

加力室液雾燃烧模型与应用

中国科学技术大学 朱祚金* 陈义良
航空工业总公司 606 研究所 张孝春

【摘要】 提出了描写航空发动机加力燃烧室内气液两相湍流燃烧的控制方程, 采用了双流体模型, 高温辐射通量模型, 双时间尺度湍流 $K-\epsilon$ 模型, 应用 SIMPLE 方法解这组方程, 对二维轴对称的涡喷加力燃烧室进行计算, 证明应用本文的液雾燃烧模型可以得出合理的计算结果。

主题词: 航空发动机 气体—液体流动 加力燃烧室 燃烧

分类号: V231.2

1 引言

文献[1]中对燃烧不稳定性与稳定器绕流的流体动力学机理进行了研究, 文献[2]在低速风洞中实验研究了火焰稳定器的绕流流场结构。

钝体绕流在数值方面开展的工作见文献[3], 实验方面的报导见文献[4]。文献[5]中数值分析了加力室内火焰与空气—燃料比的关系。文献[6]中采用区域网格方法计算了双环稳定器绕流。文献[7]利用无滑移多相流连续介质模型数值计算了带有单个 V 型环稳定器的喷气发动机加力燃烧室。文献[8]则采用多流体有滑移的湍流燃烧模型数值模拟了带有简单锥形火焰稳定器的涡扇发动机加力燃烧室内的化学反应流动。

本文提出了加力燃烧室内气液两相流燃烧的双流体模型, 并结合 Kim 双时间尺度 $K-\epsilon$ 湍流模型^[9], 高温辐射热通量模型^[10], 采用经典的 SIMPLE 方法对加力燃烧室内的气液两相湍流燃烧进行了数值模拟, 证明用本文的双流体模型得到的数值解是合理的, 对于加力燃烧室的设计和喷油优化具有重要的指导价值。

2 加力燃烧室中液雾燃烧模型

2.1 有关液相的方程

采用二维轴对称的柱坐标系 (x, r) , 设液雾相的速度为 (V_1, V_2) , 则只考虑二阶脉动相关项的液雾流体通用变量 ξ, η 的控制方程如下:

$$\frac{\partial}{\partial x}(\rho_l V_1 \xi) + \frac{1}{r} \frac{\partial}{\partial x}(r \rho_l V_2 \xi) = \frac{\partial}{\partial x} \left(\Gamma_l \frac{\partial \xi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \Gamma_l \frac{\partial \xi}{\partial r} \right) + S_\xi \quad (1)$$

$$\frac{\partial}{\partial x}(\rho_l V_1 \eta) + \frac{1}{r} \frac{\partial}{\partial x}(r \rho_l V_2 \eta) = \frac{\partial}{\partial x} \left(\frac{\rho_l \Gamma_l}{\rho_l} \frac{\partial \eta}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\frac{r \rho_l \Gamma_l}{\rho_l} \frac{\partial \eta}{\partial r} \right) + S_\eta \quad (2)$$

其中 ρ_l 是液滴的材料密度, n 是单位体积中的液滴数, m_v° 是每单位液体体积单位时间的蒸发

的质量($\text{kg}/\text{m}^3 \cdot \text{s}$), 用公式(5) 计算, $\dot{M}_0$ 是喷嘴的流量(kg/s), τ 是喷嘴所在差分网格单元的

表 1 通用方程(1)的源项

ξ	S_ξ
φ	$-\dot{m}_v \varphi + \dot{M}_0 \times \beta / \tau, \quad \Gamma_l = \rho_l v_l / \sigma_l$
n	$(\dot{M}_0 \times \beta / \tau) / (\pi d_0^3 / 6), \quad \Gamma_l \text{ 同上}$

体积, 当差分网格内喷油时, 开关变量 $\beta = 1$, 否则 $\beta = 0$ 。 d_0 是喷出液滴的平均直径, 应该根据喷嘴的雾化特性选取, 不同性能的喷嘴喷出的燃油平均滴径(也称索特滴径)也是不同的, 但为简单起见, 本文统一选取滴径 $d_0 = 60 \mu\text{m}$, 这种近似可能引起误差, 但由于燃油流量是根据

