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燃气轮机湿空气回注循环分析

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摘　要: 讨论燃气轮机湿空气回注循环, 提出分为内部和外部空气加湿回注循环两类。以部分空气回热回注循环(PRSTIG)为基础, 分析了燃气初温、压比、回注比、回热比等参数对循环效率、比功的影响。通过对两类各相关循环的特点的比较、讨论, 得出的结论是: 湿空气回经循环可使功率提高 10%～25%, 热耗降低 6%～15%, NO_x 排放量降低 15%～50%, 而且均可在现行装量上改造实施。

关　键　词: 燃气轮机; 燃气轮机回注蒸汽; 回热燃气轮机; 湿空气循环

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1　前　言

众所周知, 回热燃气轮机循环具有高效率, 而蒸汽回注循环具有高比功, 将回热燃气轮机循环与燃气轮机回注蒸汽(STIG)循环结合起来, 形成一种新的复合循环——湿空气回注循环。它又可分为两类, 即燃气轮机压气机出口空气(或压气机出口部分空气)被加湿、回热、回注的燃气轮机循环(内部空气加湿回注循环)和对由外部提供的压缩空气进行加湿、回热、回注的燃气轮机循环(外部空气加湿回注循环)。上述两类循环均有提高功率、降低热耗、减少 NO_x 排放的优点。

2　内部空气加湿回注循环

2.1　循环原理

典型的循环系统如图 1 所示。工质空气经压气机压缩后分为两部分: 一部分空气直接进入燃烧室, 另一部分空气进入喷射器, 经蒸汽引射后与之混合, 形成的混合气体在余热锅炉内被燃气轮机的排气加热(回热), 然后注入燃烧室。另一种工质水进入余热锅炉, 从排气废热中吸收热量, 水被加热成饱和蒸汽, 然后进入喷射器与空气混合。从燃烧室出口的燃气进入涡轮做功后, 涡轮排气在余热锅炉内首先加热湿空气, 然后用于产生饱和蒸汽。

该循环的特征是部分空气回热注蒸汽, 简称 PRSTIG (Partial Regenerative Steam Injected Gas Turbine)循环。

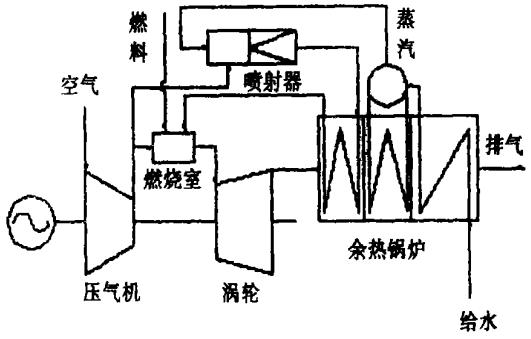

图 1　PRSTIG 循环系统示意图

实际上, 当压气机出口空气全部先进入混合器加湿后再进入燃烧室时, 则形成回热注蒸汽燃气轮机循环, 故简称"RSTIG"循环。显然, RSTIG 循环可以看作是 PRSTIG 循环分析中的一个特例。反之, 如果压气机出口的空气全部直接进入燃烧室时, 则形成 STIG 循环。

循环间的关联形式见图 2。

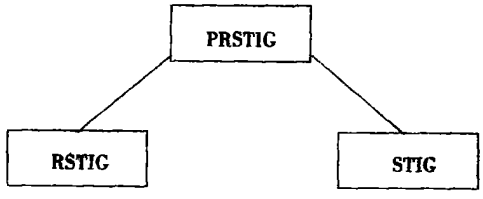

图 2　循环间的关联

2.2　循环分析

为了更具体地说明 PRSTIG 循环, 进行了计算分析, 分析中所用的主要参数值列于表 1。研究了某

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些参数在一定范围内变化的影响,此时其它参数值一般保持常数。

