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燃气轮机化学回热循环热力学过程分析

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摘　要: 化学回热循环是一种先进的燃气轮机循环方式。为系统研究燃气轮机化学回热循环热力学性能, 在循环过程热力学分析的基础上, 建立了燃气轮机化学回热循环温熵图, 定义了燃料热值相对增加率, 推导循环的热效率的数学表达式, 对该循环性能进行了分析和计算。结果表明: 化学回热循环具有较高的效率, 最大效率可达 55%以上。化学回热循环效率最佳压比取决于燃气轮机简单循环中的最佳压比, 所以化学回热循环是不受压比限制的回热循环。化学回热循环燃料蒸汽转化的深度受排气温度的影响较大, 排气温度越低燃料热值的增加率越小。

关　键　词: 燃气轮机; 化学回热循环; 性能分析
中图分类号: TK472.5　　文献标识码: A

引　言

化学回热循环是一种先进的燃气轮机循环方式, 其主要过程是利用燃气轮机排气余热产生水蒸气, 水蒸气和柴油的混合物在化学回热器内发生柴油—蒸汽转化反应, 生成氢气、一氧化碳和二氧化碳等气体混合燃料, 混合后的气体燃料注入燃烧室内进行燃烧。燃料蒸汽转化反应后仍存在过量蒸汽, 这些过量蒸汽注入燃烧室中形成了注蒸汽循环(STIG)[1~3]。所以, 化学回热循环是燃料蒸汽转化过程和注蒸汽循环的联合应用。化学回热循环可以较深度地利用燃气轮机排气余热, 该循环比普通回热循环具有更高的循环热效率, 且其回热深度不受压气机压比的限制。较早开始研究化学回热循环的是美国的加利福利亚州能源研究委员会(CEC), 随后加拿大、法国、意大利、日本、瑞典以及中国等国家都开展了该循环的研究工作。其研究结果表明该循环的热效率可以达到 50%以上[4~5]。

对于注蒸汽循环, 文献[6]从理论对其进行了详细的研究和分析, 得到了 STIG循环的本质和性能。本研究考虑了注蒸汽循环和化学回热循环的具体区别, 在文献[6]的基础上进行分析, 给出了燃气轮机化学回热循环温熵图, 分析化学回热器及燃料蒸汽转化过程, 定义了燃料热值相对增加率, 推导了循环的热效率数学表达式, 得出了化学回热循环热力学初步规律。图 1是燃气轮机化学回热循环示意图。

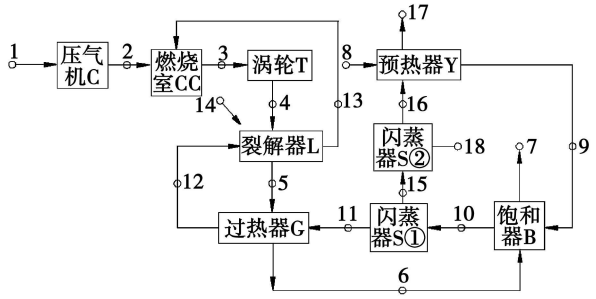

图 1　燃气轮机化学回热循环示意图

1　化学回热循环的热力过程分析

从热力学的角度看, 注蒸汽循环(STIG)就是把燃气轮机的“布雷登循环”与蒸汽轮机的“朗肯循环”并联起来, 在同一台发动机上加以实现[1]。化学回热循环则在注蒸汽循环(STIG)的基础上增加了化学回热器, 涡轮排气余热在化学回热器中被燃料和水蒸气吸收发生蒸汽转化反应提高燃料热值[3~4]。图 2给出了化学回热循环的温熵图。化学回热循环包含了以下几个过程: (1)燃气轮机简单循环过程, 即 $1^{a}-2^{a}-3^{g}-4^{g}-1^{a}$; (2)蒸汽轮机“朗肯循环”过程, 即 $8^{w}-11^{s}-13^{s}-3^{s}-4^{s}-8^{s}$过程; (3)化学回热过程, 燃气在 $4^{g}-5^{g}$过程中的放热量和蒸汽在 $4^{s}-5^{s}$过程中的放热量, $2^{a}-2^{a'}$过程包含的面积代表的热量等于化学回热器产生裂解燃料的热值提高部分。对于常规回热循环, 回热度受到 T_{4g}

