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刷式密封泄漏流动特性影响因素的研究

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摘 要: 采用基于改进 Darcian 多孔介质模型的 Reynolds-Averaged Navier-Stokes 方程求解技术, 用数值模拟的方法分析了在一定径向间隙条件下压比和刷丝束厚度对刷式密封泄漏流动特性的影响规律。根据发表的刷式密封泄漏量试验数据, 确定了刷丝束多孔介质的渗透率系数。利用所确定的刷丝束多孔介质渗透率系数, 分别计算了在一定径向间隙条件下 7 种压比和 5 种刷丝束厚度时某轴端刷式密封的泄漏量和泄漏流动形态。计算结果表明, 压比和刷丝束厚度均影响刷式密封的泄漏量, 在一定压比条件下, 泄漏量随着刷丝束厚度的增加而减小; 在一定刷丝束厚度条件下, 泄漏量随着压比的增加而增加。因为刷式密封泄漏量与压比和刷丝束厚度近似成线性变化, 所以压比和刷丝束厚度对刷式密封内泄漏流动形态的影响可以忽略。

关 键 词: 汽轮机; 刷式密封; 多孔介质模型; 泄漏量; 数值模拟

中图分类号: TK263.6 文献标识码: A

引 言

现代大功率火力发电厂技术对动力装置越来越高的要求推动了汽轮机密封技术的不断发展, 先进的转子和静子间的动密封技术可显著提高大功率汽轮机的工作效率和可靠性[1]。具有良好的转子动力学特性和密封性能的刷式密封广泛应用于航空发动机和燃气轮机密封装置中[2~3]。刷式密封技术在大功率汽轮机轴封的应用得到了各大汽轮机制造商的重视。刷式密封的泄漏量远小于迷宫式密封, 使汽轮机的泄漏损失大幅下降, 并改善了转子的稳定性[2]。刷式密封的结构如图 1 所示。刷式密封主要部件是上游环, 刷丝束和下游环组成, 其中刷丝束是直径为 0.05~0.07 mm 的细金属丝捆扎在一起, 按与轴径向 30~60° 方向排列的部件。刷丝束自由端以一定角度与轴表面接触, 既可以减少刷毛的磨损, 又可以在轴瞬间大幅径向位移后, 刷丝束可弹回并保持密封间隙不变[2]。

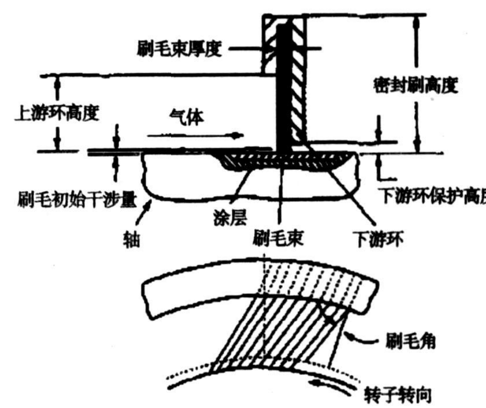

图 1 刷式密封的结构[2]

刷式密封在透平机械的成功应用要求进一步加强刷式密封内的泄漏流动特性的研究, 为拓宽刷式密封的应用范围提供理论基础。随着计算流体动力学技术(CFD)和试验测试技术的发展, 对刷式密封内流动的研究得到了飞速发展[4~8]。刷式密封的泄漏流动特性数值分析方法一般有两类方法, 一类是基于刷丝横向结构交错排列的“刷式密封简单泄漏模型”及有关修正方法[3]。另一类是基于多孔介质模型的 CFD 方法。这类方法将刷式密封的刷丝束认为是各向异性多孔介质进行处理[6~8]。基于多孔介质模型 CFD 方法由于更多地考虑了真实流动特征而得到设计和研究人员的广泛应用。Chew 等人针对传统 Darcian 多孔介质模型[6], 提出了考虑粘性阻力和内部阻力效应的改进 Darcian 多孔介质模型并成功地应用于分析刷式密封的泄漏流动特性。本文采用基于文献 [6] 提出的刷式密封多孔介质计算模型和方法, 分析工程实用的三级刷式轴封的泄漏特性及其影响因素。黄学民等人提出了采用多孔介质模型和一维动量方程对简单的单排刷式密封进行了泄漏流动分析并与试验数据进行了比较[7], 验证了所提出的方法具有一

