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冷却蒸汽进口总压对转子冷却效果影响的数值分析

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摘 要: 在不同冷汽进口总压条件下对超超临界汽轮机中压第一级进行了数值模拟, 考察了冷却通道以及主流道内的流动状况, 并对动叶表面以及叶根表面的温度场进行了研究。研究结果表明, 对应所给出的最大与最小进口总压, 冷却蒸汽对动叶吸力面的影响范围相差约 10%的相对叶高, 而叶根表面的最大温度仅相差 0.6 K左右。冷汽进口总压越大, 冷却效果越好, 但是冷汽对主流的干扰越强, 将引起流动效率下降, 因此, 最佳冷汽进口总压的选取要综合考虑冷却效果和流动效率。

关 键 词: 冷却蒸汽; 总压; 转子; 数值模拟
中图分类号: TK264.1 文献标识码: A

引 言

在材料技术发展的今天, 超超临界汽轮机的主蒸汽温度和再热蒸汽温度呈增长的趋势[1]。随着蒸汽温度的升高, 材料的力学性能有所下降, 为了保证超超临界汽轮机的部件有足够的强度和寿命, 除了采用高温强度好的钢材之外, 还应采用蒸汽冷却技术和冷却结构设计[2]。超超临界汽轮机不同的部件采用不同方案的冷却结构设计, 其中典型的中压转子冷却结构基本分为 3类[3~5]。文献 [4]所采用的三菱超超临界汽轮机中压转子蒸汽冷却方式, 对于超超临界汽轮机蒸汽冷却技术的工程应用, 冷却蒸汽流量的控制至关重要。过量的冷却蒸汽将会带来过大的对流换热系数, 进而导致高温部件产生较大的热应力。较小流量的冷却蒸汽在高温高压主蒸汽的作用下, 无法达到冷却效果的要求, 从而无法冷却和保护高温部件。如果在蒸汽冷却技术的工程应用中, 采用总压边界条件对冷却蒸汽的流量进行控制, 那么必须清楚地掌握冷却蒸汽进口总压与冷却蒸汽流量之间的定量关系, 才能选择最佳冷却蒸汽进口总压条件。本研究给出 5个计算方案, 分别给定不同的冷却蒸汽进口总压, 比较分析各个方案的冷却效果, 从而确定所采用冷却结构的冷却蒸汽最佳进口总压。

1 结构及边界条件

图 1为蒸汽轮机中压级边界条件结构简图。图 2给出了网格划分图, 动叶流道网格单元数约为 28万, 静叶流道网格单元数约为 24.5万, 冷却通道网格单元数约为 11.7万, 动叶叶根网格单元数约为 38万, 整个几何体网格单元总数约为 102.3万。本研究采用商用计算软件 CFX10对流场进行求解, 这一数量级的网格数可以满足计算的需要。