表 1　分析中所用的假定值

	数值
环境温度/℃	20
环境压力/Pa(×10^5)	1.013 25
给水温度/℃	20
燃料注入温度/℃	25
压气机效率	0.88
涡轮效率	0.90
燃烧效率	0.99
机械效率	0.985
排气温度最低值/℃	200
回热器回热度	0.85
余热锅炉节点温差/℃	15

图 3 表示 PRSTIG 循环热效率与回热比 R_a(回热空气质量流量与压气机进口空气质量流量的比值)、回注比 R_s(回注蒸汽质量流量与压气机进口空气质量流量的比值)之间的关系。回注比最佳值将曲线分为两支,上升曲线表示此时涡轮排气中有足够热量将工质加热到所要求的参数,这时空气与蒸汽组成的混合气体有较好的过热度;下降曲线表示此时因回注比偏高,只好以降低注气温度(蒸汽与空气所组成的混合气体注入燃烧室时的温度)作为补偿。这时混合气体在燃烧室内所需的吸热量增加,导致效率下降。

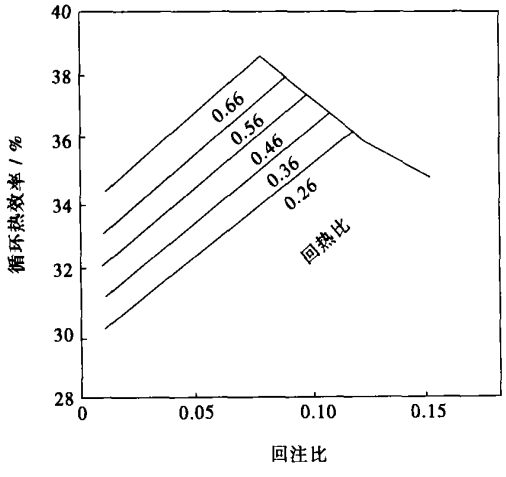


图 3　R_a、R_s 对循环热效率的影响
(燃气初温 1 273.15 K,压比 8)

图 4 表示 PRSTIG 循环比功与回注比、回热比的关系。当回热比保持一定时,回注比的增加使进入涡轮的工质质量流量增加,同时单位质量的工质做功能力也增加,故比功也随之增加。当回注比保持不变时,随回热比增加,比功略微有所下降。

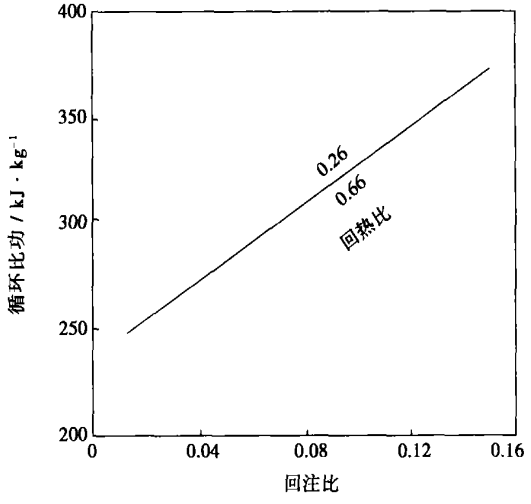


图 4　R_a、R_s 对循环比功的影响
(燃气初温 1 273.15 K,压比 8)

图 5 表示 PRSTIG 循环最大热效率(此时回注比处于最佳值)与压比、回热比之间的关系。随着压比的升高,回热温差减小,回热比的变化对循环最大热效率的影响程度减弱。因为压比适当下降可使回热温差升高,对回热有利,故回热比越大,则最佳压比越小。

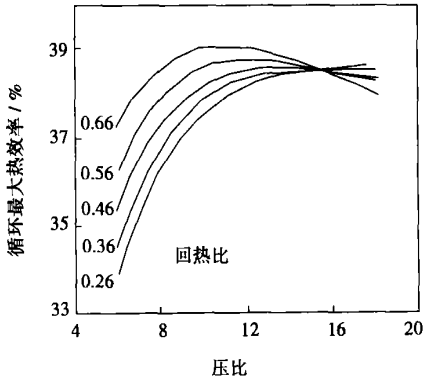


图 5　R_a、压比对循环最大热效率的影响
(燃气初温 1 273.15 K)