实际喷嘴性能来定的, 因此, 滴径 d_0 的大小仅通过影响燃油的颗粒密度对蒸发和燃烧完全度产生影响, 若加力燃烧室的燃烧段较长, 则不会对燃烧室出口流动参数和燃烧完全度有影响。

σ 为液雾的湍流扩散普兰特数, 用公式(4) 计算, σ 大于 1 说明液雾的湍流扩展系数小于气体的湍流扩散系数 v_t , 气体的湍流扩散系数 v_t 用 Kim 双时间尺度湍流 $K - \epsilon$ 计算, 详见文献[9]。

表 2 通用方程(2)的源项(Γ_l 的定义同表 1)

η	S_η
V_1	$- \frac{\varphi}{\rho_l} \frac{\partial}{\partial x} + \left\{ \frac{\partial}{\partial x} \left(\frac{\varphi \Gamma_l \partial V_1}{\rho_l} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\varphi \Gamma_l \partial V_2}{\rho_l} \right) \right\} + \frac{\dot{M}_0 V_{01} \beta}{\tau} + \sum_{i=1}^3 L_i$ $L_1 = - \frac{F_D}{\rho_l} \left\{ \varphi \left[(V_1 - U_1) - \frac{v_t}{\rho_g \sigma_p} \frac{\partial \varphi}{\partial x} \right] + \frac{\partial \varphi}{\partial x} \frac{v_t}{\sigma_p} \left(1 - \frac{1}{\sigma_l} \right) \right\}$ $L_2 = - \frac{\dot{m}_v}{\rho_l} \left\{ \varphi V_1 - \frac{v_t}{\sigma_l \sigma_p} \frac{\partial \varphi}{\partial x} \right\}$ $L_3 = 2 \frac{\partial}{\partial x} \left(\frac{v_t}{\sigma_l \sigma_p} V_1 \frac{\partial \varphi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{v_t}{\sigma_l \sigma_p} V_1 \frac{\partial \varphi}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{v_t}{\sigma_l \sigma_p} V_2 \frac{\partial \varphi}{\partial r} \right)$
V_2	$- \frac{\varphi}{\rho_l} \frac{\partial}{\partial r} + \left\{ \frac{\partial}{\partial x} \left(\frac{\varphi \Gamma_l \partial V_1}{\rho_l} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\varphi \Gamma_l \partial V_2}{\rho_l} \right) \right\} - \frac{2 \varphi \Gamma_l V_2}{\rho_l r^2} + \frac{\dot{M}_0 V_{02} \beta}{\tau} + \sum_{i=1}^3 N_i$ $N_1 = - \frac{F_D}{\rho_l} \left\{ \varphi \left[(V_2 - U_2) - \frac{v_t}{\rho_g \sigma_p} \frac{\partial \varphi}{\partial r} \right] + \frac{\partial \varphi}{\partial r} \frac{v_t}{\sigma_p} \left(1 - \frac{1}{\sigma_l} \right) \right\}$ $N_2 = - \frac{\dot{m}_v}{\rho_l} \left\{ \varphi V_2 - \frac{v_t}{\sigma_l \sigma_p} \frac{\partial \varphi}{\partial r} \right\}$ $N_3 = \frac{\partial}{\partial x} \left(\frac{v_t}{\sigma_l \sigma_p} V_2 \frac{\partial \varphi}{\partial x} \right) + \frac{\partial}{\partial x} \left(\frac{v_t}{\sigma_l \sigma_p} V_1 \frac{\partial \varphi}{\partial x} \right) + 2 \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{v_t}{\sigma_l \sigma_p} V_2 \frac{\partial \varphi}{\partial r} \right)$

其中(V_{01}, V_{02}) 是喷油速度, 当燃油采用周向喷油方式进入加力燃烧室时, 喷油速度(V_{01}, V_{02}) 可以取为零, 否则喷油速度要根据单孔燃油流量和喷嘴的直径来定义。

2.2 有关气相的方程

设气相速度为(U_1, U_2), 则只考虑二阶脉动相关项的气体流动的通用方程是:

$$\frac{\partial}{\partial x} (\rho_g \varphi U_1 \varphi) + \frac{1}{r} \frac{\partial}{\partial r} (r \rho_g \varphi U_2 \varphi) = \frac{\partial}{\partial x} \left(\varphi \Gamma_g \frac{\partial \varphi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \varphi \Gamma_g \frac{\partial \varphi}{\partial r} \right) + S_\varphi \quad (3)$$

