热力循环

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内可逆焦耳—布雷顿功热并供系统的㶲优化分析

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摘 要: 用热力学优化理论对内可逆焦耳—布雷顿功热并供系统进行了㶲优化分析。建立了以系统设计参数为变量的总㶲目标函数, 引入等效温度来计算热回收装置传热过程中的㶲, 得出了最大无量纲总㶲时功热并供系统的㶲效率及最优设计参数, 讨论了各参数对系统㶲性能的影响, 并用数值分析的方法得到最大无量纲总㶲和对应的㶲效率与其它参数的优化关系。分析显示系统性能随功热比的变化趋势不是单调的。在满足热用户需求的范围内, 对于给定的热用户温度参数, 增大系统循环温比可提高功热并供系统的㶲性能。

关 键 词: 功热并供; 总㶲; 㶲效率; 优化

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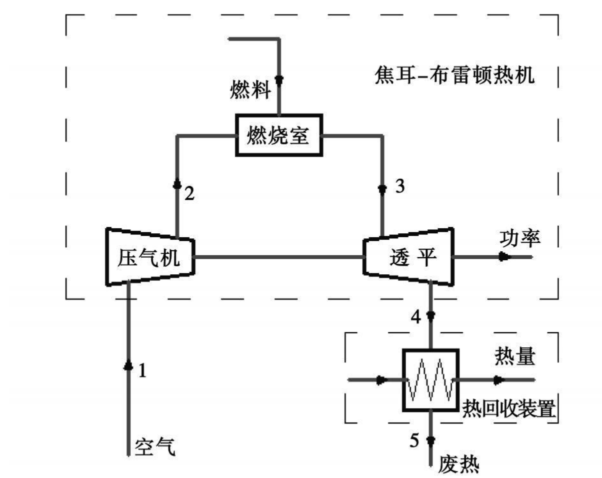
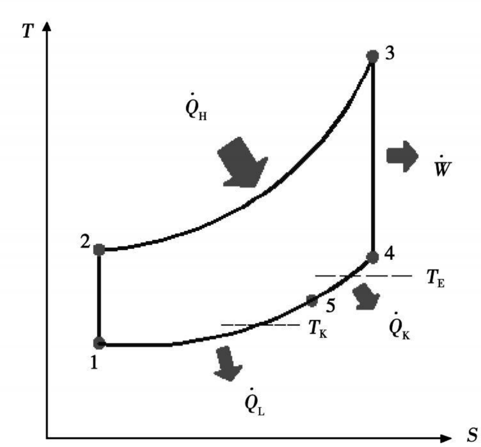
引 言

20 世纪七八十年代总能系统概念的提出, 使得热力循环研究思路发生重大变化。人们不再局限于单一循环的优势, 而更重视把不同循环有机结合起来, 在系统的高度上综合考虑能量转换过程中功和热的梯级利用, 不同品位和形式能量的合理安排以及各系统构成的优化匹配等, 将产功和供热有机结合起来的功热并供系统也由此得到越来越广泛的研究。Sahin 对内可逆卡诺功热并供循环模型进行了㶲优化分析[1]; Hao 利用总能利用率为目标函数对内可逆焦耳—布雷顿功热并供系统进行了性能优化分析[2]; Tamer 研究了燃气轮机功热并供系统的㶲性能优化问题[3]。另外, 国内一些文献也对燃气轮机及其功热并供系统做了研究, 得到了一些有意义的结论[5~7]。利用焦耳—布雷顿热机结合一个热回收装置的功热并供循环也是一个较好的模型, 考虑到功和热是不同质的能量, 本文将放弃传统的总能利用率分析模型, 建立以系统设计参数为变量的总㶲目标函数, 引入等效温度来计算热回收装置传热过程中的㶲, 用热力学优化理论对内可逆焦耳—布雷顿功热并供系统进行㶲优化分析。

1 理论模型



(a) 系统图



(b) T-S 图

图 1 焦耳—布雷顿功热并供系统

如图 1(a) 所示, 焦耳—布雷顿功热并供系统由焦耳—布雷顿热机(压气机、燃烧室和透平)和热回收装置组成。该模型仅考虑由有限温差传热引起的外部不可逆性的理论模型, 其中布雷顿循环由两个