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定的可靠性。Dogu 采用改进 Darcian 多孔介质模型和数值求解轴对称二维 Reynolds-Averaged Navier-Stokes（*RANS*）方程技术对试验的单排刷式密封进行了详细地计算和分析[8]，同时深入细致地分析了不同上游环和下游环几何结构对刷式密封流动特性的影响规律，进一步验证了多孔介质模型在刷式密封性能分析中的可靠性。

多排刷式密封在大功率汽轮机轴封的应用可提高机组的效率和经济性，但是关于多排刷式密封性能的研究报道很少，大多针对试验用的简单单排刷式密封进行分析研究。针对大功率汽轮机传统高低齿迷宫式密封的结构，为了进一步减小泄漏量，将高低齿迷宫式密封设计成 3 排刷式密封。本文采用基于改进的 Darcian 多孔介质模型数值求解三维 RANS 方程技术，对其泄漏流动特性进行研究分析，分别研究了压比和刷丝束厚度对其密封性能的影响，为刷式密封在大功率汽轮机轴封改进设计中的应用提供理论依据和技术支持。

1　多孔介质模型和渗透率系数

图2 给出了试验测试的刷式密封几何结构[4]。转子半径是 60.88 mm，刷丝束厚度 0.6 mm，上游环和下游环高度分别是 1.4 和 10.32 mm。计算区域包括上游环区域，刷丝束多孔介质区域和下游环区域。上游环和下游环流动区域是可压缩紊流流动。其流动控制方程表达如下：

$$\partial \rho u_i / \partial x_i = 0 \tag{1}$$

$$u_j \cdot (\partial \rho u_i / \partial x_j) = -\partial P / \partial x_i + \mu \partial^2 u_i / (\partial x_j \partial x_j) \tag{2}$$

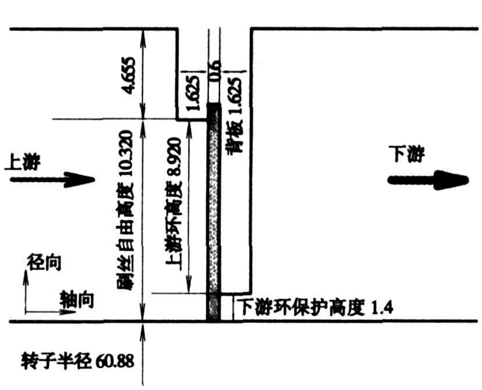

图 2　试验采用的刷式密封几何结构

刷式密封的刷丝束区域构成多孔介质流动。采用多孔介质模型处理刷丝束内流动需要确定其渗透率系数。刷丝束多孔介质渗透率系数的确定需要有刷式密封的泄漏量试验数据确定。多孔介质内流动相对于非多孔介质流动要受到附加的流体与刷丝束表面间摩擦阻力的作用。多孔介质的渗透率系数是多孔介质通过流体能力的表征参数。牛顿流体通过多孔介质的速度和压降可由 Darcy 定律给出：

$$-\mathrm{d}p/\mathrm{d}x_i = \mu u_i / K_i \tag{3}$$

其中：x_i—流动的方向；K_i—多孔介质的渗透率系数；u_i—x_i 上的流动速度；P 和 μ—流体的压力和动力粘性系数。

式(3)是只考虑了粘性阻力效应的线性化的 Darcian 多孔介质模型。针对刷式密封，文献[6] 发展了考虑粘性阻力和内部阻力的压降计算公式：

$$-\mathrm{d}p/\mathrm{d}x_i = a_i \mu u_i + b_i \rho |u_i| u_i \tag{4}$$

其中：a_i—3 个正交方向的粘性阻力系数；b_i—3 个正交方向的内部阻力系数。

式(4)简化为下列形式：

$$-\mathrm{d}p/\mathrm{d}x_i = (\alpha_i |u_i| + \beta_i) u_i \tag{5}$$

其中：α_i 和 β_i—内部阻力和粘性阻力；多孔介质的渗透率系数 K_i 由 α_i 和 β_i 确定。

式(5)表示了流体工质通过多孔介质中在压力梯度项和阻力项之间的平衡。反映了通过多孔介质的流动特性与流体工质和流动条件的相关性。数值求解 RANS 方程分析刷式密封泄漏流动特性需要将式(5)作为附加项添加在式(2)右边进行求解，以此来考虑泄漏流在刷丝束多孔介质中的渗流特性。α_i 和 β_i 由试验确定。本文采用试验测试的刷式密封泄漏量数据来确定刷式束多孔介质的 α_i 和 β_i 参数[4]。根据文献[4, 8]，确定 α_i 参数在径向和轴向分别取 1×10^5 kg/m^4 和 7.5×10^6 kg/m^4，β_i 参数在径向和轴向分别取 1×10^5 kg/(m^3·s)和 4.5×10^7 kg/

