文章编号: 1001－2060(2001)01－0080－03

三维紊流燃烧室流场的数值计算

荀柏秋[1], 曲　哲[2], 张雁秋[1], 王铁成[1], 秦　岩[1]

(1. 哈尔滨°第七〇三研究所, 黑龙江 哈尔滨　150036; 2. 哈尔滨电站工程有限公司, 黑龙江 哈尔滨　150046)

摘　要: 运用圆柱坐标系对单管回流燃烧室流场进行了数值模拟。紊流粘度模型采用 κ—ε 双方程紊流模型来估算紊流粘度, 燃烧模型采用 EBU 旋涡破碎燃烧模型来估算化学反应速度, 热辐射模型采用比较简单的 DTRM 模型来计算热辐射量。计算结果能比较准确地反映燃烧室流场的流动状态, 同时也为复杂形状的燃烧室造型提供了方法。

关　键　词: 单管回流燃烧室; 数值模拟; 紊流流动

中图分类号: TK472　　文献标识码: A

1　引言

随着科学技术的进步和燃气轮机性能的不断提高, 对于燃烧室各项工作性能指标的要求也日益苛刻, 现有的经验设计方法已不能完全满足现代先进燃烧室的设计要求; 另外, 燃烧室试验费用十分昂贵。因此, 需要利用燃烧室的三维紊流燃烧计算结果, 结合经验、半经验设计方法来实现燃烧室的设计、制造和试验检验。

本研究采用新版本的三维造型软件, 造出型面十分复杂的燃烧室火焰筒混合段, 生成 iges 格式文件, 调入流场计算软件中的软件包, 通过 BOOLEN 运算形成燃烧室火焰筒的实际计算区域、计算网格和计算边界, 生成 mess 格式文件, 调入流场计算软件中进行迭代运算。本计算采用圆柱坐标系和贴体网格, 并在流场流动复杂的区域采用加密网格的方法, 以保证计算更加准确。

2　物理模型

本文采用 GT 25000 燃气轮机单管燃烧室的火焰筒作为计算的物理模型。该燃烧室是环管形的, 在燃烧室内外壳的环形空间内布置了 16 个火焰筒。按空气和燃烧产物的流动来说, 燃烧室是逆流式的。在每个火焰筒头部装有锥形叶片旋流器。冷却方式采用气膜式。

3　数学模型

由于燃烧室流场是紊流、有涡旋和耗散的流场, 故单管燃烧室流场计算中所需的数学模型采用紊流粘性模型和紊流燃烧模型。

3.1　紊流粘性模型

紊流粘性模型采用 κ—ε 双方程紊流模型, 该模型简单且计算方便, 是燃烧计算常用模型。紊流动能 κ 和紊流动能耗散率 ε 分别由下面输运方程(1)、(2)和(3)计算得到。

$$\rho\frac{\mathrm{d}\kappa}{\mathrm{d}t}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial\kappa}{\partial x_i}\right]+G_\kappa+G_b-\rho\varepsilon-YM \tag{1}$$

$$\rho\frac{\mathrm{d}\varepsilon}{\mathrm{d}t}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_i}\right]+G_{1\varepsilon}\frac{\varepsilon}{\kappa}(G_\kappa+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa} \tag{2}$$

$$\mu_t=\rho C_\mu\frac{\kappa^2}{\varepsilon} \tag{3}$$

其中

$C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $C_\mu=0.09$, $\sigma_\kappa=1.0$, $C_\varepsilon=1.3$

3.2　紊流燃烧模型

在实际的燃烧室热态流场中, 除紊流与燃烧相互作用外, 还有化学动力因素对燃烧速率的影响, 因此, 本文采用 EBU 旋涡破碎燃烧模型来估算化学反应速度。反应速率由方程(4)和(5)计算得到。

$$R_{i',\kappa}=\nu'_{i',\kappa}M_{i'}A\rho\frac{\varepsilon}{\kappa}\frac{m_R}{\nu'_{R,K}MR} \tag{4}$$

$$R_{i',\kappa}=\nu'_{i',\kappa}M_{i'}AB\rho\frac{\varepsilon}{\kappa}\frac{\sum_p m_p}{\sum_j^N\nu''_{j',\kappa}M_j} \tag{5}$$

其中

m_p 代表生成物 P 的质量分数; m_R 代表反应物 R 的质量分数; $A=4.0$; $B=0.5$

收稿日期: 2000－01－03; 修订日期: 2000－05－15

作者简介: 荀柏秋(1968－), 男, 黑龙江双城人, 哈尔滨第七〇三研究所工程师.