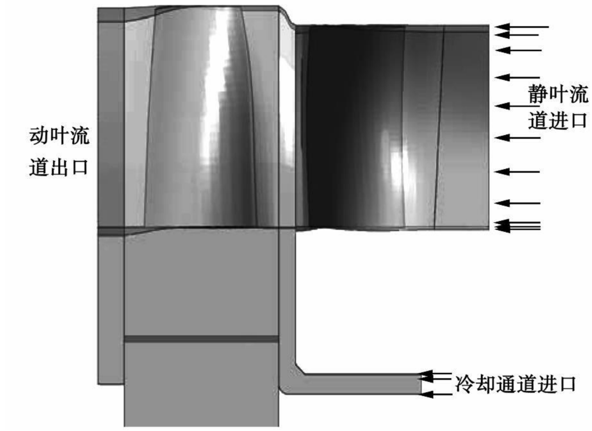

图 1 中压第一级边界条件结构简图

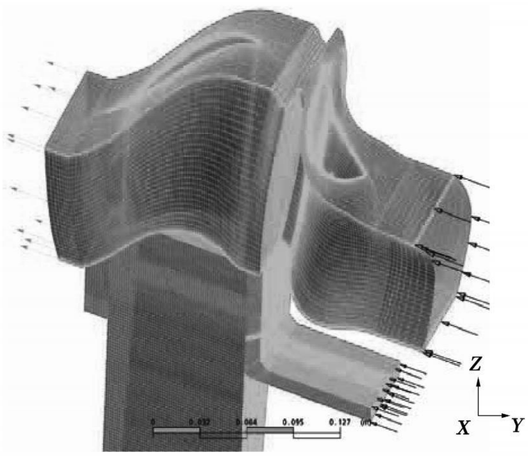

图 2 几何体网格划分

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表 1给出了进出口边界条件的各参数值，全部数据均由一维流动计算结果提供，计算模型按照 1∶1比例生成进行数值模拟。模拟软件为 ANSYS CFX 10.0版本，在并行机上进行三维气热耦合计算，数值模拟采用由 ANSYS CFX 10.0 提供的 Redich Kwong Dry Steam(干蒸汽)介质进行计算，叶根固体区域采用 Steel(钢)介质进行计算。

表 1　中压级进出口边界条件

边界位置	进口总压/MPa	进口总温/K	进口湍流度/%	出口静压/MPa
静叶流道进口	3.690 98	837	5	—
冷却通道进口	3.307 05	723	5	—
动叶流道出口	—	—	—	3.068 2

表 2给出了 5个计算方案的冷却蒸汽进口总压以及根据总压计算得到的冷却蒸汽流量。下面针对 5个方案的气热耦合数值模拟结果，对比分析这 5个方案的冷却效果。

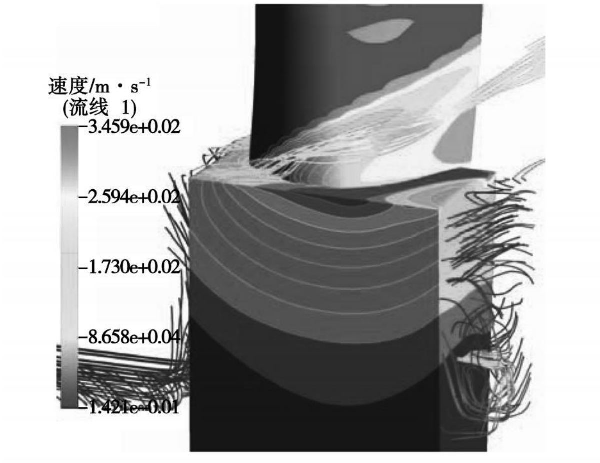
表 2　5个方案的冷却蒸汽进口总压及流量

方案	冷却蒸汽进口总压/MPa	冷却蒸汽流量/kg·s⁻¹	冷却蒸汽全周流量/kg·s⁻¹
1	3.307 05	0.105 41	6.746
2	3.303 99	0.096 57	6.180
3	3.300 93	0.087 90	5.626
4	3.297 86	0.0794 11	5.082
5	3.294 80	0.0706 63	4.522