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的限制,而化学回热度则不受该温度值的限制;(4)蒸汽产生过程。为了保证蒸汽能够注入燃烧室,必须确保蒸汽压力为燃烧室压力 1.1—1.3倍。

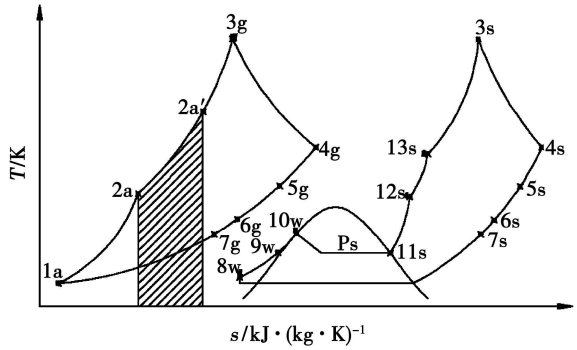

图 2 燃气轮机化学回热循环温熵图

2 化学回热循环热效率分析

2.1 化学回热循环的燃气轮机能量平衡

以 1 kg/h燃料作为研究基准点,忽略压气机抽气损失、透平冷却损失和燃料显焓,燃气轮机的能量平衡关系式为:

$$Q_a+(Q_{a,net,p}+Q_R)\eta_t+Q_{st}=P_t-P_c+Q_t \quad (1)$$

$$P_t=P_{gt}+P_{st} \quad (2)$$

式中:Q_a—空气进入压气机时携带的热能;$Q_{a,net,p}$—液态燃料的低热值;Q_R—液态燃料在化学回热器中热值提高量;Q_{st}—蒸汽注入燃烧室时携带的热量;P_t—燃气和蒸汽在涡轮膨胀做功量;P_{gt}—燃气在涡轮中的做功量;P_{st}—蒸汽在涡轮中的做功量;P_c—空气在压气机增压时的耗功量;Q_t—燃气和蒸汽在涡轮出口的热量。以上各量单位均为 kJ/h。η_t—燃气轮机燃烧室的效率。

2.2 燃烧室的热量平衡

燃气轮机燃烧室中燃烧产生的热量可以认为由两部分组成:一部分是液态燃料本身具有的热值,另一部分是经过化学回热器后热值的提高部分。

由图 3可知:燃料与蒸汽(由蒸汽发生器产生)在化学回热器中吸收涡轮排气余热,发生催化裂解反应,化学回热器中发生的燃料蒸汽裂化反应需要消耗一定量的蒸汽,蒸汽发生器产生的过饱和蒸汽除了供给化学回热器内燃料蒸汽裂化反应外,剩余部分蒸汽注入燃烧室中,吸收燃料燃烧产生的热量,将温度提高到 T_3。燃烧室中能量平衡关系为:

$$Q_a+Q_{st}+(Q_{a,net,p}+Q_R)\eta_t=Q_s \quad (3)$$

式中:Q_a—压缩空气压气进入燃烧室时所携带的热量;Q_R—液态燃料在化学回热器中发生蒸汽裂解反应后热值提高量;Q_s—燃烧室出口工质所携带的热量。

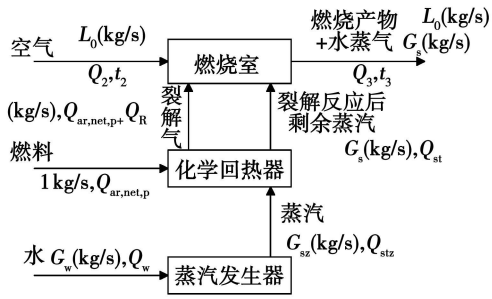

图 3 燃烧室热量平衡示意图

2.3 化学回热循环中燃料蒸汽转化过程分析

化学回热器是燃气轮机化学回热循环的重要组成部件,其工作过程为:蒸汽与液态燃料混合,在催化剂的作用下,吸收燃气轮机的排气余热,发生蒸汽转化反应,将液态燃料转化为热值较高的气态燃料,再注入燃烧室燃烧。烃类蒸汽转化反应是吸热可逆反应,化学反应过程热是由反应平衡方程和各组分的生成焓所决定,其产物各种组分含量由反应的化学计量式确定[7~9]。蒸汽转化反应化学计量通式为:

$$CH_m+R_{sc}H_2O=aCO+bCO_2+(1-a-b)CH_4+(R_{sc}-a-2b)H_2O+(3a+4b-\frac{4-m}{2})H_2 \quad (4)$$