4　热辐射模型

热辐射模型采用比较简单的 DTRM 模型来计算热辐射量。DTRM 方程见下面方程(6) 和(7)。

$$\mathrm{d}I/\mathrm{d}S + \alpha I = \alpha\sigma T^4/\pi \tag{6}$$

$$I(S) = \frac{\sigma T^4}{\pi}[1 - \exp(-\alpha S)] + I_0\exp(-\alpha S) \tag{7}$$

5　网格生成

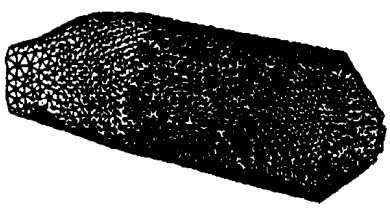

图 1　网格图

只要给出网格尺寸, 软件 FLUENT 中的软件包 GAMBIT 具有自动生成网格的功能。为使计算更加准确, 本研究在流场流动复杂的区域采用加密网格的方法。由于计算区域形状比较复杂, 本研究只能采用四面体网格, 网格总数为 30 099 个。图 1 为用此方法生成的网格。

6　计算对象和边界条件

6.1　计算对象

本文计算 GT 25000 燃气轮机用单管逆流式燃烧室, 火焰筒外径为 175 mm, 内径为 164 mm, 火焰筒长度为 522 mm, 火焰筒进口装有锥形叶片旋流器, 火焰筒壁面分别装有主燃孔、掺混孔和冷却孔。在额定状态下, 燃烧室入口空气质量流量为 78.26 kg/s, 火焰筒内空气质量流量为 65.85 kg/s, 来流为航空煤油和空气的均匀混合气。

6.2　边界条件

计算状态为额定状态, 燃烧室入口空气总压为 2.052 3 MPa, 空气温度为 769.9 K, 燃烧室总空气过量系数为 3.316, 旋流器后空气过量系数为 0.445, 火焰筒内空气过量系数为 2.79。火焰筒主燃空气、燃料、二次射流孔和掺混孔入口均采用速度边界; 火焰筒壁面采用定温墙体边界, 温度取为 1 230 K(约为 950 ℃); 火焰筒出口截面采用压力边界, 压力值取为 0.1 MPa, 温度为 300 K。火焰筒壁面上取气流速度和紊流参数为零, 靠近壁面采用壁面函数。

