文章编号: 1001－2060(2004)04－0347－04

超临界汽轮机再热第一级叶片固粒冲蚀特性的数值分析

戴丽萍, 俞茂铮, 王贤钢, 侯平利
(西安交通大学 动力工程多相流国家重点实验室, 陕西　西安　710049)

摘　要: 采用数值方法计算与分析了超临界汽轮机再热第一级的固体颗粒三维运动特性, 根据固体颗粒撞击叶片的位置、速度与撞击角以及叶片材料的抗冲蚀性能综合分析了静叶与动叶的冲蚀机理及冲蚀特性, 指出静叶吸力面冲蚀是从动叶反弹回来的固粒撞击所引起的。此外, 还分析了动静叶轴向间距及机组负荷对反弹至静叶的颗粒数量的影响, 结果表明, 随着轴向间距的减小和负荷的降低, 反弹回静叶的颗粒数量增加。

关　键　词: 超临界汽轮机; 固粒冲蚀; 再热第一级; 数值分析

中图分类号: TK263　　文献标识码: A

1　前　言

超临界与超超临界汽轮机的调节级和再热第一级叶片容易受到从锅炉管道内壁剥落的高硬度氧化铁固体颗粒的冲蚀。叶片冲蚀导致汽轮机通流效率降低, 功率下降, 检修周期缩短, 维护费用上升。多种材料的冲蚀试验结果表明, 材料的冲蚀率与固粒的撞击速度及碰撞角度有关[1]。因此利用数值计算方法分析固粒在级中的三维运动特性, 从而确定各种尺寸颗粒撞击叶片的位置、撞击速度和碰撞角是分析冲蚀机理、冲蚀位置及抗冲蚀方法的有效手段。国外的某些制造厂已采用这一方法在产品的防冲蚀研究中取得了良好的效果[1]。我国正在研究具有自主知识产权的超临界与超超临界汽轮机, 掌握级中的固粒三维运动特性计算方法并用以分析叶片的冲蚀机理与特性, 对于产品设计优化及防治对策的制定都具有现实意义。文献[2]对调节级喷嘴中固体颗粒的二维运动特性与叶片的冲蚀特性进行了计算与分析。本文采用叶栅三维流场的数值计算方法和固粒运动的拉格朗日方法及固粒反弹模型计算分析了一台超临界汽轮机再热第一级在设计工况与半负荷工况下固粒的三维运动特性及叶片冲蚀机理与特性, 指出了改善叶片抗冲蚀性能的途径。

2　流场与固粒运动特性的计算方法

2.1　流场的计算

采用控制容积积分法和压力修正算法, 结合 κ-ε 湍流模型数值求解三维稳态 $N-S$ 方程组, 方程组在文献[3]中有详细论述, 文献[3]还根据现有叶栅气动特性实验资料考核了计算方法的适用性。本文的计算中, 给定边界条件为: 在静叶栅进口给定总温和总压; 在动叶栅出口给定背压。

2.2　固粒运动特性计算

在计算所得流场的基础上, 采用离散颗粒轨迹模型计算固粒的运动特性。根据再热级蒸汽工作条件, 对固粒在流场中所受各种作用力可只考虑惯性力和气流的粘性阻力, 将颗粒形状假设为球形, 根据国外学者对两相流研究的结果[4], 颗粒的运动方程可表示为:

$$\mathrm{d}\vec{u}_\mathrm{p}/\mathrm{d}t = F_\mathrm{D} \cdot (\vec{u} - \vec{u}_\mathrm{p}) \tag{1}$$

式中: $\vec{u}$ — 气相速度; $\vec{u}_\mathrm{p}$ — 固粒速度; t — 时间。F_D 的表达式为:

$$F_\mathrm{D} = \frac{18\mu}{\rho_\mathrm{p} d_\mathrm{p}^2} \frac{C_\mathrm{D} Re}{24} \tag{2}$$

式中: μ — 气体的动力粘性系数; ρ — 气体密度; ρ_p — 固粒密度; d_p — 固粒直径; Re — 固粒雷诺数。阻力系数 C_D 是 Re 的函数, 可按常用的关系式确定[4]。固粒反弹模型如图 1 所示, 图中入射速度 $u_{\mathrm{p}1}$ 与碰撞切面的夹角 β_1 为撞击角, 反弹速度 $u_{\mathrm{p}2}$ 与切面的夹角 β_2 为反弹角。氧化铁固粒撞击再热第一级 12Cr 叶片壁面后的反弹速度与方向角按如下近似关系[5] 计算:

收稿日期: 2003－11－04;　修订日期: 2003－12－22

作者简介: 戴丽萍(1979－), 女, 山东武城人, 西安交通大学博士研究生.