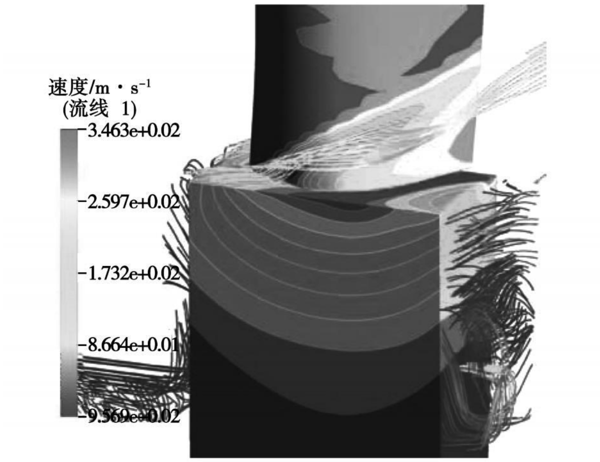
2　计算结果对比分析

2.1　冷却蒸汽的流动情况

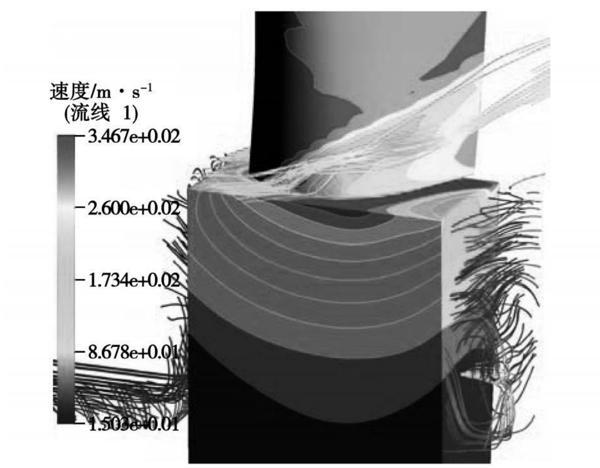
图 3为 5个方案动叶栅内冷却蒸汽的流线分布。如图所示，随着冷汽进口总压的降低，流入主流的相对冷汽流量(相对冷汽总流量的比例)逐渐减少，通过冷汽通道孔的相对冷汽流量增加。这主要是因为在主流参数不变的条件下，通过冷汽通道孔与通过隔板叶轮之间的轴封喷入主流的两股冷汽的流量分配与它们遇到的流阻成反比，冷汽通道孔对冷汽的阻力远小于轴封、主流对冷汽的阻力，因此大部分冷汽通过冷汽通道孔。此外，进入主流的冷汽量正比与冷汽、主流交界处的压差，冷汽进口总压降低，该处压差减小，进入主流的冷汽流量减少。这样一来，当冷汽进口总压降低时，冷汽流量降低，通过冷汽通道孔的流量降低的较少，而喷入主流的冷汽量减少较多。因此，随着冷汽总压降低，冷却效果下降，对主流的干扰减弱。



