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燃烧室特性的数值研究

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一、基本方程和物理模型

本计算中来流为完全发展的紊流均匀可燃混气(煤油＋空气)。对于图 1 所示二元紊流燃烧流场,用按Favre平均后的基本方程的通式:

$$\frac{\partial}{\partial X_j}\bar{\rho}\tilde{u}_i\tilde{\phi})=\frac{\partial}{\partial X_j}\left(\Gamma_{\phi eff}\cdot\frac{\partial\tilde{\phi}}{\partial X_j}\right)+\tilde{S}_{\phi} \quad (j=1,\ 2) \qquad (1)$$

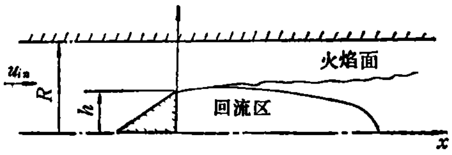

图 1　计算对象示意图(R＝0.1m, h＝0.05m)

式中ϕ分别代表速度u、v,总焓h,紊流动能k,紊流动能耗散率ε,燃料成分脉动均方值g,辐射通量R_x、R_y。$\Gamma_{\phi eff}$为有效紊流输运系数,源项$\tilde{S}_{\phi}$的表达式见表1。

表 1　源 项 $\tilde{S}\phi$ 表 达 式

Φ	$\Gamma_{\phi,eff}$	$\tilde{S}\phi$
$\tilde{U}_j$	μ_{eff}	$-\frac{\partial\bar{p}}{\partial x_j}+\frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\partial\tilde{u}_j}{\partial x_i}\right)-\frac{2}{3}\left(\bar{\rho}k+\mu_{eff}\frac{\partial\tilde{u}_k}{\partial x_k}\right)\delta_{ij}\right]$
$\tilde{h}$	μ_{eff}/σ_h	$\tilde{U}_j\frac{\partial}{\partial x_j}\left[-\frac{2}{3}\left(\bar{\rho}k+\mu_{eff}\frac{\partial\tilde{u}_k}{\partial x_k}\right)\right]-\frac{2}{3}\bar{\rho}k\frac{\partial\tilde{u}_k}{\partial x_k}+\tilde{S}_h$
k	μ_{eff}/σ_R	$-\bar{\rho}\widetilde{U_i''U_j''}\frac{\partial\tilde{u}_i}{\partial x_j}-\frac{\mu_t}{\bar{\rho}^2\sigma_t}\frac{\partial\bar{\rho}}{\partial x_i}\frac{\partial\bar{\rho}}{\partial x_i}-\bar{\rho}_{\varepsilon}$
ε	$\mu_{eff}/\sigma_{\varepsilon}$	$-C_1\frac{\varepsilon}{k}\left(\bar{\rho}\widetilde{U_i''U_j''}\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\mu_t}{\bar{\rho}^2\sigma_t}\frac{\partial\bar{\rho}}{\partial x_i}\frac{\partial\bar{\rho}}{\partial x_j}\right)-C_2\frac{\bar{\rho}\varepsilon^2}{k}$
$\widetilde{m+u}$	μ_{eff}/σ_{fu}	$-\tilde{R}_{fu}$
g	μ_{eff}/σ_g	$Cg_1\ Gg_1-Cg_2\bar{\rho}\varepsilon/kg$
Rx	$1/(a+s)$	$a(\sigma T^4-Rx)+S(Ry-Rx)/2$
Ry	$y/(a+s+1/y)$	$[a(\sigma T^4-Ry)+S(Rx-Ry)]y/2$

表 1 中$\mu_{eff}=\mu_t+\mu_u$,μ_{eff}为有效紊流粘性系数,μ_t为紊流粘性系数,由 k-ε 双方程紊流模型

$$\mu_t=C_{\mu}\cdot\bar{\rho}k^2/\varepsilon \qquad (2)$$

其中紊流模型常数$C_{\mu}=0.09$,$C_1=1.44$,$C_2=1.73$[1]$\sigma_t=0.9$,$\sigma_k=1.0$,$\sigma_{\varepsilon}=1.3$。