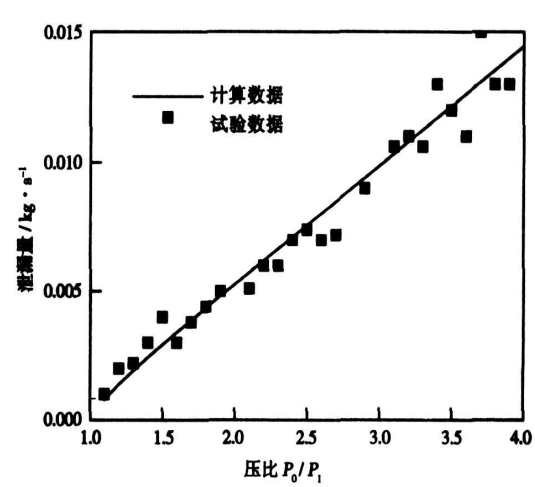

图 3　刷式密封泄漏量的计算值与试验数据的比较

(m^3·s)。图 3 给出了采用改进 Darcian 多孔介质模型数值求解 RANS 方程技术和渗透率参数所得到的泄漏量数值结果与试验数据的比较。计算压比工况范围是 1.01 ~4。从图 3 可以看出所确定的刷丝束多孔介质模型和相应渗透率系数可以有效地计算刷式密封的泄漏量。

2　计算模型和数值方法

利用所确定的刷丝束多孔介质渗透率系数, 采用数值求解三维 RANS 方程技术, 对典型的轴端刷式密封的泄漏流动特性进行分析研究, 同时比较迷宫式密封的泄漏流动特性。图 4 给出了二维高低齿迷宫式密封和刷式密封的结构图。高低齿迷宫式密封的轴端直径是 675 mm, 凸台高是 2.5 mm, 相邻长齿间安装两个短齿。高低齿与轴表面的径向间隙是 0.55 mm。刷式密封的结构是将高低齿迷宫式密封的长齿部分设计成刷式密封, 刷丝束与轴表面的径向间隙是 0.25 mm。

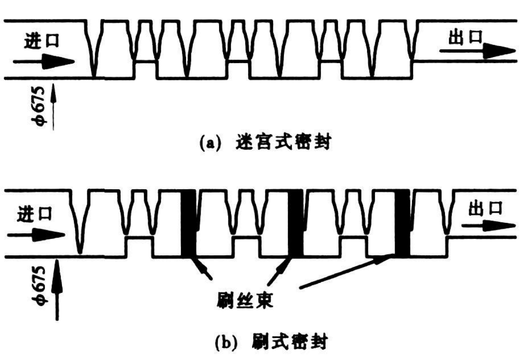

图 4　迷宫式密封和刷式密封结构图

图 5 给出了迷宫式密封的三维计算网格。图 6 表示了刷式密封二维和三维计算网格。采用多块结构化网格技术对两种密封进行网格生成, 二维网格数是 4 万个, 三维网格数是 40 万个。三维网格是在二维网格的基础上周向旋转 5°生成的。采用商用 CFD 软件 Fluent 数值求解 RANS 控制方程。有限体积方法离散控制方程, 采用 Simple 算法和标准 $k-\varepsilon$ 两方程紊流模型进行求解, 对流项和扩散项分别采用二阶和一阶迎风差分格式。数值分析迷宫式密封和刷式密封的边界条件设置是给定进口总温总压, 出口边界给定静压。轴表面设置成旋转固壁, 转速是 3 000 r/min, 密封周向方向的两个面设置成周期性边界条件。对于迷宫式密封的其余壁面均是静止固壁; 对于刷式密封, 迷宫齿表面是静止固壁, 刷丝束表面是内部边界, 刷丝束内部区域设置成多孔介质区域, 内部阻力系数和粘性阻力系数分别取值是根据试验确定的数值。迷宫式密封和刷式密封的设计工况是进口总温是 516.12 ℃, 进口总压 14.69 MPa, 出口静压是 14.14 MPa。计算不同压比时是将进口总温总压确定, 改变出口静压, 分别计算从 1.02 到 1.14 每个 0.02 工况下的 7 种压比。计算刷丝束厚度分别取 2.0、1.8、1.6、1.4 和 1.2 mm 时 5 种厚度的泄漏量和流动特性。