式中:R_{sc}—水碳比;m—碳氢比;a、b—关键组分反应转化量。

式(4)中的各系数由反应原料、反应条件(温度、压力、水碳比)以及反应平衡常数确定,从而确定某条件下的反应方程[10]。由于化学计量通式由关键反应的平衡常数所决定,平衡常数计算式为:

$$K_1=\frac{p^2y_{H_2}^3y_{CO}}{y_{CH_4}y_{H_2O}}=\frac{p^2n_{H_2}^3n_{CO}}{n_{CH_4}n_{H_2O}} \quad (5)$$

$$K_2=\frac{y_{CO_2}y_{H_2}}{y_{CO}y_{H_2O}}=\frac{n_{CO_2}n_{H_2}}{n_{CO}n_{H_2O}} \quad (6)$$

反应方程的确定后,化学回热器中蒸汽转化反应的过程热为:

$$\triangle H_r=\sum_i v_i\triangle H_{iR}-\sum_i v_i\triangle H_{ip}==Q_R \quad (7)$$

式中:$\triangle H_{iR}$—原料组分 i 的生成焓;$\triangle H_{ip}$—产物组分 i 的生焓;V_i—各组分的化学计量数。

为了区别燃料发生蒸汽转化反应产物的低值燃烧热增加率,将燃料热值提高部分与燃料原热值之比定义为热值增加率 R,即:

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$$R=\frac{Q_R}{Q_{ar\ net\ p}} \tag{8}$$

化学回热循环热值增加率 R值的物理意义为: 单位燃料发生蒸汽转化反应后, 产生的气态燃料热值与原料燃料的比。所以, 燃烧室中燃烧产生的热量可以认为由两部分组成: 一部分是液态燃料本身具有的热值, 一部分是经过化学回热器后热值提高的部分。

2.4　化学回热循环的热效率

将式 (1)、式 (3)及式 (8)联立, 整理后可得:

$$\eta_R=\frac{(1+R)\eta_{rl}(P_{gt}+P_{st})\eta_M}{Q_{gt}+Q_{st}}=\frac{(1+R)\eta_{rl}(\eta_{gt}+A\eta_{st})\eta_M}{1+A} \tag{9}$$

式中: A—热量分配比, 其物理意义为燃料在燃烧室燃烧过程中产生的热量在燃气和蒸汽之间分配的比例关系, $A=Q_{st}/Q_{gt}$; η_{gt}—热能 Q_{gt}为基准定义的燃气轮机的循环效率; η_{st}—热能 Q_{st}为基准定义的蒸汽透平的当量效率。

根据式 (9), 化学回热循环的热效率主要是由 $(1+R)\eta_{gt}/(1+A)$和 $A\eta_{st}/(1+A)$两部分组成。其中, $(1+R)\eta_{gt}/(1+A)$表示燃气透平对化学回热循环效率的贡献值, $A\eta_{st}/(1+A)$则表示虚拟的蒸汽透平对化学回热循环热效率的贡献值[6]。对比文献[6]所提供的注蒸汽循环的热效率表达式, 增加了化学回热过程中所引起的燃料热量提高率项。

3　组成化学回热循环各系统的能量平衡

在图 1所示的化学回热循环过程图中, 蒸汽发生系统采用闪蒸方式。为便于进行热力学分析, 分别建立燃烧室、化学回热器、过热器、饱和器和预热器的能量守恒方程[11~12]。

燃烧室能量方程为:

$$\{1+\alpha I_\sigma+(1-\gamma)G_{stz}\}\cdot h_{13}+\gamma G_{stz}\cdot h_8=\{1+(1-\gamma)G_{stz}\}\cdot\left(Q_{ar\ net\ p}+Q_R\right)\cdot\eta_{rl}+\alpha I_\sigma\cdot h_{12}+\gamma G_{st}\cdot h_{13} \tag{10}$$

化学回热器能量方程为:

$$\{1+\alpha I_\sigma+(1-\gamma)G_{stz}\}\cdot\left(h_4-h_5\right)+\gamma G_{stz}\cdot\left(h_4-h_5\right)=Q_R \tag{11}$$