7　计算结果

计算结果如图 2 ~ 图 6 所示。图 2 为计算对称

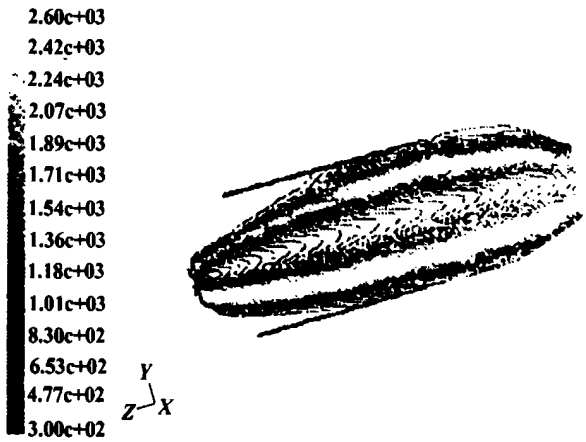

图 2　对称面温度场

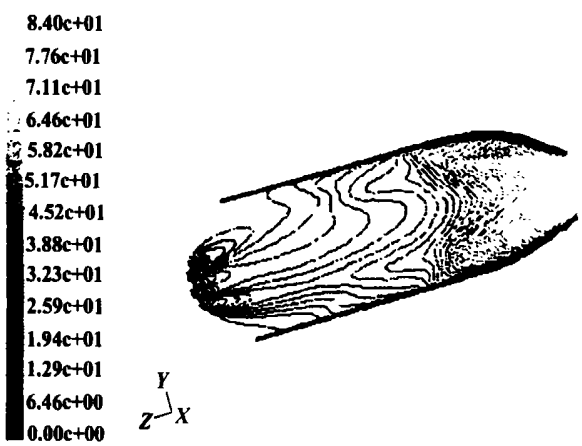

图 3　对称面速度场

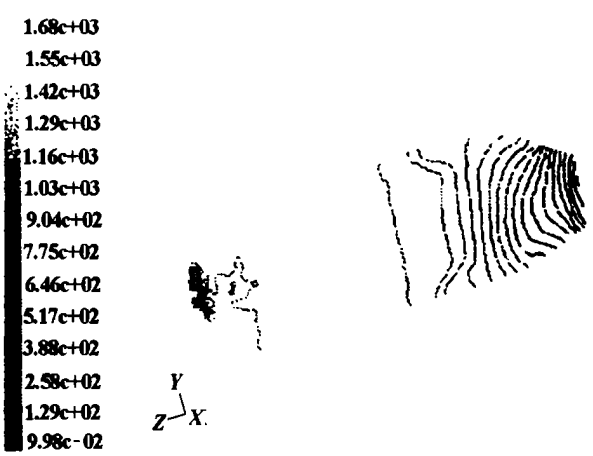

图 4　对称面压力场

面处的温度场。由图可知，在旋流器后附近主燃区燃气温度高，而在燃烧室出口处，因掺混冷却空气进入，使燃气温度降低，满足了涡轮叶片对燃气温度的要求。火焰筒近壁处，由于气膜冷却，满足了火焰筒材料的低温要求。图 3 为计算对称面处的速度场。由图可知，旋流器中心产生回流区，可以保证燃烧的可靠性、充分性和稳定性。火焰筒近壁处，由于冷却气流的进入，速度因叠加而增高。图 6 为计算出口截面处的温度场。由图可知，出口截面温度场分布均匀，呈对称状，这样可使涡轮叶片受热更加合理。

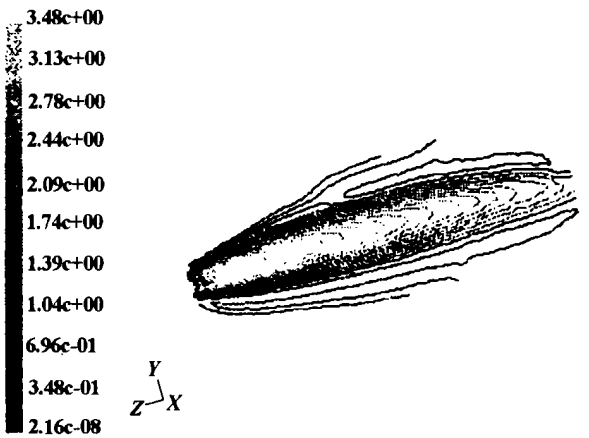

图 5 对称面辐射场

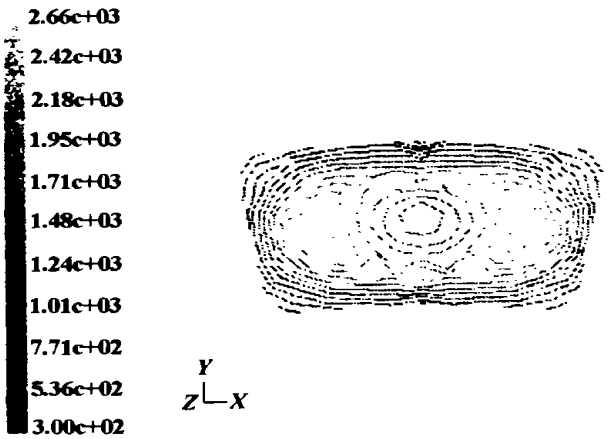

图 6 出口截面温度场

参考文献：

[1] 焦树建. 燃气轮机燃烧室[M]. 北京：机械工业出版社，1981.
[2] 陈义良，张孝春. 燃烧原理[M]. 北京：航空工业出版社，1992.
[3] 严传俊. 三维贴体坐标下燃烧室流场的数值模拟[J]. 燃烧科学与技术学报，1995，**1**(1)：54—62.
[4] 赵坚行，刘全忠. 数值模拟涡轴发动机的燃烧室流场[J]. 燃烧科学与技术学报，1995，**1**(4)：292—298.

