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喷管碳基喉衬的烧蚀

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一、计算方法和结果

喷管材料的烧蚀主要是热和化学作用的结果。热量来自碳与燃气中的氧化元素之间的异相化学反应，以及对流和幅射传热。本文中的解析模型用来预测喷管温度分布及烧蚀率。在处理联结核心流及喷管壁面的边界层流动时，把传热传质数值作为壁内导热计算的输入数据。边界层的边界条件是由一维无粘定常流的解来确定的。在材料响应的分析中介入了幅射边界条件，在 UTC 数据[1]上引入了一个有效辐射系数。用有限元计算方法求解瞬态热传导方程来确定喷管壁内温度分布随时间的变化关系。

在实验工作的起始阶段使用了双基推进剂来验证温度场分布的解析模型。喷管喉部截面和沿着喷管的温度测量是用镍-铬/镍-硅热电偶来完成的。

1. **控制方程** 为了预测燃气环境中喷管材料的响应，对以下三方面进行了分析。

(1) **核心流场。** 利用一维等熵膨胀流动的计算来求解无粘位流流场[2]。温度 T_g、密度 ρ_g 和速度 u_g 等流动参数可通过标准的气体动力学关系与 Ma 联系起来：

$$T_g(x) = T_c/[1 + (\gamma - 1)M^2a/2] \quad (1)$$

$$\rho_g(x) = \rho_c/[1 + (\gamma - 1)Ma^2/2]^{1/(\gamma-1)} \quad (2)$$

$$u_g(x) = \sqrt{\gamma RT_g(x)}Ma \quad (3)$$

定义流量函数为：

$$q(Ma) = Ma\{2[1 + (\gamma - 1)Ma^2/2]/(\gamma + 1)\}^{-(\gamma+1)/2(\gamma-1)} \quad (4)$$

解上述方程可求得核心流场中 Ma 的轴向分布。

(2) **边界层流动。** 忽略彻体力，无热扩散（*Soret* 效应或 *Dufour* 效应）和压力扩散。可压、有化学反应的湍流边界层守恒方程为[3]：

$$\partial(r\bar{\rho}\tilde{u})/\partial x + \partial(r\bar{\rho}\tilde{v})/\partial r = 0 \quad (5)$$

$$\bar{\rho}\tilde{u}\frac{\partial\tilde{u}}{\partial x} + \bar{\rho}\tilde{v}\frac{\partial\tilde{u}}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\mu_{eff}\frac{\partial\tilde{\mu}}{\partial r}\right] - \frac{d\bar{p}}{dx} \quad (6)$$

$$\bar{\rho}\tilde{u}\frac{\partial\tilde{Y}_i}{\partial x} + \bar{\rho}\tilde{v}\frac{\partial\tilde{Y}_i}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\frac{\mu}{S_c}\right)_{eff}\frac{\partial\tilde{Y}_i}{\partial r}\right] \quad (7)$$

其中（～）表示 *Favre* 平均，（－）表示时间平均量。边界层的边缘条件为：外边缘 $\tilde{u}=u_e$，$\tilde{Y}_i=Y_{ie}$；固-气界面 $\tilde{u}=0$，$\tilde{T}=T_w$ $\tilde{v}_w=-\rho_c\dot{r}_c/\bar{\rho}_g$。为了使方程组在求解时封闭，采用了涡粘模型[4]来处理雷诺应力。设湍流边界层分为内外两层，内层外层涡粘性系数分别为：

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$$(\varepsilon_m)_i = L^2(r/r_0)^{0.4}|\partial u/\partial y|\gamma_{tr}, \qquad 0 \leqslant y \leqslant y_c$$

$$(\varepsilon_m)_o = 0.0168\left|\int_0^{\infty}(u_e - u)dy\right|\gamma_{tr}, \qquad y_c \leqslant y \leqslant \delta$$