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等压过程和两个等熵过程组成，具体 $T-S$ 图如图 1(b)所示。

由热力学基本方程，可得到焦耳—布雷顿功热并供系统的功率输出和热量输出分别为：

$$W=\dot{m}c_p[(T_3-T_2)-(T_4-T_1)] \tag{1}$$

$$Q_k=\dot{m}c_p(T_4-T_5) \tag{2}$$

式中：$\dot{m}$—质量流量；c_p—定压质量比热，设为定值；如图 1 所示，T_1、T_2、T_3、T_4 和 T_5—压气机入口温度(环境温度)、压气机出口温度、透平进口温度、透平出口温度和热交换器出口温度。

由热力学第二定律可得：

$$T_2/T_1=T_3/T_4=\theta \tag{3}$$

式中：θ—布雷顿循环的绝热过程温比；为方便后面的讨论，还需定义以下参数：循环温比 $\phi=T_3/T_1$；热用户温度参数 $\psi=T_k/T_1$，其中 T_k 为热用户所需的温度；热回收温比 $\alpha=T_5/T_1$，反应废热回收利用的程度。

将各参数代入式(1)和式(2)可得：

$$W=\dot{m}c_pT_1(\phi-\theta-\frac{\phi}{\theta}+1) \tag{4}$$

$$Q_k=\dot{m}c_pT_1(\frac{\phi}{\theta}-\alpha) \tag{5}$$

功热比：

$$R=\frac{W}{Q_k}=(\phi-\theta-\frac{\phi}{\theta}+1)/(\frac{\phi}{\theta}-\alpha) \tag{6}$$

由式(6)可得：

$$\alpha=\frac{\phi}{\theta}-\frac{1}{R}(\phi-\theta-\frac{\phi}{\theta}+1) \tag{7}$$

分析不难得出 α 和 θ 满足下列不等式：

$$\psi\leqslant\alpha\leqslant\phi/\theta \tag{8}$$

对于给定的 ϕ、ψ和 R，联合式(7)和式(8)可得到参数 θ 的取值范围：

$$1\leqslant\theta\leqslant\theta_1 \tag{9}$$

其中：

$$\theta_1=\frac{R\psi+\phi+1-\sqrt{(R\psi+\phi+1)^2-4\phi(R+1)}}{2}$$

输出功率的㶲为：

$$E_W=W \tag{10}$$

输出热量的㶲为：

$$E_Q=Q_k(1-\frac{T_1}{T_E}) \tag{11}$$

式中：T_E—等效温度，将图 1 中 4～5 过程的传热温度 T_E 等效成卡诺循环中的恒定温度[3]，则此过程传递的热量可写成：

$$Q_k=T_E\Delta S_{4\sim5} \tag{12}$$

在等压过程中：

$$\Delta S_{4\sim5}=\dot{m}c_p\ln\frac{T_4}{T_5} \tag{13}$$

由式(12)和式(13)可得：

$$T_E=Q_k/\dot{m}c_p\ln\frac{T_4}{T_5} \tag{14}$$

综合式(5)、式(7)、式(11)和式(14)可得输出热量的㶲为：

$$E_Q=\dot{m}c_pT_1(\frac{\phi-\theta-(\phi/\theta)+1}{R}-\ln\frac{R\cdot\phi}{\theta_2-(1+\phi)\theta+(1+R)\phi}) \tag{15}$$

功热并供系统的总㶲为：

$$E_T=E_W+E_Q \tag{16}$$

将式(4)和式(15)代入式(16)可得：

$$E_T=\dot{m}c_pT_1[(1+\frac{1}{R})(\phi-\theta-\frac{\phi}{\theta}+1)-\ln\frac{R\cdot\phi}{\theta^2-(1+\phi)\theta+(1+R)\phi}] \tag{17}$$