图 6 表示 PRSTIG 循环最佳回注比(此时循环具有最大热效率)与压比、回热比之间关系。

图 7 表示循环性能与燃气初温之间的关系。由

图可见,燃气初温仍是影响PRSTIG 循环性能的主要因素。

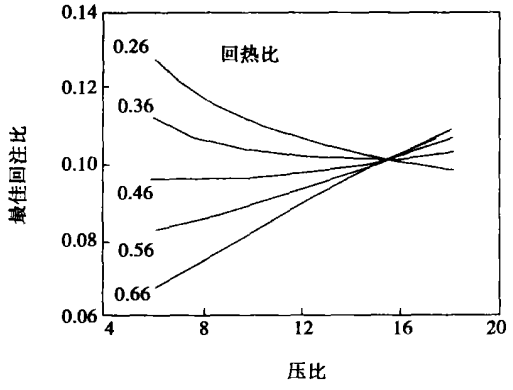
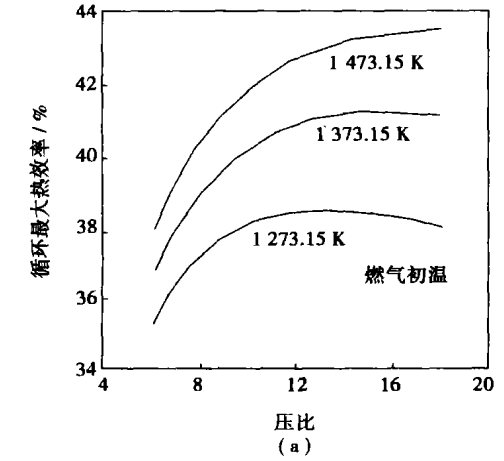


图 6 R_a、压比对循环最佳回注比的影响
(燃气初温 1 273.15 K, 压比 8)



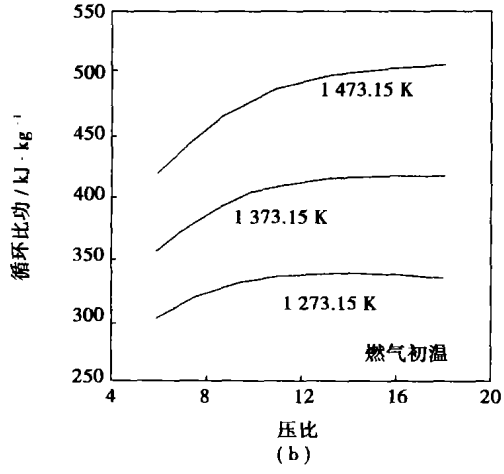


图 7 燃气初温对循环性能的影响(回热比 0.46)

综上所述,影响和决定PRSTIG 循环性能的独立参数主要有 4 个:燃气初温、压比、回注比及回热比。PRSTIG 循环性能的获得,取决于这 4 个参数的匹配。

为了更深入地了解循环的特点,将 STIG 循环、RSTIG 循环、PRSTIG 循环性能加以简单对比,计算参数选自表 1,同时取燃气初温 1 273.15 K,回热比 0.46。

图 8 表示 STIG 循环、RSTIG 循环、PRSTIG 循环最大热效率与压比之间的关系。由图中可以看出:每种循环均存在一最佳压比,此时循环具有最大热效率的最佳值,并且最佳压比(STIG)> 最佳压比(PRSTIG)> 最佳压比(RSTIG)。由于回热的影响,当压比超过某一值 π_1 后,RSTIG 循环的最大热效率低于PRSTIG 循环的最大热效率,压比继续升高到另一值 π_2 后,PRSTIG 循环的最大热效率低于 STIG 循环的最大热效率。

