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气膜冷却平板通道的数值模拟

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摘　要: 对无肋和带 45° 肋气膜冷却平板通道的三维对流换热与导热耦合传热问题进行了数值模拟。网格划分采用非结构化网格, 湍流模型为 SST $k-\omega$ 模型, 近壁处采用壁面函数法, 采用 SIMPLEC 算法求解速度和压力的耦合。计算获得了无肋和带 45° 肋气膜冷却平板的流场分布和平板内外表面的平均温度和平均换热系数。计算结果表明, 带 45° 肋的气膜冷却平板表面平均温度较无肋气膜冷却平板表面平均温度低, 而近气膜孔区域冷、热表面平均换热系数较无肋时高, 而且肋的存在对增大冷空气出流比有利。

关　键　词: 肋; 气膜冷却; 温度; 换热系数; 数值模拟; 出流比
中图分类号: O241; TK124　　文献标识码: A

1　引　言

对于高温表面(如: 涡轮发动机高温叶片)的气膜冷却来说, 一般为了提高冷却效果, 在冷气通道内往往布置了许多短肋, 以此来增大扰动, 强化内部换热, 提高冷却效果。采用这样的结构必须详细了解气膜冷却通道内的流场分布和肋对内外表面温度的影响。目前, 国内外对带肋通道内的流场研究比较多: Stephens M A 等人研究了一侧带 90° 肋的通道的流场特性和换热系数分布[1]; Yong-Jun Jang 等用雷诺应力湍流模型研究了一侧带 45° 肋的旋转通道内流场分布和壁面换热系数的分布[2]。Chanteloup D 研究了对于通道内同时带有肋和气膜孔出流的情况[3], 主要研究的是 45° 肋和气膜孔出流对通道流场的影响。文献[4] 的研究表明带角度的肋比 90° 肋的强化换热效果更好。

本文则对无肋气膜冷却平板和带 45° 肋的气膜冷却平板通道内外气体的对流换热与平板导热进行了耦合数值模拟, 分析了带 45° 肋对于平板内外表面的平均温度和平均换热系数的影响, 并对比了出流比(气膜孔出流的冷空气质量流量与流道进口冷空气质量流量之比)的变化, 力求得到对气膜冷却高温表面的工程设计具有指导意义的结论。

2　物理模型与数值计算方法

2.1　物理模型

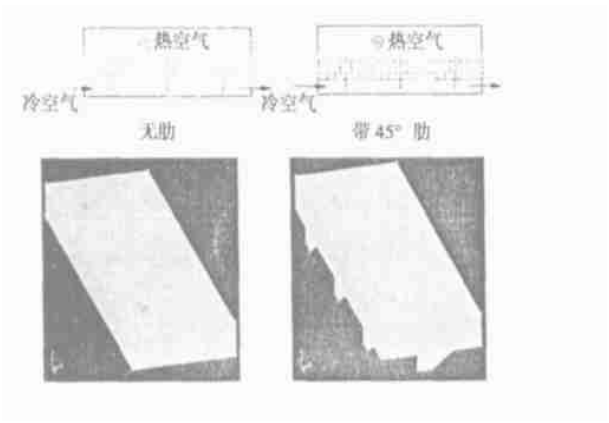

图 1　气膜冷却平板物理结构图

图 1 给出了无肋和带 45° 肋气膜冷却平板结构简图和计算通道结构简图。冷空气进入冷却流道后, 一部分从气膜孔喷出, 进入热空气流道与主流混合后流出。平板长 30 mm, 宽 10 mm, 厚 5 mm; 平板每隔 10 mm 布一直径为 2 mm 圆孔, 均匀布置; 肋为 1mm×1mm, 45° 布置; 主流通道高 6 mm, 宽 30 mm; 冷却通道宽 10 mm, 高 3mm。

2.2　湍流模型

文中计算采用了 SST $k-\omega$ 模型。近壁处湍流采用壁面函数法处理。

2.3　边界条件和计算工况

热空气进口给定质量流量为 0.01 kg/s, 温度为 400 K, 进口 $Re=3.14\times10^4$。冷空气进口给定质量流量为 0.001 ~ 0.003 kg/s, 温度为 300 K, 进口 Re 为 8 407 ~ 25 221。出口给定静压值为 101.325 kPa。通道外边界认为是绝热条件。

