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# 突扩管中受限射流的计算方法研究

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突扩型燃烧室的结构简单可靠，近年来已引起广泛注意。为了计算时均流场和湍动流场，必须考虑迴流区及附面层全方位的压力梯度，给计算方法带来困难。

本文由时均的N—S方程和K—$\varepsilon$湍流模型出发，将Patankar[1]解耦技术推广到可压缩流，采用牛顿迭代法和稀疏矩阵技术，由连续和动量方程直接求解压力和速度场，继而获得温度、湍能和密度场。算例表明，计算结果与实验比较符合，可供实际计算使用。

对于定常轴对称湍流流动，若以受限壁半径R、射流入口对称轴处速度$U_o$、密度$\rho_o$、温度$T_o$为特征量，无因次主管方程可写为下式：

$$[\partial(\bar{\rho}\bar{u}\bar{r}\varphi)/\partial\bar{x}+\partial(\bar{\rho}\bar{v}\bar{r}\varphi)/\partial\bar{r}-\partial(\bar{r}\Gamma_\phi\partial\varphi/\partial\bar{x})/\partial\bar{x}-\partial(r\Gamma_\phi\partial\varphi/\partial\bar{r})/\partial\bar{r}]/\bar{r}=S_\phi$$

式中$\varphi$、$\Gamma\varphi$和$S\phi$除连续方程中分别为1，0，0外其余列入下表

| 方　程 | $\varphi$ | $\Gamma\varphi$ | $S\varphi$ |
|---|---|---|---|
| $\chi$动量 | $\bar{U}$ | $\bar{\mu}_e$ | $-\partial\bar{p}/\partial\bar{x}+\partial(\bar{\mu}_e\partial\bar{U}/\partial x)/\partial\bar{x}+\partial(\bar{r}\bar{\mu}_e\partial\bar{V}/\partial\bar{x})/\bar{r}\partial\bar{r}$ |
| $\gamma$动量 | $\bar{V}$ | $\bar{\mu}_e$ | $-\partial\bar{p}/\partial x-2\bar{\mu}_e\bar{V}/\bar{r}^2+\partial(\mu_e\partial\bar{U}/\partial\bar{r})/\partial\bar{x}+\partial(\bar{r}\bar{\mu}_e\partial\bar{V}/\partial\bar{r})/r\partial\bar{r}$ |
| 能　量 | $\bar{C}p\bar{T}$ | $\bar{\mu}_e/\sigma_T$ | $(r^2-1)M_o^2\{-\bar{p}(\partial\bar{r}\bar{V}/\bar{r}\partial\bar{r}+\partial\bar{U}/\partial x+2\mu_e[(\partial\bar{U}/\partial\dot{x})^2+(\partial\bar{V}/\partial\bar{r})^2+(\bar{V}/\bar{r})^2]+\bar{\mu}_e(\partial\bar{U}/\partial\bar{r}+\partial\bar{V}/\partial\bar{x})^2\}$ |
| 湍动能 | $\bar{K}$ | $\bar{\mu}_e/\sigma_k$ | $\bar{G}-C_D\bar{\rho}\bar{\varepsilon}$ |
| 湍能耗散 | $\bar{\varepsilon}$ | $\bar{\mu}_e/\sigma_\varepsilon$ | $(C_1\bar{\varepsilon}\bar{G}-C_2\bar{\rho}\bar{\varepsilon}^2)/\bar{K}$ |
| 状　态 | | | $\bar{p}=\rho\bar{T}/(\gamma M_o^2)$ |

表中：$\bar{\mu}e=C_u\bar{\rho}\bar{K}^2/\bar{\varepsilon}+\mu_I$，$\bar{G}=\bar{\mu}_e\{2[(\partial U/\partial\bar{x})^2+(\partial\bar{v}/\partial\bar{r})^2+(\bar{v}+\partial\bar{v}/\partial\bar{x}+\partial\bar{U}/\partial r)^2$参照二维平面情况，计算常数取为：$C\mu=0.09$，$CD=1.0$，$C1=1.44$，$C2=1.92$，$\sigma_T=0.9$，$\sigma_K=1.0$，$\sigma_\varepsilon=1.217$。

采用交错网格，基本方程离散为(图1)

$$a_p\varphi_p=\sum a_i\varphi_i+S\varphi r\Delta x\Delta r \qquad i=E,S,W,N$$

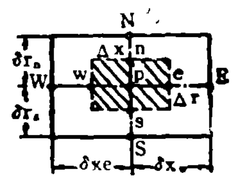


图1　节点P的控制体

式中：$a=DA(|P|)+[[\pm F,\ 0]]$；$F=\rho Ur\Delta r$或$\rho Vr\Delta x$；$D=\Gamma\varphi r\Delta r/\delta x$或$\Gamma\varphi r\Delta x/\delta r$；$P=F/D$。计算中，函数A选用指数形式。

本文假设为绝热壁，壁面边界条件为：$U=V=\varepsilon=K=0$，$\partial T/\partial r=0$。对称轴处边界条件为：$V=0$，$\partial\varphi/\partial r=0$。入口和出口条件可根据计算要求或实际情况设置。本文假定入口为均直流，出口气流沿轴向不再变化。用壁函数法计算近壁处参数。

**基本方法求解步骤**（1）预置各变量初值。（2）用混合长理论由连续和动量方程初步计算压力和速度场。（3）沿等X线由能量、湍能和状态方程逐步求温度、湍动能、湍能耗散率和密度场。（4）联立求解连续和动量方程，确定压力和速度场的新值。（5）重复（3）、（4）得收敛解。