表 3 通用方程(3)的源项

η	$S\eta$
1	$\dot{m}_e \varphi_t \left\{ \frac{\partial}{\partial x} \left(\frac{\mu_t}{\sigma_{\varphi}} \frac{\partial \varphi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_t}{\sigma_{\varphi}} \frac{\partial \varphi}{\partial r} \right) \right\}, \quad \sigma_{\varphi} = 1.0$
U_1	$- \varphi_g \frac{\partial P}{\partial x} + \left\{ \frac{\partial}{\partial x} \left(\varphi_g \Gamma_g \frac{\partial U_1}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \varphi_g \Gamma_g \frac{\partial U_2}{\partial r} \right) \right\} + \sum_{i=1}^3 L_i^*, \quad \Gamma_g = \mu_t$ $L_1^* = -L_1 \times \rho_l, \quad L_2^* = -L_2 \times \rho_l$ $L_3^* = 2 \frac{\partial}{\partial x} \left(\frac{\mu_t}{\sigma_l \sigma_{\varphi}} U_1 \frac{\partial \varphi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_t}{\sigma_l \sigma_{\varphi}} U_1 \frac{\partial \varphi}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_t}{\sigma_l \sigma_{\varphi}} U_2 \frac{\partial \varphi}{\partial r} \right)$
U_2	$- \varphi_g \frac{\partial P}{\partial x} + \left\{ \frac{\partial}{\partial x} \left(\varphi_g \Gamma_g \frac{\partial U_1}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \varphi_g \Gamma_g \frac{\partial U_2}{\partial r} \right) \right\} - \frac{2 \varphi_g \Gamma_g U_2}{r^2} + \sum_{i=1}^3 N_i^*, \quad \Gamma_g = \mu_t$ $N_1^* = -N_1 \times \rho_l, \quad N_2^* = -N_2 \times \rho_l$ $N_3^* = \frac{\partial}{\partial x} \left(\frac{\mu_t}{\sigma_l \sigma_{\varphi}} U_2 \frac{\partial \varphi}{\partial x} \right) + \frac{\partial}{\partial x} \left(\frac{\mu_t}{\sigma_l \sigma_{\varphi}} U_2 \frac{\partial \varphi}{\partial x} \right) + 2 \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_t}{\sigma_l \sigma_{\varphi}} U_2 \frac{\partial \varphi}{\partial r} \right)$
f	$\dot{m}_e \varphi_t \left\{ \frac{\partial}{\partial x} \left(\frac{\mu_t f}{\sigma_{\varphi}} \frac{\partial \varphi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_t f}{\sigma_{\varphi}} \frac{\partial \varphi}{\partial r} \right) \right\}, \quad \Gamma_g = \mu_t / \sigma_f, \quad \sigma_f = 0.9$
m_{fu}	$\dot{m}_e \varphi_t + R_{fu} \cdot \varphi_g + \left\{ \frac{\partial}{\partial x} \left(\frac{\mu_t m_{fu}}{\sigma_{\varphi}} \frac{\partial \varphi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_t m_{fu}}{\sigma_{\varphi}} \frac{\partial \varphi}{\partial r} \right) \right\}, \quad \Gamma_g = \mu_t / \sigma_{fu}$
h_g	$\left\{ \frac{\partial}{\partial x} \left(\frac{\mu_t h_g}{\sigma_{\varphi}} \frac{\partial \varphi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_t h_g}{\sigma_{\varphi}} \frac{\partial \varphi}{\partial r} \right) \right\} + \dot{m}_e \varphi_t \left[\frac{1}{2} (V_1^2 + V_2^2) + C_{pl} T_l \right] - R_{fu} \varphi_g H_u + Q_R$ $\sigma_{\varphi} = 1.0, \quad \Gamma_g = \mu_t / \sigma_h, \quad \sigma_h = 0.9$