过热器能量方程为:

$$\{1+\alpha I_\sigma+(1-\gamma)G_{stz}\}\cdot\left(h_5-h_6\right)+\gamma G_{stz}\cdot\left(h_5-h_6\right)=G_{stz}\cdot\left(h_{12}-h_{11}\right) \tag{12}$$

饱和器能量方程为:

$$\{1+\alpha I_\sigma+(1-\gamma)G_{stz}\}\cdot\left(h_6-h_7\right)+\gamma G_{stz}\cdot\left(h_6-h_7\right)=\frac{G_{stz}}{x_1}\cdot\left(h_{w10}-h_{w9}\right) \tag{13}$$

预热器能量方程为:

$$x_2(1-x_1)\cdot\frac{G_{stz}}{x_1}\cdot\triangle h=\frac{G_{stz}}{x_1}(h_{w9}-h_{w8}) \tag{14}$$

闪蒸器控制方程为:

$$x_1=\frac{h_{w10}-h_{w15}}{h_{w11}-h_{w15}} \tag{15}$$

$$x_2=\frac{h_{w15}-h_{w18}}{h_{w16}-h_{w18}} \tag{16}$$

联立上述能量方程可得化学回热器出口蒸汽与进口蒸汽比值为 γ, 即 $\gamma=G_{st}/G_{stz}$, 进而求出组成系统各部件的热力参数。

4　化学回热循环性能计算与分析

根据前面化学回热循环热力学过程分析及计算过程推导, 在下述条件下进行化学回热循环性能的计算分析。燃料选用 -10号柴油, 其平均分子式可表示为 $C_{14.14}H_{25.17}$, 碳氢比为 m= 1.78, 蒸汽转化反应过程中, 水碳比为 $R_{sc}=4$, 反应压力为 3.5 MPa。其它燃气轮机参数按照现代较先进的燃气轮机参数选取。根据计算结果, 分析了不同工况燃气轮机化学回热循环各参数, 图 4 ~图 7为燃气轮机化学回热循环性能的变化关系曲线。

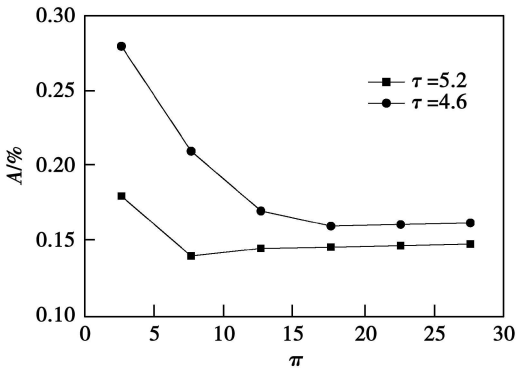

图 4　A随 π 和 τ的变化关系曲线

通过分析表明:

(1) 图 4表明了化学回热循环中燃料在燃烧室燃烧过程中产生的热量在燃气和蒸汽之间分配的比例关系随着压比和温比的变化关系。 $A=Q_{st}/Q_{gt}$在恒温比下随着压比的升高而降低, 随着温比的升高而增加; 当温比一定的情况下, 燃气吸收燃料产生的

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热量 Q_g随压比的增加先渐趋增大，超过一定压比后又逐渐减小，而蒸汽吸收燃料产生的热量 Q_{st}与 Q_{gt}的变化规律相反。

