpha G / \alpha \eta + \partial H / \partial \zeta = \partial F_v / \partial \xi + \alpha G_v / \alpha \eta + \partial H_v / \partial \zeta \quad (1)$$

其中 $Q = J^{-1}[\rho, \rho u, \rho v, \rho w, E]^T$, F, G, H 为沿各方向输运通量项, F_v, G_v, H_v 为沿各方向粘性通量项。 ρ, u, v, w, E 分别为密度、速度及内能。

在计算空间,运动方程(1)可以应用格林定理写成积分形式,并以有限体积公式离散。采用中心差分格式,微元交接面的参数由直接平均相邻两微元中心的独立变量获得。格式固有的奇偶振荡特性仍无法消除,而且为了抑制激波前后及驻点附近的参数振荡,必须加入人工粘性。人工粘性基本为 Jameson^[1]所用二阶与四阶混合耗散项。为使人工粘性对解的污染最小,将边界处人工粘性置为零,并且在内部将人工粘性处理为通量守恒形式。为尽可能减少人工粘性,对人工粘性应用了 Swanson^[2]提出的特征值标度法。

方程(1)由空间离散成为一常微分方程组 $\partial Q / \partial \alpha = -R(Q)$ 。对方程组采用显式四步 Runge-Kutta 格式积分至得到定常解,为节省计算时间,物理和人工粘性项只在第一步计算,以后保持不变。积分格式如下: $Q^0 = Q^n, Q^i = Q^{i-1} + \alpha_i \Delta t R(Q^{i-1}), \alpha_i = 1/(5-i), i = 1, 2, \dots, 4, Q^{n+1} = Q^4$ 。采用了类似 Arnone^[3]的当地时间步长及变系数残值光顺加速收敛技术。

2 算例校核

由于程序为三维的,因而比较时是在三维平板层流解任意横截面上与 Blasius 相似解进行对比。计算网格有 $45 \times 39 \times 19$ 点,流动雷诺数为 9560,外流马赫数为 0.5,马赫数选取最好高于 0.3,否则程序收敛很慢,而且从对比可看出误差较大,这也表明了格式用于不可压流的限制。另外,校验的关键还在于近壁网格间距大小,太大则会使比较结果不理想,一般此间距要满足 $y^+ < 5$ 。边界条件也是影响比较结果的关键。图 1 给出了在平板前缘后 20%、40%、60%、80%、95% 板长处速度相似的情况,可见结果与 Blasius 相似解^[4]在沿流向各站都符合很好。

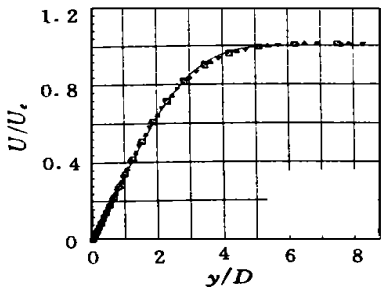
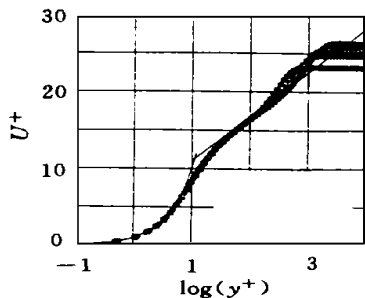
图 1 与平板层流相似解^[4]的比较

图 2 平板湍流边界层计算与经验公式计算比较

为校核湍流模型应用的合理性, 本文以 Baldwin-Lomax 模型计算了平板湍流流动。为了进行对比, 板长取为 1.23 m, 计算域高为 0.08 m, 基于板长及总参数的雷诺数为, 来流马赫数为 0.5, 计算网格 60×62 。图 2 给出了在平板前缘后 20%、40%、60%、80%、95% 板长处速度型分布, 其与 Vandrist^[4] 经验公式计算符合很好(图 1 和 2 中, $\bullet$ $x/c = 20\%$, $\blacklozenge$ $x/c = 40\%$, $\square$ $x/c = 60\%$, $\blacktriangle$ $x/c = 95\%$; 图 1 中—为理论值, 图 2 中—为 Vandrist 经验公式), 速度型的线性粘性底层、过渡层、对数律层特征被很明显地捕获。图 3 是本计算与 Wilcox 公认计算的对比情况, 可见符合很好, 从而验证了湍流模型应用的可靠性。

