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燃烧流场初场赋值的催化边界数学模拟法

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在用有限差分迭代求解的数值方法中，最突出的困难之一是流场初场赋值，特别是温度初场赋值。初场猜测的好坏直接影响方程组收敛解是否存在和收敛性好坏。本文提出了一种初场赋值的催化边界数学模拟法，克服了初场猜测的盲目性。

一、理论分析

本文建议在稳态燃烧流场的点火源附近、或在点火装置停止工作后起点火作用的回流区设置催化边界，通过数值求解来建立初场。代替过去凭经验估计的方法。在催化边界面上按完全燃烧处理（对贫油混气，可赋值$m_{fu}=0$）。这样，由于未引入外能源，基本方程并不改变，而催化边界的存在却起着强制着火的作用，从而可以在冷态初场基础上建立稳态燃烧流场。这种设置催化边界的燃烧流场控制方程组的迭代求解过程，实际上就是物理点火过程的近似数学模拟。当然，设置催化边界后的微分方程组的解不能代表稳态燃烧流场的真实解（方程相同，但边界条件不同），而只能作为初场赋值依据，必须在此初场基础上，按实际控制方程组的边界条件，才能求得稳态燃烧流场数值解。

二、算　　例

本文对图1所示燃烧流场进行数值计算。来流为化学恰当比下的丙烷和空气的均匀予混可燃气（$U_{in}=40m/s$，$U_{in}=0$，$T_{in}=600K$，$K_{in}=0.025U_{in}^2$，$\varepsilon_{in}=K_{in}^{3/2}/0.03H$），数值计算中控制微分方程组见表1，数值求解采用SIMPLE算法[1]，催化边界设在钝体后缘面BC。计算表明，无论采用紊流燃烧模型Ⅰ或紊流燃烧模型Ⅱ，经过50次至100次迭代求解，

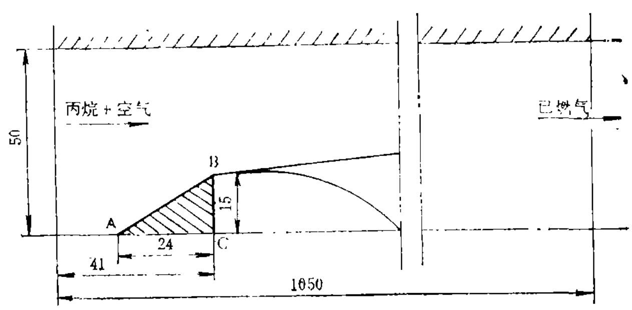

图1　二元可燃混气在带钝体火焰稳定器的有界管流中流动

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就能求得可用初值。最后撤消催化边界，继续迭代，即可求得指定精度的稳态燃烧流场数值解。

三、讨　　论

1．本文方法是一种具有普遍意义的方法，克服了初场经验赋值的盲目性。而燃烧流场初值求解过程可以从冷态流场出发（例如整个初场可按来流压力、温度、流速均匀赋值），因此便于推广和掌握。

2．用本方法确定燃烧流场初值的过程，实际上是物理点火过程的近似数学模拟，所以它提供的初场与稳态燃烧流场的真实解比较接近，加快了方程求解收敛速度。初场求解精度越高，初场与流场数值解越接近。因此，对初场求解精度的选取无严格要求。由于初场求解精度提高而带来的CPU时间增加，可以从方程组自身求解收敛速度加快中得到补偿。

3．当燃烧效率较高时，回流区基本上已完全燃烧，催化边界的引入并不严重歪曲物理现实。因此，提高初场求解精度，可以把初场求解结果作为数值计算的近似解处理，如图 2 所示（迭代精度都是$\varepsilon=10^{-3}$，采用紊流燃烧模型 I 计算）。与之相反，当燃烧效率较低时，不管初场求解精度多高，初场都不能作为近似解处理。图 3 （$\varepsilon=10^{-3}$，用紊流燃烧模型 I 计算）用极端情况作为算例阐明了这一论断。

