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汽轮机转子蒸汽冷却计算模型构建研究

吕智强, 韩万金
(哈尔滨工业大学能源科学与动力工程学院, 黑龙江 哈尔滨 150001)

摘　要: 提高初参数是火力发电实现节能与环保两项国策的重要措施。在蒸汽初温提高的条件下, 为确保汽轮机部件的强度与寿命, 需要在提高材料耐热性的同时采取蒸汽冷却技术, 降低转子的温度与热应力。针对工程要求计算方法快捷、精确的特点, 本文构造了转子根部冷却的一维参数计算模型, 该模型综合考虑了冷却蒸汽对叶片表面的射流冲击冷却以及冷却蒸汽流过转子根部时的热传导冷却。应用该模型计算了超临界机组中压缸第一级转子经冷却后的温度场, 并与三维计算结果比较, 证明该模型能满足工程要求。

关　键　词: 超临界汽轮机; 蒸汽冷却; 冷却模型; 转子

中图分类号: TK263.6　　　　文献标识码: A

引　言

发展超临界机组是火力发电节约能源、改善环保和提高发电效率、降低发电成本的必然趋势。随着蒸汽温度的升高, 材料的力学性能有所下降, 为了保证汽轮机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[1]。GE 公司的 klaus 和 H.G.Neft 给出了用于超临界汽轮机冷却设计方案[2~3], 该方案使第一级叶片温度降低约 30 ℃, 采用冷却有效地降低了叶片的热应力水平。

国内关于超临界蒸汽冷却的研究还处于起步阶段。史进渊等人研究了超临界汽轮机的汽流激振和固体颗粒磨蚀问题[1,5]。文献[1]中只论述了一些超临界汽轮机的冷却结构。目前, 在国内研究冷却方案的选择、冷却流动机理等问题的文献公开发表的还不多。本文从冷却过程的特点分析入手, 将转子根部冷却分为两类不同的冷却过程, 并对不同的冷却过程建立相应的数学模型, 为冷却方案的选择提供理论计算模型。

1　转子根部冷却方案及冷却模型的建立

图 1 给出了转子根部冷却的示意图。冷却蒸汽经根部区域一部分进入转子榫头与轮盘之间间隙, 另外一部分直接进入转子根部的主流道。此外从根部间隙流出的蒸汽一部分从转子与隔板的间隙进入下一列叶栅, 另外一部分视转子出口根部压力的大小有可能进入转子后的主流场。图 2 与图 3 为冷却通道的局部放大图。

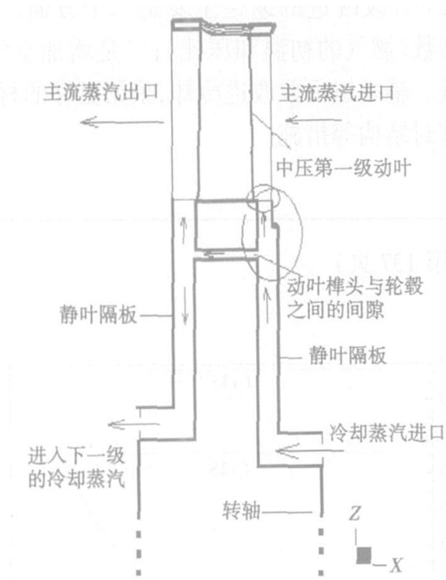

图 1　某汽轮机中压转子冷却方式

图 2 为冷却蒸汽流路示意图, 进入动叶根部的冷却蒸汽的流量取决于冷却蒸汽的滞止参数以及动叶后叶根的静压值; 而进入动叶主流道的冷却蒸汽流量以及在动叶主流道内掺混区域的大小, 与冷却蒸汽的滞止参数以及第一级静叶后根部的静压值有关。根据上述物理过程, 将冷却蒸汽分成两股汽流分别计算, 构建相应的动叶根部间隙的热传导数学模型以及动叶根部的射流冲击冷却模型。图 3 为射流冲击与掺混过程的简图, 射流冲击冷却模型就以此物理过程为依据, 确定射流高度(掺混区域的大小), 然后进行相应的叶片表面冷却计算。

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作者简介: 吕智强(1973－), 男, 吉林九台人, 哈尔滨工业大学博士研究生, 现任哈尔滨汽轮机厂有限责任公司高级工程师.