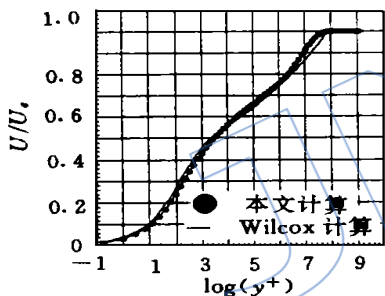


图 3 平板湍流计算与 Wilcox 计算的比较

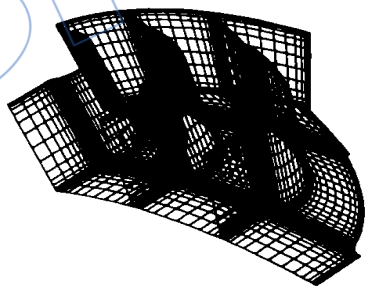


图 4 导向器计算用三维网格

Goldman 涡轮导向器在 1982 年由 Goldman^[5] 等人进行了详细的激光测速, 它已广为用作校验标准。该导向器环共有 36 片叶片, 轮毂比均为 0.85, 叶尖直径为 508 mm。本文计算设计工况, 此时出口轮毂静压为 0.67 倍的进口总压, 基于轴向弦长的雷诺数为 173000, 通过该环形叶栅的设计等效流量为 4.828 kg/s。计算网格采用简单 H 型网格, 网格点数为 $74 \times 23 \times 19$, 栅向最小网格间距为 5×10^{-4} 倍栅距, 展向最小网格间距为 1×10^{-3} 倍展长, 网格三维图如图 4 所示。计算假定流动为完全湍流流动。图 5 为计算的收敛史, 在大约 1500 步以后, 残差不再下降而只是摆动, 此时结果可视为收敛。图 6 给出了根、中、尖三个展向位置的叶表压力分布情况与实验的对比(图 6-8 中, — 计算, $\bullet$ Goldman 实验), 在压力面计算与实验符合很好, 而在吸力面上, 前后

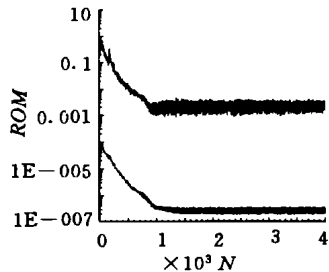


图 5 Goldman 算例的残差收敛史

缘附近压力振荡与实验有一定偏差,这主要是由于简单型 H 网格对于叶片前后缘描述的不完善性及网格严重畸变造成的,预计采用 C 型或 O 型网格及采用法向动量方程求解壁面压力可

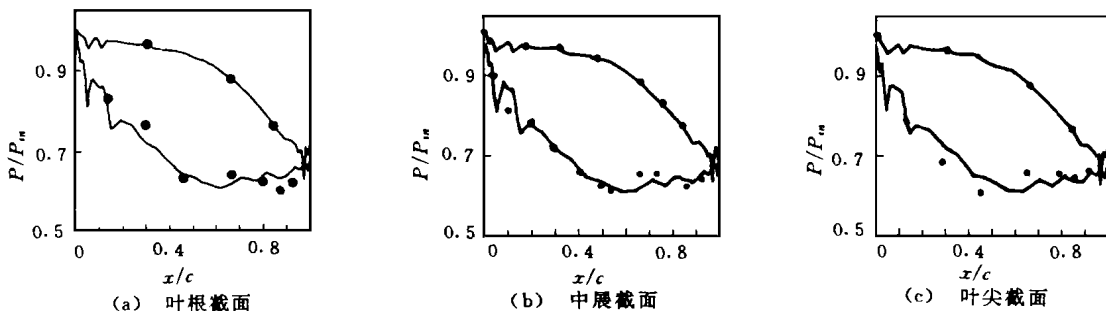


图 6 压力分布计算与实验比较

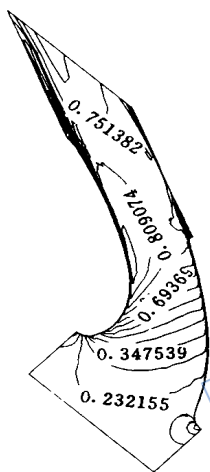


图 7 中展截面等马赫线

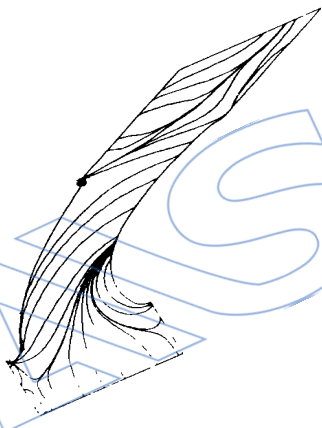


图 8 叶根截面流动迹线



图 9 子午向前缘前流动迹线

以使数值模拟涡轮叶栅更为精确。图 7 为中展截面的等马赫线图,与 Chima^[6]的计算符合很好。图 8 为叶根流动迹线图,图 9 为子午面上前缘前的流动迹线图,从图上可以明显看出前缘马蹄涡的卷起。

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performance of the atomizer with lower swirling strength is better than that of the atomizer with higher swirling strength near the atomizer exit, but downstream the both atomizers possess same atomization performance.

