叶轮机叶片排中三维流场的数值计算

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〔摘要〕采用时间相关有限体积法，完成了一种计算叶轮机械叶片排中三维无粘流场的计算机程序，实算结果表明本方法数值计算稳定，收敛速度快且与实验数据吻合较好，是一种有效的工程实用分析方法。

关键词　时间相关　三维流场　数值计算　叶轮机械
分类号　TK263

1　前言

随着叶轮机械的不断发展和完善，特别是近年来向高负荷、高效率、大流量的目标发展，叶型的弯扭程度不断加大，使得采用传统的二元流动模型已不能准确地模拟叶轮内部的复杂流场，因此必须以三元模型来取代。但是，这类复杂三元问题的求解在过去是非常困难的。当今计算机技术已发展到很高的水平，高速度高内存计算机的出现，使得叶轮机械内部复杂三元流动的数值模拟成为可能。进入八十年代以来，国内外学者对该问题进行了大量的研究，取得了明显的进展[1,5]。大多数是采用时间相关法来计算。国内有关叶栅三维流动的数值分析起步较晚，适用于工程的方法还不多，急需工程实用的叶轮机叶片排全三元流场的分析方法。本文的目的就是在已有叶栅流动计算工作的基础上，发展一种便于工程实用的叶轮机叶片排中三维流场的数值计算方法。

2　控制方程及网格划分

在圆柱座标系下，支配叶栅三维无粘绝热非定常 Euler 方程的积分型式是：

$$\frac{\partial}{\partial t}\int_{\Delta V} U dv + \int_S H \cdot \vec{\xi} ds + \int_{\Delta V} K dv = 0$$

其中：

$$U = \begin{vmatrix} \rho \\ \rho w_u \\ \rho w_r \\ \rho w_Z \\ \rho e_R \end{vmatrix} \qquad K = \begin{vmatrix} 0 \\ \rho w_r w_u / r + 2\rho\Omega w_r - [\rho \\ (w_u + r\Omega)/r]^2 + \rho / r \\ 0 \\ 0 \end{vmatrix}$$

$$H = \begin{vmatrix} \rho w_u i_u + \rho w_r i_r + \rho w_Z i_Z \\ (\rho w_u^2 + p) i_u + \rho w_u w_r i_r + \rho w_u w_Z i_Z \\ \rho w_r w_u i_u + (\rho w_r^2 + p) i_r + \rho w_r w_Z i_Z \\ \rho w_Z w_u i_u + \rho w_Z w_r i_r + (\rho w_Z^2 + p) i_Z \\ (\rho e_R + p) w_u i_u + (\rho e_R + p) w_r i_r + (\rho e_R + p) w_Z i_Z \end{vmatrix}$$

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式中：$e_R = e + 0.5w^2 - 0.5\Omega r$；$\vec{\xi}$ 是有限体积 $\triangle V$ 的表面 ds 上的外法向矢量；w_u、w_r、w_Z 是相对速度 w 的三个分量；i_u、i_r、i_Z 是三个方向的单位矢量。p 是压力；ρ 是密度；r 是流面半径；Ω 是角速度；e_R 是相对滞止转焓。

上式构成了求解三维叶栅相对流动的基本方程。若求解叶栅中的绝对流动，可令 $\Omega = 0$ 即可；若求解叶栅风洞中的流动，则 $\Omega = 0, r = \infty$。

叶栅流场的求解区域如图 1 所示。取两个相邻叶片的压力面和吸力面以及轮毂和机匣组成的空间为控制体，为了提高数值计算的准确性，上下游两个区域向外延伸一定长度。叶栅前后缘处设有尖劈，计算中将尖劈当作叶面处理。