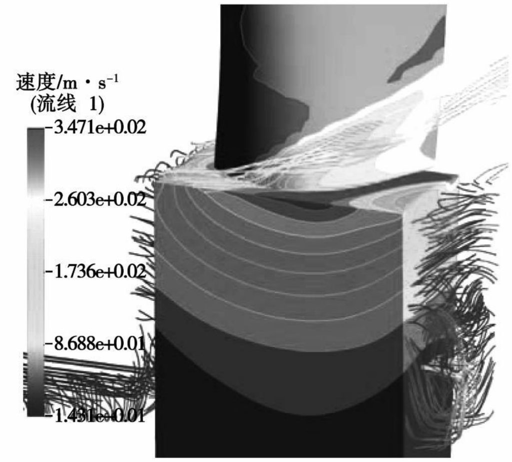
(a) 冷却蒸汽进口总压3.307 05 MPa



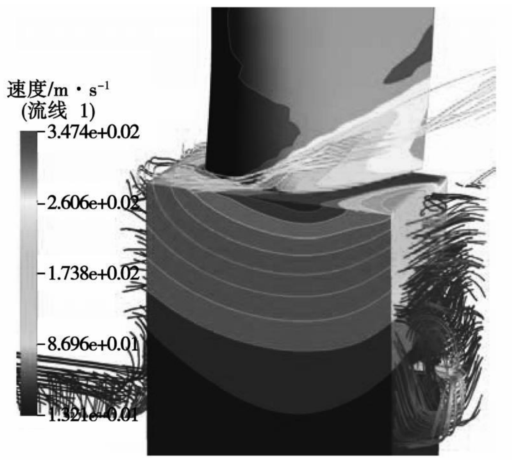
(b) 冷却蒸汽进口总压3.303 99 MPa



(c) 冷却蒸汽进口总压3.300 93 MPa



(d) 冷却蒸汽进口总压3.297 86 MPa

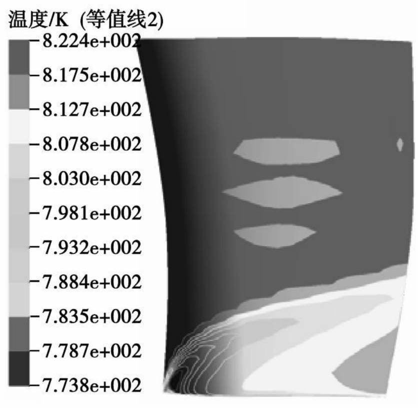


(e) 冷却蒸汽进口总压3.294 80 MPa

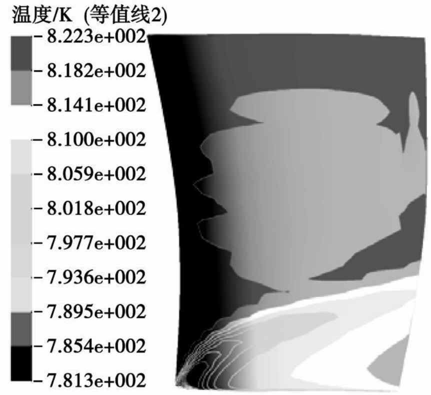
图 3　5个方案动叶栅内冷却蒸汽的流线分布

2.2 动叶吸力面的温度场

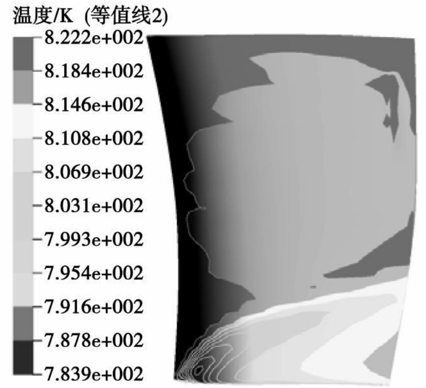
图 4为 5个方案动叶吸力面温度分布云图。比较冷却蒸汽不同进口条件下温度的数值范围, 随着进口总压的降低, 进入动叶栅流道的冷却蒸汽流量减少, 动叶吸力面最低温度值逐渐升高, 低温区域逐渐减少, 从而冷却效果降低。随着进入动叶栅冷却蒸汽流量的减少, 冷却蒸汽在动叶吸力面上进行冷