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved.　http://www.cnki.net

$$u_{p2}/u_{p1} = 1.0 - 2.03\beta_1 + 3.32\beta_1^2 - 2.24\beta_1^3 - 0.472\beta_1^4 \quad (3)$$

$$\beta_2/\beta_1 = 1.0 + 0.409\beta_1 - 2.52\beta_1^2 + 2.19\beta_1^3 - 0.531\beta_1^4 \quad (4)$$

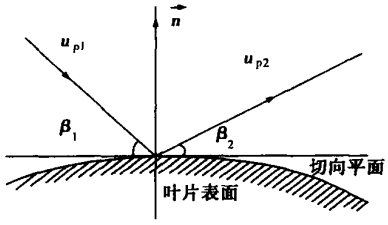

图 1 固粒反弹模型

3 设计工况下固粒运动特性与叶片冲蚀特性分析

所计算的再热第一级热力设计参数为: 进口蒸汽压力为 5 MPa, 进口温度 560 ℃, 出口压力 4.05 MPa。几何参数为: 静叶轴向长度 $B = 79.8$ mm, 安装角 $\beta_1 = 45^\circ$, 叶高 $h = 106$ mm, 叶片数 $z = 60$, 节径 $d = 1\,284$ mm; 动叶轴向宽度 $B = 53.5$ mm, 安装角 $\beta_2 = 70^\circ$, 叶高 $h = 110$ mm; 节径 $d = 1\,285$ mm, 叶片数 $z = 100$, 动叶栅的旋转速度 $n = 3\,000$ r/min。

氧化铁固粒撞击叶片壁面的冲蚀率 ε(单位质量固粒冲击材料表面所去除的材料体积或质量)与固粒的碰撞角 β_1 及碰撞速度 u_{p1} 有关。在 500 ℃下, 氧化铁粒子对 12Cr 的马氏体材料冲蚀的实验结果表明[5], 在碰撞角为 30° 左右冲蚀率达到最大值, 并且冲蚀率与碰撞速度的三次方到四次方成正比。12Cr 的冲蚀率与碰撞角的关系如图 2 所示[6]。根据叶片材料的抗冲蚀性能可知, 可以根据计算得到的固粒撞击角是否避开 20° 至 35° 的高冲蚀率区以及碰撞速度的大小来分析叶片的冲蚀性能。

根据电厂的锅炉锅水及过热器疏水所含氧化物颗粒尺寸的测量结果, 固粒尺寸大多分布在 5 ~ 100 μm 的范围[7], 以下分别取颗粒直径为 10 μm、46 μm 及 100 μm 三种尺寸的固粒进行计算。计算时, 在静叶栅的计算进口边界沿栅距方向均匀布置 10 个固粒。图 3(a)、(b)分别表示颗粒运动轨迹以及中间截面运动轨迹在周向方向的投影。由图可见, 大部分固粒撞击在压力面出口区域, 反弹后流出静叶栅通道。

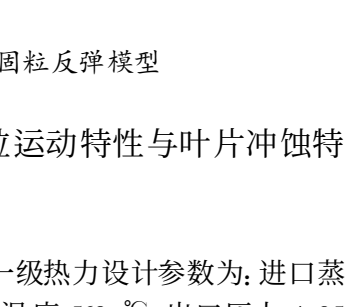

图 2 12Cr 材料冲蚀率与碰撞角的关系

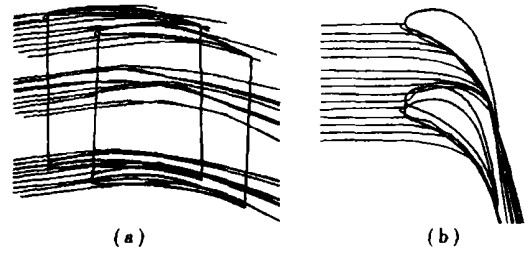

图 3 静叶栅中的固粒运动轨迹(d_p=46 μm)