其中 L 为 *Prandtl* 混合长度，γ_{tr}是考虑转捩区的间歇因子。

（3）　**材料的响应。**　用一维瞬态热传导方程来求喷管的温度分布及烧蚀率。假设没有周向和轴向的热传导，并设材料的热物性为常值。因此

$$k\partial^2 T/\partial y^2 = \rho_c c\partial T/\partial t \tag{8}$$

气-固界面上的边界条件为：

$$(\overline{\rho v}\,Y_i)_s - (\overline{\rho}D\partial Y_i/\partial r)_s = \dot{W}_i \tag{9}$$

$$-k\partial T/\partial y = -\rho_c\dot{r}_c\Delta H_r + h(T_s - T) + \sigma\varepsilon(T_s^4 - T^4) \tag{10}$$

式中 $\dot{W}_i$ 为组分 i 的消耗率；D 为扩散系数，由层流和湍流扩散系数组成；ρ_c 为材料的密度；$\dot{r}_c$ 为烧蚀率；ΔH_r 为每摩尔碳的平均反应热；k 是热传导系数；σ 为 *Boltzmann* 常数。对流换热系数取自 *Bartz* 公式[9]。用有效辐射系数 ε 来考虑气流与壁之间的多次反射：

$$\varepsilon = 1/(1/\varepsilon_s + 1/\varepsilon_w - 1)$$

其中燃气发射率 $\varepsilon_s = 1 - exp\,(-0.808n\rho d_t/16)$，即与含铝量百分数 n 及喉径 d_t 有关。壁面发射率取为常数 $\varepsilon_w = 0.6$。

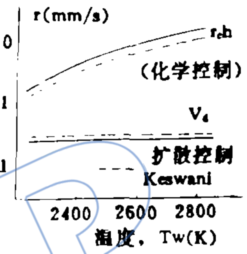

图1　烧蚀率随表面温度的变化

为了求解热传导方程，设外壁面为绝热条件：$\partial T/\partial y = 0$。初始条件则为 $T\ (y,\ t)\ = T_i$。

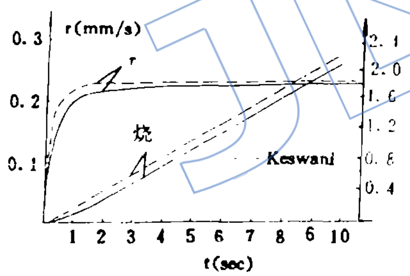

图2　喷管喉部烧蚀率、总烧蚀量随时间的变化

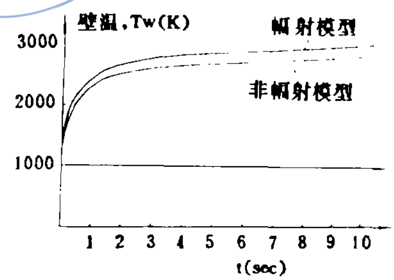

图3　辐射对喉壁表面温度的影响

2. **数值解法**　首先将（x，r）座标系的轴对称流动方程变换成（$\bar{x}$，$\bar{y}$）座标的二维流动方程：

$$d\bar{x} = dx, \quad d\bar{y} = -(r/r_0)dr;$$

$$\bar{\psi}(\bar{x},\bar{y}) = -(1/r_0)\psi(x,r);$$

其中 $r = r_0 - y$，进一步的变换可使变换后沿轴向采用较大的步长进行计算。

$$d\eta = \rho/\rho_0(u_0/\sqrt{\bar{x}})^{1/2}d\bar{y}$$

并引入无因次流函数 $f\ (\bar{x},\ \eta)$：$\bar{\psi}\ (\bar{x},\ \bar{y})\ = f\ (\bar{x},\ \eta)\ \rho_0\sqrt{u_0\nu\bar{x}}$

经变换后得到一组三阶非线性方程、采用 *BOX* 法[5]按下面四个步骤来求解：(1)将偏微分方程组转化成一阶方程组。(2)数值离散化。(3)用牛顿法使差分方程线性化。(4)用分块消去

法求解方程组。边界层的解为喷管壁的响应提供了输入条件。对于无辐射边界可用隐式迭

代有限差分法求解热传导方程。对于有辐射边界可用显式有限差分法求解。

3. **计算结果** 对于若干算例用以上方法进行了计算。计算结果如图1、2所示。辐射对壁温有一定的影响(图3),这是因为在发动机工作的大部分时间内,喷管烧蚀是由扩散控制的。