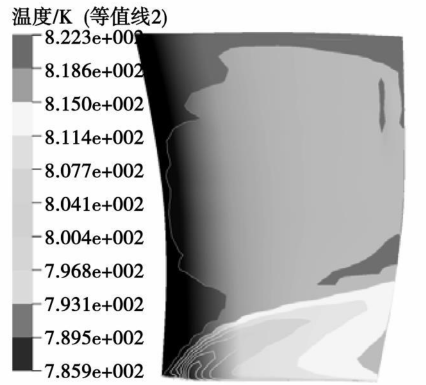
(a) 冷却蒸汽进口总压3.307 05 MPa



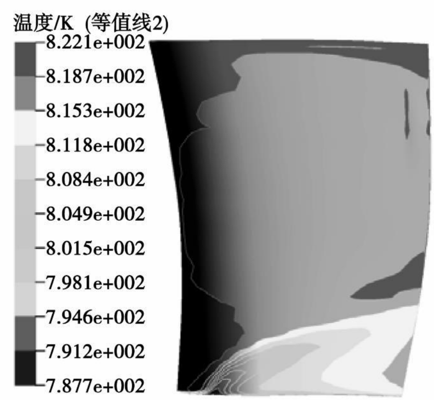
(b) 冷却蒸汽进口总压3.303 99 MPa



(c) 冷却蒸汽进口总压3.300 93 MPa



(d) 冷却蒸汽进口总压3.297 86 MPa



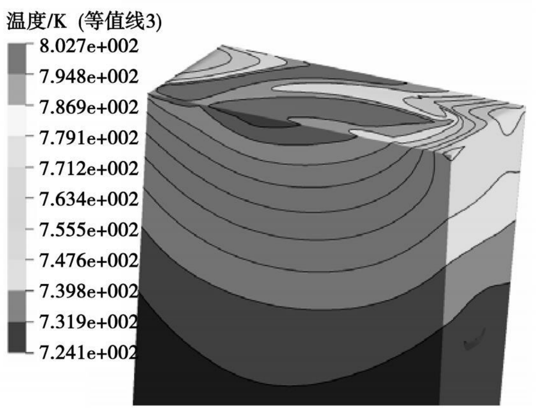
(e) 冷却蒸汽进口总压3.294 80 MPa

图 4　5个方案动叶吸力面温度分布云图

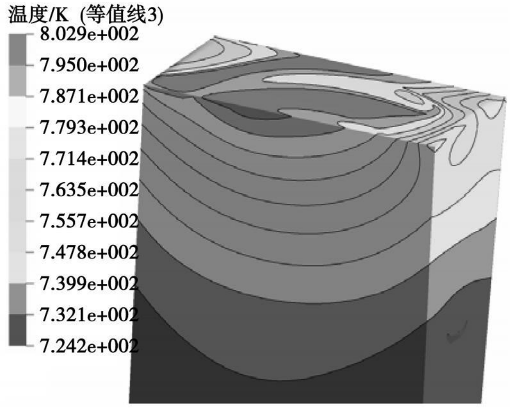
却的影响范围随之变小，并且冷却蒸汽在沿叶展方向的抬高程度逐渐降低，冷却蒸汽进口总压为3.307 05 MPa时，冷却蒸汽在动叶吸力面的影响范围达到 30%叶高，当冷却蒸汽进口总压降低到3.294 80 MPa时，冷却蒸汽在动叶吸力面上的影响范围最高点仅为 20%叶高。

如图所示，随着冷却蒸汽进口总压的降低，低温区核心由动叶前缘区域附近沿流向后移，并且区域范围不断变小。其原因是：随着冷却蒸汽进口总压的降低，进入高温主流的冷却蒸汽流量减少，掺混入主流的冷却蒸汽在较大流量时具有一定动能并在动叶根部前缘区域产生冲击冷却过程，随着冷却蒸汽流量的减少，冷汽一进入主流，就被主流掺混并被主流带动流向下游区域，并且大流量的高温主流更容易将较小流量的冷却蒸汽进行加热。因此，在冷却蒸汽进口总压减低的过程中，冷汽与主流混汽的恢复温度上升，使得动叶吸力面上的冷却区域向下游移动，并且低温核心区域逐渐变小。显而易见，伴随冷汽进口压力的下降，冷汽流量降低，动叶上最大温差值减小，并靠向尾缘，从而减小了动叶承受的热应力。