则无量纲功热并供系统的总㶲为：

$$\overline{E}_T=\frac{E_T}{\dot{m}c_pT_1}=(1+\frac{1}{R})(\phi-\theta-\frac{\phi}{\theta}+1)-\ln\frac{R\cdot\phi}{\theta^2-(1+\phi)\theta+(1+R)\phi} \tag{18}$$

㶲效率：

$$\eta_E=E_T/E_H \tag{19}$$

式中：E_H—输入系统的总㶲。

$$E_H=\dot{m}c_p(T_3-T_2)(1-\frac{T_1}{T_3})=\dot{m}c_pT_1(\phi-\theta)\times(1-\frac{1}{\phi}) \tag{20}$$

将式(17)和式(20)代入式(19)得：

$$\eta_E=[(1+\frac{1}{R})(\phi-\theta-\frac{\phi}{\theta}+1)-\ln\times\frac{R\cdot\phi}{\theta^2-(1+\phi)\theta+(1+R)\phi}](\phi-\theta)^{-1}(1-\frac{1}{\phi})^{-1} \tag{21}$$

2　优化结果及讨论

对于给定的循环温比 ϕ、热用户温度参数 ψ及功热比 R，可求出式(18)关于 θ 的最大值。令 $\frac{d\overline{E}_T}{d\theta}=0$ 可得到：

$$(1+\frac{1}{R})(\frac{\phi}{\theta^2}-1)+\frac{2\theta-\phi-1}{\theta^2-(1+\phi)\theta+(R+1)\phi}=0 \tag{22}$$

当 θ 满足式(22)时，即 $\theta=\theta^*$ 时，系统的无量纲总㶲 $\overline{E}_T$ 取得最大值。但是，由不等式(8)可知，θ 的取值范围为$[1, \theta_1]$，因此，$\theta=\theta^*$不总是使 $\overline{E}_T$ 取得最大值的点。又由分析可知，在 $\theta\in[0, \theta^*]$ 的范围内，$\overline{E}_T$ 随 θ 的增大而增大，所以当 $\theta^*\in[1, \theta_1]$ 时，$\theta=\theta^*$ 为 $\overline{E}_T$ 的最大值点，否则，$\theta=\theta_1$ 为 $\overline{E}_T$ 的

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最大值点，即：

$$\theta_{et}^{*}=\begin{cases}\theta=\theta^{*} & \theta_1\geq\theta^{*}\\ \theta=\theta_1 & \theta_1<\theta^{*}\end{cases}\tag{23}$$

其中 θ_1 由式(9)确定。将式(23)分别代入式(18)和式(21)可得系统的最大无量纲总㶲及其对应的㶲效率分别为：

$$E_{T\max}=\begin{cases}(1+\dfrac{1}{R})(\phi-\theta^{*}-\dfrac{\phi}{\theta^{*}}+1)-\ln\dfrac{R\cdot\phi}{\theta^{*2}-(1+\phi)\theta^{*}+(1+R)\phi}, & \theta_1\geq\theta^{*}\\ (1+\dfrac{1}{R})(\phi-\theta_1-\dfrac{\phi}{\theta_1}+1)-\ln\dfrac{R\cdot\phi}{\theta_1^{2}-(1+\phi)\theta_1+(1+R)\phi}, & \theta_1<\theta^{*}\end{cases}\tag{24}$$

$$\eta_{E}^{*}=\begin{cases}\left[(1+\dfrac{1}{R})(\phi-\theta^{*}-\dfrac{\phi}{\theta^{*}}+1)-\ln\dfrac{R\cdot\phi}{\theta^{*2}-(1+\phi)\theta^{*}+(1+R)\phi}\right](\phi-\theta^{*})^{-1}(1-\dfrac{1}{\phi})^{-1}, & \theta_1\geq\theta^{*}\\ \left[(1+\dfrac{1}{R})(\phi-\theta_1-\dfrac{\phi}{\theta_1}+1)-\ln\dfrac{R\cdot\phi}{\theta_1^{2}-(1+\phi)\theta_1+(1+R)\phi}\right](\phi-\theta_1)^{-1}(1-\dfrac{1}{\phi})^{-1}, & \theta_1<\theta^{*}\end{cases}\tag{25}$$