混合分数定义为 $f = m_{fu} - m_{o_2} / S$, S 为燃烧反应化学当量比。 C_{pl} 、 T_l 和 H_u 分别是喷油的比热、温度和热值, Q_R 是辐射换热率。燃烧反应假定为简单单步化学反应, 以涡旋破碎模型计算燃烧反应速率, 同时用阿累尼乌斯燃烧反应速率模型加以修正, 实际燃烧速率取绝对值较小燃烧速率值。

2.3 联系气相和液相的辅助公式

液雾的湍流扩散普兰特数^[11]:

$$\sigma_l = 1 + (2/3) \rho_l k_p / [v_l F_D (1 + \varphi \rho_l / \rho_g \varphi_g)] \quad (4)$$

其中体积的气体分数为 $\varphi_g = 1 - \varphi$, 单位液体体积的蒸发率^[11]:

$$\dot{m}_v = (12 \mu_g / d^2 Pr) [1 + 0.269 Re^{0.581} Pr^{0.33}] (\ln(1+B) / (1+B)^{0.67}) \quad (5)$$

传质数 $B = C_{pg}(T_g - T_l) / L_t$, μ_g 和 Pr 分别是高温高压下混合气的动力粘度和层流普兰特数。计算公式见文献[12], 单位液体体积受到的阻力系数为^[13]:

$$F_D = (18 \mu_g / d^2) [1 + 0.15 Re^{0.687} + 0.02 Re / (1 + 42500 / Re^{1.16})] / (1+B)^{0.25} \quad (6)$$

其中相对运动雷诺数 $Re = \rho_g d |V_j - U_j| / \mu_g$, 两相流体介质中液滴的平均直径是 $d = (6 \varphi /$

$\pi m)^{1/3}$, 气相化学反应速率的公式见文献[14]。

2.4 加力室工况参数

在加力燃烧室入口截面上, 气流速度取 $U_{in} = 303.5 \text{ m/s}$, $V_{in} = 0.0$, 静温取 $T_{in} = 1020 \text{ K}$; 静压取 $P_{in} = 2.79 \times 10^5 \text{ Pa}$, 氧气质量分数: $m_{O_2 in} = 0.1586$, 航空燃油分子式: C_8H_{16} 。加力室喷嘴位置安排在接近火焰稳定器的上游, 总的加力喷油的质量流量是加力室入口气流质量流量 3.8%。

3 计算结果与讨论

高速气流对环形火焰稳定器(A、B、C)的绕流产生的火焰稳定回流区可见于图 1(a)中, 在组成扩压通道的内锥头部表面发生了流动分离, 分离旋涡对液雾流动和温度场均产生明显影响, 如图 1(b)所示的液雾流场表明分离旋涡的卷吸使接近内锥表面区域内也含有液雾流体。

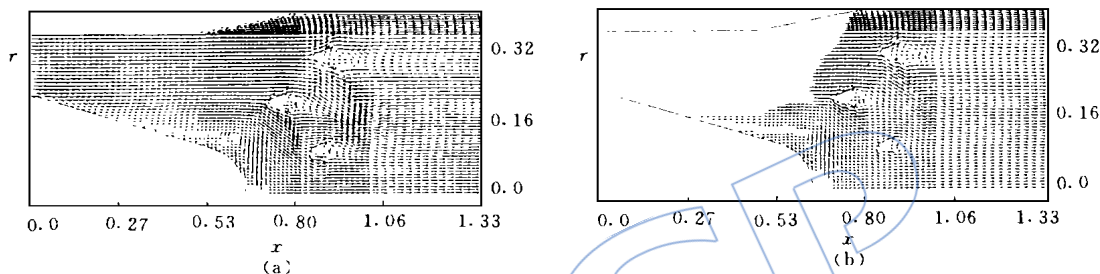


图 1 矢量表示的速度场(a)气相流场(b)液相流场

温度等值线用最大温度 2222 K 归一化以后画在图 2(a)中, 从温度等值线的走向, 可见从回流区向外侧存在比较大的热量运输, 因为回流区边界附近具有比较大的温度梯度。在火焰稳定器 B 的下游的区域内气流温度值比较高。从图 2(b)给出的用最大滴径归一化的液滴平均直径的等值线分布, 可见液滴滴径在喷油