（何静芳 编辑）

（接 50 页）

其冷却效果与改进前基本相近。但是，由于每台冷却器的成本低于原润滑系统，与原来的设计相比，每台轴承箱的制造成本均可降低。因此，这种改进设计值得大力推广。

6 经济效益

据通辽电厂反映，改造前平均每年更换油泵、压力表、流量计等附件 50 余次，需人民币 14 万元(12 台磨年检修费)。对轴承箱进行改造后，由于取消了油泵、压力表、流量计等附件，不但每台轴承箱成本降低了 2 万元，而且每年可节省 14 万元的维修费用。除此以外，改进后磨煤机运行将更加稳定，彻底排除因润滑系统故障而引起的跳磨，大大减轻检修运行人员的劳动强度，效益是十分明显的。此改进方法研制成功后，又对双辽电厂风扇磨进行了改造，同样取得了良好的效果。

参考文献：

[1] 蒋宏利. SKF 轴承综合型录[M]. 上海：上海科学技术文献出版社，1991.

（复 编辑）

Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. —2001, 16 (1). —70 ~ 72

A mathematical model was set up for an asymmetrical rotor-bearing system. With the help of this model the authors have analyzed the influence of a variety of factors on the stability of the asymmetrical rotor-bearing system. Among such factors one can enumerate external damping, rotor rigidity anisotropic factor, support rigidity anisotropic factor and the relative flexibility factor of the support. As a result of the analysis and numerical simulations it has been found that the rotor rigidity anisotropy and the system damping are the major factors contributing to the loss of stability of the system. To solve the issue of instability of the asymmetrical rotor-bearing system in engineering practice the authors have proposed a method aimed at enhancing the support rigidity symmetry of a rotor-bearing system, which has been proved effective in practice. **Key words**: asymmetrical rotor-bearing system, stability analysis, rigidity, anisotropy

湍流㶲传递方程及其应用＝**Exergy Transfer Equation for Turbulent Flows and Its Applications** [刊, 汉] / Wang Song-ping (Qingdao University, Qingdao, China, Post Code: 266071), Chen Qing-lin, Hua Ben (South China University of Science and Technology, Guangzhou, China, Post Code: 510641) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —73 ~ 76

The authors have derived an exergy transfer equation for turbulent flows. On this basis a study was conducted of the exergy transfer for a convection heat exchange tube with a wall surface constant heat flux. The distribution of exergy loss rate caused by viscosity dissipation, radial and axial heat conduction was calculated. The calculation results of the total exergy loss rate for a unit volume indicate that the total exergy loss per unit volume is a multi-value function of heat exchange tube geometric parameters and boundary conditions. For a given geometric parameter there exists a boundary condition, which gives a minimum value of the total exergy loss rate for a unit volume, and vice versa. The above conclusion can to a certain extent serve as a guide for the optimized design of heat exchangers and the optimal selection of heat exchangers under given boundary conditions. **Key words**: turbulent flow, exergy transfer equation, distribution of exergy loss rate

某舰用锅炉过热器胀接接头弹塑性有限元分析＝**Finite Element Analysis of the Elastic Plasticity of a Naval Boiler Superheater Expanded-joint** [刊, 汉] / Zhou Chuan-yue (Harbin Institute of Technology, Harbin, China, Post Code: 150001), Li Gui-ying, Ma Yun-xiang (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —77 ~ 79

Through the use of a large-sized finite element general program ANSYS the contact analysis model of an expanded joint has been set up for the expanded joint structure of a naval boiler superheater and a finite element analysis of three-dimensional plasticity conducted. A study was performed of the effect of material properties and operating temperatures, etc on the residual contact pressure of the expanded joint. Also given in this paper are some proposals, which can serve as a guide for engineering design as well as for the prevention of failures and malfunctions. **Key words**: expanded joint, finite element method (FEM), analysis of elastic plasticity, residual stress, program ANSYS

三维紊流燃烧室流场的数值计算＝**Numerical Calculation of the Three-dimensional Turbulent Flow Field of a Gas Turbine Combustor** [刊, 汉] / Xun Bai-qiu, Qu Zhe, Zhang Yanqiu, *et al* (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —80 ~ 82