本文采用了Spalding提出的旋涡破碎模型[2],对混气

$$R_{fu,t}=-C_R\bar{\rho}g^{1/2}\varepsilon/k \qquad (3)$$

式中$g=\tilde{m}_{fu}^{\prime 2}$由输运方程求得。源项中常数$C_{g1}=2.8$,$C_{g2}=2.0$,$C_R=5$,$\sigma_g=0.7$,$G_{g1}=\mu_{eff}(\partial\bar{m}_{fu}/\partial X_j)$。

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上述模型没有考虑温度对燃烧速率R_{fu}的影响、为此引入了Arhenius公式：

$$\widetilde{R}_{ft,A} = -0.5\bar{\rho}^2 m_{fu} m_{ox} \exp(-E/RT) \quad (4)$$

$$\widetilde{R}_{fu} = -M_{in}(|\widetilde{R}_{fu,A}|, |\widetilde{R}_{fu,t}|) \quad (5)$$

表1 $\widetilde{S}_h = 2a(R_x + R_y - 2\sigma T^4)$ a和s为单位长度介质的吸收率和散射系数； $a = 0.2m_{fu} + 0.1m_{pr}$；取$S = 0.01$；$R_x$、$R_y$为x、y向的辐射通量，用热通量法辐射模型求解。

二、边界条件和计算方法

本文的气流流动属椭圆形，需要规定四周的边界条件。进口截面来流假定为已完全发展的紊流，气流参数均布，即$V_{in} = 0.0$，u_{in}，$m_{fu,in} = \text{Const}$，$k_{in} = 0.02u_{in}^2$，$\varepsilon_{in} = k^{3/2}/(0.03R)$，$g_{in} = 0.01m_{fu}^2$。在燃烧室出口截面上取$\partial\widetilde{\phi}/\partial x = 0.0$，中心轴线上取$\partial\widetilde{\phi}/\partial y = 0.0$，在固体壁面上取气流速度和紊流参数为零，对近壁面网格点采用壁面函数处理，稳定器斜壁面用台阶法处理。对控制方程组采用混合差分格式离散化，根据流场的初步分析，对计算域配置非均匀网格，结点数为39×26，运用SIMPLE法迭代求解。为了考虑辐射对效率的影响，本文采用了在相同油气比下，实际温升与理论温升之比的燃烧效率定义对效率进行计算。

本文用数值分析稳态流场研究非稳态的熄火特性。首先在火焰稳定器壁面设置点火边界，即假设稳定器后缘壁面和附近网格点的温度为绝热火焰温度，燃料成分$m_{fu} = 0.0$。计算表明：若条件合适，油气比恰当，这点火源能使整个流场燃烧，火焰扩张，形成稳定的燃烧流场，即使去掉这点火源，仍能保持稳定燃烧。但贫油到一定程度，只要把点火源撤除，已出现的燃烧流场将逐渐消失，反应流成为冷态流，可认为此时火焰很接近吹熄。因此，通过数值计算逐步将均匀混气的油气比从恰当比算到贫油，求出贫油熄火极限。

三、计算结果及讨论

1. **燃烧效率** 由图2可知燃烧效率随进口速度增加而逐渐下降；随进口温度提高，燃烧效率增加。并在相同进口条件下，锥形稳定器燃烧室的燃烧效率高于圆盘稳定器燃烧室的燃烧效率，这些规律与实验现象一致。图3给出燃烧效率随着余气系数逐渐接近于1而逐渐增加达到最大值。图4为计算所得，可见随着长度增加，燃烧逐渐完全，效率不断提高。