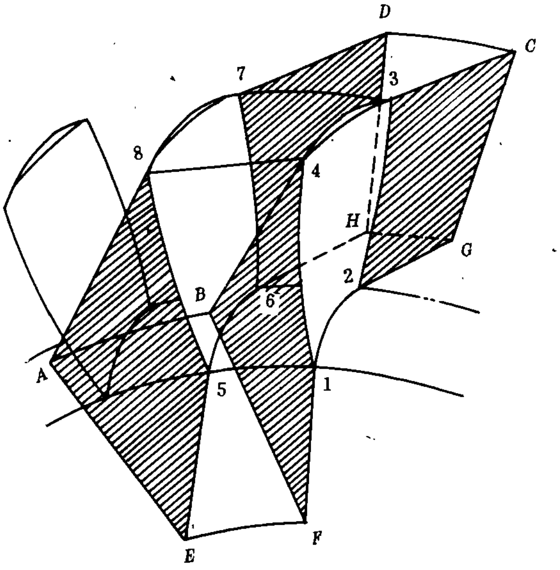

图 1　求解区域

在物理域中划分网格的基本原则是，在保证空间能清晰分辨流动全部重要特征的条件下使网格数目最少，以提高计算效率。因此，本文在气流参数变化较大的区域采用较密的网格，在变化较小的区域采用较稀的网格。网格生成采用简单的几何方法，三个截面的网格如图 2 所示

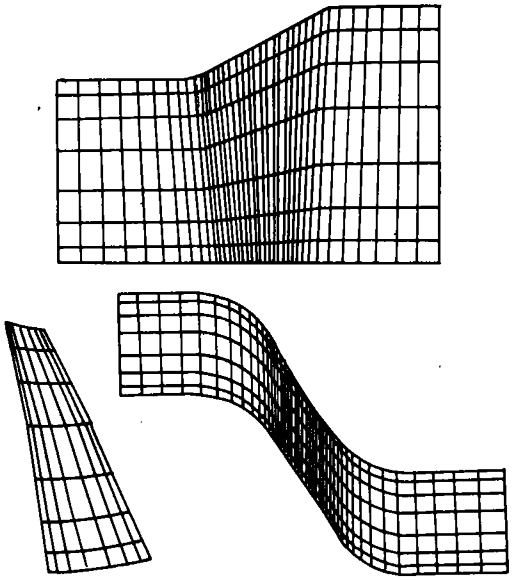

图 2　计算网格

3　数值求解方法

方程采用时间分裂 Mac Cormack 显式两步格式求解，它具有时间和空间的两阶精度，差分方程如下。

$$U_{i,j,k}^{n+1} = L_Q(\triangle t)L_r(\triangle t)L_Z(\triangle t)U_{i,j,k}^{n}$$

其中：L_Q；L_r；L_Z 分别是周向 Q；径向 r；轴向 Z 的一维算子。

各算子分别是：

对算子 $L_Z(\triangle t)$

$$\overline{U_{i,j,k}^{n+1}} = U_{i,j,k}^{n} - (H_{i,j,k}^{n}S_2 + H_{i,j,k-1}^{n}S_1) \times \triangle t/\triangle V_{i,j,k} - A_Z K_{i,j,k}^{n+1}\triangle t$$

$$U_{i,j,k}^{n+1} = 0.5[U_{i,j,k}^{n} + \overline{U_{i,j,k}^{n+1}} - (H_{i,j,k+1}^{n}S_2 + H_{i,j,k}^{n+1}S_1)\triangle t/\triangle V_{i,j,k} - A_Z K_{i,j,k}^{n+1}\triangle t]$$

对算子 $L_r(\triangle t)$

$$\overline{U_{i,j,k}^{n+1}} = U_{i,j,k}^{n} - (H_{i,j,k}^{n}S_4 + H_{i,j-1,k}^{n}S_3) \times \triangle t/\triangle V_{i,j,k} - A_r K_{i,j,k}^{n+1}\triangle t$$

$$U_{i,j,k}^{n+1} = 0.5[U_{i,j,k}^{n} + \overline{U_{i,j,k}^{n+1}} - (H_{i,j,k+1}^{n}S_4 + H_{i,j,k}^{n}S_3)\triangle t/\triangle V_{i,j,k} - A_r K_{i,j,k}^{n+1}\triangle t]$$

对算子 $L_Q(\triangle t)$

$$\overline{U^{n+1}_{i,j,k}} = U^{n}_{i,j,k} - (H^{n}_{i,j,k}S_6 + H^{n}_{i-1,j,k}S_5) \times \Delta t/\Delta V_{i,j,k} - A_Q K^{n+1}_{i,j,k}\Delta t$$

$$U^{n+1}_{i,j,k} = 0.5[U^{n}_{i,j,k} + \overline{U^{n+1}_{i,j,k}} - (H^{n}_{i+1,j,k}S_6 + H^{n}_{i,j,k}S_5)\Delta t/\Delta V_{i,j,k} - A_Q K^{n+1}_{i,j,k}\Delta t]$$