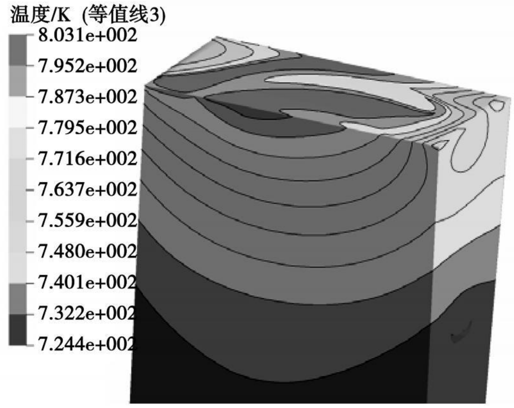
2.3 叶根表面温度场



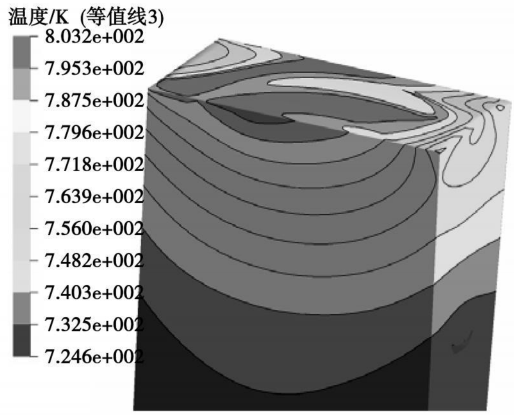
(a) 冷却蒸汽进口总压3.307 05 MPa



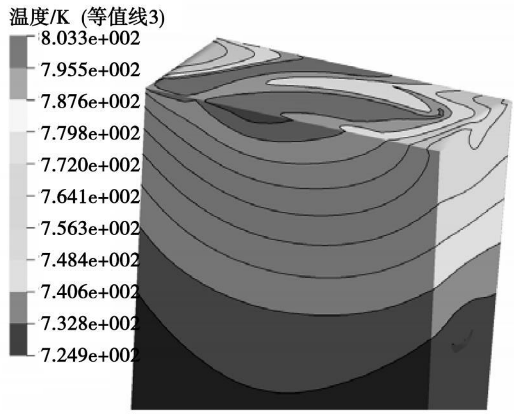
(b) 冷却蒸汽进口总压3.303 99 MPa



(c) 冷却蒸汽进口总压3.300 93 MPa



(d) 冷却蒸汽进口总压3.297 86 MPa



(e) 冷却蒸汽进口总压3.294 80 MPa

图5 5个方案叶根表面温度等值线云图

图5为5个方案叶根表面温度等值线云图。如图所示，各个方案叶根表面温度最小值相差不大，最大值仅有较小的温差。对于5个方案，冷却蒸汽最大进口总压对应的叶根表面最大温度值为802.7 K，最小进口总压对应的叶根表面最大温度值为803.3 K，温差0.6 K。由图还可以看到，轮毂表面

的温度变化比较剧烈, 在安装叶片的对应位置, 主蒸汽加热叶片, 叶片通过叶根与轮毂的接触面将热流向叶根传递, 在那里形成高温区, 其余区域为冷汽覆盖部分, 温度较低。轮毂表面高低温两区之间存在较大的温度梯度。随着冷汽进口总压的降低, 进入主流的冷却蒸汽流量减少, 通过叶根流道覆盖于轮毂面上的混汽的恢复温度增高, 因此, 轮毂面上高温区域低温区之间的温度梯度逐渐减小。由此可见, 冷却蒸汽进口总压的降低, 对叶根前后侧面的冷却效果影响不大, 仅降低了冷汽对轮毂表面的冷却效果。

3 结　论

(1) 冷却蒸汽进口总压是决定中压转子冷却效果和流场性能的关键参数。随着冷却蒸汽进口总压的减小, 通过中压第一级冷却蒸汽通道孔的冷汽相对流量增大, 进入主流的相对冷汽量下降。

(2) 冷却蒸汽进口总压对叶根表面温度的影响很小, 主要影响动叶吸力面的温度场, 最大与最小压力下冷却蒸汽对叶片吸力面的影响范围相差大约 10% 相对叶高。冷汽进口总压愈小, 动叶吸力面最低温度值愈大, 发生的位置移向下游。这使得动叶中的最大温差降低, 动叶承受的热应力减小。

(3) 冷却蒸汽进口总压越大, 冷却效果越好, 但是冷汽对主流的干扰越强, 将引起流动效率下降, 因此, 最佳冷汽进口总压的选取是冷却效果和流动效率的综合结果。

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新技术、新信息

新低速船用发动机企业—QMD成立

据《Diesel & Gas Turbine Worldwide》2009年 6月号报道, Waertsilae(瓦锡兰)、CSIC(中船重工)和 MHI(三菱重工)合资成立低速船用发动机合资 QMD企业(青岛齐耀瓦锡兰菱重麟山船用柴油机公司)。