2.4　数值计算方法

考虑到气膜孔和肋处流动比较复杂, 对气膜孔和肋处网格进行了加密。整个计算域网格数为(1)无肋: 47 515; (2)带 45° 肋: 294 269。

本文 $N-S$ 方程采用隐式稳态求解, 压力修正

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采用SIMPLEC 算法，各参数的离散采用二阶精度的迎风格式，各方程采用亚松驰，解的收敛标准是残差小于 1×10^{-3}。

3 计算结果分析

在相同冷空气流量时，图 2 表示无肋时垂直于热空气流动方向的某一截面冷空气流动速度矢量图，图 3 表示有 45°肋时同一截面处冷空气流动速度矢量图。由图可以看出，有肋时冷空气在肋后形成了一个漩涡，增大了流动的扰动情况。图 4 表示带 45°肋的平板冷却流体的壁面粒子示踪图。由图可以看出，由于 45°肋的存在，使得冷空气的流动非常复杂，增大扰流程度。

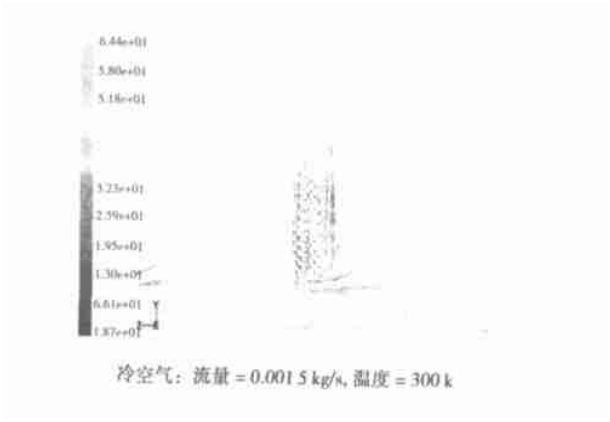

图 2 无肋时冷空气流动

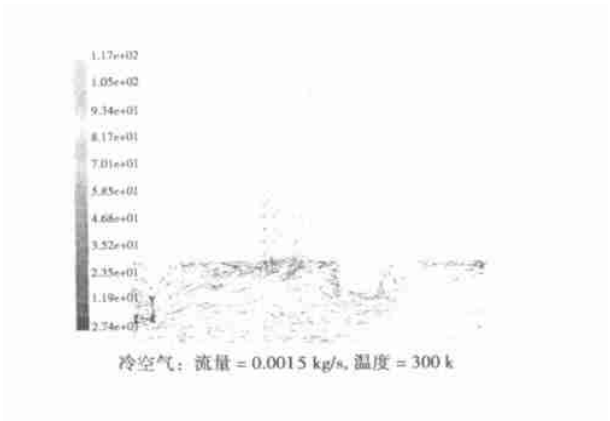

图 3 有 45°肋时冷空气流动

图 5 和图 6 表示无肋和带 45°肋气膜冷却平板热表面(平板与热空气接触面)、冷表面(平板与冷空气接触面)的平均温度随冷空气流量的变化。由图可以看出，随冷空气流量的增大，换热效果增大，无论是否带肋，平板热表面和冷表面的平均温度下降，

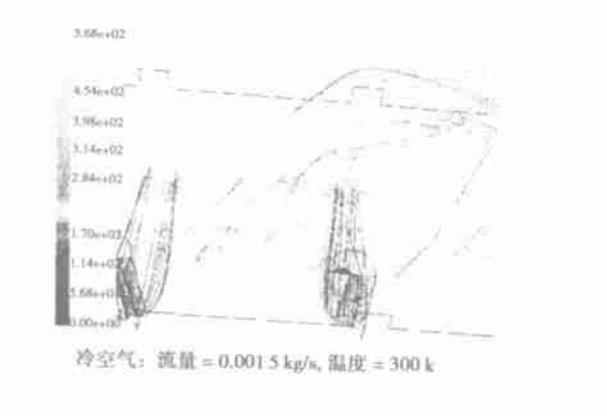

图 4 壁面粒子示踪图

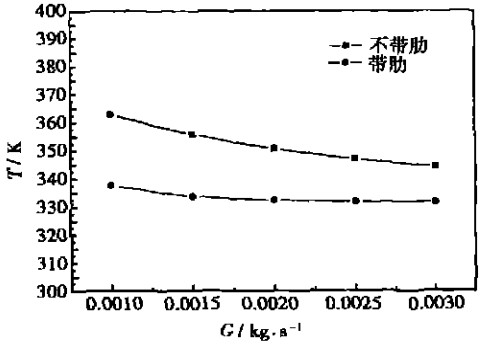

图 5 热表面平均温度随冷空气流量的变化

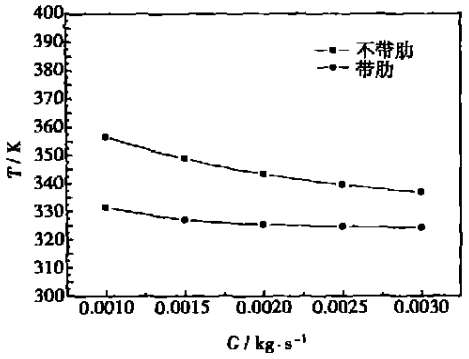

图 6 冷表面平均温度随冷空气流量的变化

带 45°肋时气膜冷却平板热、冷表面的平均温度比不带肋时要低，这是因为肋的存在使冷空气流动的扰动增大，换热效果增强，使得冷表面平均温度下降，相应的使热表面平均温度也下降。

图 7 和图 8 示出了无肋和带 45°肋气膜冷却平板热表面、冷表面上的平均换热系数随冷空气流量

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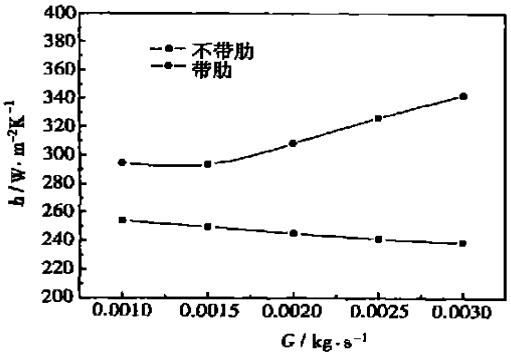

图 7　热表面平均换热系数随冷空气流量的变化

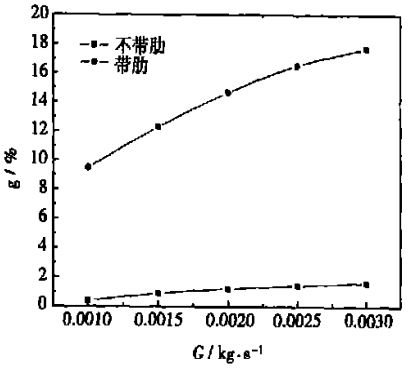

图 9　气膜孔出流比随冷空气流量的变化

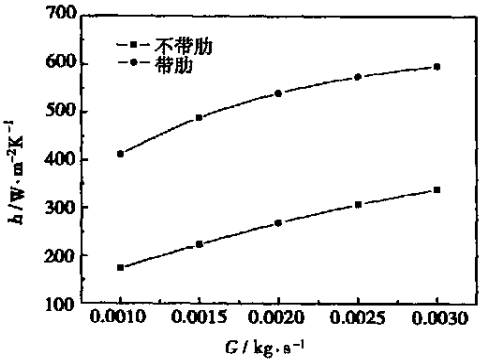

图 8　冷表面平均换热系数随冷空气流量的变化

的变化。由图可以看出,在近气膜孔表面,带 45°肋时气膜冷却平板热、冷表面的平均换热系数比不带肋时要高。这是因为肋的存在,使得冷空气的流动扰动增大,换热增强,冷表面平均换热系数增大,热流密度增大,相应热表面平均换热系数增大。由图还可以看出,随冷空气流量的增大,无论是否带肋,平板冷表面的平均换热系数增大。但是,对于热表面的平均换热系数,无肋时随着冷空气流量的增大而略有减小,这是因为此时的气膜孔出流比很小(见图9),二次流的湍流作用也很小,气膜的影响使换热系数略有下降。带 45°肋时,气膜孔的出流比较大,二次流的湍流作用显现出来,热表面的平均换热系数升高,并且随冷空气流量的增大而升高;而在小流量时,二次流的湍流作用并不明显,此时的热表面平均换热系数变化不明显。

图9表示不带肋和带45°肋时气膜孔出流比 g 随冷空气流量的变化。由图可以看出,无论是否带肋,气膜孔的出流比都随冷空气质量流量的增加而增大,但带 45°肋时的气膜孔出流比增大幅度大于无肋时的气膜孔出流比增大幅度,并且带 45°肋时的气膜孔出流比要远高于无肋时的气膜孔出流比,说明冷空气流道内肋的存在对于气膜冷却的冷气出流有利。

4　结　论

数值模拟结果表明:

(1)带 45°肋气膜冷却平板冷流道内流动比较复杂,扰流程度很大,具有很强的三维流动结构。

(2)带 45°肋气膜冷却平板热表面、冷表面平均温度比无肋气膜冷却平板的热表面、冷表面平均温度低,说明肋的存在对降低固体温度有利。

(3)带 45°肋气膜冷却平板近气膜孔热表面、冷表面平均换热系数比无肋气膜冷却平板的近气膜孔热表面、冷表面平均换热系数高,因此肋的存在使固体的气膜孔下游近孔区域平均换热系数增大。

(4)在带 45°肋气膜冷却平板气膜孔出流比远大于无肋时的气膜孔出流比,并且随冷空气流量的增大而升高。

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锅炉水冷壁高温氧化试验的热分析动力学研究＝**Dynamics Study of the Thermal Analysis of Boiler Water-wall High-temperature Oxidation Tests**[刊, 汉] /ZHAO Hong, WU Guang-jun, LING Be-lin, et al (Education Ministry Key Laboratory for Energy Clean Utilization and Environmental Engineering of the Research Institute of Thermal Energy Engineering under Zhejiang University, Hangzhou, China, Post Code: 310027) //Journal of Engineering for Thermal Energy &Power. —2005, 20(4). —397～401

To analyze the high-temperature corrosion problem in boiler water-walls, high-temperature oxidation tests were conducted of boiler water-wall material 20 g on a high-temperature atmosphere test rig. By using the dynamics method of thermal analysis the test data were processed and analyzed. As a result, the oxidation activation energy and a pre-exponential factor were obtained under the condition of pure air at 810～920 ℃. An analysis was conducted of the shape and element composition, etc of the oxidation products by employing a scanning electronic microscope equipped with an energy spectrum analyzer and the average oxidation speed of 20 g in the oxidation process obtained. **Key words**: material 20 g, high-temperature oxidation, dynamics of thermal analysis, high-temperature corrosion

同轴旋转分层流燃烧器一次风扩展角α的实验研究＝**Experimental Research on the Primary-air Expansion Angle of a Coaxial Swirl and Stratified-flow Burner**[刊, 汉] /ZHANG Hua, ZHANG Ming-chuan, WANG Jing (Mechanical and Power Engineering Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) //Journal of Engineering for Thermal Energy &Power. —2005, 20(4). —402～406

By using a CCD video camera a visual research was conducted of the aerodynamic characteristics at the outlet of a coaxial swirl and stratified-flow low NOx burner. A series of processing were performed of the collected images and data with the primary-air expansion angle being defined. The primary and secondary air flow ratio was analyzed and the impact of the primary and secondary-air blade location on the primary-air expansion angle assessed. The law governing the variation of the expansion angle was also studied. All the above work has laid a foundation for the stratification mechanism research of the coaxial swirl and stratified-flow burner. **Key words**: coaxial swirl and stratified-flow burner, aerodynamic field, visualization, image processing, primary air expansion angle

超细褐煤粉的热解特性及其热解机理＝**Pyrolysis Characteristics of Super-fine Pulverized Lignite and Its Pyrolysis Mechanism**[刊, 汉] /REN Geng-po, ZHANG Chao-qun (Mechanical &Power Engineering Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200240), WEI Li-hong, et al (School of Energy Science &Engineering under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy &Power. —2005, 20(4). —407～410

By employing the traditional method of thermogravimetry it is very difficult to accurately deduce the reaction mechanism of pyrolysis. In view of this, the authors have on the basis of pyrolysis curves and kinetic equations made use of a dual extrapolation method and obtained the pyrolysis mechanism for Yuanbaoshasn lignite at an average particulate diameter of 10.68 μm. It has been ascertained that its pyrolysis mechanism at the low temperature section assumes an Anti-Jander three-dimensional diffusion equation. Meanwhile, the pyrolysis characteristics of Yuanbaoshan lignite of different particulate samples were also studied along with an analysis of the impact of temperature rise rate and particulate size on the pyrolysis characteristics of the pulverized lignite. **Key words**: super-fine pulverized lignite, dual extrapolation method, thermogravimetric analysis, particulate size, pyrolysis mechanism