连续方程：

$$m_0 - m_2 - m_3 = 0 \tag{1}$$

能量方程：

$$m_0 h_0^* - m_2(h_2 + c_2^2/2) - m_3(h_3 + c_3^2/2) = 0 \tag{2}$$

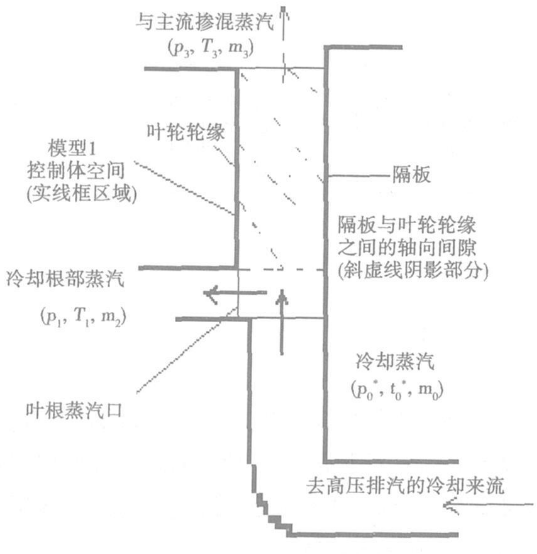

图 2　冷却蒸汽流路局部放大图

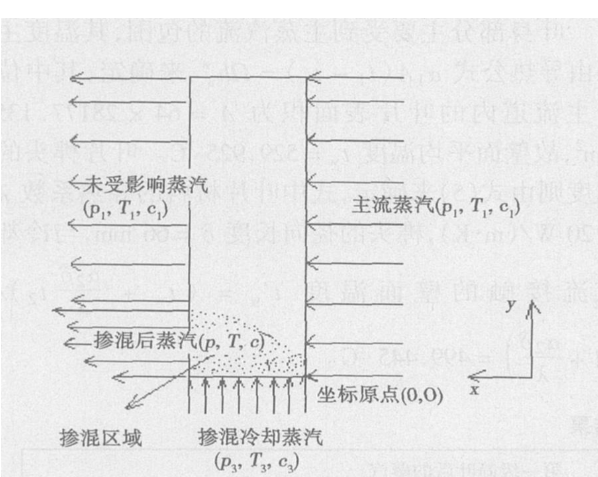

图 3　动叶根部射流冲击过程示意图

在确定流入动叶叶根的流量时需要用到流量修正系数，该流量采用下式计算：

$$m_2 = N\varphi\beta m_{2\max}$$

式中：N—叶片数；流量系数 $\varphi = 0.6$；β—彭台门系数，由下式计算：

$$\beta = \frac{G_n}{G_{nc}} = \frac{A_n\sqrt{\dfrac{2k}{k-1}\left(\varepsilon_n^{\frac{2}{k}} - \varepsilon_n^{\frac{k+1}{k}}\right)\dfrac{p_0^*}{v_0^*}}}{A_n\sqrt{k\left(\dfrac{2}{k+1}\right)^{\frac{k+1}{k-1}}\dfrac{p_0^*}{v_0^*}}} = \sqrt{\frac{2}{k-1}\left(\varepsilon_n^{\frac{2}{k}} - \varepsilon_n^{\frac{k+1}{k}}\right)} \Big/ \sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{3}$$

式中：m—质量流量；h—焓值，角标 0—冷却蒸汽进口；角标 2、3—流入动叶根部与进入动静叶间隙的物理参数。

射流模型：

$$\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} = a_x,\ \frac{\mathrm{d}^2 y}{\mathrm{d}t^2} = a_y$$

初始条件：

$$\frac{\mathrm{d}x}{\mathrm{d}t}\Big|_{(0,0)} = c_1,\ \frac{\mathrm{d}y}{\mathrm{d}t}\Big|_{(0,0)} = c_3 \tag{4}$$

式中：a_x、a_y—射流沿 x 与 y 方向的加速度。对于过热蒸汽微团，忽略其重力，只考虑由于压差所引起的运动变化，在 x 方向上 $\Delta m a_x = \Delta p_x \Delta F_x$，即 $\rho\Delta l\Delta F_x a_x = \Delta p_x$，对其积分有 $a_x = \dfrac{p_1 - p_3}{\rho\delta}$，式中：$\delta$ 为第一级隔板与叶轮间的轴向间隙；ρ 为混合后过热蒸汽的密度；在混合区域由于主流速度远大于来自根部间隙冷却来流速度，只存在两种过热蒸汽压差的作用，可近似地认为 $a_y = a_x$。假设动叶温度是均布的，把动叶片看成两部分，位于主流道内的部分为第一部分，其榫头为第二部分。第一部分受到主流的冲刷，壁面平均温度很高。由导热公式 $\alpha_1 A(t_1 - t_w) = \Omega h_s^*$，确定叶片表面温度。