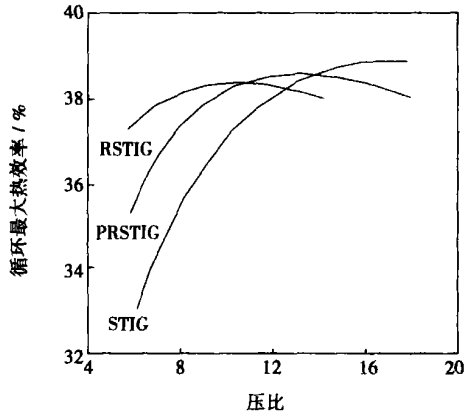


图 8 压比对循环最大热效率的影响

图 9 表示 3 种循环的最大热效率与最佳回注比间的关系(此时压比固定为 8)

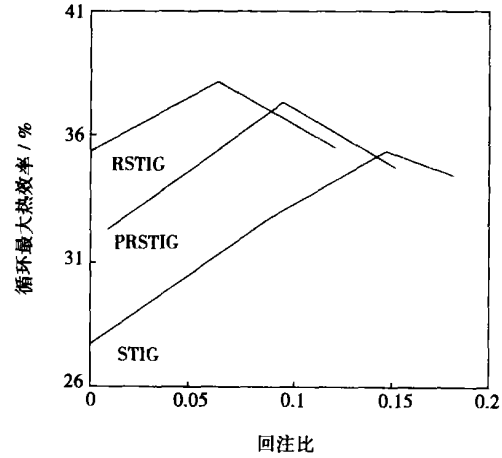


图 9 回注比对循环热效率的影响

3　外部空气加湿回注循环

3.1　循环原理

典型的循环系统如图 10 所示。空气由外部的、单独的用电机驱动的压缩机(带间冷器)增压进入空气饱和器,空气被湿化后经热回收装置,利用燃气轮机排气废热进行预热后注入燃气轮机燃烧室的上游。另一种工质(水)进入热回收装置,从排气废热中吸收热量,水被加热成饱和蒸汽,然后进入空气饱和器对增压空气加湿。从燃烧室出口的燃气进入涡轮做功后,涡轮排气在热回收装置内首先加热湿空气,然后用于产生蒸汽。