气膜冷却平板通道的数值模拟＝**Numerical Simulation of a Gas Film-cooled Flat Plate Channel**[刊, 汉] /LU Ben, JIANG Pei-xue (Key Laboratoy of Thermal Energy Power Engineering and Thermal Sciences of the Thermal Energy Engineering Department under Tsinghua University, Beijing, China, Post Code: 100084), LI Ling-bo (Ling Ao Nuclear Power Company Limited, Shenzhen, China, Post Code: 518124) //Journal of Engineering for Thermal Energy &Power. —2005, 20(4). —411～413

A numerical simulation was performed of the coupled heat transfer problem involving the three-dimensional convection heat exchange and heat conduction in a gas film-cooled flat plat channel without ribs and with 45o ribs. A non-structured

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network was adopted for network division. The turbulent flow model is of a SST k - ω one. A wall function method has been adopted for the near-wall location. The coupling of speed and pressure was solved by using a SIMPLEC algorithm. Through calculations obtained were for the gas film-cooled flat plate without ribs and with 45o ribs a flow field distribution and the average temperature and average heat exchange factor at the flat plate inner and outer surface. The calculation results indicate that the channel flow-field structure of the gas film-cooled flat plate with 45o ribs is relatively complicated. The surface average temperature of the flat plate is lower than that of the gas film-cooled flat plate without ribs. However, the cold and hot surface average heat exchange factor near the gas-film pore zone is higher than in the case when no ribs are provided. Furthermore, the presence of ribs is favorable for enhancing cold-air outward flow ratio. **Key words**: rib, gas film cooling, temperature, heat exchange factor, numerical simulation, outward flow ratio

行星齿轮啮合刚度对其振动特性的影响＝**Impact of Planetary-gear Meshing Rigidity on Its Vibration Characteristics**[刊, 汉] / WANG Chun-guang, CHANG Shan, LI Ying-sheng (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy & Power. —2005, 20(4). —414 ~416, 420

A multi-freedom mathematical model was set up for a single-stage straight-tooth planetary gear transmission. Within this system, on the basis of the special features of planetary gear natural frequency and vibration mode, deduced were a formula showing the sensibility of an eigenvalue to meshing rigidity and the relationship between this eigenvalue and meshing strain energy. The results of an analysis indicate that the meshing rigidity has a relatively great influence on the intrinsic characteristics of two rotating modes, two groups of displacement mode and two planetary modes. Through the distribution of meshing strain energy one can clearly detect the influence of meshing rigidity changes on the system intrinsic characteristics. **Key words**: planetary gear, meshing rigidity, vibration characteristics

带监督项的模糊前馈反馈控制在船用锅炉水位控制中应用＝**Fuzzy Feedforward and Feedback Control with a Supervision Item and Its Applications**[刊, 汉] / XIAO Hang, CHEN Bing, NI Ning (Teaching & Research Section of Steam Power, Naval Engineering University, Wuhan, China, Post Code: 430033), TIAN Guang (Military Representative Office Resident at Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy & Power. —2005, 20(4). —417 ~420

Because of a "false water level" for the boiler drum, a controlled object in a marine steam power plant and of the difficulty of establishing a precise mathematical model the use of an onventional control strategy often fails to ensure the control quality of the drum water level. In case of high frequency of operating regime changes there often occur such failures as "water overflow" or "boiler dry". To cope with the problem, the authors have proposed a fuzzy feedforward and feedback control scheme with a fuzzy supervision item. Under this control scheme the use of fuzzy feedforward compensation makes it possible to measure the influence of interference to the system output and a fuzzy supervisor is utilized to attenuate the impact caused by a non-minimal relative link. The application of the proposed control scheme on an experimental machine unit has demonstrated its satisfactory results.

电站锅炉安装过程干涉现象的评判方法＝**A Method for Appraising Interference Phenomena during the Hoisting of a Utility Boiler**[刊, 汉] / RUI Xiao-ming, CUI Yan-bin, MA Zhi-yong, (School of Energy & Power Engineering, Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, North China Electric Power University, Beijing, China, Post Code: 102206) //Journal of Engineering for Thermal Energy & Power. —2005, 20(4). —421 ~424

On the basis of a self-developed practical boiler hoisting construction work involving a rapid model building and data structuring a study was undertaken of the computer appraisal technique with regard to the interference phenomena in the hoisting of a utility boiler, making it possible to accurately judge the interference situation of the structural items to be hoisted and already installed items. The utilization of the above technique can be conducive to effectively enhancing the design quality of boiler hoisting schemme , accelerate installation speed and increase construction work cost-effectiveness. Key words: boiler erection, interference analysis, CAD

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