对于榫头的温度计算，它的上部接受动叶叶根传导过来的热量，下部受到冷却蒸汽的冷却，榫头的周围看成是绝热的，列出数学描述为：

$$\begin{cases} \dfrac{\mathrm{d}^2 t}{\mathrm{d}x^2} = 0 \\ x = \delta,\ -\lambda\dfrac{\mathrm{d}T}{\mathrm{d}x} = \alpha_2(t - t_2) \\ x = 0,\ t = t_w \end{cases} \tag{5}$$

汽流参数的全部计算过程如图 4 所示。

2　算例分析

应用上述模型，对某型超临界汽轮机的中压第一级进行了蒸汽冷却计算。计算所采用的已知参数为其热平衡参数。第一级静叶前主流蒸汽的参数：压力 $p_1^* = 3.714\,75$ MPa，温度 $t_1^* = 565.618$ ℃，流入动叶前总流量为 1 455.58 t/h，反动度 $\Omega = 0.381\,8$，绝热焓降 $h_s^* = 67.83$ kJ/kg。高压排汽的冷却蒸汽参数：压力 $p_0^* = 3.327$ MPa，温度 $t_0^* = 441.843$ ℃，流量 $m_1 = 24$ t/h；进入动叶根部蒸汽口的过热蒸汽面积与压力分别为：$A_2 = 64 \times 35.9564 = 2\,301.209\,6$

mm^2, p_2 = 3.174 MPa。主流道的面积为 A_3 = 55 059.506 34 mm^2。转子叶片数为 64 片，单只叶片的表面积为 28 177.135 mm^2。第一级隔板与叶轮间的轴向间隙为 15 mm。

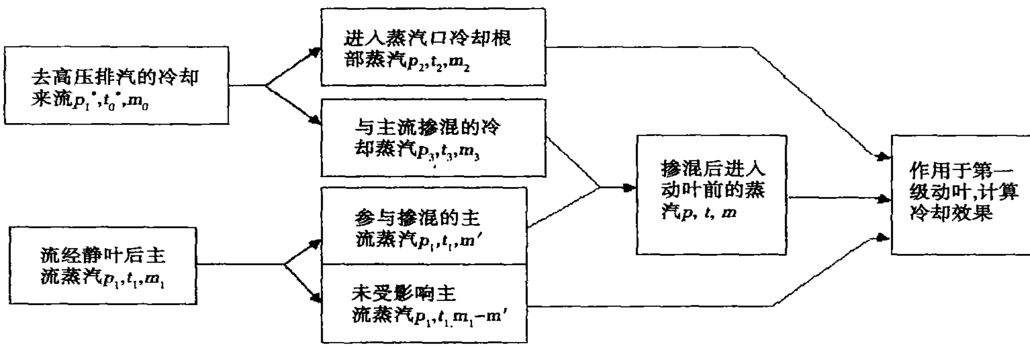

图 4　汽流参数计算步骤过程图

2.1　根部射流掺混区的计算

由式(4)可推导得掺混区沿叶高方向的最大高度为 $y_{max}=\dfrac{\rho c_3^2\delta}{p_1-p_3}$ = 7.304 8 mm。此外，由动叶的几何参数可确定第一级动叶前流道面积为 A = 528 032.3 mm^2；掺混后流入第一级动叶流道的面积为 A' = 26 980.881 mm^2。主流掺混部分的流量为 m' = 1455.58 × A'/A = 74.375 8 t/h。由公式(1)、(2)推导得出掺混区的压力与温度为 3.567 6 MPa、533.793 ℃。

2.2　动叶片表面平均放热系数的确定

对于位于主流道内的动叶片周围过热蒸汽的平均放热系数，由于掺混后的压力和温度与占大多数的主流相差不大，可以用主流参数来计算其平均放热系数，误差很小。主流过热蒸汽雷诺数为 $Re_1=\rho_1 c_1 l_1/\eta_1$，式中密度 ρ_1 = 9.207 5 kg/m^3，流速 c_1 = 92.397 1 m/s，特征长度 l_1 = 129.5mm。由平均放热系数准则公式 $Nu=0.81Re^{0.5}$，得出主流的放热系数 $\alpha_1=\dfrac{Nu_1\lambda_1}{l_1}=\dfrac{0.81Re_1^{0.5}\lambda_1}{l_1}$ = 903.001 $W/(m^2\cdot K)$。