2. **熄火极限** 本文对堵塞比为30%的锥形稳定器进行了贫油熄火极限计算，依次计算了$\alpha = 1.1$，1.33、1.54和1.67。撤消了点火源后，在前三个α情况下仍能自行维持稳定燃烧。但当$\alpha = 1.67$时，燃烧流场逐渐消失，转变为熄火的冷态流场。由图5可知，随着α增大，温度和燃烧效率不断下降。当$\alpha > 1.6$时燃烧效率为零。由此可推断熄火极限在$\alpha = 1.54$和1.67之间，近似取为1.6，这与文献[3]实验数据$\alpha = 1.56$基本相符。

3. **回流区尺寸** 图6计算结果表明，锥形稳定器在$T_{in} = 600\text{K}$，$\alpha = 1.25$时，回流区长度随来流速度增加而加长，这与文献[4]用圆盘稳定器所得的实验变化趋势一致，由图7可知，随余气系数加大回流区长度也增加，这个变化规律与文献[5]上实验规律相符。

由以上结果可得以下结论：

1. 计算所得贫油熄火极限和燃烧效率、回流区尺寸等随进口参数（速度、温度、余气系数）的变化规律与实验规律基本相符，从而说明本计算方法合理，选用的模型是可行的。

2. 回流区尺寸计算值偏小主要来自紊流模型，吹熄极限的近似性来自于燃烧模型及稳定流处理方法。研究的深入有待于模型改进及进行非稳态流处理。

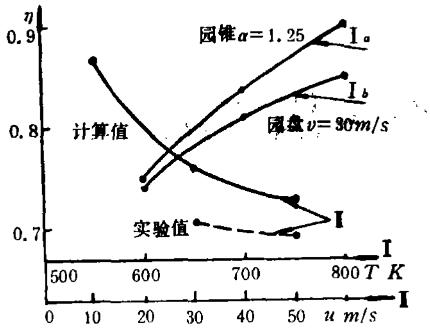

图 2　速度、温度对燃烧效率的影响（α=1.25　I：u_{in}=30m/s　Ia为圆锥，Ib为圆盘；II　T_{in}=600K，圆盘）

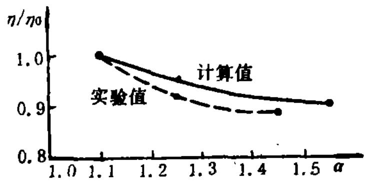

图 3　余气系数对燃烧效率的影响（锥形，η_0=0.753，T_{in}=600K，u_{in}=30m/s）

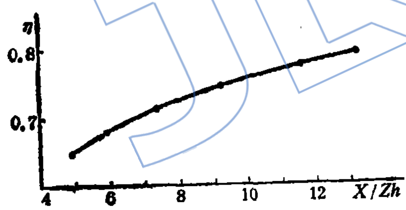

图 4　燃烧效率随回流区长度的变化（锥形，α=1.25，T_{in}=600K，u_{in}=30m/s）

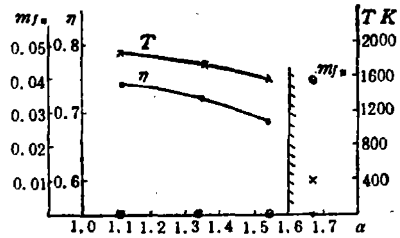

图 5　燃烧效率和温度随α的变化（T为进口温度，m_{fu}为$m_{fu,in}$）

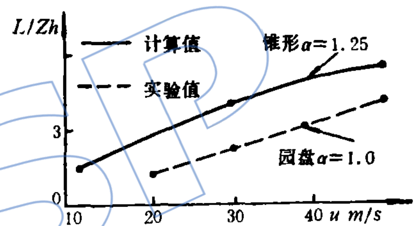

图 6　回流区长度随速度变化

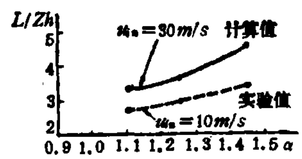

图 7　回流区长度随余气系数的变化（锥形，T_{in}=600K）

参 考 文 献

〔1〕 Zeng, C.F, Zhao, J.X., "A Preliminary Calculation of the Combustion Recirculating Flow Behind Flame-Holders", Beijing International Gas Turbine Symposium and Exposition, 85-IGT-29, 1985.