图 4 表示了不同尺寸的固粒碰撞角和碰撞速度沿相对轴向位置的变化关系(相对轴向位置为离叶栅前缘的距离 X 和整个叶栅轴向宽度 B 的比值)。径向流入位置 1、2 和 3 分别代表靠近上端壁、中间截面和靠近下端壁的位置。由图可见, 径向位置对固粒运动特性影响很小, 在相同的轴向位置上, 不同径向位置的固粒撞击速度和碰撞角度非常接近。由于绝大部分 10 μm 固粒的碰撞角在 20° 以下, 因此对叶片造成的冲蚀会比较小; 46 μm 的固粒在压力面出口区域碰撞角大多落在 20° ~ 35° 的高冲蚀率区, 并且在相对轴向位置 0.8 ~ 1.0 时固粒撞击速度增加非常快, 出口区域达到 120 m/s 左右, 因此对叶片冲蚀比较严重; 100 μm 的固粒碰撞角在相对轴向位置 0.6 时处于高冲蚀率区, 但固粒速度较低(低于 50 m/s), 因此不会对叶片造成严重的冲蚀。

图 5(a)、(b)分别表示从静叶栅三个径向位置上流出的尺寸为 46 μm 的固粒在动叶栅中的运动轨迹以及中间截面流出的颗粒轨迹在圆周方向的投影。由图可见, 固粒在动叶栅中运动时有明显的径向位移, 这主要是由于固粒具有一定的周向速度, 因而产生离心运动。从静叶栅顶部区域流出的固粒会撞击在动叶围带上, 造成围带冲蚀损伤或者堆积在汽缸槽道中; 此外, 还可看出, 由于静叶栅出口处固粒绝对速度小于汽相, 因此有相当部分固粒撞击在动叶吸力面进口区域, 并且反弹至轴向间隙区和相邻动叶压力面。另有小部分固粒不与叶片碰撞, 直接流出动叶栅。