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本文采用牛顿迭代法[2]和稀疏矩阵技术求解连续方程和动量方程，获得全流场各节点压力和速度的新值。例如，节点P处离散后X向动量方程为

$$f_P = a_P u_P - a_E u_E - a_W U_W - a_S u_S - a_N u_N - (p_E - p_P)\Delta r \cdot r_P = 0$$

根据牛顿迭代法，可写为下式，式中i代表第i次迭代；$\Delta u_P^i$、$\Delta u_E^i$……分别表示各变量第i次迭代修正值。对N个节点，可得3N个线性代数方程，联立求解可得修正值。

$$\frac{\partial f^i}{\partial u_P}\Delta U_P^i + \frac{\partial f^i}{\partial u_E}\Delta U_E^i + \frac{\partial f^i}{\partial u_W}\Delta U_W^i + \frac{\partial f^i}{\partial u_S}\Delta U_S^i + \frac{\partial f^i}{\partial u_N}\Delta U_N^i + \frac{\partial f^i}{\partial v_P}\Delta V_P^i$$

$$+ \frac{\partial f^i}{\partial v_N}\Delta V_N^i + \frac{\partial f^i}{\partial p_P}\Delta P_P^i + \frac{\partial f^i}{\partial p_W}\Delta P_W^i = -f_P^i$$

**结果与讨论**用本方法计算了不同结构形式受限射流突然膨胀后的流动特性。图 2 ～ 4 为单股射流突然膨胀的计算结果，受限壁与射流直径比为 1∶0.52。由图 2 可见管壁突然扩张，

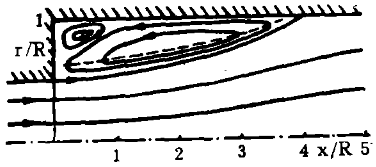


图 2　单股射流流线

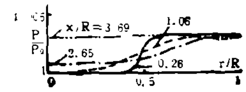


图 3　单股射流压力分布

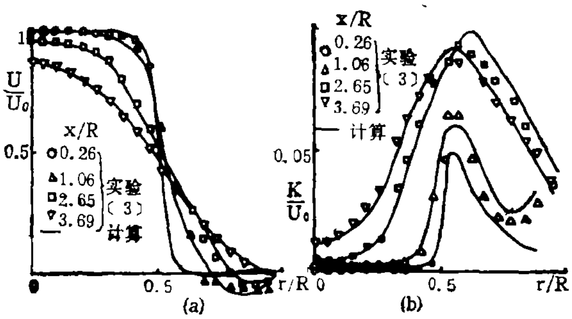


图 4　单股射流轴向速度分布(a)和湍动能分布(b)

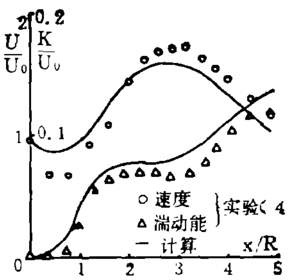


图 5　同轴射流速度、湍动能分布

在入口附近形成回流区，并在管角处产生二次回流。沿流动迴流区逐渐缩小，约在X/R = 4处迴流区消失。由图 3 和 4 可见计算值与实验比较符合，能较好地反映射流扩展过程及突扩管处的迴流特点。图 4 a、d对照，在速度剧烈变化时，湍动能较大，计算能较好地反映湍动能的变化。

图 5 的射流入口速度比为3.0，受限壁与同轴射流直径比为1∶0.36∶0.13。理论计算能较好地反映射流之间相互交混及管壁突扩处的迴流特性。

计算表明，采用40×20个网格，迭代15次后可得满意的收敛结果，所需机时约300秒（Vax机CPU）。如果考虑不同浓度气体混合情况，本方法可用于确定气体混合过程的浓度分布。

## 参 考 文 献

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measurements of their wakes. The variation laws and relationship of these characteristics are analyzed. In our test conditions, the cascade with better forward flow characteristic has worse reversed one.

# ABSTRACTS OF TECHNICAL NOTES

## A COMPUTATION METHOD FOR A CONFINED JET IN SUDDEN EXPANSION DUCT

**Bao Guohua and Jiang Zhenxin**

*(Northwestern Polytechnical University)*

A confined turbulent flow in a sudden expansion duct is computed by a numerical method of time-averaged Navier-Stokes equations with k-$\varepsilon$ model. The pressure and velocity are obtained by using Newton's method and sparse matrix techniques. The numerical examples show that the computation results are in satisfactory agrefement with the experimental data.

## A METHOD FOR CONFIGURATION OF ANNULAR DIFFUSER

**Li Changlin** *(Northwestern Polytechnical University)*

A new method for calculation of annular diffuser configuration is offered, which takes pressure loss and perpendicularity of air-through section to the center airflow-line into consideration. When there exists large declination of center flow-lines at inlet and exit, this method is more reasonable than the conventional one which ignores these two factors.

## INVESTIGATION ON SIMULATION OF FOREIGN OBJECT IMPACT DAMAGE TO COMPRESSOR BLADE

**Sun Zhende** *(Naval Aeronautical Engineering Institute)*

**Lu Qixin** *(Nanjing Aeronautical Institute)*

An experimental method for simulation of foreign object impact damage to a compressor blade is investigated. The impact damage mechanism is analyzed by the aid of a scanning electron microscope. A reasonable experimental method is proposed by comparing the bullet damage with the pendulum impact damage.