其中：$A_Z = [0,0,0,0,0]$；$A_r = [0,0,1,0,0]$；$A_Q = [0,1,0,0,0]$；S_1、S_2、S_3、S_4、S_5、S_6 是控制体六个表面的表面积。

为了消除三个一维算子计算三维问题时计算顺序的影响，保证格式具有二阶精度，所以采用时间分裂格式由 U^n 计算 U^{n+2} 时，应将计算顺序颠倒，即：

$$U^{n+2}_{i,j,k} = L_Q(\Delta t)L_r(\Delta t)L_Z(\Delta t)L_Z(\Delta t) L_r(\Delta t)L_Q(\Delta t)U^{n}_{i,j,k}$$

本文采用线性人工粘性项，即对于(i,j,k)点上的参数以该点及其相邻六点的参数值作加权平均来引入数值阻尼。

计算 $L_Z(\Delta t)$ 时

$$U_{i,j,k} = (U_{i,j,k+1} + U_{i,j,k-1} + \psi_Z U_{i,j,k})/(\psi_Z + 2)$$

计算 $L_r(\Delta t)$ 时

$$U_{i,j,k} = (U_{i,j+1,k} + U_{i,j-1,k} + \psi_r U_{i,j,k})/(\psi_r + 2)$$

计算 $L_Q(\Delta t)$ 时

$$U_{i,j,k} = (U_{i+1,j,k} + U_{i-1,j,k} + \psi_Q U_{i,j,k})/(\psi_Q + 2)$$

式中：$U_{i,j,k}$ 是经过人工粘性项修正后的气流参数，ψ_Z、ψ_r、ψ_Q 为人工阻尼系数，改变其大小即可改变人工粘性的大小。计算中可先取较小的 ψ 值，待流场收敛到一定程度时增大 ψ 值，这样可得到较理想的计算结果。实际计算中，在保证 CFL 的条件下，各算子的 ψ 值可以采用不同的值，以加快求解速度。

边界条件是：进口边界给定 ρ^*，T^*，气流方向角，其它条件由特征条件决定。出口边界给定一点的静压，由径向平衡方程确定其它半径处的压力，速度和密度的一阶导数为零。在物面边界上气流速度与物面相切。周期边界上气流参数满足周期条件。

4 计算结果及分析

用上述计算方法编制了计算机程序，这里给出两个计算实例。

对于收敛通道中大弯度静子叶栅，数据见文献[3]。计算网格取(41 × 11 × 11)，来流 $M = 0.3728$。图 3 绘出的叶根(3a)，叶中(3b)及叶尖(3c)三个截面上叶片表面等熵马