〔2〕 Spalding, D.B., "Mixing and Chemical Reaction in Steady Confined Turbulent Flames", 13th Symposium (Int) on Combustion, 1971.

〔3〕 洪岩，"燃烧室钝体火焰稳定器吹熄特性研究"，南京航空学院硕士论文，1985。

〔4〕 Winterfeld G., "On Processes of Turbulent Exchange Behind Flame Holders", Tenth Symposium (Int) on Combustion, 1965.

〔5〕 Fujii, S. et al, "A Comparison of Cold and Reacting Flows Around a Bluff-Body Flame Stabilizer", ASME J.Fluids Engineering Vol.103, June 1981.

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DYNAMIC DISTORTION IN FLOWFIELD DOWNSTREAM OF TRANSONIC SHOCK-BOUNDARY LAYER INTERACTION

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Abstract

The dynamic distortions in flowfield under transonic shock-turbulent boundary layer interaction of different intensity are investigated in a 2-D convergent-divergent duct. The power spectrum and probability density functions of the total pressure signals are analyzed. The control technique of this dynamic distortion is also presented.

REGULATION OF DISTORTION FLOWFIELD BY AXISYMMETRIC TURBULENCE GENERATORS

Shi Wangxing

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Abstract

This paper provides a regulation law for distortion flowfield by axisymmetric turbulence generators, which can meet the demands for simulating the static and dynamic inlet distortions simultaneously. The distortion flowfield is regulated by variation of throat area ratio and working pressure ratio. The experiments show that the absolute deviation of the turbulence regulated by this law is less than 0.01.

NUMERICAL STUDY OF CHARACTERISTICS OF BURNER

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Abstract

The combustion efficiency and blowoff characteristics of burner with bluff-body flame holders are investigated with both numerical and experimental methods. The k-ε turbulence model is employed to describe the turbulent viscosity and the EBU. Arrhenius combustion model is adopted to determine the reaction rate. The radiation model of heat flux method is used to predict heat radiation flux. Because of the large variation of density in combustion flowfield, the density-weighted average variables have been adopted in conservation equation. The com-

parison of numerical results with experimental data indicates that the numerical method presented is generally feasible.

A NEW APPROACH TO IMPROVEMENT OF FANS

Su Hanshou

(Beijing Institute of Aeronautics and Astronautics)

Abstract

This paper presents experimental results of 3-D flowfields in the fan tip region for two actual fans. It is shown that the fan performance can be significantly improved as proplets are attached to the blade tips. The improving mechanism have been studied and can be stated as follows: The proplets retain the tip vortex and thus the tip induced loss is reduced remarkably, and the additional propulsion moment is gained because the proplets partly balance the drag moment due to profile loss in the tip section. The conclusions presented in this paper may be applied to the tip section of propeller or helicopter rotor for performance improvement.

APPLICATION OF UNSTEADY FLOW REFRIGERATION TO RECORVERY OF PETROLEUM GAS

Shen Zhenhua

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Abstract

The refrigeration principle of "thermal separator" is analyzed in light of unsteady flow dynamics and a simplified physical model is presented to improve the refrigeration efficiency. The analytical study shows that it is necessary to control the pressure ratio P_4/P_1 properly and to match the length of working pipes with the size and revolution speed of the unit in order to increase its efficiency. The unit may be used for recovery of petroleum gas, cold storage and central airconditioning.

APPLICATION OF DAMAGE RULES TO TIME-DEPENDENT FATIGUE LIFE PREDICTION

Dong Zhaoqin, Duan Zuoxiang, He Jinrui

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Abstract

Linear Damage Rule (LDR) and Interaction Damage Rule (IDR) are compared and applied to Strain Range Partitioning(SRP) and Strain Energy Partitioning(AEP)