By the use of a cylindrical coordinate system a numerical simulation was conducted of a single-tube return-flow combustor flow-field. A turbulent flow viscosity model was employed to evaluate the turbulent flow viscosity with the help of a k-ε dual equation turbulent flow model. A combustion model was utilized to assess chemical reaction speed with the help of a EBU (eddy-break-up) vortex breakage combustion model. Thermal radiation magnitude was calculated by using a thermal radiation model with the help of a relatively simple DTR (discrete transfer radiation) model. The results of the calculation have been found to reflect quite accurately the flow condition of the combustor flow field. Moreover, these results have al-

so played a beneficial role in devising a method for the modeling of combustors with a complicated shape. **Key words**: single-tube return-flow combustor, numerical simulation, turbulent flow

舰船锅炉炉膛热力计算方法的修正＝**Revision of the Thermodynamic Calculation Method for a Naval Boiler Furnace** [刊, 汉] / Li Zhi-tao, Zhang Yu-hui, Chen Bing, *et al* (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —83 ~ 85

With regard to the specific features of a naval boiler furnace the authors have analyzed and compared the calculation results obtained when using various methods set forth in "the United Standards of 1973" etc. In the present paper recommended is a revision method adapted for the thermodynamic calculation of boiler furnace off-design conditions. **Key words**: naval boiler, thermodynamic calculation, furnace heat transfer

国产 200 MW 汽轮机转子在线热应力监测与寿命管理＝**On-line Monitoring of Rotor Thermal Stresses and Service Life Management for a Chinese-made 200 MW Steam Turbine** [刊, 汉] / Li Ai-jun, Xie Dan-mei, Yang Jun, Wang Jian-mei, Liu Xian-fei (Power Engineering Department, Wuhan University of Water Resources and Electrical Power, Wuhan, China, Post Code: 430072), Huang Shu-hong, Shen Tao (Power Engineering Department, Central China National University of Science & Technology, Wuhan, China, Post Code: 430074) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —86 ~ 88

Through the use of an object-oriented language the authors have developed a software designed for the on-line monitoring of rotor stresses and service life management for a Chinese-made 200 MW steam turbine. In addition to thermal stress monitoring the software is also capable of abnormal data inquiry, offering guidance for start-up and shutdown operations as well as their recollection, etc. **Key words**: steam turbine, rotor, thermal stress, service life

能源消费与国民经济发展的灰色关联分析＝**Grey Correlation Analysis of Energy Consumption and National Economy Development** [刊, 汉] / Huang Fei (Wuxi Division under the Harbin Institute of Technology, Wuxi, China, Post Code: 214151) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —89 ~ 90

Grey correlation analysis is a kind of systemic analytical method. Through the use of this analysis it is possible to identify the major factors which influence the evolution and variation of key variables. Analyzed in this paper is the grey correlation of energy consumption and national economy development. The results obtained therein may serve as reference data for relevant administrative departments and sectors. **Key words**: grey correlation analysis, energy consumption, national economy development

亚临界炉锅水 pH 降低原因分析及预防对策＝**An Analysis of the Causes of Boiler Water pH Value Reduction in a Subcritical Pressure Boiler and Some Measures Taken for Its Prevention** [刊, 汉] / Yang Zhong-hao (North China Institute of Water Resources and Hydroelectric Power Engineering, Zhengzhou, China, Post Code: 450045) // Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —91 ~ 92, 100

In connection with a series of boiler water quality failures occurring at a certain power plant an analysis was conducted of the cause of the decrease in boiler water pH value. As a result, it is ascertained that the above-cited decrease has been caused by the leakage of mixed bed resin into the main system. The use of a water distribution device equipped with stainless steel trapezoid-shaped wound wires and a negative-pressure reverse-rinsing resin catcher has led to the prevention of the above-mentioned failure. **Key words**: thermal power plant, operation, accident analysis, feedwater, boiler water pH value

新型的烟气分析设备及其应用＝**A New Type of Flue-gas Analyzing Device and Its Applications** [刊, 汉] / Wang Tie-cheng, Liu Min, Xun Bai-qiu, *et al* (Harbin No. 703 Research Institute, Harbin, China, Post Code: