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前缘气膜孔对涡轮静叶冷却效果影响的数值模拟

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摘　要: 采用全三维数值模拟技术, 利用 $k-\varepsilon$ 双方程湍流模型和 SIMPLE 算法, 通过求解三维粘性可压缩 Favre 平均 Navier－Stokes 方程, 对某新型燃气轮机第一级气膜冷却静叶叶栅的三维湍流流场进行了数值模拟。分别通过改变燃气轮机前缘气膜孔的参数, 计算出叶片外表面的温度分布和冷却空气流量大小。结果表明, 前缘气膜孔的直径、数目以及射流方向对叶片表面冷却效果的影响是非常显著的。从而提出了一种叶片前缘气膜冷却设计的新方案, 为工程设计提供了有价值的参考。

关　键　词: 燃气轮机; 前缘气膜冷却; 数值模拟; 涡轮; 第一级静叶
中图分类号: TK474.7　　文献标识码: A

1　前　言

随着现代燃气轮机对功率和效率的不断追求, 涡轮进口温度不断得到提高, 涡轮部件热负荷也大大增加。其中涡轮第一级静叶受到的热负荷最大, 必须对它进行有效的冷却。而叶片前缘直接面对高温燃气的冲击, 因此对前缘气膜冷却的研究便显得非常重要[1]。

气膜冷却首先关注的就是叶片表面的温度分布, 其中气膜孔的设计直接影响叶片的冷却效果。另一方面, 气膜冷却的气源一般都引自压气机, 从整机性能上来讲, 其流量的多少直接影响到整个发动机的功率和效率。如何在保证叶片热负荷强度允许的条件下, 尽量少地牺牲冷却空气, 一直是气膜冷却设计的主要原则之一。现今有关气膜孔设计基本都停留在经验设计的基础上, 但是不同冷却对象的叶型、工作参数有一定差异, 特别是一些新设计的高温比、大流量、长寿命的重型燃气轮机, 仅仅依靠一些经验性的设计思想还不足以最大限度地减少冷却空气量并优化冷却效果。借助于现今高速发展的实体建模软件、CFD 软件以及计算机技术, 完全有能力对新设计的气冷叶片进行实体仿真, 根据仿真结果, 设计师可以方便地通过修改气膜孔的尺寸、位置、入射角度等参数, 在叶片冷却和冷气消耗量上达到一个合理地匹配, 这对改善燃气轮机总体性能具有重要意义。

2　物理模型

一般而言, 气膜冷却叶片除了前缘出口, 通常都还有尾缘出口, 理想的气膜冷却叶片仿真是对包括叶片前缘、尾缘出口在内的内外部流场与叶片导热进行耦合数值模拟, 但是由于目前计算机速度以及 CFD 软件的不足, 对实际叶片采用内外流场与固体叶片导热的耦合计算还比较困难。因此, 本文没有考虑叶片壁面热传导对壁温的耦合影响, 而只是单纯考虑前缘气膜孔的冷却空气与流道内的热燃气掺混在叶片表面附近形成的冷却气膜对叶片表面温度分布的影响。这一方面是由于尾缘出口冷气主要影响叶片尾缘附近的尾迹流场温度, 对于叶片表面温度分布并无明显影响, 前缘冷却气膜则是叶片表面温度分布的主要影响因素。另一方面是在通过对带有实际冷却腔并有尾缘出口的该型燃机叶片的数值模拟结果表明, 所得到的叶片表面温度分布与本文中的计算结果一致, 但耗时甚多。如果单单从研究叶片表面气膜冷却温度分布出发, 本文所采用的计算模型的经济性和实用性都较高。

本文所研究的是某重型燃气轮机带气膜冷却的第一级静叶, 图 1(a)提供了其前缘冷却气膜孔的分布。该叶片的气膜孔一共有 6 排, 在孔径的布置方面, 各排孔的尺寸和侧向倾角都不相同, 每排孔在径向的布置特征也不相同。第一排和第六排孔为间距相等的水平直射孔, 第二排～第五排孔的径向布置图如 1(b)所示。

首先应用 CAD 软件根据实体尺寸建立了叶栅通道, 并在轴向往前缘上游和尾缘下游分别延长了

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一个弦长作为计算域。所研究的叶栅共有 40 个叶片组成,选择其中的一个流道为计算区域,周向为周期性边界条件,叶片表面开孔作为冷气进口。计算采用商用软件 Fluent,计算域如图 2 所示。

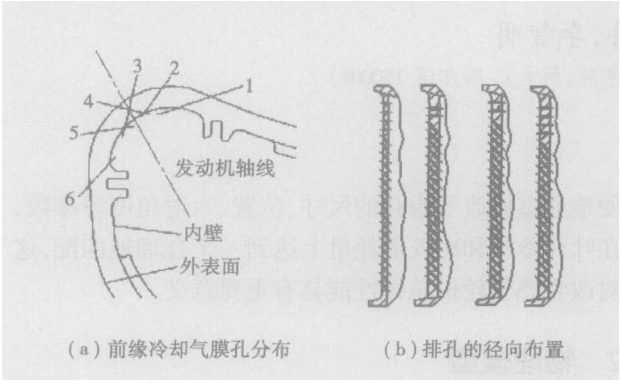

图 1 叶片气膜孔分布

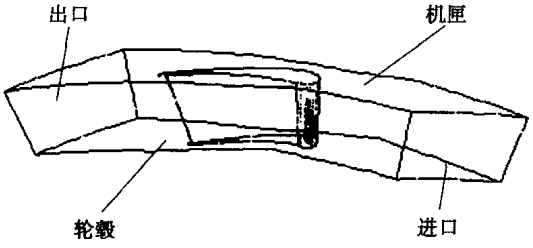

图 2 计算域

3 计算方法

采用有限体积法及全隐式多网格耦合求解技术求解三维定常粘性 $N-S$ 方程。湍流模型为标准 $k-\varepsilon$ 模型加壁面函数法。计算域整体为粗密自动过渡的非结构划网格。

边界条件分别为燃气轴向的流量进口和气膜孔沿入射方向的压力进口。总燃气流量为 320 kg/s,总温 1 483 K;冷却空气压力为 1.49 MPa,总温 671 K;出口给定平均静压为 0.82 MPa,所有壁面都设置为绝热边界。

4 计算结果及分析

4.1 实际气膜冷却叶片表面冷却效果

为了更好地比较气膜冷却的效果,首先针对无气膜冷却时的叶片进行了数值模拟。图 3 为叶背表面的静温分布,可以看到叶背表面的静温相对较低,除头部外均为 1 360 K 以下。图 4 给出了叶盆表面的静温分布,可以看到由头部至叶片尾缘静温单调下降,头部高温区的范围比较大。可知无冷却时叶片表面的高温区主要集中在叶片头部以及叶盆大部分区域,这也应该是气膜冷却的核心区域。

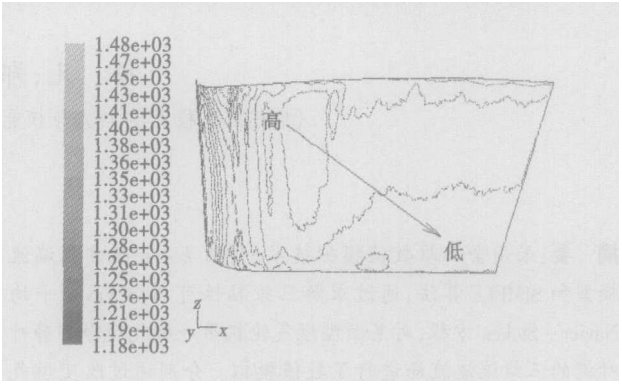

图 3 无冷却时叶背表面静温云图

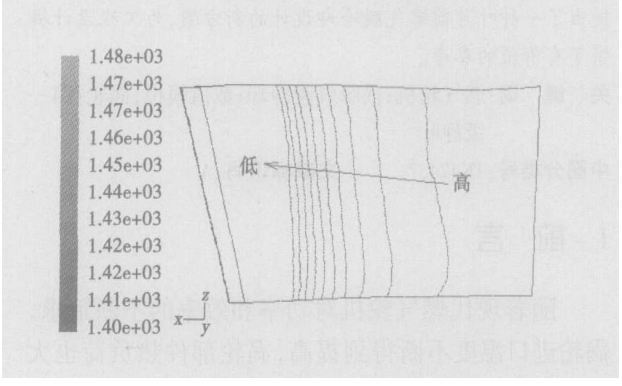

图 4 无冷却时叶盆表面静温云图

对实际气膜冷却叶片进行的仿真计算。图 5 给出了叶片表面高温区(静温 1 380 ~ 1 480 K)的温度分布,可以看出叶片头部基本上已经被气膜很好地覆盖住,表面静温大多控制在 1 350 K 以下。但是也可以明显地看到第二排孔与第三排孔之间存在一条冷却薄弱区,此处静温保持在 1 420 ~ 1 440 K,沿径向呈带状分布。为了考察造成这一高温区域的真正原因,现在对原该承担这一冷却任务的第三排孔进行分析。图 6 提供了滞止区局部放大的温度云图,此时可以清晰地看到第三排孔出气的流动特征,受主流燃气的影响绝大部分的冷气都贴着叶背向下游流去,而只有极少量的冷气得以沿叶盆流出,而直接造成了这一高温区。

另外,与无冷却时叶盆的温度分布趋势相比,有冷却的叶盆表面的静温分布并不是由头部向尾缘递减,而是先增后减,核心区出现在叶盆的中央部位,逐步向头尾两端扩散,核心区最高静温为 1 445 K。初步分析产生这种现象的原因为,由于吹风比很大,

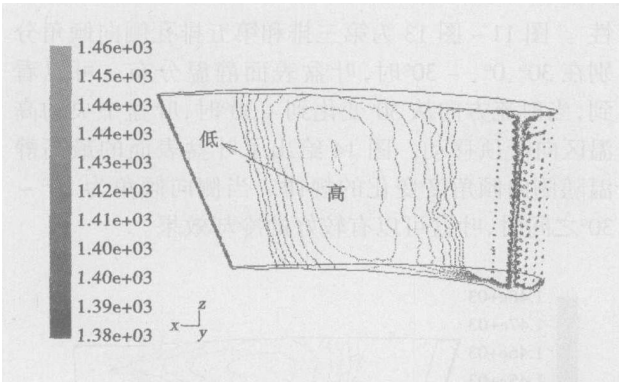

图 5　实际气冷叶片表面静温分布

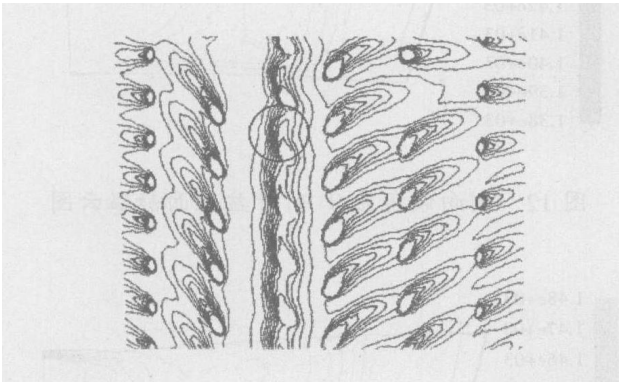

图 6　前缘气膜孔局部温度云图

冷却空气在喷出后不远处就与叶盆壁面分离, 与叶盆壁面相接触的混合气仅仅是部分掺混了燃气且流速较低, 故静温下降并不明显。而当燃气由叶盆中央区流向叶栅喉部的过程中, 燃气不断加速使静温进一步得到下降, 叶盆壁面温度也随之下降[2]。

此外, 参照图 5 可以发现在叶片头部叶根和叶顶处均有一很小的冷却盲区。冷却气流没有覆盖该盲区就直接向下游流出。如果结构设计允许的话, 在这两处增加几个冷气射流孔可以明显改善该处的壁面冷却效果。

4.2　孔排的设置对气膜冷却效果的影响

为了改善第三排和第四排气膜孔之间的冷却薄弱区, 使冷却叶片的头部有更均匀的气膜覆盖, 现改变第三排孔的位置, 将其沿叶盆向尾缘方向分别移动 0.6 mm、0.8 mm、1.0 mm、1.2 mm 和 1.5 mm 距离, 以考察对冷却效果的影响。图 7 为第三排气膜孔位置改变后叶片头部气膜覆盖区(静温 1 250 K 以下)的温度云图。从图上可以看到, 第三排孔对该冷却薄弱区的影响是显著的, 当移动 1.5 mm 时, 该薄弱区已经消失了。图 8 给出了叶片前缘滞止区沿径向(z 轴)的静温分布随移动距离的变化, 同样可以看到, 随移动位置的增大, 滞止区的冷却效果越来越好。其主要原因是叶片驻点位置位于第二排和第三排孔之间, 通过改变位置使第三排孔向驻点移动, 从而有更多的冷却空气能沿叶盆流出, 这样就可以使第二排和第三排孔之间的冷却薄弱区逐渐变小直到消失。

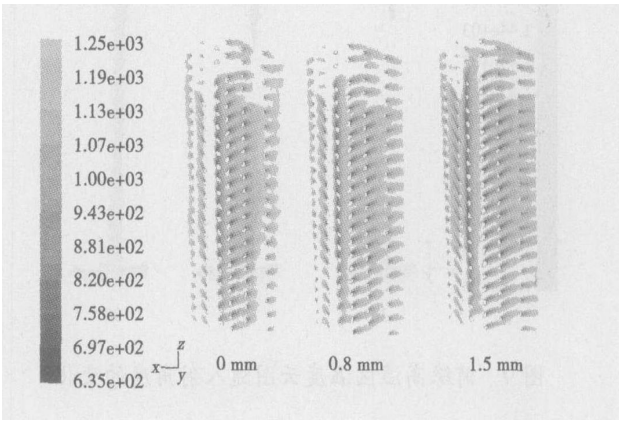

图 7　前缘气膜覆盖区随第三排孔位置的变化

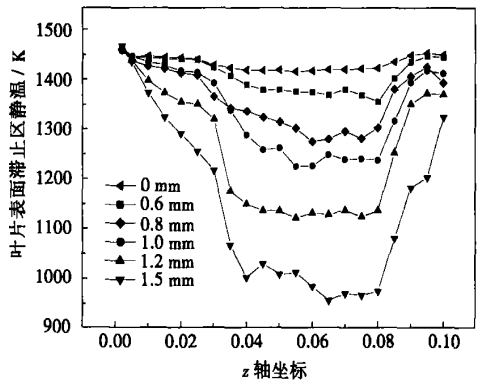

图 8　滞止区径向静温分布随第三排孔位置的变化

4.3　射流角度对气膜冷却效果的影响

气膜孔冷却的射流角度包括入射角和侧向倾角, 它们对叶片表面的冷却有着不一样的影响。基于改进头部冷却后的模型, 本文分别通过改变侧向倾角和入射角度, 对叶片表面冷却效果的影响进行了研究[3~4]。

入射角度也就是冷却气流入射方向在流面内与叶片表面切线方向的夹角。针对第三排孔, 分别考察了入射角度为 30°、40°、50°、60°、70°、80°、90°、100° 时对气膜冷却的影响。图 9 给出了入射角度为 30°、70°、90° 时叶片前缘高温区静温分布图, 图 10 为头部滞止区沿径向静温分布随入射角度的变化规律。可以看出, 冷却空气从气膜孔射出后, 依靠主流将冷气

压向壁面，使冷气附着在壁面上形成气膜。如果冷气的入射角度太大，射流就可能脱离壁面而射入主流不能形成壁面气膜，从而失去热防护作用。显然入射角越小，气膜就越不容易脱离壁面。

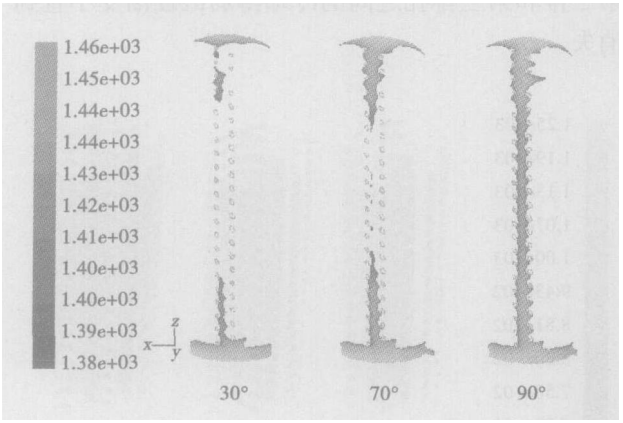

图 9 前缘高温区温度云图随入射角度的变化

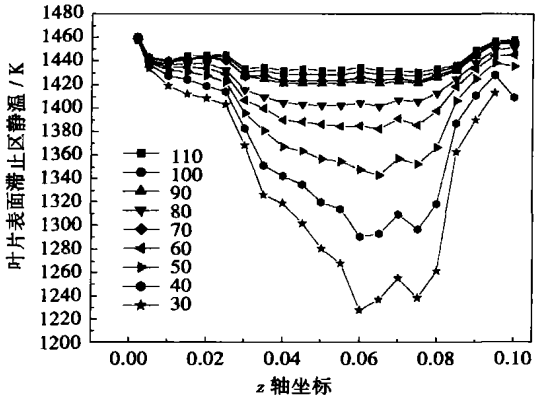

图 10 滞止区径向静温分布随入射角度的变化

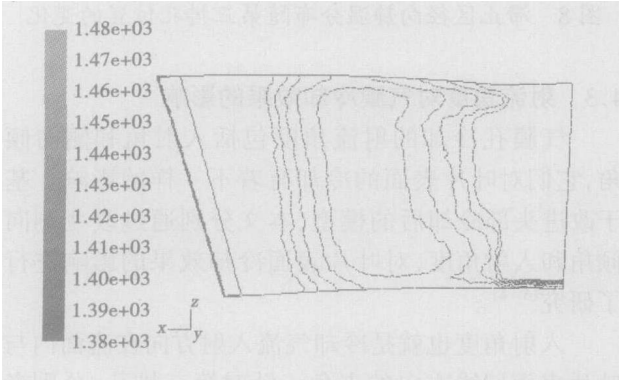

图 11 侧向倾角为 30° 时叶盆表面静温云图

侧向倾角为射流方向与叶片法线方向在子午面内的夹角，射流方向偏向叶顶方向为正向。侧向倾角的存在有助于改善径向气膜冷却效果的不均匀性。图 11～图 13 为第三排和第五排孔侧向倾角分别在 30°、0°、－30° 时，叶盆表面静温分布。可以看到，当射流方向从 30° 变化到－30° 时，叶盆中央的高温区向叶顶移动。图 14 给出了叶盆表面的最高静温随侧向倾角度变化的规律。当侧向倾角为 20°～30° 之间时，叶盆可以有较好的冷却效果。

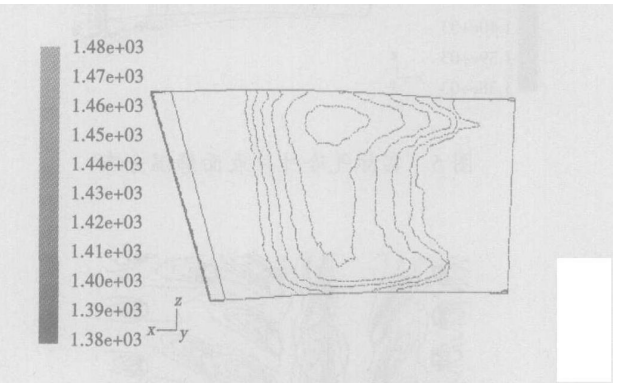

图 12 侧向倾角为 0° 时叶盆表面静温云图

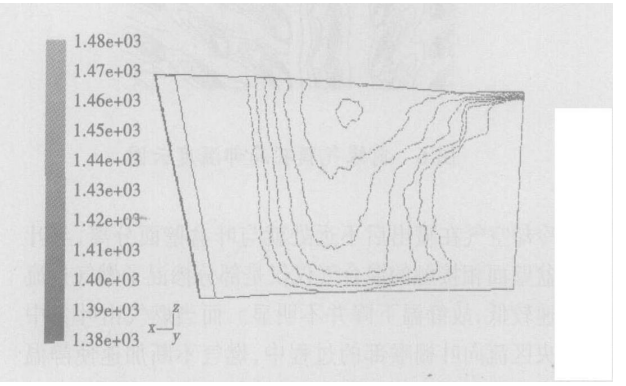

图 13 侧向倾角为－30° 时叶盆表面静温云图

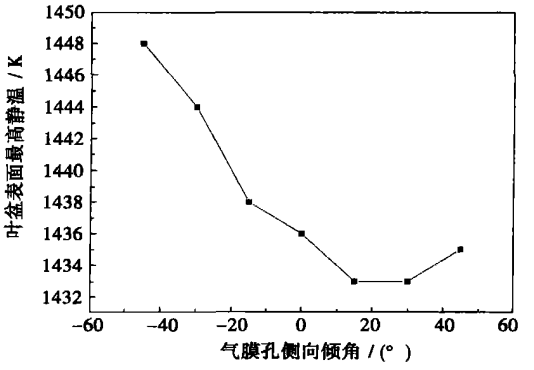

图 14 叶盆表面最高静温随侧向倾角的变化

4.4 气膜孔孔径对气膜冷却效果的影响

本文分别针对气膜孔孔径为 ϕ1.0 mm、

φ1.2 mm、φ1.4 mm、φ1.6 mm 的叶片进行了数值模拟, 得出了冷却空气流量和叶盆表面最高静温随气膜孔孔径的变化规律。从图 15 和图 16 中可以看到, 随着气膜孔孔径的增大, 冷却空气的消耗随之增大, 叶片表面的冷却效果也得到改善[5]。

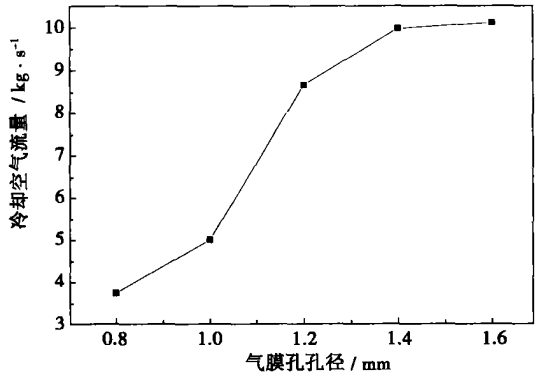

图 15　冷却空气流量随气膜孔孔径的变化

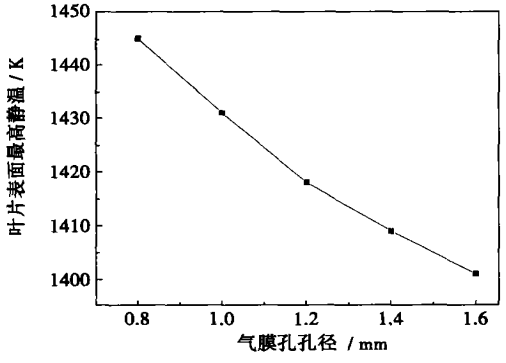

图 16　叶盆表面最高静温随气膜孔孔径的变化

5　结　论

通过对比有无冷却以及改变气膜孔参数后叶片表面的冷却效果, 可以得到以下几个结论:

(1) 该型空冷叶片的冷却气膜基本上可以较好地覆盖住叶片的前缘, 但是在头部仍存在有一条明显的冷却薄弱区, 通过改变第三排孔的位置可以使它消除。叶背的温度相对较低, 叶盆的高温区在中央部位。

(2) 对滞止点附近气膜孔的设计必须特别注意, 准确地估算出滞止点的位置对叶片前缘的冷却尤为重要, 合理地安排各排孔之间的位置以及射流方向, 可以使叶片前缘有很好的气膜覆盖。

(3) 增大气膜孔孔径可以明显地改善叶片表面的冷却效果, 但是将以消耗更多的冷却空气为代价。

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(何静芳　编辑)

舰用动力装置

用于护卫舰的 CODAG 装置

据《Diesel & Gas Turbine Worldwide》2005 年 9 月号报道, 德国海军在"Sachsen"级护卫舰上率先装备了 CODAG(柴燃并车使用联合)系统, 该系统由 1 台燃气轮机和 2 台柴油机组成, 其中的齿轮传动轮系既可以用于速度转换又可以用于扭矩转换, 并且还可作为 2 个可调螺距螺旋桨之间的连接部件。

在 CODAG 系统中, 燃气轮机的功率通过 CCG(横向连接齿轮箱)被传递到 2 个主减速齿轮箱上; 2 台柴油机设置在船舶中部, 可以通过一体的液力偶合器和高弹性的方向轴把功率传递到主齿轮箱上。

该护卫舰采用的低噪声传动装置, 通过人字齿轮啮合方式来降低噪声。

(吉桂明　供稿)

化工动力多联产系统及其集成优化机理＝**Chemical Engineering Power Polygeneration System and Its Integrated Optimization Mechanism**[刊, 汉] /LIN Ru-mou, JIN Hong-guang, GAO Lin (Research Institute of Engineering Thermophysics under the Chinese Academy of Sciences, Beijing, China, Post Code: 100080) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —331 ~ 337

The theory of system integrated optimization represents a most important scientific issue playing a key role in the development of a polygeneration system. In this regard, relevant research has been carried out under the support of a national major scientific research project. Research results achieved at a substage are described by the authors, including: the basic concept, intrinsic characteristics and specific features of a chemical engineering power polygeneration system along with an exposition of the approaches proposed for the study of the system integration principles as well as the optimization integration means embodying such principles. Moreover, the polygeneration system has been classified into five basic categories on the basis of the system integration structured layers, namely, simple parallel-connected type, synthesized parallel-connected type, simple series-connected type, synthesized series-connected type and series and parallel-connected synthesized type etc. Some specific cases with an analysis of their main characteristics etc. are presented. **Key words**: polygeneration system, chemical engineering and power, integrated optimization, basic types

活性炭床加微波辐射脱硫脱硝的研究＝**A Study of the Desulfuration and Denitration on Active Carbon Beds Provided with Microwave Irradiation**[刊, 汉] /MA Shuang-chen, ZHAO Yi, MA Xiao-ying, et al (Environment College under the North China Electric Power University, Baoding, China, Post Code: 071003) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —338 ~ 341

A brief description is given of the microwave heating principles and the development of microwave chemistry along with an overview of microwave-based desulfuration and denitration. By the use of a microwave device and active carbon, a study of the simulation of flue gas with a simultaneous desulfuration and denitration has been conducted. With the help of this technology, 96% of the carbon monoxide and sulfur dioxide can be directly decomposed into environment-friendly nitrogen as well as valuable and recoverable elementary sulfur. Analyzed is the microwave-induced catalytic reduction-based desulfuration and denitration mechanism, pointing out that the microwave reduces the activation energy of the above-cited removal reactions. This indicates that the microwave not only promotes the process of reactions with its thermal effect but also gives full play to its catalytic action. **Key words**: microwave, desulfuration, denitration, induced catalytic reduction, active carbon

影响冷热电联产系统经济性因素的灰关联分析＝**An Analysis of the Ash Correlation of Various Factors Influencing the Cost-effectiveness of a Combined Refrigeration, Heat and Power Trigeneration System**[刊, 汉] /FENG Xiao-ping (Civil Engineering Department of the Jiangnan University, Wuxi, China, Post Code: 214122), ZHANG Bei-hong (Shanghai Academy of Architectural Science, Shanghai, China, Post Code: 200032), LONG Wei-ding (Sino-German Engineering College under the Tongji University, Shanghai, China, Post Code: 200092) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —342 ~ 344

Multifarious are the factors influencing the operational efficiency of a combined heat and power cogeneration system. To identify the major influencing factor and the dominant/subordinate relationship from among a variety of factors constitute an important task for the cost-effectiveness analysis of a system. Analyzed are the factors influencing the cost-effectiveness of a gas turbine based heat and power cogeneration system in Shanghai region by adopting a mathematic model involving an ash correlation analysis in an ashy color theory. The results show that according to the current price of natural gas, electricity purchase and sales price in Shanghai City, one can conclude that among the five factors, namely, gas turbine efficiency, investment outlays for gas turbines, price of natural gas, electricity purchase price and sales price, the natural gas price is the most conspicuous factor having a maximum impact on the cost-effectiveness of the gas turbine based heat-and-power cogeneration system. **Key words**: Gas turbine, heat and power (refrigeration) cogeneration, cost-effectiveness, ash correlation analysis, correlation degree

前缘气膜孔对涡轮静叶冷却效果影响的数值模拟＝**Numerical Simulation of the Impact of Leading-edge Gas-film Pores on Cooling Effectiveness in Turbine Stator Blades**[刊, 汉] /YANG Fan, ZHENG Hong-tao, LI Zhi-ming (Power and Nuclear Energy Engineering College under the Harbin Engineering University, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —345 ~ 349

Through the adoption of a full three-dimensional numerical simulation technology and by use of a $k-\varepsilon$ dual equation turbulent model and algorithm SIMPLE, a numerical simulation was conducted of the three-dimensional turbulent flow field of the film cooled stator-blade cascade at the first stage of a new type of gas turbine. The simulation was accomplished by solving a three-dimensional viscous compressible Favre-averaged Navier-Stokes equation. Through a change in parameters of the leading-edge film pores of the gas turbine, the temperature distribution on the outer surface of stator blades and its cooling-air flow rate have been calculated respectively. The results show that the diameter, quantity and jet flow direction of leading-edge film pores can very conspicuously impact on the blade surface cooling effectiveness. In view of the above, a new version is proposed for the blade leading-edge film cooling design, providing a valuable guide for relevant engineering designs. **Key words**: gas turbine, leading-edge film cooling, numerical simulation, turbine, first stage stator blades

一种新型微热管传热性能的实验研究=**An Experimental Study of the Heat Transfer Performance of Innovative Micro HeatPipes**[刊, 汉] /TANG Qiong-hui, XU Jin-liang, LI Yin-hui, et al (Guangzhou Energy Source Research Institute under the Chinese Academy of Sciences, Guangzhou, China, Post Code: 510640) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —350 ~ 354

An experimental study is conducted of a new type of flat-plate micro heat pipes featuring a zero-chamfer curved surface. Based on heat resistance, the thermodynamic performance of micro heat pipes is studied under such conditions as different inclination angles, working media and liquid-filling ratios. To facilitate its analysis, the total heat transfer resistance of the heat pipes is divided into four items: heating heat-transfer resistance, heat-transfer resistance of evaporation section, heat-transfer resistance of condensation section and heat-sink heat-transfer resistance. The following conclusions have been arrived at through tests: the factors that cause the main change in the total heat-transfer resistance of the micro heat pipes are the heat-transfer resistance of both the condensation section and the evaporation one. Compared with corresponding flat-plate type heat exchangers without working media, the main heat-transfer resistance of a test piece becomes the heat sink one. The heat-transfer resistance in both the evaporation section and the condensation section accounts for a relatively small proportion. According to different liquid filling ratios and inclination angles, the heat transfer limit of a micro heat pipe will be caused respectively by local dry burning and a transition from nuclear boiling to film boiling. The experiments show that this new type of micro heat pipe has bright application prospects, but an in-depth study of its operating mechanism is still needed. **Key words**: flat-plate type micro heat pipe, working medium, inclination angle, liquid filling ratio, electronic cooling

超声波除垢与强化传热实验研究=**An Experimental Study of Incrustation Removal and Intensified Heat Transfer by Ultrasonic Techniques**[刊, 汉] /FU Jun-ping, LI Lu-ping (Energy Source and Power Engineering College under Changsha University of Science and Technology, Changsha, China, Post Code: 410076), LIU Ze-li, LI Qiu-yi (Huayin Zhuzhou Thermal Power Generation Co. Ltd., Zhuzhou, China, Post Code: 412000) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —355 ~ 357

An experimental study is conducted of the matching relations between ultrasonic wave power on the one hand and incrustation inhibition and removal on the other as well as of the effect of sonic cavitation-intensity on heat transfer coefficient when the Reynolds number of fluid in a tube amounts to 5.11×10^4. The research results show that the ultrasonic waves attain an incrustation inhibition effect iveness when the ultrasonic wave power is below 200 W and become effective in removing incrustation when the ultrasonic wave power is over 200 W. The incrustation removal effect is in direct proportion to the magnitude of the ultrasonic wave power. Furthermore, the ultrasonic wave power has an obvious effect on heat transfer intensification. When the ultrasonic wave power is 300 W, the heat transfer coefficient will be 765 W/(m^2 ·K), achieving an optimum heat transfer effect. In addition, a preliminary study is performed of the possible impact on incrustation removal effect when a change in ultrasonic-wave propagation direction takes place. **Key words**: ultrasonic incrustation removal, cavitation intensity, heat transfer

螺纹槽管错排管束的传热特性及流动阻力特性研究=**A Study of Heat Transfer Performance and Flow-resistance Characteristics of Staggered Tube Bundles Composed of Spirally Fluted Tubes**[刊, 汉] /AN Yue-li, ZHAO Li, HUANG Xin-yuan (Energy Source and Power Engineering College under the Shandong University, Jinan, China, Post Code: 250061) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —358 ~ 361

As a kind of effective intensified heat transfer elements, spirally fluted tubes are widely used. On the basis of experim-