现代化的 QMD于 2009年 3月开始投入运转并且是中国最先进的发动机厂之一。QMD设备和加工过程的自动化、试验台的灵活多样性、全负荷并联试验两台大功率发动机的能力, 连同高效的内部保障都使它成为世界上具有最强生产力的厂商之一。

在全部建成后, 总投资约为 1亿欧元(9.5亿人民币)的 QMD年生产能力将达到 746 MW(一百万马力)。

QMD已持有价值约为 2.7亿美元的订单。订单上的发动机被指定用于中国造船厂, 主要型号是 Waertsilae RT-flex50、RT-flex60C和 RT-flex82C以及 MHI UEC50发动机。

(吉桂明　摘译)

process of the EDC-five-step model is relatively low and the outlet temperature uniformity is optimal with its maximum non-uniformity being assessed at 28%. As a result, the NO_x emissions have been minimized. The research results show that the model in question can more rationally predict the flow field distribution of the combustor. Key words: gas turbine combustor, turbulent flow combustion model, numerical simulation

航空燃气轮机推力功势效率研究 = Study of the Thrust Work-potential Efficiency of an Aero Gas Turbine [刊, 汉] / HE Xing, SUN Feng-rui (College of Shipbuilding and Power, Naval University of Engineering, Wuhan, China, Post Code: 430033) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(1). —17~20

By using the thrust work-potential, one of the work-potential indexes in the second law of thermodynamics, derived was the expression of the thrust work-potential efficiency of various components in an aero gas turbine with the influence of various parameters on the above efficiency being analyzed and a criterion for "tending to be one simultaneously" of various efficiencies being proposed. As a result of the theoretical analysis and numerical calculation, an error in the reference literature [No. 2] was corrected. The research results show that the thrust work-potential efficiency not only assumes a close natural relationship with the component efficiencies, but also enjoys an intrinsic logic correlation with other thermodynamic parameters (such as pressure ratio). What differs from the component efficiencies is the fact that the thrust work-potential efficiency can unitedly evaluate the component efficiencies of an aero gas turbine from the viewpoint of converting a kind of energy to available work, thus laying a solid foundation for the further study of the energy conversion and utilization performance of various types of aero gas turbines. Key words: aero gas turbine, the second law of thermodynamics, thrust work-potential, efficiency

马赫数对振荡涡轮叶片非定常流动影响的数值模拟 = Numerical Simulation of the Influence of Mach Number on the Unsteady Flow in Oscillating Turbine Blades [刊, 汉] / ZHANG Zheng-qiu, ZOU Zheng-ping, LIU Huo-xing, et al (National Key Laboratory on Aero-engine Aerodynamics and Thermodynamics, Beijing University of Aeronautics and Astronautics, Beijing, China, Post Code: 100083) // Journal of Engineering for Thermal Energy & Power. —2010, 25(1). —21~24

The key parameters influencing flutter stability were studied along with an exploratory investigation of the significance of the judgement criterion of the law governing the change of the flutter stability with the aforementioned parameters on the flutter stability. On the basis of further improving the solution-seeking program for the unsteady Reynolds Number averaged N—S equation and based on an influence coefficient method, a numerical simulation was performed of the influence of the outlet Mach number on the three-dimensional flow around the oscillating turbine blades in various vibration modes. The numerical simulation results show that the developed program features a relatively good accuracy for simulating the flow in the oscillating cascade, and the outlet Mach number will exercise a definite influence on the unsteady flow inside the cascade and the unsteady pneumatic force on the blade surface. Moreover, the law governing the influence of the outlet Mach number on the unsteady flow under various modes is found to be not always identical. Key words: oscillating cascade, unsteady flow, vibration mode, numerical simulation, Mach number

冷却蒸汽进口总压对转子冷却效果影响的数值分析 = Numerical Analysis of the Influence of the Cooling-steam Inlet Total Pressure on Rotor Cooling Effectiveness [刊, 汉] / LIU Zhi-qiang, LIU Shun-long (College of Energy Source and Power, Harbin Engineering University, Harbin, China, Post Code: 150001), ZHOU Xun (College of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(1). —25~29