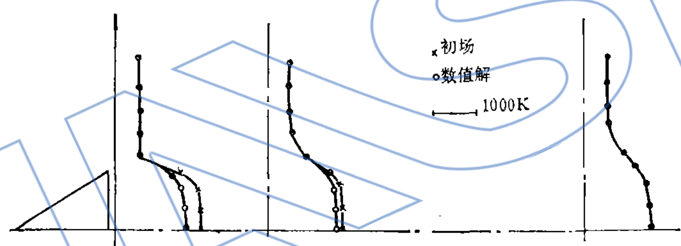

图 2　燃烧效率为100％时温度初场与数值解比较

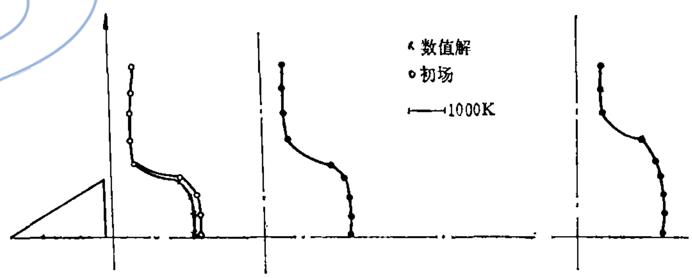

图 8　燃烧效率为85％时温度初场与数值解比较

4．本方法的导出有一定理论根据，并已为计算实践所证实。但是椭圆微分方程组有限差分迭代求解的收敛性、稳定性理论还不成熟[2]，因此它和椭圆微分方程组有限差分迭代求解中其他问题的处理原则和方法一样，其正确性和适用性是相对的。

所采用的基本方程的通用形式为

$$\frac{\partial(\rho u\phi)}{\partial x}+\frac{\partial(\rho v\phi)}{\partial y}=\frac{\partial}{\partial x}\left(\mu_{eff}/\sigma_{\phi}\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}/\sigma_{\phi}\frac{\partial\phi}{\partial y}\right)+S_{\phi}$$

式中U、V为速度，$\mu_{eff}=\mu_l+0.099k^2/\varepsilon$为有效粘性系数，$\mu_l$ 为层流粘性系数，$\rho=P/RT$为密度，k为紊流动能而ε为其耗散率[1]。

通用方程中ϕ的含义为内能E、燃料成份数m_{fu}、燃料成份数脉动时均值g，氧成份数脉动时均值g_{ox}、燃料与氧脉动相关量g_{fo}，其相应的σ_ϕ值均为0.9，而源项S_ϕ列表如下：

Φ　　　　S_ϕ

E

$$-P\nabla\cdot\vec{V}+G_k+\frac{\partial}{\partial x}\left[\mu_{eff}H_u\left(\frac{1}{\sigma_{fu}}-\frac{r}{\sigma_\varepsilon}\right)\frac{\partial m_{fu}}{\partial x}\right]+\frac{\partial}{\partial y}\left[\mu_{eff}H_u\left(\frac{1}{\sigma_{fu}}-\frac{r}{\sigma_\varepsilon}\right)\frac{\partial m_{fu}}{\partial y}\right]$$

m_{fu}　　R_{fu}

g

$$C_{g1}\mu_{eff}\left[\left(\frac{\partial m_{fu}}{\partial x}\right)^2+\left(\frac{\partial m_{fu}}{\partial y}\right)^2\right]-C_{g2}\rho\frac{\varepsilon}{k}g-2A_0\rho^2m_{fu}m_{0x}\exp\left(-\frac{E}{RT}\right)\left(\frac{g_{fo}}{m_{0x}}+\frac{g}{m_{fu}}\right)$$

g_{ox}

$$C_{g1}\mu_{eff}\left[\left(\frac{\partial m_{ox}}{\partial x}\right)^2+\left(\frac{\partial m_{ox}}{\partial y}\right)^2\right]-C_{g2}\rho\frac{\varepsilon}{k}g_{ox}-2A_0\rho^2m_{fu}m_{0x}\exp\left(-\frac{E}{RT}\right)\left(\frac{g_{fo}}{m_{fu}}+\frac{g_{ox}}{m_{ox}}\right)$$

g_{fo}

$$C_{g1}\mu_{eff}\left[\frac{\partial m_{fu}}{\partial x}\frac{\partial m_{ox}}{\partial x}+\frac{\partial m_{fu}}{\partial y}\frac{\partial m_{ox}}{\partial y}\right]-2.0\rho\frac{\varepsilon}{k}g_{fo}-A_0\rho^2m_{fu}m_{ox}\exp\left(-\frac{E}{RT}\right)\left[\frac{(m_{ox}+sm_{fu})g_{fo}}{m_{fu}m_{ox}}+\frac{sg}{m_{fu}}+\frac{g_{ox}}{m_{ox}}\right]$$