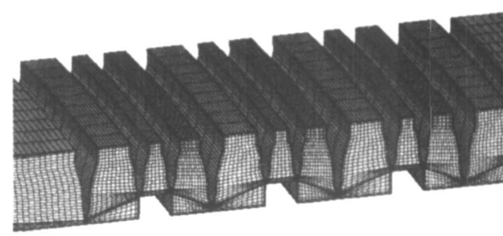

图 5　迷宫式密封三维计算网格

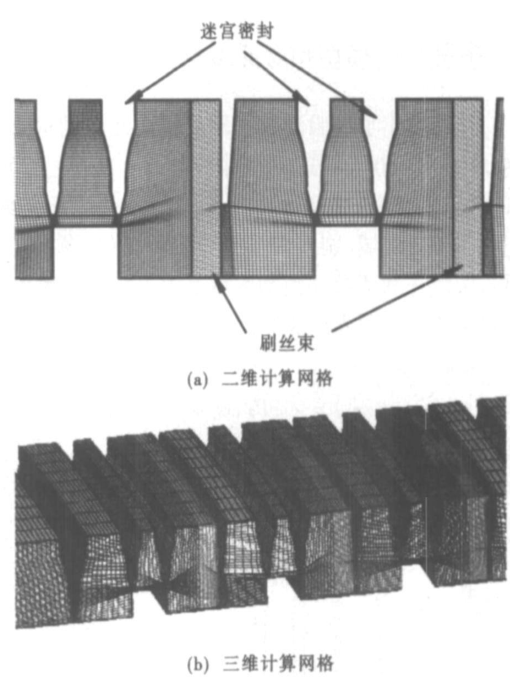

图 6　刷式密封计算网格

3　结果分析与讨论

图 7 给出了刷式密封结构参数是刷丝束厚度 1.6 mm 和径向向间隙是 0.25 mm 时在 7 种压比下的不同网格数所计算的泄漏量。根据图 7 的计算结果表明, 只要网格数在 40 万以上, 所采用的数值计算方法得到泄漏量与网格数无关。因此本文的计算

分析均采用计算网格数是 40 万左右。

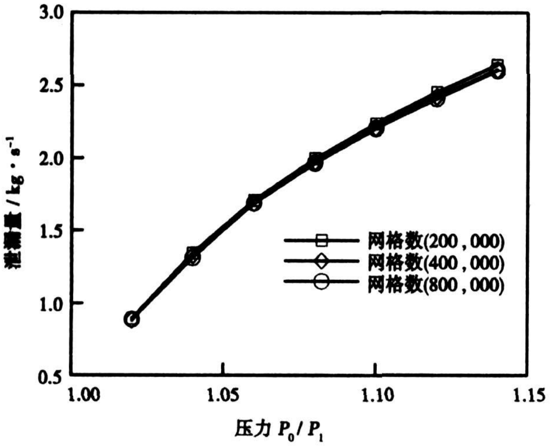

图 7　不同网格数计算的刷式密封泄漏量

图 8 表示了设计工况压比 1.04 时高低齿迷宫式密封二维流线图和静压等值线分布。从图 8 可以看出,从长齿间隙泄漏射流进入旋转轴与相邻长短齿间的腔室内,撞击到凸台上,形成一个逆时针的大旋涡。从短齿与凸台间隙进入两个相邻短齿间空腔内形成一个大的旋涡和顶部区域的小旋涡。从短齿泄漏射流进入相邻短长齿间的空腔内,由于凸台和长齿的作用,形成两个旋转方向相反的旋涡。迷宫齿间隙的泄漏流动如此循环进行,直到密封的出口。正是由于密封齿与轴表面和凸台间空腔内形成的旋涡流动,有效地将泄漏射流动能转化为热能,起到了一定的密封作用。压力在每经过一个密封齿均有下降,直到等于密封的出口压力。