二、实验方法和结果

为了测量喷管的材料响应,使用了一个实验发动机来做试验。管状装药的内孔直径为25mm,外径为115mm,在喷喉及其上下游各距7mm处用热电偶进行了温度测量(图4)。测量结果如图5、6所示。其中 a 表示测量深度。

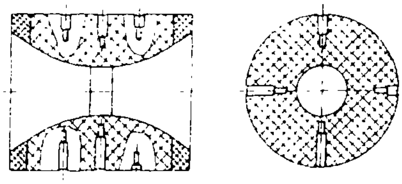

图4 热电偶的测量孔

综合以上方法得出如下结论:(1)为了估算喷管烧蚀量,本文在流场分析中考虑了湍流边界层,并引入了涡粘模型。(2)本文方法可适用于喷管烧蚀的工程预测。(3)本文引入了有效辐射系数来考虑导向喷管壁的辐射热流。

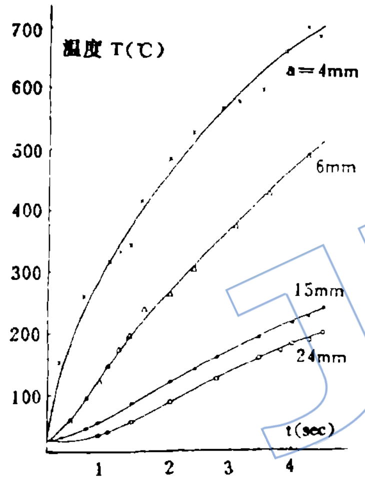

图5 喷喉截面的温度变化

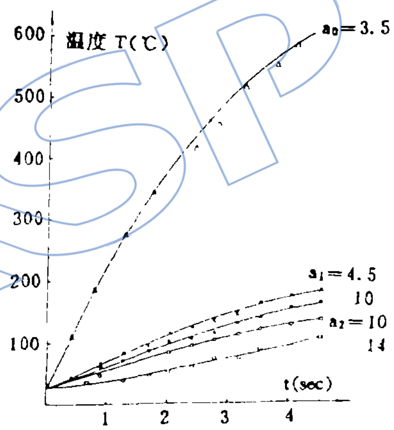

图6 喉部(a_0),上游(a_1)及下游(a_2)的温度分布

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FLOW SIMILARITY IN IGNITION PROCESS OF JET ENGINE

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ABSTRACT An analytical study on the flow similarity in ignition process is completed in respect to the effects of the air flow on the local fuel and oxygen distribution near the plug. For lean light off limitation, a momentum criteria is derived from the motion equation of fuel droplet. The criteria states that the ignition velocity rises with the increase of altitude. It is in quite good agreement with the experimental data. Moreover, it can be explained as that the ignition process changes gradually with the decrease of p_a into-optimum range when the fuel flow is kept constant. This case is a very conventional fuel control scheme for ignition ot the jet engine.

AN IMPORTANT ROLE OF CONDENSED-PHASE INTERFACE REACTION HEAT IN COMBUSTION PROCESS OF COMPOSITE PROPELLANTS

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ABSTRACT The condensed-phase interface reaction heat of AP/HTPB composite solid propellant and the influence of some burning rate catalysts on the interface reaction heat are studied with the aid of diferential scanning calorimetry. The experiments demonstrate that the catalysts which increase the condensed-phse interface reaction heat raise the burning rate of the propellant.

EROSION EVALUATION OF NOZZLE THROAT INSERTS

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ABSTRACT A study has been conducted to evaluate the temperature distribution and recession behavior of graphite nozzles in rocket motors by solving two-dimensional transient heat transfer equations. Flowfield analysis takes in account the effects of Al_2O_3 concentration through the contribution of particles on the stream density and temperature. The analytical model assumes that there is radiant exchange between the gas stream and the wall. An effective emissivity is used in this parallel plate radiation model. The results calculated in radiation and non-radiation conditions are compared for aluminized propellants, and also checked with data of Keswani and Kuo. The laboratory motor tests with double base propellants have been performed for verification of the analytical model. The temperature profiles in the nozzle have been measured at four locations with Cr-Ni/Ni-Si sheathed thermocouples. The present model is in general agreement with the available experimental data