2.3　第一级动叶片表面温度计算

叶身部分主要受到主蒸汽流的包围，其温度主要由导热公式 $\alpha_1 A(t_1-t_w)=\Omega h_s^*$ 来确定，其中位于主流道内的叶片表面积为 A = 64 × 28177.135 mm^2，故壁面平均温度 t_w = 529.925 ℃。叶片榫头的温度则由式(5)来确定，式中叶片材料的导热系数 λ = 20 W/(m·K)，榫头的径向长度 δ = 66 mm，与冷却汽流接触的壁面温度 $t'_w=\left(t_w+\dfrac{\alpha_2\delta}{\lambda}t_2\right)\Big/\left(1+\dfrac{\alpha_2\delta}{\lambda}\right)$ = 499.445 ℃。

表 1　计算结果

		冷却根部的蒸汽	进入主流的蒸汽	第一级静叶后的蒸汽	
一维计算结果	温度 t/℃	430.513	434.3	545.793	效果总计:
	静压力 P/MPa	3.174	3.172 5	3.405	无冷却时叶片表面平均温度
	密度 $\rho/kg\cdot m^{-3}$	9.898 2	10.082 4	9.207 5	为 533.793 ℃;
	流量 $m/t\cdot h^{-1}$	17.126 7	6.873 3	1 455.58	冷却后叶片根部表面平均温度
	流速 $c/m\cdot s^{-1}$	205.775 8	3.44	92.397 1	499.445 ℃
三维计算结果	温度 t/℃	430.513	432.7	545.972	效果总计:
	静压力 P/MPa	3.174	3.171 5	3.411	无冷却时叶片表面平均温度
	密度 $\rho/kg\cdot m^{-3}$	9.898 2	10.162 3	9.215 5	为 532.853 ℃;
	流量 $m/t\cdot h^{-1}$	17.126 7	6.834 3	1 455.58	冷却后叶片根部表面平均温度
	流速 $c/m\cdot s^{-1}$	217.822	3.721 4	92.796 3	500.642 ℃。

注：三维计算结果源于文献[6]，其中叶片表面和叶根表面平均温度是温度场的面积平均结果。

综上所述, 应用本文构建的一维转子冷却计算方法, 计算超临界机组中压第一级转子的冷却效果, 得出了如下结果(见表 1): 与无冷却时叶片表面的平均温度(533.793 ℃)相比, 有冷却时叶片根部表面平均温度(499.445 ℃)降低了 30.48 ℃, 降温效率达到 3.795%。该数值不仅与本算例设计参数符合得较好, 还与作者采用商用软件 CFX 所进行的三维数值计算结果(冷却使动叶根部表面平均温度降低了 32.211 ℃)相吻合[6]。此外, 该算法比起全三维计算来说具有简单快捷的优点, 这说明所开发的算法能够满足工程设计的需要。

3　结　论

(1) 从典型中压缸的冷却机理入手分析, 将冷却过程分解为转子根部热传导冷却以及转子表面冲击冷却两种方式, 构建了由热传导模型与射流冲击掺混模型组成的一维转子冷却计算方法。

(2) 对超临界机组中压第一级进行了一维流计算。结果表明, 叶片根部蒸汽冷却方式, 一方面可以较明显地降低叶片表面的温度, 另一方面基本不改变动叶流道内的流动效率, 是一种较好的冷却方式。

(3) 与应用三维商用软件得到的计算结果相比较, 本文所开发的冷却计算方法与其精度大致相当, 而且具有简单快捷的优点, 可以满足工程上对冷却效果评估的需求。

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(编辑　渠　源)

运行保障

蒸燃联合装置动力机组动力特性的构成和利用

据《Электрические станции》2006 年 6 月号报道。在蒸燃联合装置动力机组的动力特性中应该包含燃气轮机装置、余热锅炉、汽轮机装置的特性以及厂用电量和热量的关系。

燃气轮机装置特性的额定参数是电功率和外部空气的温度。其构成特性被固定, 并且以后通过修正考虑的外部因素是大气压力、空气的相对湿度、转速和接入防冰系统。燃气轮机装置的动力特性可以补充加入进、出口阻力的关系以及它们的偏差对主要特性的修正系数。