Key Words Atomizing Measurements Drop size Fuel- nozzles

NUMERICAL SIMULATION FOR MATCHING DIFFUSER WITH LINER IN A SMALL DIRECT- FLOW COMBUSTOR

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ABSTRACT

Numerical simulation was carried out for inside and outside flow- fields of the liner in a small direct- flow combustor with special structural arrangement, numerical tests of combustor performance were performed for matching of different diffusers with the liner. The program employs two- equations (K- ϵ model) to describe turbulent characteristics. The combustion following vaporization was simulated by a two- step chemical reaction combustion model. Arrhenius- EBU model was used to determine the reaction rate, and the air flow mass distribution was taken as a bridge to link the inside and outside flow- fields of the liner. The calculated results indicated that two strong recirculation zones emerged when air flowed into combustor annular cavity from prediffuser, the inside and outside flowfields were very unsymmetrical. The inclination of the prediffuser was an important geometrical parameter for the combustor performance.

Key Words Small turbine engines Combustion chambers Numerical simulation Flow fields

A STUDY ON EFFECTS OF ENVIRONMENTAL FACTORS ON ALUMINUM OXIDE PARTICLE SIZES

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ABSTRACT

On the basis of diffusional combustion model of metal combustion and heterogeneous nucleation mechanism, the average particle sizes of the product Al_2O_3 in aluminum combustion were calculated. The results show that the temperatures on the combustion surface and on the metal surface increase with enhancing pressure, and the average particle size of the condensed product decreases as pressure increases. The effect of the pressure on the parameters is larger than that of the temperatures.

Key Words Aluminium powder Environmental factors Combustion products

CALCULATION OF 3D CASCADE FLOW WITH N- S EQUATION

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ABSTRACT

A cell- centered finite volume method was developed to solve Reynolds- averaged Navier- Stokes equation with Jameson's Runge- Kutta scheme. In its

programming special attention was paid to the addition of artificial viscosity, so that the solution could not be polluted. Baldwin–Lomax Turbulence model is applied to programming. The program has been verified by plate laminar flow, plate turbulent flow and Goldman Turbine vane flow. Firstly, the calculation of the plate laminar flow coincided with Blasius similarity solution; Secondly, the result of the plate turbulent flow was confirmed well with empirical formula and the calculation of Wilcox; Finally, with respect to the Goldman turbine vane flow field, the comparison was made between calculated results and experimental data of pressure distribution over blade profile. It indicated their consistency except fluctuations of the calculated results at leading and trail edge of vane blade. The source of the fluctuations lied in simple H type grid which could not describe the true blade profile and caused so big shear that the calculation scheme was deteriorated. The calculated Mach contour lines agreed to the simulation results of China. All of those indicated that the program suits to designing system of turbomachinery.

Key Words Cascade flow Three dimensional flow Numerical computation

FRACTURE MECHANICS ANALYSIS OF FATIGUE STRENGTH OF LAP- WELDED JOINTS

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ABSTRACT According to the elastic fracture mechanics, a parameter of lap stress intensity K_0 was used to describe the fatigue strength of lap- welded joints. Various influential factors of the K_0 have been analysed by finite element method. Therefore an empirical formula for K_0 was deduced. From fatigue experiments of the lap- welded joints specimens made by two kinds of material (GH150 and 1Cr18Ni9Ti), two $\Delta K - N$ curves were obtained. The fatigue life of various complicated lap- welded joints can be estimated more accurately with the $\Delta K - N$ curves presented in this paper.

Key Words Lap welding Fatigue strength Linear elastic fracture mechanics

FAULT DIAGNOSIS OF ROTATING MACHINERY USING BACK PROPAGATION NEURAL NETWORK

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ABSTRACT The faults of rub between rotor and stator, misalignment test rig of the shafting, and unbalance of the rotor are simulated at a compressor test rig. The normal vibration signals of the rotor and the signals of the various emerging faults are registered and sampled by an automatic signal processor. Then a new- developed back propagation neural network is employed to learn the fault diagnosis from the sampled faults and a new method for accelerating the learning speed has been proposed in this paper.

Key Words Rotor Neural networks Fault diagnosis