当 $R\rightarrow\infty$ 时，输出热量的㶲趋近于零，内可逆功热并供系统转化成简单的内可逆功率输出系统，因此功热并供系统的总㶲等于系统功率输出，即 $E_T=E_W=W$。此时，由式(21)可解得 $\theta^{*}=\sqrt{\phi}$，而当 $R\rightarrow\infty$ 时，$\theta_1\rightarrow\phi$，结合式(23)可得到 $R\rightarrow\infty$ 时：

$$\theta_{et}^{*}=\theta^{*}=\sqrt{\phi}\tag{26}$$

将式(26)代入式(25)可得到 $R\rightarrow\infty$ 时系统最大无量纲总㶲对应的㶲效率为：

$$\eta_{E}^{*}=\frac{\sqrt{\phi}-1}{\sqrt{\phi}(1-1/\phi)}\tag{27}$$

对于内可逆功率输出循环系统，其能效率和㶲效率之间的关系为：

$$\eta=\eta_E(1-\frac{T_1}{T_3})=\eta_E(1-\frac{1}{\phi})\tag{28}$$

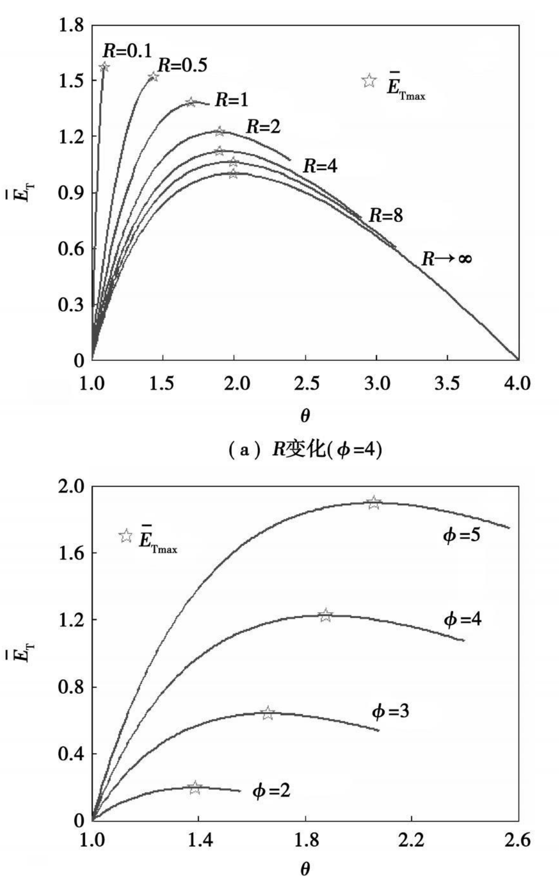
结合式(27)和式(28)可知，当 $R\rightarrow\infty$ 时系统最大无量纲总㶲对应的能效率等于 CA 效率[8]：

$$\eta^{*}=\eta_{CA}=1-\frac{1}{\sqrt{\phi}}\tag{29}$$

即内可逆功率输出循环模型是内可逆功热并供循环模型的特例。

图2 反映了循环温比 ϕ 和功热比 R 一定时，无量纲总㶲 E_T 随参数 θ 的变化关系。由图可知，对于给定的其它参数，可得到无量纲总㶲关于 θ 的最大值，且最大无量纲总㶲随 R 的减小和 ϕ 的增大而增大，由图 5 也可得到这个结论。