动叶吸力面上的颗粒的撞击位置集中在相对轴向位置 0 ~ 0.2 的范围, 因此吸力面进口边也可能会

?1994-2016 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

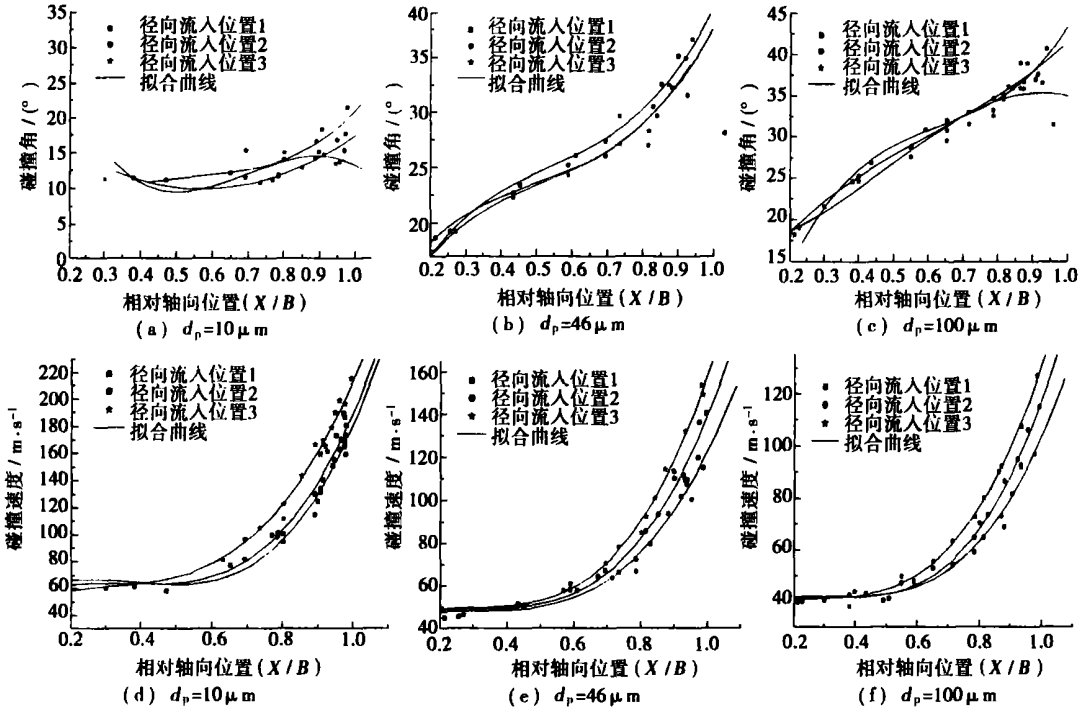

图 4　静叶压力面上固粒碰撞角和碰撞速度沿轴向位置的变化

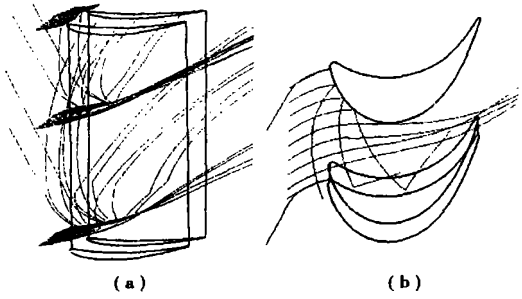

图 5　动叶栅中的固粒运动轨迹(d_p= 46 μm)

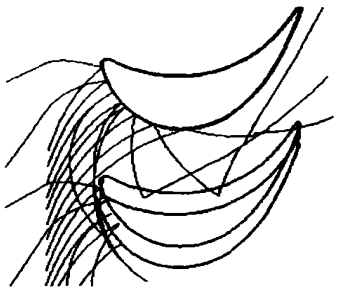

图 6　50%负荷下 46μm 固粒在动叶栅叶中的运动轨迹周向投影

产生冲蚀。颗粒的撞击角度和速度分布比较分散, 这里不再画图表示。动叶压力面上颗粒撞击位置非常分散, 其中中间轴向位置处较小尺寸颗粒的撞击角会落在高冲蚀率区, 因此, 会引起一定的冲蚀。

4　50%负荷下固粒运动特性与叶片冲蚀特性分析

50%负荷工况下固粒在静叶栅与动叶栅通道中的运动轨迹与设计工况下的类似, 这里不再讨论。以下只着重分析反弹回间隙区的颗粒运动特性。

图 6 表示了 50%负荷下 46 μm 的固粒在动叶栅中的运动轨迹。由图可见, 部分颗粒会被气流夹带流出叶栅通道, 另有部分颗粒撞击在吸力面上, 从动叶反弹至静叶吸力面, 如图 7 所示。

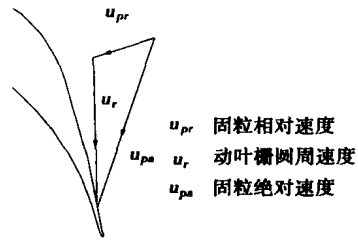

图 7　反弹固粒相对静叶吸力面的撞击速度

100 μm 的固粒反弹后撞击在静叶吸力面上的撞击参数如图 8 所示。由图可知, 撞击区域非常集中, 碰

?1994-2016 China Academic Journal Electronic Publishing House. All rights reserved.　http://www.cnki.net

撞角处在高冲蚀率区，而且碰撞速度也很大（超过200 m/s），因此静叶吸力面出口区是容易受到严重冲蚀的区域，某些汽轮机再热第一级静叶的冲蚀情况也与此分析相一致[6]。