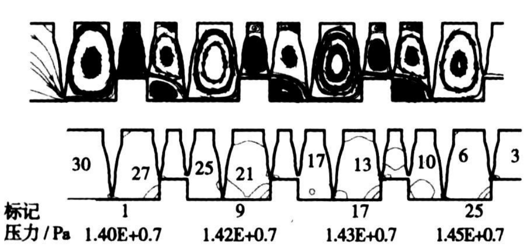

图 8　压比 1.04 下迷宫式密封的流线图和静压等值线分布

图 9 和图 10 分别表示了设计工况 1.04 压比下刷丝束厚度是 2.0 和 1.2 mm 时刷式密封内泄漏流动流线图和静压等值线分布。从图 9 和图 10 的流线图可以看出,刷式密封内流动形态与迷宫式密封有较大的区别,由于刷丝束的多孔介质特性,从迷宫式泄漏的射流直接撞击到刷丝束上,一部分经过多孔介质刷丝束渗流过进入下一个腔室,另一部分形成回流在腔室内构成一个较大的旋涡流,将泄漏射流的动能转化为热能。对于刷丝束厚度是 2.0 和 1.2 mm 的刷式密封,泄漏流动形态在刷丝束相邻的腔室基本类似。从图 9 和图 10 的静压等值线分布可以看出泄漏流经过刷丝束后的压力下降大于经过迷宫齿时的情况。由此可以看出刷丝束可以有效地阻止泄漏流,提高密封效果。

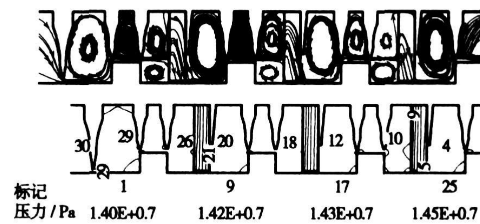

图 9　压比 1.04、刷丝束厚度 2.0 mm 时的刷式密封流线图和静压等值线分布

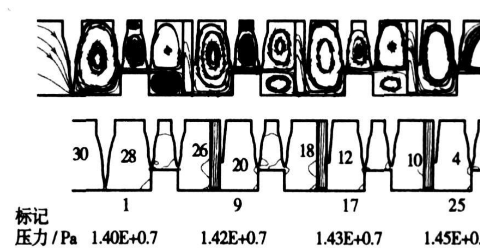

图 10　压比 1.04 刷丝束厚度 1.2 mm 时的刷式密封流线图和静压等值线分布

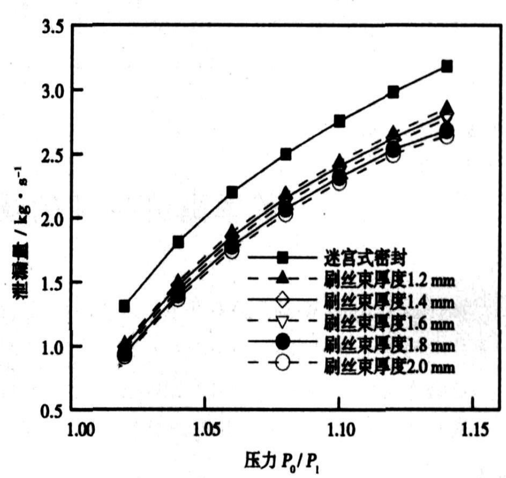

图 11　不同压比和刷丝束厚度下刷式密封计算的泄漏量

图 11 给出了在 7 种压比和 5 种刷丝束厚度条件下刷式密封泄漏量以及与迷宫式密封的比较。从

图11 可以看出,对于 5 种刷丝束厚度条件下,刷式密封的泄漏量均小于相同压比下的迷宫式密封。对于迷宫式密封,泄漏量近似与压比成线性关系,压比对迷宫式密封的泄漏流动形态影响较小。对于刷式密封,压比和刷丝束厚度对其泄漏量的影响近似成线性关系,所以压比和刷丝束厚度对其泄漏量有影响,对其内部泄漏流动形态的影响很小。在相同压比条件下,随着刷式束厚度的增加,刷式密封的泄漏量减小,但是减小的幅度不大。

4 结 论

对某三级刷式密封的泄漏特性及其影响因素进行了数值研究。数值方法采用基于改进 Darcian 多孔介质模型的 RANS 方程求解技术和多块结构化计算网格,分别计算了 7 种压比和 5 种刷丝束厚度条件下的三级刷式密封的泄漏流动特性。

采用试验用刷式密封泄漏量数据确定了刷丝束多孔介质的渗透率系数。数值研究结果表明,在相同压比条件下,刷式密封的泄漏量小于迷宫式密封的泄漏量。刷式密封内的泄漏流动特性表明泄漏流动只能从刷丝束中渗流通过,而迷宫式密封可以从迷宫齿间隙处泄漏通过,导致刷式密封的泄漏量在相同压比条件下小于迷宫式密封。