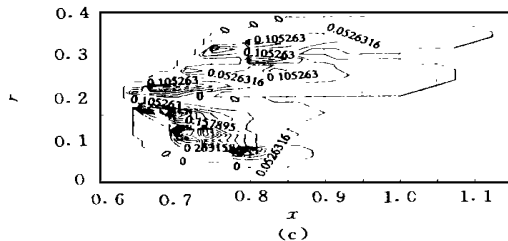
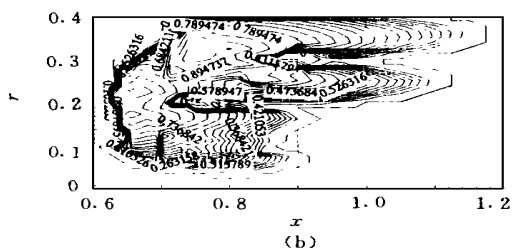
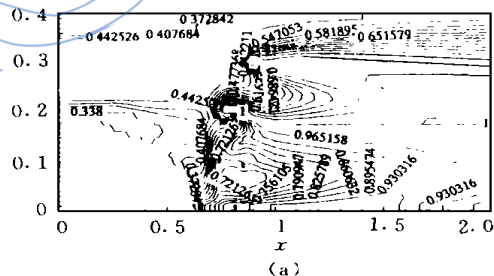


图 2 加力燃烧室内的等值线图(a)温度等值线(b)液滴平均直径等值线(c)液滴容积分数等值线

节点和稳定器产生的混合层中比较密集, 在加力室气流环境下燃油液滴群蒸发得很快, 在下游 $x > 1.3 \text{ m}$ 时, 液滴滴径已经比燃油注射时采用的平均滴径 $60 \mu\text{m}$ 小两个数量级了。从图 2(c)给出的归一化的液滴相容积分数 φ 等值线分布, 可见液滴的高温蒸发使液滴容积分数 φ 出现很大的空间变化梯度, 剧烈的湍流燃烧使 φ 很快趋于零。

流量加权平均的燃烧完全度和总压恢复系数与轴向坐标 x 的关系在图 3 中给出。在燃烧反应剧烈的稳定器下游区域, 燃烧效率升高得很快, 而总压恢复系数的变化趋势则正好相反, 它很快降低。在燃油剧烈燃烧过程完成以后, 气体流动的变化趋势呈缓和的状态。

4 结 论

提出的关于航空发动机加力燃烧室内气液两相湍流燃烧的控制方程, 不仅适合对航空动力装置中的湍流两相流动进行数值研究具有重要的应用价值, 而且对于热能工程中的两相流动与传热问题的研究也具有明显的参考价值。通过实际计算表明, 应用本文的加力室模型可以得到比较切合实际的结果, 对于加力燃烧室的设计和燃油配制优化, 具有很重要的指导意义。