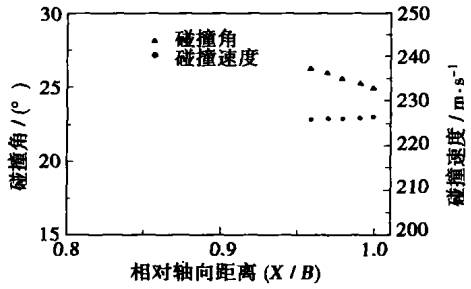

图 8 50%负荷下 100μm 反弹固粒撞击静叶吸力面的角度与速度

5 动静叶轴向间距与机组负荷对静叶冲蚀影响

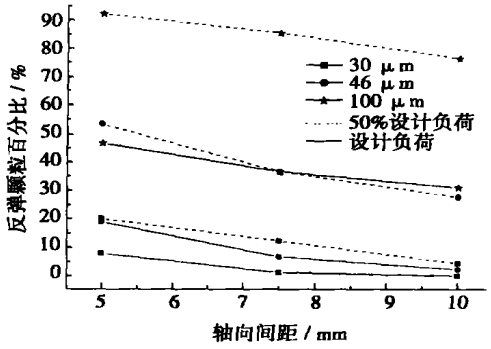

图 9 反弹回静叶的颗粒百分比与轴向间距及负荷的关系

反弹回静叶栅吸力面的固粒的数目与轴向间距及机组负荷有关，因此可以调整轴向间距来减轻静叶吸力面的冲蚀。图 9 表示了在设计负荷和 50%负荷下不同尺寸的颗粒在轴向间距为 5 mm、7.5 mm 和 10 mm 时反弹回静叶的百分比。由图可见，在设计负荷下、轴向间隙为 5 mm 时，尺寸小于 46μm 的颗粒能够反弹回静叶的比例较少，均在 20%以下，而 100μm 的颗粒反弹至静叶的比例可达 45%，随着轴向间隙的增大，反弹回的颗粒数量减少，轴向间距为 10 mm 时，可以认为尺寸小于 46μm 的颗粒基本上不会反弹至静叶。由图还可看出，负荷对反弹回静叶的颗粒数量的影响非常大，50%负荷时反弹颗粒数量比 100%设计负荷时可增大一倍。为了减少反弹回静叶的颗粒数量，还可以采用增大动叶吸力面进口边几何角（也即提高级的设计反动度）的措施，这一问题有待进一步开展研究。

6 结 论

（1）采用固粒三维运动特性数值计算方法可以确定不同工况下固粒在再热第一级中的总体运动特性。设计者可以根据叶片材料的抗冲蚀性能试验数据以及计算得到的固粒碰撞速度和碰撞角判断叶片可能冲蚀区域及冲蚀严重程度，为制定改善级的抗冲蚀性能措施提供信息。

（2）所计算汽轮机再热第一级静叶吸力面出口区域会受到从动叶进口边反弹回的固粒撞击并产生严重冲蚀，适当增大动静叶轴向间距可有效减少反弹至静叶片的固粒数量，减轻吸力面的冲蚀。静叶压力面出口区域及动叶吸力面进口区域也会受到固粒的直接撞击而冲蚀，应引起运行人员注意。

（3）负荷工况对固粒在级中的运动特性有较大影响，低负荷工况下固粒更易从动叶反弹至静叶吸力面，引起吸力面严重冲蚀，因此应尽量避免汽轮机在低负荷下长期运行。

参考文献：

[1] KAWAGISHI H, KAWASSAKI S, IKEDA K, et al. Protective design and boride coating against solid particle erosion of first-stage turbine nozzles[J]. **ASME Power Division**, 1990, **10**: 23—29.

[2] 戴丽萍，俞茂铮，王贤刚，等. 超临界汽轮机调节级喷嘴固粒冲蚀特性的预测与抗冲蚀方法[J]. 汽轮机技术，2002，**44**(6)：329—332.

[3] 朱光宇，俞茂铮，程代京. 透平叶栅二次流涡系演变及气动特性的数值模拟[J]. 西安交通大学学报，2002，**36**(11)：1142—1146.

[4] MORSI S A, ALEXANDER A J. An investigation of particle trajectories in two-phase flow systems[J]. **J Fluid Mech**, 1972, **55**(2): 193—208.

[5] BEACHER B, TABAKOFF W, HAMED A. Improved particle trajectory calculations through turbomachinery affected by coal ash particles [J]. **Journal of Engineering for Power**, 1982, **104**(1): 64—68.