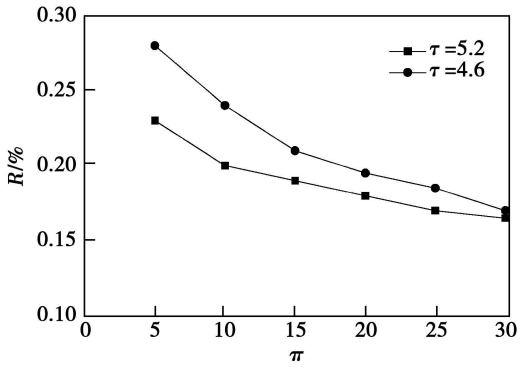

图 5 R随 π 和 τ的变 化关系 曲线

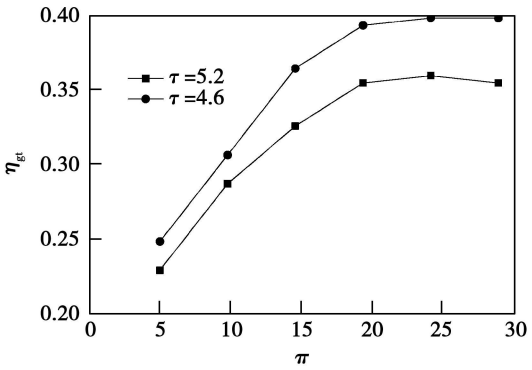

图 6 η_g随 π 和 τ的变 化关系 曲线

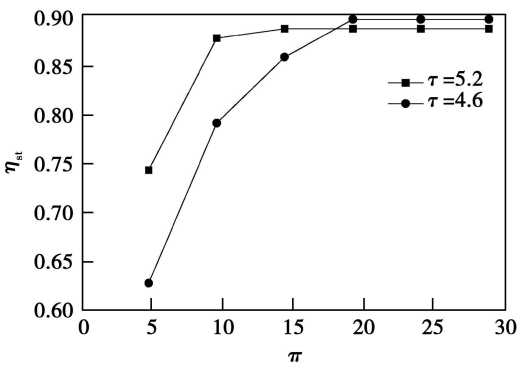

图 7 η_s随 π 和 τ的变 化关系 曲线

(2)从图 5可以看出，热值提高率 R随着温比的升高而升高，随着压比的升高而降低，这与排气温度相关，燃料蒸汽转化过程中温度愈高燃料转化率越高，其热值增加率就越大。

(3)在化学回热循环中，燃气轮机本体的循环效率与压比、温比的关系与简单循环相同，而虚拟蒸汽涡轮的效率却很高。原因在于注入燃烧室的蒸汽温度 T_{13s}与涡轮的排气温度 T_4非常接近，如图 6和图 7所示。

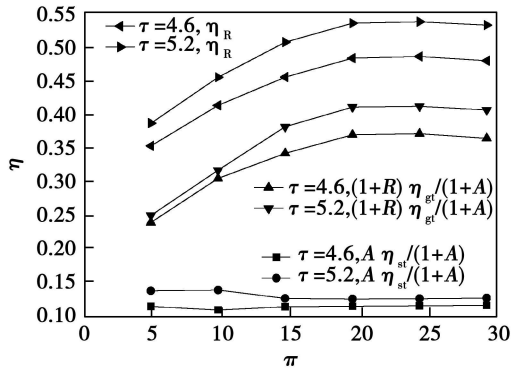

图 8 η_R, $(1+R)\eta_{gt}/(1+A)$, $A\eta_{st}/(1+A)$ 随 π 和 τ的变化关系 曲线

(4)图 8中给出了当 τ＝5.2和 4.6时，这 $(1+R)\eta_{gt}/(1+A)$和 $A\eta_{st}/(1+A)$两部分热效率份额随机组的压缩比 ε而变化的关系曲线。由图可知，$A\eta_{st}/(1+A)$随压比的变化较小，循环热效率随压比的变化主要取决于燃气轮机循环热效率 η_g随压比的变化规律，即化学回热循环中效率最

以上这些分析，与注蒸汽循环的结论是非常相近的，这也验证也化学回热循环是注蒸汽循环和燃料裂解回热的结合。

5 结 论

(1)本研究给出了燃气轮机的化学回热循环过程和热力循环的温熵图，在温熵图的基础上分析表明，化学回热循环是燃料蒸汽转化反应与注蒸汽循环相结合的新型热力循环，其同时具备 STIG循环的特性。

(2)化学回热循环效率的由两部分组成，其最佳压比取决于燃气轮机简单循环中的最佳压比，所以化学回热循环是不受压比限制的回热循环。

(3)化学回热循环燃料蒸汽转化的深度受排气温度的影响较大，排气温度越低燃料热值的在增加率越小。

以上分析仅从循环热力学的方向进行论证和分析，以求得出影响该循环效率的关键因素。对于燃气轮机化学回热循环的可实现性还应针对具体的燃气轮机进行性能分析，得到化学回热循环的运行特

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性。

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新技术、新产品

用于满足未来电力生产的先进的氢涡轮

据《Gas Turbine World》2009年 5—6月号报道, 在与 GE和 Siemens单独的、但是类似的三阶段合同下, DOE(美国能源部)先进氢涡轮开发计划进入它研发活动的第四年。

关于先进氢涡轮计划的近期目标集中在:

· 效率。装置的纯效率(HHV)比基本的燃烧合成气的 F级联合循环装置高 2% ~3%。

· 初投资费用。总的装置费用比目前的基于煤的额定输出功率为 600 MW和更大功率的 IGCC(整体煤气化联合循环)电站低 20% ~30%。

· 排放。对于用高含氢量合成燃料运行的联合循环装置, 限制其 NO_x排放为 2 mg/kg或更低。

为了达到提高效率并减少投资费用的目标, 将要求先进的高温和高压比燃气轮机。先进氢燃气轮机循环优化和投资费用权衡的研究指出, 用于其压气机设计的理想压比大约是 30∶1, 与此相比较, 基本燃气轮机压气机的压比仅为 18∶1。

先进的燃烧系统在能够以更高的燃烧温度(接近 1 649 ℃)运行同时, 还要满足严格的 NO_x排放的限制。

增加效率和输出功率的目标将取决于开发新的能承受更高温度的材料系统。在此领域的努力已集中在改进的热障涂层, 它提供了低导热性屏障, 以便阻止热量从热燃气流传递到被冷却的超耐热合金的发动机部件。测试表明, 一种改进的粘合涂层能使 TBC(热障涂层)的剥落寿命增加 40%。

(吉桂明　摘译)

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range of 4%. In the operation range of the hybrid power system, the catalytic combustor can always maintain a high fuel conversion rate being invariably over 99% when the inlet temperature is higher than 770 K. The change of the inlet flow speed and fuel concentration has no conspicuous influence on the fuel conversion rate. It is feasible to use the catalytic combustor for the hybrid power systems. Key words: catalytic combustor; catalytic combustion; integral honeycomb carrier; hybrid power system; combustion conversion rate

PEvGT循环参数优化及热力性能分析 = Parameter Optimization and Thermodynamic Performance Analysis of a Part Flow Evaporative Gas Turbine (PEvGT) Cycle[刊, 汉] / WANG Jing, ZHANG Shi-jie, XIAO Yun-han (Key Laboratory on Advanced Energy and Power, Engineering Thermophysics Research Institute, Chinese Academy of Sciences, Beijing, China, Post Code: 100190) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(2). — 155 ~ 160

Part flow evaporative gas turbine (PEvGT) cycle is the combination of a humid air turbine (HAT) cycle and a steam-injected gas-turbine (STIG) one. It not only enjoys a relatively high power generation efficiency, but also can provide steam to outside users. In the meantime, it can accomplish a flexible regulation of the heating/power ratio and possess latent potentialities for application in the domain needing a supply of both heat and power. In addition to conducting a parameter optimization of two types of PEvGT cycle in different configurations, the authors have also analyzed their thermodynamic performance and combined heat-and-power supply cogeneration characteristics. It has been found that during a pure power generation operation, the humidified air ratios corresponding to the maximal efficiency points of the two types of cycle are between 0% and 20%. When the non-humidified air is mixed with the humidified air and steam before the recuperator (PEvGT-2 cycle), the optimum pressure ratio of both PEvGT-2 cycle and HAT one is around 10. The maximal efficiency of the PEvGT-2 cycle (51.4%) is 0.8 and 3 percentage points higher than that of the HAT cycle and the STIG one respectively. Following a mixing of the humidified air with the steam before the recuperator when the mixture of the humidified air and steam is blended with the non-humidified air after the recuperator (PEvGT-1 cycle), the optimum pressure ratio of the PEvGT-1 cycle is comparatively high and its maximal efficiency corresponds with that of the STIG cycle. During a heat-and-power cogeneration operation, two types of PEvGT cycle enjoy a heat and power load flexibility similar to that of the STIG cycle and when the steam output proportions of both PEvGT-1 and PEvGT-2 cycle are kept identical, their power generation efficiencies will be 0.7% ~ 1.5% and 3.4 ~ 12 percentage points respectively higher than that of the STIG cycle. Key words: part flow evaporative gas turbine (PEvGT) cycle; humid air turbine (HAT) cycle; steam-injected gas-turbine (STIG) cycle; parameter optimization; heat and power cogeneration