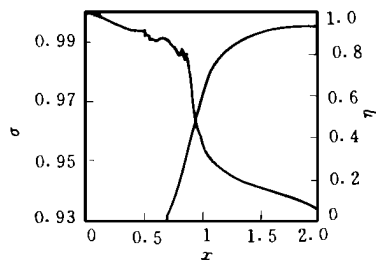


图3 燃烧完全度 η 和总压恢复系数 σ 与 x 的关系

参 考 文 献

- 1 Fujii S, Eguchi K A. Comprison of Cold and Reacting Flows Around a Bluff Body Flame Stabilizer. ASME J. Fluid Engineering, 1981, 103: 323- 342
- 2 Ravichandran M, Ganesan V. Aerodynamic Flow Investigation in an Isothermal Model of an Afterburner. Experiments in Fluids, 1994, 17: 59- 67
- 3 Vatisstas G H, L in S, Kwok C K. Bluff Body Flameholder Wakes- a Simple Numerical Solution. AIAA, 1982: 82- 1177
- 4 Taylor A M K P, Whitelaw J H. Velocity Characteristics in the Turbulent Near Wakes of Confined Axisymmetric Bluff Bodies. J. Fluid Mechanics, 1984, 139: 391- 416
- 5 Chuang S H, Jiang J S. Diffusion Flame Analysis of an Afterburner as a Function of Air- Fuel Ratio. Int. J. Num. Methods Fluids, 1990, 11: 303- 316
- 6 Lee D, L in J S. Computation of Near Nonreacting Flows of a Two Ring Flame Stabilizer Using a Zonal Grid Method. Num Heat Transfer, 1991, Part A20: 65- 79
- 7 Elgobashi S, Pratt D T, Spalding D B, et al. Unsteady Combustion of Fuel Spray in Jet Engine Afterburners. Proc. III Int. Symp. Air Breathing Engines, Munich, Germany: 1977: 446- 471
- 8 Zhang X, Chui H. Numerical Modeling of Afterburner Combustion. Int. J. Turbo and Jet Engines, 1987, 14: 251- 262
- 9 蔡晓丹, 陈义良. 多时间尺度湍流模型的应用. 工程热物理学报, 1994, 15(4): 387
- 10 范维澄, 陈义良, 洪茂玲. 计算燃烧学. 合肥: 安徽科学技术出版社, 1987
- 11 Siminin O, Viollet P L. Numerical Modelling of Devolatization in Pulverized Coal Injection Inside a Hot Coflowing Air Flow. Lecture Notes in Engineering(Turbulent Reacting Flows), 1989, (40): 824- 846
- 12 陈义良, 张孝春, 孙慈等. 燃烧原理. 北京: 航空工业出版社, 1992
- 13 Abou Ellail M M M, Ebou Arab T W. Prediction of Two Phase Flow and Heat Transfer in Vertical Pipes. Proc. 5th Symposium on Turbulent Shear Flows Ithaca N Y, 1985: 8. 1- 8. 7
- 14 王应时, 范维澄, 周力行等. 计算燃烧学. 北京: 科学出版社, 1986

(责任编辑 杨再荣)

A TWO- PHASE AFTERBURNER COMBUSTION MODEL

Zhu Zuojin and Chen Yiliang

(13th Dept. University Science and Technology of China, Hefei 230026)

Zhang Xiaochun

(Shenyang Aeroengine Research Institute, Shenyang)

ABSTRACT

According to the fundamental concept of two- fluids, the governing equations for description of gas- droplets turbulent combustion in an afterburner of jet engine have been formulated, in which the important injection effect of the droplets in afterburner has been taken into detailed consideration. The Farve average method has been employed to represent the effects of turbulent combustion in the afterburner. The multiple time scale turbulent $k-\epsilon$ model proposed by Kim is applied to calculating the eddy viscosity of the turbulent field. The heat flux radiation model has been taken to consider the effect of radiation at high temperature, the simple one step chemical reaction model is used to approximate the combustion of kerosene. The chemical reaction rate is assumed to be controlled by eddy break up process, and the reaction rate is modified by premixed reaction model in Arrhenius form. The application of SIMPLE algorithm indicates that the present twofluid model can calculate the two- phase turbulent combustion in the jet engine afterburner and obtain reasonable results.

Key Words Aircraft engines Gas- liquid flow Afterburners Combustion

NUMERICAL SIMULATION OF COMBUSTOR FLOWS

Xu Hang and Huang Yang

(4th Dept. Beijing University of Aeronautics and Astronautics, Beijing 100083)

ABSTRACT

A method has been developed for calculation of three- dimensional flows in aeroengine combustor including diffuser and flametube, inner and outer annuluses. The 3D body- fitting grid has been generated to deal with the complex geometry of the combustor. The non- staged grid scheme and $k-\epsilon$ turbulence model has been adopted. The mass flowing through primary holes, dilution holes and film cooling holes has been calculated. The calculated results are consistent reasonably with the experimental measurements.

Key Words Numerical simulation Combustion chambers Turbulence

AEROENGINE TEST AUTOMATION OF ADAPTIVE CONTROL WITH RESTRAINTS

Fan Ding

(7th Dept. Northwestern Polytechnical University, Xi'an 710072)

Li Runzhi

(Southern Powerplant Machinery Corporations, Zhuzhou)

ABSTRACT

An automatic control system of aeroengine test has been designed, based on the method of model reference adaptive control with restraints. According to its simulation results, this method has good adaptability when the controlled member contains non- linear elements or the controller member varies in a large range. The simulation results also show that ,the controlled system still has satisfactory performance index by regulating