[6] TABAKOFF W, SHANO V. Erosion rate testing at high temperature for turbomachinery use[J]. **Surface and Coatings Technology**, 1995, **76/77**: 75—80.

[7] SUMNER W J, VOGAM J H, LINDINGER R J. Reducing solid particle erosion damage in large steam turbine[A]. **Proceeding of American Power Conference[C]**, Chicago Illinois: the American Power Conference Illinois Institute of Technology, 1985, 196—212.

?1994-2016 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

复杂反应流自适应化学理论计算的研究现状＝**The Present Status of Research on an Adaptive Chemistry (AdapChem) Concept for Calculating Complex Reaction Flows** [刊, 汉] / QIAO Yu, XU Ming-hou (National Key Laboratory of Coal Combustion under the Huazhong University of Science & Technology, Wuhan, China, Post Code: 430074), Pisi Lu (Department of Chemical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139), //Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). — 331 ~ 335.

Professor Green of the Department of Chemical Engineering under the Massachusetts Institute of Technology has proposed an adaptive chemistry (AdapChem) concept, under which by the use of a consistent splitting method conservation equations can be divided into two organic parts, namely, a chemical equation and a flow equation. Depending on different reaction conditions, the above method makes it possible to perform in-domain numerical simulations of non-complex detailed and elementary reaction models by using a multitude of simplified chemical reaction models. As a result, an effective approach is provided for avoiding the loss of efficiency under the condition of retaining chemical precision. However, to further improve AdapChem, it is necessary to introduce a radiation model, which has not been taken into account previously. In this connection, the authors have employed a discrete coordinate method. The simulation results of a CH_4/air flame have shown that with the radiation model being incorporated the graphical expression of calculation results did not undergo significant changes and there was also a rational reduction in temperatures. **Key words**: adaptive chemistry, consistent splitting method, simplified model, discrete coordinate method.

循环流化床燃烧技术的研究展望＝**Prospective Research Progress of Combustion Technology for Circulating Fluidized Beds** [刊, 汉] / YU Long (Harbin Boiler Works Co. Ltd., Harbin, China, Post Code: 150040), LU Jun-fu, YUE Guang-xi (Department of Thermal Engineering, Tsinghua University, Beijing, China, Post Code: 100084), WANG Zhi-wei (National Thermal Power Research Institute, Xi'an, China, Post Code: 710032) //Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). — 336 ~ 342.

Some major issues currently receiving focused attention are addressed, which are mainly concerned with the further development of circulating fluidized-bed combustion technology. They include: combustion efficiency achievable when burning various ranks of coal, water circulation during operations with supercritical parameters, the diffusion of particles and gases in gas-solid dual-phase flows under the condition of large bed sections, emissions of NO_x and SO_2 and their control, flow problems near side-wall zones, etc. **Key words**: circulating fluidized bed, boiler, prospective research progress.

应用全息谱技术诊断热变形不均匀引起的振动故障＝**Vibration Failures Due to the Non-uniform Thermal Deformation Diagnosed by the Use of Hologram Spectral Techniques** [刊, 汉] / LIU Shi, QU Liang-sheng (Intelligent Instrumentation and Monitoring-diagnosis Research Institute under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) //Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). — 343 ~ 346.

When a traditional method based on FFT (Fast Fourier Transformation) frequency spectrum analysis is used, it is very difficult to effectively differentiate between the thermal effects-induced serious vibration problems and rotor loss-of-balance failures occurring in a turbogenerator. With the help of a rotor model built by the authors the difference between the above two types of problem and failure is analyzed from a theoretical viewpoint. Meanwhile, these failures were identified and differentiated by making use of hologram differential spectrum technology and an initial-phase point analysis method. Specific cases in engineering applications have verified the effectiveness of the above-mentioned method. **Key words**: vibration, failure diagnosis, hologram differential spectrum.

超临界汽轮机再热第一级叶片固粒冲蚀特性的数值分析＝**Numerical Analysis of the Erosion Characteristics of Solid Particles in the First Reheat Stage Blades of a Supercritical Steam Turbine** [刊, 汉] / DAI Liping, YU Mao-zheng, WANG Xian-gang, et al (National Key Laboratory of Multi-phase Flows in Power Engineering under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) //Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). —347 ~ 350.