余热锅炉不同于传统的锅炉, 其效率不是由废气中的热量决定, 而是由余热锅炉出口燃气中的热量与燃气轮机装置出口燃气中的热量的比值确定。余热锅炉的动力特性可以补充加入沿燃气行程的最后受热面入口水温度的关系, 以及它的偏差对主要特性的修正系数。

汽轮机装置的特性是它的电功率取决于高压蒸汽流量和从抽汽拨出的热量的关系, 这一关系由试验得到。

用得到的燃轮机装置、余热锅炉和汽轮机装置的特性和厂用热量和电量的关系一起计算, 并考虑动力机组主要指标之间的从属关系, 这些指标是燃料供到燃烧室的热量、外部空气的温度、发出的电能和热量、燃料利用率等。

因此, 蒸燃联合装置的动力特性允许对在宽广的负荷范围内和在外部因素各种组合条件下单个部件和整个动力机组工作效率的分析。

(吉桂明　供稿)

应用于氦气压气机的相似模化方法验证＝**Verification of an Analog Modeling Method for Helium Compressors** [刊，汉] /ZHONG Sheng-jun，XU Li-min，JIN Jie-min，et al (Harbin No.703 Research Institute，Harbin，China，Post Code：150036)// Journal of Engineering for Thermal Energy & Power.—2007，22(2).—129～133

In consideration of an approximate modeling method featuring an equal inlet and outlet specific volume ratio with an axial helium compressor stage serving as a model and to solve an analog modeling problem existing between a helium compressor and an air one，a numerical simulation verification calculation has been conducted by using computational fluid mechanics software NUMECA. The calculation results have been compared with the test ones. It has been known from the numerical simulation verification that the performance curves obtained from formulae calculation differ relatively little with those obtained from the numerical simulation. The air flow angle difference between different working media，i.e. helium and air，is also very small. However，it has been learned from the air test results that the pressure ratio curves obtained from the formulae calculation are basically identical to those obtained from the test results，but there exists a certain difference of their adiabatic efficiency curves. To sum up，it can be shown that for a helium compressor with conventional blade profiles，a mach number lower than 0.4 and pressure ratio below 2，the analog modeling method in disregard of an equal mach number is effective and practical. **Key words**：helium，compressor，analog modeling，numerical simulation，air test

方差分析在电厂燃气轮机性能监测系统中的应用＝**Application of a Variance Analysis for the Performance Monitoring Systems of Power Plant Gas Turbines**[刊，汉] /XIA Di，WANG Yong-hong (Turbomachine Research Institute under Shanghai Jiaotong University，Shanghai，China，Post Code：200030)，HAN Gang (Shanghai Zhadian Gas Turbine Power Plant，Shanghai，China，Post Code：200438)// Journal of Engineering for Thermal Energy & Power.—2007，22(2).—134～137，141

A new set of gas turbine performance monitoring methods has been established by using variance analysis and time sequence models. It can eliminate the influence of atmospheric temperatures and power factors and only reflect the change in gas turbine operating performance. The variance reference line thus obtained can be used for the real-time performance monitoring of a gas turbine unit. To overcome the impact of atmospheric temperatures and other factors on various parameters of the gas turbine，only one variance standard has been used the whole year round. The method employs a time sequence model to seek the variance of the operating data. To eliminate the impact of different operating regimes on the monitoring of parameters，a method was adopted to monitor only the typical operating regimes. **Key words**：time sequence，gas turbine，monitoring standard，variance analysis

不断升级改进的LM2500燃气轮机＝**Constantly Upgraded and Improved LM 2500 Gas Turbines**[刊，汉] /WANG Chong，JIN Jie-min (Harbin No.703 Research Institute，Harbin，China，Post Code：150036)，TIAN Guang (Naval Representative Office Resident at Harbin No. 703 Research Institute，Harbin，China，Post Code：150036)// Journal of Engineering for Thermal Energy & Power.—2007，22(2).—138～141

Because of their superior performance，reliability and availability，gas turbines of LM2500 series have become a type of gas turbines most widely used at this range of power ratings. The development course of LM 2500 gas turbines has been given and its upgrading and improvement situation described along with their main structural features. Displayed are the excellent design and main performance derived from aero-derivative engine technologies. In addition，an analysis is performed of the basic strategies and technical approaches for LM2500＋，LM2500＋G4 upgrading and improvement as well as their design changes and main performance. It is noted that increasing air mass flow rate is a most common，conservative，low risk and effective method for engine upgrading and improvement. Usually，a No.0 stage is added to a compressor and the blade design of corresponding stages is adjusted (broaden the outlet area). **Key words**：gas turbine，upgrading and improvement