图3 反映了无量纲总㶲 E_T 随系统㶲效率 η_E 的变化关系。当 R 较小的时候，无量纲总㶲 E_T 随㶲效率 η_E 的增大而增大，在 $\theta=\theta_1$ 时同时达到最大值；随着 R 的增大，E_T 在 $\theta=\theta^{*}$ 处取得最大值，η_E 在 $\theta=\theta_1$ 处取得最大值。显然，存在一个 R 的临界值 R'，当 $R\leq R'$ 时，E_T 和 η_E 能同时达到最大值，当 $R>R'$ 时，对于给定的 ϕ 和 ψ 存在一个 E_T 最大的最佳温比 θ_{et}^{*} 和㶲效率最高的最佳温比 θ_{ef}^{*}，两者的差值较大，通常无法兼得。由图3 还可看出，最大无量纲总㶲 $E_{T\max}$ 及最大㶲效率对应的无量纲总㶲 E_T^{*} 均随 R 的增大而减小，而最大无量纲总㶲对应的㶲效率 η_E^{*} 的变化情况则与 R 的临界值 R' 有关，当 $R\leq R'$ 时，η_E^{*} 随 R 的增大而增大，η_E^{*} 反之随 R 的增大而减小，因此功热并供系统的系统性能不总是随 R 的减小而增大的。



(a) R变化(φ=4)

(b) φ变化(R=2)

图 2　无量纲总㶲 E_T 随参数 θ 的变化关系

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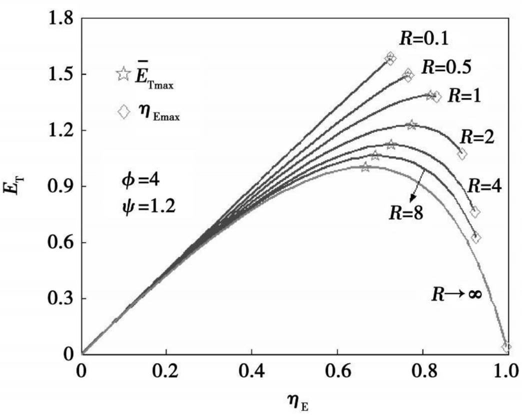
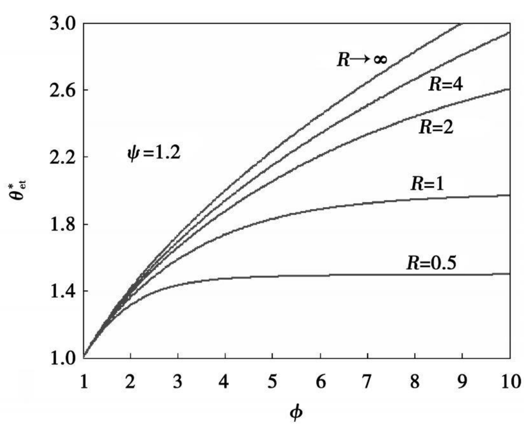
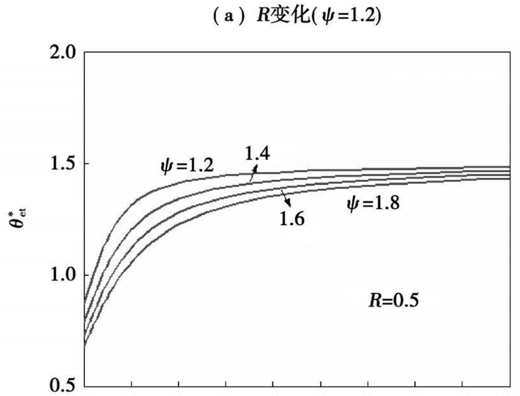


图 3　无量纲总㶲 E_T 随效率 η_E 的变化关系

由于 θ 是布雷顿功热并供循环中一个较为重要的参数，本研究还分析了其它参数对 θ 优化值 (θ_{et}^*) 的影响。如图 4 所示，θ_{et}^* 随 φ、R 的增大而增大，随 ψ的增大而减小，对于给定的 φ、R 、ψ，可由式(9)、式(22)和式(23)求出 θ_{et}^*。



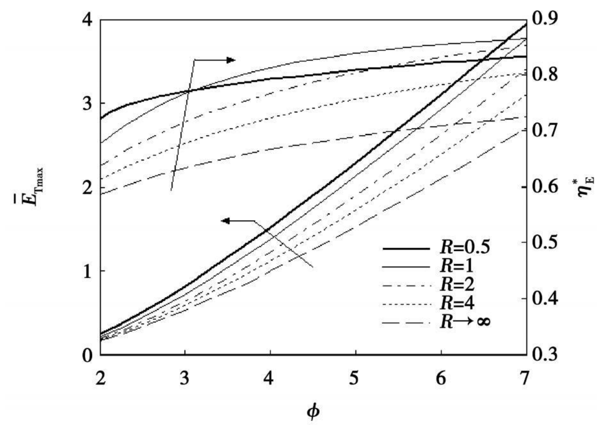
（a） R变化(ψ=1.2)