The three-dimensional motion characteristics of solid particles in the first reheat stage of a supercritical steam turbine were

?1994-2016 China Academic Journal Electronic Publishing House. All rights reserved.　http://www.cnki.net

calculated and analyzed by using a numerical method. A comprehensive analysis was performed of the erosion mechanism and features specific to stator and rotor blades on the basis of the impact location and velocity of solid particles on blades, impact angle and blade material erosion-resistance behavior. It is noted that the suction side erosion of the stator blades is caused by the impact of solid particles rebounding from the rotor blades. Furthermore, also analyzed was the influence of the turbine load and the axial clearance between the stator and rotor blades on the number of particles rebounding to stator blades. The results of the analysis indicate that an decrease in axial clearance and a reduction in turbine load has given rise to an increase in the quantity of particles rebounding to the stator blades. **Key words**: solid particle erosion, supercritical steam turbine, reheat stage, numerical analysis.

二次再热超临界供热机组热力系统经济性定量分析方法=**Economic-quantitative Analysis Method Used for the Thermodynamic System of a Supercritical Heat Supply Unit with a Double Reheat** [刊, 汉] / LI Yang, XING Qin-an, YAN Jun-jie, et al (Energy and Power Engineering Institute under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). —351 ~353, 362.

A supercritical heat-supply unit with a double reheat employs steam extraction from a low-pressure turbine cylinder for supplying process heat. On the basis of the above arrangement, a method for calculating equivalent enthalpy drop and steam extraction efficiency for the above unit is obtained by making use of an equivalent thermal-drop theory and performing a theoretical analysis and mathematical deduction. A mathematical model based on an economic-quantitative analysis has been derived for the above-mentioned turbine unit, thereby extending the application range of the equivalent heat-drop theory to heat supply units with a double reheat. By using this model it is possible to effect a convenient, rapid and accurate analysis of the thermodynamic system cost-effectiveness of the above supercritical heat supply unit. **Key words**: double reheat, thermodynamic system, quantitative analysis, heat supply unit.

基于支持向量机的燃气轮机故障诊断=**Gas Turbine Fault Diagnosis Based on a Support Vector Machine** [刊, 汉] / LUO Ying-feng, ZENG Jin (Mathematics Department, Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). — 354 ~357.

With respect to eight kinds of commonly seen typical faults a fault diagnosis model is set up based on a support vector machine. Specific sample calculations have demonstrated the effectiveness of such a model. A comparison with a neural network method has shown that under the condition of a small quantity of samples the support vector machine-based method is superior to the neural network method in terms of calculation results, generalization ability and efficiency. When a relatively small number of diagnosis samples is involved, the above method may provide a new approach for creating an intelligent system of highly practical value for the condition monitoring and fault diagnosis of gas turbines. **Key words**: gas turbine, support vector machine, fault diagnosis system.

固体氧化物燃料电池与燃气轮机联合发电系统模拟研究=**Simulation Study of a Combined Power Generation System Incorporating a Solid-oxide Fuel Cell and a Gas Turbine** [刊, 汉] / LU Li-ning, LI Su-fen, SHEN Sheng-qiang (Power Engineering Department, Dalian University of Science & Technology, Dalian, China, Post Code: 116024), LU Li-yu (Inner Mongolia Dalate Power Plant, Baotou, China, Post Code: 014300) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). — 358 ~362.

A solid-oxide fuel cell (SOFC) is a new type of energy featuring high efficiency and low pollution. A calculation model is set up for a combined power generation system, which comprises a solid-oxide fuel cell with natural gas serving as its fuel and also a gas turbine (GT). The calculation results of the above system indicate that the combined power generation system composed of SOFC and GT can attain a power generation efficiency of 68% (based on low heating value). With the waste heat being put to use the energy utilization rate of the whole system can surpass 80%. The impact of such parameters as SOFC operating pressure and its current density on the system performance was analyzed. An increase in its operating pressure can lead to an increase in cell electricity generation and power generation efficiency of the system. On the other hand, an increase in current density may result in a decrease of electricity generation for both the SOFC and the

?1994-2016 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net