At various cooling-steam inlet total pressures, a numerical simulation was performed of the IP (Intermediate Pres-

sure) No. 1 stage of an ultra-supercritical steam turbine with the flow state in both the cooling path and the main flow passage being investigated. Moreover, the temperature field of the rotating blade surface and blade root surface was also studied. The research results show that corresponding to the given maximum and minimum inlet total pressures, the difference of the areas on the rotating blade suction surface being influenced by the cooling steam is about 10% of a relative blade height while that of the maximum temperature difference on the blade root surface, only around 0.6 K. The higher the inlet total pressure of the cooling steam, the better the cooling effectiveness. The interference of the cooling steam to the main stream, however, is also stronger, leading to a drop of the flow efficiency. Consequently, the optimum cooling steam inlet total pressure should be chosen by taking a comprehensive consideration of the cooling effectiveness and flow efficiency. Key words: cooling steam, total pressure, rotor, numerical simulation

600 MW汽轮发电机组轴系标高测试及振动故障治理＝Shafting Elevation Measurement and Vibration Troubleshooting of a 600 MW Turbo-generator Unit[刊，汉] / TIAN Xin-qi, GAO Wei (National Engineering Research Center for Vibration of Thermal Power Units, Southeast University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(1). —30～33

There exists a serious hidden trouble capable of causing an unstable vibration in a 600 MW turbo-generator unit of a power plant. During the load carrying period of the unit, a low frequency vibration at 17.5 Hz suddenly occurred to shaft No. 5 and 6 with an amplitude component equaling to 170 μm. A measurement and analysis of the change of the relative elevation, vibration and oil film pressure of the shafting system of the unit have induced one to conclude that the irrational elevation of the shafting system constitutes one of the main causes leading to an unstable vibration of the unit. The authors described the vibration measurement conditions of the unit and the methods for measuring and testing the shafting elevation. In conjunction with the measurements of the elevation, the law governing the change of the shafting elevation with the operating condition was analyzed. The measurement results indicate that from the cold state to the hot one, bearing No. 5 is relatively elevated by 1.180 mm in comparison with bearing No. 4. After a comprehensive analysis, a shafting elevation adjustment version was worked out and implemented in the cold state. Bearing No. 5 was elevated by 0.9 mm relative to bearing No. 4, thereby thoroughly solving the unstable vibration problem of the shafting system. Key words: shafting elevation, measurement, vibration, turbo-generator unit, elevation adjustment

燃气轮机热电联供系统性能评估案例＝Performance Evaluation Case of a Gas Turbine-based Heat-and-Power Cogeneration System[刊，汉] / LI Feng (Department of Architectural Engineering Science, Tsinghua University, Beijing, China, Post Code: 100084), ZHAO Xi-ling, FU Lin (Energy Source Research Institute, Beijing Tsinghua Urban Planning and Designing Institute, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(1). —34～38

A gas turbine heat-and-power cogeneration system in a heat supply plant was studied and compared comprehensively with a coal-fired and gas-fired cogeneration system. The performance evaluation played an important role in rationally utilizing cooling-heating-and-power (CHP) energy. Regarding the energy-saving property of the heating and power cogeneration system, when the gas-steam combined cycle power plant and the gas-fired boiler serve as a reference for comparison, the annually averaged energy-saving rate hits 8.9%. In a comparison of the operation economy, when the gas turbine system is compared with the coal-fired boiler system, a lump sum of RMB 460 000 yuan can be saved each year, and an amount of RMB 1.82 million yuan saved annually in comparison with the gas-fired boiler system. In the meantime, the cost saving will increase with an increase of the kilowatt-hour price and decrease with an increase of the gas price. In addition, when the gas turbine system is compared with the coal-fired boiler one, the cost saving will increase with an increase of the coal price. As regards emissions, when the gas tur-