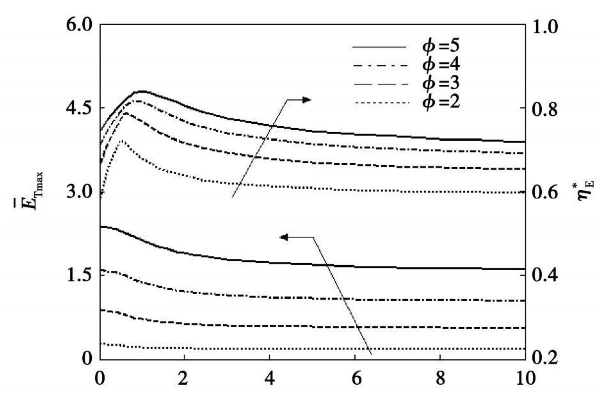
（b） ψ变化(R=0.5)

图 4　θ_{et}^* 随 φ 的变化关系

图 5 由数值分析的方法得出了功热并供系统最大无量纲总㶲 E_{Tmax} 及其对应的㶲效率 η_E^* 随参数 φ、R 的变化关系。如图所示，对于给定的满足热用户需求的温度参数 ψ，E_{Tmax} 和 η_E^* 均随循环温比 φ 的增大而增大，显然，E_{Tmax} 随 φ 的增大而增大得要迅速一些。E_{Tmax} 随 R 的增大而减小，η_E^* 随 R 的变化情况与 R 的临界值 R′有关，这与图 3 所得的结论一致。由图 5(b)还可以看出，系统性能随 R 的变化趋势不是单调的，在给定的参数 φ、ψ下，取得 η_E^* 最优值的 R 取值范围为 0.3～1。



（a） 随循环温比 φ 的变化关系



（b） 随功热比R的变化关系

图 5　最大无量纲总㶲 E_{Tmax} 及其对应的㶲效率 η_E^* 随各参数的变化关系（ψ=1.2）

3　结　论

对内可逆焦耳—布雷顿功热并供系统进行了㶲优化分析，分析显示内可逆焦耳—布雷顿功率输出模型为内可逆焦耳—布雷顿功热并供循环模型的一个特例。在满足用户温度需求的范围内，对于给定的参数 ψ，增大系统循环温比 φ 可提高功热并供系统的㶲性能。对于给定的循环温比 φ、热用户温度参数 ψ，存在一个临界的功热比 R′，当 R ≤R′时，E_T 和 η_E 能同时达到最大值，当 R> R′时，使 E_T 最

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大的最佳温比 θ_{et}^{*}和使火用效率最高的最佳温比 θ_{ef}^{*}差值较大，通常无法兼得。还利用数值分析的方法得到了最大无量纲总火用及其对应的火用效率与其它参数的优化关系，分析显示系统性能随功热比 R 的变化趋势不是单调的，在给定的参数 ϕ、ψ下，取得 η_E^{*} 最优值的 R 取值范围约为 0.3～1。这为功热并供系统设计参数的选择提供了理论基础。

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（编辑　伟）

新技术、新工艺

动力锅炉的现代化改造

据《Электрические Станции》2008 年 3 月号报道，在保证严格的安全性要求的条件下，制定并在动力装置中采用燃料高效的燃烧方法可以节省燃料并减少有害物质的排放。

为了提高炉膛出口烟气的温度、在低过量空气条件下保持过热蒸汽的温度，以及最少降低有害物质排放，俄罗斯中央锅炉涡轮机研究所制订了下列措施的燃料标准的高效低毒性燃烧方法：