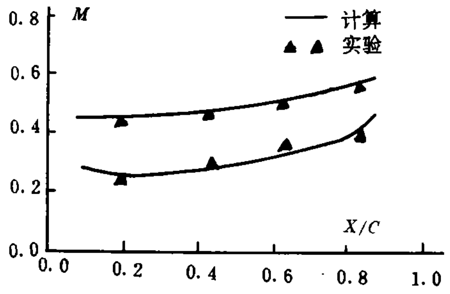

图 3a 叶片根部表面马赫数分布

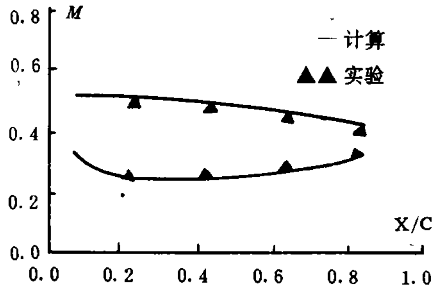

图 3b 叶片中部表面马赫数分布

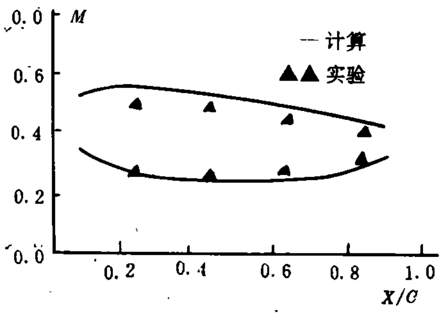

图 3c 叶片尖部表面马赫数分布

赫数的数值计算结果与实验结果吻合较好，说明计算结果是可信的。本文还对一跨音涡轮进行了验算，叶型数据和实验结果取自文献〔2〕。计算网格为(49 × 11 × 11)，图 4 是计算结果与实验结果的比较，从叶根图 4*a*，叶中图 4*b* 和叶尖图 4*c* 三个截面上的无量纲速度分布可以看到，本文的数值计算是成功的。

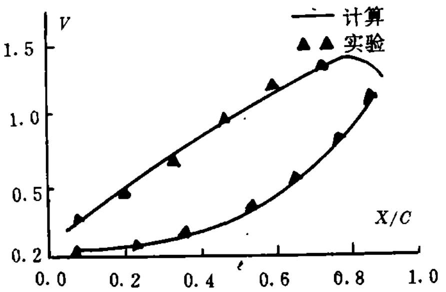

图 4*a*　叶片根部表面速度分布

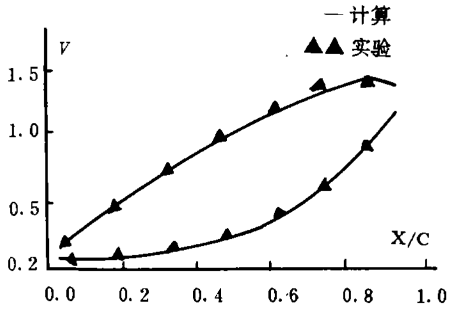

图 4*b*　叶片中部表面速度分布

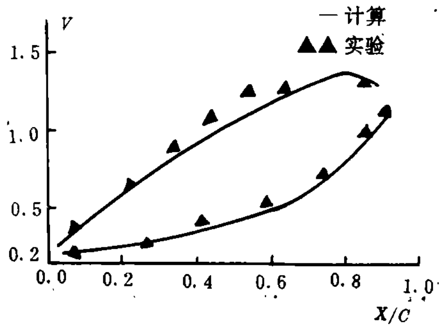

图 4*c*　叶片尖部表面速度分布

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煤粉锅炉炉膛的计算

据"Теплоэнергетика"1993 年 9 月号报道，俄罗斯中央锅炉透平研究所科学生产联合体(НПОЦКТИ)制定了利用零——一维计算模型的炉膛过程计算方法。与标准的方法不同，此方法可计算烧尽、烟气的温度和成分、沿燃烧室高度的热流以及硫的排放量。计算例子表明了利用零——一维计算模型能合理地估算各个结构和状态参数对炉膛燃烧过程的影响，计算具有足够的精度。指出，上述计算方法既能用于新锅炉的设计，也能用于锅炉的改造和换算到其它牌号燃料的燃烧。锅炉运行时应用此方法是特别有效的，它允许有效地对锅炉工况中某种变化的后果进行预先的估计。

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ratio. **Key words**: *circulating fluidized bed, combustion efficiency, circulation ratio*

(215)**Selection and Application of S-type Fan Pulverizing Mills**······ Cheng Qinggang (*Harbin Electric Power plant Equipment Design Institute*)

It is well-known that the main factors influencing the performance parameters of fan pulverizing mills include coal quality characteristics, fan mill construction features and operating mode. In selecting traditional fan mills correction factors, such as coal grindability, coal fineness and raw coal moisture content, are taken into account to determine the performance parameters of the fan mills. Practice has shown that such a selection method is not proper and lacks versatility. Trial grinding of coal types constitutes a relatively reliable method for the selection of fan mills and the design of coal pulverizing systems. The present paper deals with a $s_{02.300}$ fan mill testing system set up on the basis of flow and geometry-similar theory, Through. the experimental verification of Zhalenor and Houlinghe mine lignites the relevant parameters of trial grinding have been implanted into a heavy-duty fan mill selection design, thus providing design institutes with a reliable basis for the rational selection of fan mills and related pulverization systems. **Key words**: *fan pulverizing mill, trial grinding, type selection, application*