刷式密封的泄漏量随着压比的增加而增加,随着刷丝束厚度的增加而减小。压比和刷式束厚度对刷式密封内泄漏流动形态的影响可以忽略,这是由于其泄漏量近似与压比和刷丝束厚度成线性关系。由于刷丝束的材料特性,刷丝束径向间隙取值可以远小于迷宫式密封。研究结果对于汽轮机轴端采用多排刷式密封代替迷宫式密封可以有效地减小泄漏量,提高机组效率。

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(编辑 何静芳)

热电联产

效率高达 90％的管道补燃热电联产装置

据《Gas Turbine World》2006 年 9～10 月号报道,德国曼海姆附近的 Kartonfabrik Buchmann 纸板厂增加了一个带补燃的热电联产装置。

依据 4 MW Rolls-Royce 501－KB5 燃气轮机发电机组设计了该热电联产装置。

纸厂将利用天然气对余热锅炉进行补燃,用来生产蒸汽。当装置以满供热电方式运行时,它的效率接近 90％。

501－KB5 具有可获得排气热量,在基本负荷下其排气流量为 15.7 kg/s,排气温度为 559 ℃。

即使在不补燃的方式下,该热电联产装置的蒸汽产量约为 10.5 t/h。

(吉桂明 供稿)

conditions of heat transfer and mechanics theory have been automatically generated based on the historical operating data and structural geometric parameters. A mesh dissection was conducted of a geometric model by using a Delaunay non-structural automatic dissection algorithm. The load spectrum treatment and damage build-up were seamlessly inserted into a finite-element analysis process. On this basis, formed was an integrated system of rotor service-life evaluation based on a complicated numerical method. The above system can provide such functions as the analysis of rotor steady-state and transient temperature, stress and strain fields as well as the evaluation of rotor damage and service life, thus visually displaying the distribution of rotor damage fields and their evolution, and at the same time overcoming some technically intractable hindrances specific to traditional methods. **Key words**: steam turbine rotor, finite element, service life evaluation, fatigue

汽轮机转子涡动汽流激振力分析与 CFD 数值模拟＝**Analysis and CFD（Computational Fluid Dynamics）Numerical Simulation of Steam Flow Excitation Force Leading to a Whirling of Steam Turbine Rotors** [刊，汉] /LIU Xiao-feng，LU Song-yuan（College of Energy Source and Environment under Southeast University，Nanjing，China，Post Code：210096）// Journal of Engineering for Thermal Energy &Power. — 2007，22(3). —245～249

During the whirling of a steam turbine rotor, its shaft center will deviate from that of the stator, thus producing a Thomas/Alford steam-flow excitation force leading to a loss of stability due to vibrations. In such a case, however, the calculation formula of a traditional blade-tip clearance excitation force can not provide an overall and a correct evaluation of the above force. With the whirling of the rotor and the secondary flow around the blade shroud being comprehensively taken into account in rotating blade passages, the whirling-caused excitation force was analyzed based on the work done by the steam. In the gland seal of the blade tip shroud, CFD values were used to simulate a three-dimensional viscous flow field of the leaking steam, thus determining the magnitude of the steam excitation force. The research results show that under the condition of a small static and dynamic eccentricity, the excitation force in the rotating blade passages induced by the dynamic eccentricity of the rotor whirling is greater than that induced by the static eccentricity, and the pre-swirling velocity of steam flows in the shroud gland has an important influence on the excitation force in the clearance. The non-symmetric steam admission is another important source of the steam excitation force. **Key words**: steam turbine, tip clearance excitation vibration, eddy whirling of rotor, computational fluid dynamics（CFD）

刷式密封泄漏流动特性影响因素的研究＝**A Study of the Influence of Brush-type Seals on Leaking Steam Flow Characteristics** [刊，汉] /LI Jun, YAN Xin, FENG Zhen-ping（Research Institute of Turbo-machinery under Xi'an Jiaotong University，Xi'an，China，Post Code：710049）// Journal of Engineering for Thermal Energy &Power. — 2007，22(3). —250～254