(1) 应用专用的新一代低排放燃烧器；

(2) 具有低过量空气的燃烧；

(3) 分级供入氧化介质(在燃烧天然气时)；

(4) 烟气再循环。

使用中央锅炉涡轮机研究所的燃烧器时，NO_x 排放量比改造前减少 20%～25%。

在额定负荷、以供入再循环烟气的方式燃烧天然气时，NO_x 排放量不超过 125 mg/m^3。

制定的燃烧方法，是在整个负荷范围内能保证系统安全启动、稳定燃烧。

使用具有可调节供气部分的燃烧器不仅得到 NO_x 的低排放，而且也影响过热蒸汽的温度、燃烧核心区内温度的分布特性。

（吉桂明　供稿）

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curacy, calculation efficiency, gas-heat coupling

带后导叶轴流式通风机内流特征的数值模拟＝**Numerical Simulation of the Inner Flow Characteristics of an Axial Fan with Rear Guide Vanes**[刊,汉] / YE Xue-min, LI Jun, WANG Song-ling, et al (College of Energy Source and Power Engineering, North China Electric Power University, Baoding, China, Post Code: 071003)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(2). —163～166

Axial fans with adjustable rotating blades are very often used due to their relatively wide high-efficiency zone. By utilizing software Fluent and with an OB-84 type axial fan incorporating adjustable rotating blades and rear guide vanes serving as an object of study, the SIMPLE method was employed to seek solutions to the $N-S$ equation and Realizable $k-\varepsilon$ turbulent flow model with a simulation of the inner flow characteristics on the radial and axial characteristic stream surface of the impeller being conducted under design and off-design operating conditions. It has been found that the fan total pressure gradually increases along the radial direction. There exist a high-pressure zone in the tail portion of the pressure surface and a reverse pressure gradient on the suction surface, and the total pressure at the trailing edge decreases remarkably. When the fan operates under off-design conditions, a vortex will first emerge at the trailing edge, forcing the return flow of a portion of fluid and forming a relatively big flow resistance. The total pressure along the cascade flow path assumes a linear increase, which mainly results from a static pressure. The fan total pressure and efficiency characteristic curves obtained from the numerical simulation are in good agreement with the test results, and the simulation results can relatively well reflect the overall operating performance of the fan. **Key words**: axial fan, rear guide vane, inner flow characteristics, numerical simulation

超高负荷吸附式压气机叶栅气动性能分析＝**Analysis of the Aerodynamic Performance of a Super-highly Loaded Adsorption Type Compressor Cascade**[刊,汉] / CHEN Shao-wen (College of Energy Source and Power, Harbin Engineering University, Harbin, China, Post Code: 150001), GUO Shuang, LU Hua-wei, CHEN Fu (College of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(2). —167～171

Numerically studied was the influence of boundary layer elimination by a suction at a low speed on the aerodynamic performance of a super-highly loaded compressor cascade. The distribution of the total pressure loss, diffusion factor and airflow angle along the blade height was analyzed, and the limit streamline and profile static pressure on the suction surface were given. It has been found that the boundary layer elimination by suction can effectively improve the cascade aerodynamic performance, and the low-energy fluid removal through a suction can decrease the separation of the suction surface and the corner area, increasing the capacity of the flow path and enhancing the cascade load and diffusion capacity. In addition, the larger the suction air flow rate, the more conspicuous the improvement. A suction at a location of 60% axial chord can achieve the best effectiveness. The influence of the suction location on suction effectiveness is larger than that of the suction air flow rate. To appropriately increase the suction air flow rate can enhance the suction effectiveness, and the selection of an optimum suction location and air flow rate is correlated with the diffusion process and separation degree inside the cascade. **Key words**: super-highly loaded compressor cascade, boundary layer elimination through a suction, suction location, suction air flow rate

内可逆焦耳—布雷顿功热并供系统的㶲优化分析＝**Exergy Optimization Analysis of an Endo-reversible Joule-Brayton Power-and-heating Cogeneration System**[刊,汉] / XIE Ping, HUANG Yue-wu (College of Environment Science and Engineering, Donghua University, Shanghai, China, 201620) // Journal of Engineering for Thermal Energy & Power. — 2009, 24(2). —172～176