汽轮机转子蒸汽冷却计算模型构建研究＝**A Study of the Establishment of Turbine Rotor Steam-cooling Calculation Models**[刊，汉] /LU Zhi-qiang，HAN Wan-jin (College of Energy Sciences and Engineering under Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —142 ~145

To raise initial parameters is an important measure for achieving energy savings and environmental protection, two national policies for coal-fired power plants. Under the condition of an enhanced initial steam temperature, the heat endurance properties of materials need to be upgraded simultaneously with the adoption of a steam cooling technology to lower the temperature and thermal stress of the turbine rotor, thereby guaranteeing the strength and service life of turbine parts and other components. In meeting the features of a quick and accurate calculation method required by engineering designs, a one-dimensional parameter calculation model was established for blade root cooling of rotors. The model can comprehensively accommodate all the influencing factors, including the jet-flow impact cooling of steam on the blade surface and heat conduction cooling by steam passing through the rotor root portion. The model has been used to calculate the temperature profile in the first stage of the medium pressure cylinder of a supercritical steam turbine unit. The comparison of the calculation results with three-dimensional ones indicates that the model can meet relevant engineering design requirements. **Key words**: supercritical steam turbine, rotor, steam cooling, cooling model

轴系特定结构扭转刚度及其对扭振特性的影响= **The Torsional Rigidity of a Shafting Specific Structure and its Effect on the Torsional Vibration Characteristics**[刊,汉] /XIE Dan-mei, DONG Chuan (College of Power and Mechanical Engineering under Wuhan University, Wuhan, China, Post Code: 430072), LIU Zhan-hui (Henan Electric Power Test Academy, Zhengzhou, China, Post Code: 450052)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —146 ~148

With a domestically-made 660 MW supercritical steam turbine generator unit serving as an object of study, the torsion rigidity of shafting specific structures (such as stepped shaft, wholly-wrought wheel disks) and its effect on torsion vibration were calculated and discussed as a major focus. The formulae for calculating the material length λ in the stepped shaft not involved in the complete distortion was first derived with the λ value being determined in a range from 0 to 0.125 d_1。Then, a rigidity modeling method was presented for the material not involved in the complete distortion where there is an abrupt change in shaft diameter, unifying the treatment of the wholly-wrought rotor and stepped shaft. The calculation results of the shafting of a domestically-made 660 MW turbo-generator unit in a power plant indicate that the torsional vibration frequency obtained as a result of treating the shafting structure by using the derived formulae and modeling method under discussion is in good agreement with the result of empirical methods. The algorithm involved is characterized by its convenience for computer programming and assurance of a high calculation accuracy. **Key words**: turbo-generator unit, stepped shaft, wholly-wrought wheel disk, rigidity, torsional vibration

铁载氧体整体煤气化链式燃烧联合循环系统性能研究=**Performance Study of an Oxygen-bearing Iron Oxide-based Combined Cycle System Featuring Integrated Coal-gasification Chemical-looping Combustion**[刊,汉]/ MOU Jian-mao, XIANG Wen-guo (Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology under the Southeast University, Nanjing, China, Post Code: 210096), DI Teng-teng (Sichuan Electric Power Vocational College, Chengdu, China, Post Code: 610072)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —149 ~153

Chemical looping combustion can effectively separate out CO_2 with a simultaneous release of energy. A simulation study of the performance of a combined cycle system featuring integrated coal-gasification chemical-looping combustion with $FeO/Fe_3O_4/Fe_2O_3$ serving as an oxygen carrier has been conducted by using software ASPEN PLUS. In the meantime, the effect of air reactor temperature, cooling-air flow rate and supplementary firing temperature at the turbine inlet on such parameters as system efficiency, oxygen consumption rate and CO_2 emissions etc. was also studied. The simulation results indicate that when the supplementary firing temperature at the turbine inlet is kept at 1350 ℃ and the air reactor temperature increases from 850 ℃ to 1100 ℃, CO_2 emissions will drop from 396 g/(kWh) to 210 g/(kWh); the system efficiency will decrease from 44.04% to 43.19%. An increase in cooling-air flow rate will also reduce the system efficiency. When the supplementary firing temperature at the turbine inlet goes up, the CO_2 emissions will increase accordingly. There exists an optimum compression ratio at a given turbine inlet temperature. **Key words**: chemical-looping combus-