By employing techniques for seeking a solution to Reynolds-Averaged Navier-Stokes equation based on an improved Darcian porous medium model，a numerical analysis and study has been conducted of the law governing the influence of pressure ratio and bristle pack thickness on the leaking steam flow characteristics of brush-type seals under the condition of a given radial clearance. Based on the test data published for leaking steam flow rates of brush type seals，determined was the permeability coefficient of the porous medium of the bristle pack. By using the permeability coefficient of the bristle-pack porous medium thus obtained，calculated respectively were the leaking steam flow rates and flow patterns of brush type seals at the ends of a shaft under the condition of 7 pressure ratios and 5 kinds of bristle pack thickness at a given radial clearance. The calculation results indicate that both the pressure ratio and bristle pack thickness can influence the leaking steam flow rate of a brush type seal. Under the condition of a given pressure ratio，the leaking steam flow rate will decrease with an increase of bristle pack thickness. At a given bristle pack thickness，the leaking steam flow rate will increase with an increase of pressure ratio. As the leaking steam flow rate of a brush type seal assumes approximately a linear variation relationship with the pressure ratio and bristle pack thickness，the impact of the latter two items on the leaking steam flow patterns in a brush type seal can be virtually neglected. **Key words**: steam turbine, brush-type seal, porous medium model, leaking steam flow rate, numerical simulation

10 MW 氦气轮机涡轮轮盘强度的计算方法＝**A Method for Calculating the Strength of Wheel Disks of a 10 MW Helium Gas Turbine** [刊, 汉] / XU Jun, ZHANG Rui-yan, LIU Han (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036), BAI Xiang-lin (College of Electromechanical Engineering under Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —255 ~ 258

To date, the strength calculation and analysis of turbine disks has all along been conducted, using an "equal-thickness ring method" theory. As such a simplification has not taken into account the effect of rigidity of tenon and mortise boss on force transmission, the disk rim stress values thus obtained may sometimes exhibit a sizable error, making it impossible to analyze the stress concentration at the eccentric holes of the disk and at the root of tenon teeth. However, relatively accurate stress analytic results can now be obtained by establishing a real entity model for a wheel disk of complicated structure through the use of software Pro/E and by performing a finite element analysis and calculation, using software ANSYS. By adopting the above-mentioned two methods, calculated and analyzed was a gas turbine disk together with several stages of blades. It has been verified that the "equal-thickness ring method" theory can macroscopically reflect the force-bearing status of the disk. In the meantime, it can be proved that the selection of various parameters for the finite element method is correct, thus providing a technical reference for the strength analysis of other structures of a similar nature. **Key words**: helium gas turbine, wheel disk, strength analysis, contact stress

燃用超低热值燃料的燃气轮机及其热力分析＝**A Super-low heating-value-fuel-fired Gas Turbine and Its Thermodynamic Analysis** [刊, 汉] / WANG Yan-jie, WENG Yi-wu, YIN Juan (College of Mechanical and Power Engineering under Shanghai Jiaotong University, Shanghai, China, Post Code: 200030), SU Shi (Commonwealth Science and Industry Research Organization, Brisbane, Australia, Q14001) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —259 ~ 263

On the basis of a catalytic combustion mode, presented is a method for utilizing super-low heating-value fuel. A description is given of the structural makeup and working principle of a gas turbine operating on the above fuel and combustion mode along with an analysis of the relevant technical key points. The feasibility of a stable catalytic combustion of the above fuel has been verified through tests. With a gas turbine rated at hundreds of kilowatts serving as an example, calculated and analyzed was a thermodynamic cycle of a gas turbine unit. The results indicate that a gas turbine plant firing the above-mentioned fuel can be realized with an output of effective power, thus providing a feasible method and basis for the research and development of a super-low heating-value-fuel-fired gas turbine system. **Key words**: super-low heating-value fuel, catalytic combustion, gas turbine characteristics, thermodynamic cycle

基于小波分析的柴-燃联合动力装置信号消噪＝**Elimination of Noise from Signals for a CODOG Plant Based on a Wavelet Analysis** [刊, 汉] / TIAN Ying (College of Mechanical and Electronic Control Engineering under Beijing Jiaotong University, Beijing, China, Post Code: 100044), LI Shu-ying (College of Power and Energy Engineering under Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —264 ~ 266

During the tests of a CODOG (combined diesel or gas turbine) plant on a test stand, to eliminate the impact of various kinds of noise and interference on measurement signals, minimize the test error of measured data and ensure a normal use of the test data, the following measures were taken to realize the elimination of noise from the signals with the displace-