(221)**A study on Louvered pulverized Coal Concentrator Resistance Characteristics**······Xing Chunli, Sun Shaozeng, Wu shaohua, Sun Enzhao, Qin Yukun (*Harbin Institute of Technology*)

With the use of a horizontal concentration pulverized coal burner it is possible to effect a simultaneous realization of highly efficient burning of pulverized coal, prevention of slagging, stable combustion and low NO_x emissions. A novel type of inertia-based concentrator of pulverized coal, the louvered concentrator plays a key role in attaining the combustion of horizontal concentrated pulverized coal. Its successful application necessitates the study of the following four issues: resistance characteristics, the distribution of air flow and pressure, concentration characteristics and wear-resisting properties. This paper focuses on the investigation of the effect of structural parameters on concentrator resistance loss. The test results show that with the increase on the number of louvered concentration grid units and their clearance and the increase in concentration grid inclination the resistance loss of the louvered concentrator tends to decrease. **Key words**: *pulverized coal combustion, louvered concentrator, classification*

(226)**The Mechanism and Solution Metods of Boiler Tube Failure**······ Xu Lijun(*Hua Dong Institute of Technology*), Qu Guobin (*Harbin boiler works*), Liu Daoping(*China Mineral University*)

This paper has analyzed the leading mechanism of boiler tube failures and proposed prevention methods and solution methods of boiler tube failures. **Key words**: *utility boiler, boiler tube failure*

(230)**Mumerical Calculation of Three-dimensional Flow Fields in Turbomachine Blade Rows**······ Du Zhaohui, Weng Peifen, Zhong Fangyuan (*Shanghai Jiaotong University*)

With the help of a time dependent finite volume method the authors have worked out a computer program of the calculation of three-dimensional non-viscous flow field in turbomachine blade rows. The actual calculation results demonstrate the stability of the numerical calculation of the said method, high convergent speed and relatively good agreement with experimental data, fully attesting to the fact that the recommended method is an effective and analytical one suited to engineering applications. **Key words**: *time-dependent*, *numerical calculation*, *turbomachine*, *three-dimensional flow field*

(234) **Some Technical Issues Related to the Land-based Testing of a 4400 kW Gas Turbine Power Plant** ……Xiao Lide (*Harbin Marine Boiler & Turbine Research Institute*)

The author describes three technical issues encountered during the land-based testing of a 4400 kW gas turbine power plant: engine low-frequency vibrations, power turbine overspeed and engine-borne noise. Some observations on the analysis and solution of the above-cited issues are given and related conclusions presented. **Key words**: *gas turbine*, *vibration*, *overspeed*, *noise*

(237) **Automatic Control System for a 130 t/h Gangue-fired Fluidized Bed boiler**…… Fan Bening (*Computer Application and Development Research Centre of Hei Long Jiang Province*)

The control functions of a microcomputer-based control system for a 130 t/h fluidized bed boiler is described. Presented are the configuration approach applicable to fluidized bed combustion control, provision of indications in case of interruption of coal feeding and measures to cope with unfavorable effect of coal quality fluctuations on control quality. The said control system has been put into commercial operation with satisfactory results. **Key words**: *fluidized bed boiler*, *automatic control system*, *system structure*, *gangue*

(241) **The Design of a Drum Boiler Single-element Feedwater Regulator with compensation of Non-minimum Phase Characteristics**…… Yu Daren, Yang Yongbin (*Harbin Institute of Technology*)

When a steaming economizer is used there will emerge in the boiler drum water level control system a relatively serious phenomenon of indicating a false water level in the case of a sudden increase in feedwater flow rate. In terms of control model this exhibits itself as a non-minimum phase system of control system, resulting in a deterioration of control quality. To overcome this defect, the authors have come up with a design method with compensation of non-minimum phase characteristics to enhance the drum water level regulation qulaity. The said method features a simplified principle and easily lends itself to the realization of simulation results, thus attaining a good control effectiveness. **Key words**: non-minimum phase Characteristics, regulation, Smith Pre-evaluator, boiler drum level, classification

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