燃气轮机化学回热循环热力学过程分析 = An Analysis of the Thermodynamic Process of a Gas Turbine-based Chemical Recuperative Cycle[刊, 汉] / TAN Zhi-yong, ZHENG Hong-tao (College of Power and Energy Source Engineering, Harbin Engineering University, Harbin, China, Post Code: 150001), HAN Qing, LI Qi (CSIC No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(2). — 161 ~ 165

The chemical recuperative cycle represents an advanced gas turbine-based one. To systematically study its thermodynamic performance, established was an entropy-temperature diagram for the above cycle based on a thermodynamic analysis of the cyclic process, and defined was a relative growth rate of the heating value of the fuel. Moreover, a mathematical expression for the thermal efficiency of the cycle was derived along with an analysis and calculation of the cyclic performance. It has been found that the chemical recuperative cycle features a relatively high efficiency and its maximal value can be over 55%. The optimum pressure ratio of the cycle in question depends on

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the optimum pressure ratio of the gas turbine-based simple cycle. Hence, the chemical recuperative cycle can be regarded as one not restricted by the pressure ratio. The depth of the fuel-steam conversion in the chemical recuperative cycle is relatively heavily affected by the exhaust gas temperature. The lower the exhaust gas temperature, the less the growth rate of the heating value of the fuel. Key words: gas turbine, chemical recuperative cycle, performance analysis, entropy-temperature diagram, thermal efficiency, pressure ratio

水和水蒸气热力性质IAPWS-IF97计算模型分析及算法设计 = An Analysis of IAPWS-IF97 Formulae-based Model for Calculating Water and Steam Thermodynamic Properties and Its Algorithm Design [刊, 汉] / ZHOU Yan-ming, LI Ji-geng, LIU Huan-bin, ZHANG Ding-hua (National Key Laboratory on Pulp Preparation and Papermaking Engineering, South China University of Science and Technology, Guangzhou, China, Post Code: 510641) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(2). —166 ~171

By adopting an object-oriented method, implemented was the latest industrial formulae-based IAPWS-IF97 (2007. 8 Revision) for calculating water and steam thermodynamic properties. The calculation models for various zones were analyzed in detail with their corresponding implementation algorithms being designed. The basic equations, derivative equations, calculation formulae in various attributes and reversely derived equations for all the zones were implemented. The supplementary equation B23 equation and B2bc equation for the metastable steam regions in two zones were also executed. The authors have presented the regional differentiated algorithm, sub-regional differentiated algorithm in two zones and Newton iterative algorithm in three zones to determine the density ρ from pressure P and temperature T. They have also described in detail the latest IAPWS-IF97 implementation method, matters meriting attention and relevant derivative processes, and supplemented the verification values of the computer program for specific heat capacity of equicapacitance c, thus enhancing the consistency of B23 with boundary T_s(P) as well as that of B2bc with boundary P_s(T). The application of the above in the papermaking industry indicates that the implemented method enjoys such a variety of merits as comprehensiveness, accuracy, speedy and automatic testing etc. Key words: IAPWS-IF97, water and steam, thermodynamic properties, industrial formulae, papermaking industry

TiO_2纳米颗粒对相变悬浮液流变和导热系数特性影响研究 = Study of the Influence of TiO_2 Nano-particles on the Rheology and Heat Conduction Coefficient Characteristics of a Phase-change Suspension [刊, 汉] / JIN Jian, LIU Pei-qing, LIN Gui-ping (College of Aeronautical Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing, China, Post Code: 100191), DING Yu-long (College of Particle Science and Engineering, University of Leeds, Leeds, UK, Post Code: LS9 JT) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(2). —172 ~176

By using an experimental method, studied were the viscosity and heat conduction coefficient of a phase-change suspension after it has been mixed with TiO_2 nano-particles. The research results show that when the concentration of the nano-particles does not exceed 5%, the suspension can still be viewed as a Newtonian fluid and its viscosity will increase nonlinearly with an increase of the concentration of the nano-particles. When the concentration of the mass nano-particles equals to 5%, the viscosity of the phase-change suspension will rise by about 23%. The addition of the nano-particles is capable of significantly improving the heat conduction coefficient of the suspension in question. When the concentration of the nano-particles is 5%, the heat conduction coefficient of the phase-change suspension will increase by about 7%. When the concentration of the nano-particles is relatively low, the growth margin of the heat conduction coefficient of the phase-change suspension caused by the nano-particles will be higher than that of the water. The authors have analyzed from different perspectives the advantages of using the new type of

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