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The exergy optimization analysis of an endo-reversible Joule-Brayton power-and-heating cogeneration system has been performed by using the theory of thermodynamics optimization. Established was the target function of a total exergy with system design parameters serving as variables, and introduced was an equivalent temperature for calculating the exergy of a heat recovery device in its heat transfer process. The exergy efficiency and optimum design parameters of the power-and-heating cogeneration system at a maximum non-dimensional total exergy were obtained, and the influence of various parameters on the system exergy performance was also discussed. By adopting a numerical analytic method, obtained were a maximum non-dimensional total exergy and optimization relationship between the corresponding exergy efficiency and other parameters. It has been found through an analysis that the system performance does not exhibit a monotone tendency of variation with the power-heating ratio. Within the range satisfying the demand of heat-users and for a given heat-user temperature parameter, it is possible to enhance the exergy performance of the power-and-heating cogeneration system by increasing the system circulating temperature ratio. The endo-reversible Joule-Brayton power output model represents a special case of the model for endo-reversible Joule-Brayton power-and-heating cogeneration cycles. **Key words**: power and heating cogeneration, total exergy, exergy efficiency, optimization

300 MW 燃煤锅炉 O_2/CO_2、烟气再循环燃烧的数值模拟＝**Numerical Simulation of O_2/CO_2 Recycled Flue Gas Combustion in a 300 MW Boiler**[刊, 汉] / LIU Yan-feng, LIANG Xiu-jun, GAO Zheng-yang (College of Energy Source and Power Engineering, North China Electric Power University, Baoding, China, Post Code: 071003), WANG Jian-qiang (Hebei Subsidiary of China Nuclear Power Engineering Co. Ltd., Shijiazhuang, China, Post Code: 050001)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(2). —177～181

With a 300 MW tangentially corner-fired pulverized coal boiler serving as an object of study, the three-dimensional framework and mesh generation of a furnace was established by using software ICEM. A proper mathematical model for in-furnace turbulent flows, combustion and heat transfer was chosen in TASCFLOW to numerically simulate the pulverized-coal combustion process in O_2/CO_2 atmosphere at a volumetric ratio of oxygen assessed at 29%. It has been found that when the mixture of O_2/CO_2 was uniformly fed into the furnace, the pulverized-coal ignition and combustion will be delayed to a definite extent as compared with the case characterized by the presence of combustion-supporting air. The high-temperature zone in the flame center and furnace tends to be expanded conspicuously with the flame center being located more close to the furnace center and somehow moving upward along the furnace height. When the flue gas is recycled, oxygen is directly fed into the furnace, which would be favorable for the pulverized-coal ignition and combustion, greatly increasing the temperature in the furnace. **Key words**: O_2/CO_2, flue gas recirculation, 300 MW boiler, combustion, numerical simulation

5 000 t/d 干法水泥线余热发电热工参数的计算分析＝**Calculation Analysis of the Thermotechnical Parameters of a Waste-heat Power Generation System in a 5 000 t/d Dry-method Cement Production Line**[刊, 汉] / DONG Chen, ZHAO Qin-xin, ZHOU Qu-lan, et al (College of Energy Source and Power Engineering, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049)//Journal of Engineering for Thermal Energy & Power. — 2009, 24(2). —182～187

For a 5 000 t/d new type dry-method cement kiln system, a pure low-temperature dual-pressure waste-heat power generation system was designed, and a theoretical calculation analysis of various parameters of the system, performed. Obtained was a law governing the influence on the power generated by the system by the following items: main steam temperature and pressure, feedwater temperature, high-pressure node temperature difference and approach point temperature difference, low-pressure steam temperature and pressure, low-pressure node temperature difference and approach point temperature difference as well as system feedwater temperature within the system mentioned earlier. The calculation results show that a relatively large number of factors have a bearing on the power generated by the cement kiln waste-heat power generation system. When a waste-heat power generation system is being designed, its power generated and cost-effectiveness

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