表中$H_u=4.0\times10^7J/(k_gK)$为燃料热值、 $g=\overline{m'^2_{fu}}$、 $g_{ox}=\overline{m'^2_{ox}}$、 $g_{fo}=\overline{m'_{fu}m'_{ox}}$、 $C_1=1.44$[3]、$C_2=2.0$[3]　$s=3.636$为化学恰当比，G_K为紊流动能产生率[1]。而燃料消耗率取决于燃烧模型：

紊流燃烧模型Ⅰ：$R_{fu}=-\min\{A\rho\varepsilon/km_{fu},\ FP^2m_{fu}m_{xo}\exp[-E/(RT)]\}$

式中　$A=5$、$F=0.5$　$E/R=1.84\times10^4K$

紊流燃烧模型Ⅱ[3]：$R_{fu}=-\min\{C_R\rho\varepsilon/kg^{1/2},\ FP^2m_{fu}m_{ox}\exp[-E/(RT)]\}$

式中$C_R=1.07$，$F=10^{10}$，$E/R=1.84\times10^4K$

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CONSTRUCTIONAL IMPROVEMENTS IN A TURBOPROP ENGINE

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Abstract

The principal constructional improvements in the reducer, compressor, combustor, turbine and bearings of a turboprop engine are summarized. Practice shows that the constructional improvements in the reducer and the turbine are of the most importance in prolonging the service life of this turboprop engine.

AN EXPERIMENTAL STUDY ON DISTRIBUTION OF COLD AND HOT AIRFLOWS IN COMBUSTOR

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Abstract

The flow distribution in an annular combustor at different Mach numbers and heating ratios was investigated experimentally. An empirical relationship for coordination between the cold and the hot flow distributions has been established with the aid of the least square method based on the experimental results. The data calculated are in good agreement with the test ones. Therefore, the aim of the study is realized that the empirical formula enables us to predict the combustor flow distribution at different Mach numbers and heating ratios according to the flow distribution at a given low Mach number with cold air flow.

AN APPROACH TO SPECIFY THE INITIAL CONDITIONS IN COMBUSTION FLOW BY SIMULATING A FICTITIOUS CATALYSTIC BOUNDARY

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Abstract

In numerical calculation of steady combustion flow field, the governing differential equations can be discretized with finite difference schemes and solved with iterative method. But their convergence solution can be attained only with good estimates of initial conditions. Instead of empirical estimate of the initial conditions, an approach to specify the initial conditions is presented, based on the mathematical simulation of the forced ignition. In the result, the initial conditions can be determined computationally by setting a catalytic boundary in the combustion zone.

RADIATION CORRECTION OF MEASURING TEMPERATURE IN COMBUSTOR

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Abstract

In tests of combustor heat loss arises from radiation in measuring temperature with a thermocouple. Therefore, it is necessary to make a correction for it. An approach to neglect some minor factors and to simplify some coefficients in the energy balance equation is recommended in this paper. A simplified calculation method is thus deduced for this correction. The temperatures corrected by this method quite agree with the temperatures calculated from gas analysis data.

A FORMULA FOR AVERAGE CONVECTIVE COEFFICIENT IN LAMINAR BOUNDARY LAYER OVER A PLATE WITH UNHEATED LEADING EDGE

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Abstract

A dimensionless expression for average convective coefficient in laminar boundary layer over a flat plate with unheated leading edge is derived. By approximate integration, it is transformed into the following formula:

$$\overline{Nu_L} = 0.664 Re_L^{1/2} Pr^{1/3} [1 - (x_0/L)^{3/4}]^{2/3}$$