该循环的特征是外部空气加湿预热,故简称 HAI(Humid Air Injection)循环。

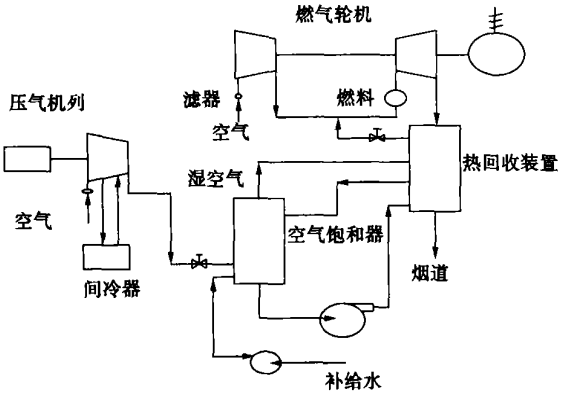


图 10　HAI 系统示意图

实际上,当外部增压空气不经加湿而仅在热回收装置中预热后即注入燃烧室时,则形成干空气回注循环,简称 DAI(Dry Air Injection)循环。

显然,DAI 循环可以看作是 HAI 循环分析中的一个特例。

此外,如果外部增压空气为零,则形成 STIG 循环。

循环间的关联形式见图 11。

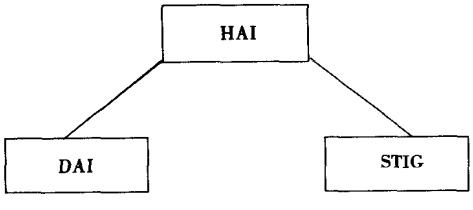


图 11　循环间的关联

3.2　循环分析

(1)HAI 系统功率的增量与注入的湿空气流量成正比。

(2)相对于干空气回注,注湿空气可降低对总流量的需求量,也节省了外部压缩机的耗功(否则需对更大的空气流量增压)。

(3)注湿空气的效果(功率、热耗率)明显优于注干空气。

(4)为尽可能降低外部空气增压的耗功,通常用多个压气机串联,其间采用中间冷却器。

为更具体地说明,引用美国南加里福尼亚大河能源中心 3 号燃气轮机(PG7241FA),在环境温度 35 ℃,海平面,不同加湿条件下的设计性能见表 2。

表 2　Fr7A 注湿/干空气的性能比较

	湿空气	湿空气	干空气	现装置
加湿度/%	7.5	5.5	—	—
净功率/MW	182.6	177.0	166.4	150.4
热耗率(LHV)/kJ	9 664	9 896	10 255	10 297

该机已进行了 HAI 循环的初期验证试验,试验是在 35 ℃,3.5%的加湿量下进行的,这是 GE 公司对 Fr7FA 蒸汽回注增功的限定,涡轮转子入口温度也有所降低(按"干"控制线运行),试验结果表明功率增加 18.3 MW。当按"湿"控制线运行时,功率可增加近 22.3 MW。

为更进一步说明,例举了相关数据(见表 3),它取自 Hill 能源系统和 PB 动力提出的一份在四台 GE Fr7B 调峰机组上装湿空气回注装置的建议书。表中表示了现已运行的 Fr7B 燃气轮机,其净功率按平均降低 8%计(由于长期运行),以天然气为燃料,环境温度 29.4 ℃(85 ℉)为设计点,无湿空气回注与 7.6%湿空气回注情况下性能的全面对比。从增益栏中可以看出,所获的增功部分是在极高的效率下实现的。

4　现实可行性

本文讨论的循环特点是均可在现有装置上改造实施。在设计和机械方面有些类似 STIG 装置,也有功率增量不能超过运行极限的制约,最大允许扭矩的制约,压气机喘振裕度、燃气温度、火焰稳定性和发电机容量的制约。

对于没有装干式低 NO_x 燃烧室的燃气轮机,注湿空气的效果更好,因为非 DLN 燃烧室允许在更高的含水量下运行,这导致更高的相对功率增量和更

低的热耗。不仅如此,注湿空气也成为一种低成本的控制 NO_x 的技术。在 Fr7B 燃烧室上的试验表明,燃用天然气并注湿空气后,NO_x 排放从 100 mg/kg降至 50 mg/kg 以下。

注干空气不如注湿空气有效,但注干空气对部件寿命完全没有影响(与蒸汽回注相比)。注空气的功率增量相对较小,但在缺水的地方(如天然气管线增压站)可能是有吸引力的。因为这是一个扩充增压站容量而投资较少的方法,不必另外增加燃气轮机。对有多台燃气轮机装置的增压站,干空气回注系统可最佳化,服务于总的增功需求,可明显降低成本,增加系统的可靠性、可用性和灵活性。

实际上本文所讨论的循环介于 STIG 与 HAT 之间,各有各的特点及各自的适用场合,PRSTIG 在日本已有正式产品及应用,HAI 在美国已进行了实机试验并正在评审项目建议书。

表 3 Fr7B 注湿空气的性能预测

	25 °F(-3.9 ℃)	40 °F(4.4 ℃)	59 °F(15 ℃)	80 °F(26.7 ℃)	85 °F(29.4 ℃)	95 °F(35 ℃)
HAI 电站净出力/kW	72 820	69 500	65 540	60 940	59 800	57 400
热耗率(LHV)/kJ	11 014	11 130	11 310	11 579	11 647	11 795
效率/%	32.7	32.4	31.8	31.1	30.9	30.5
现电站净出力/kW	59 200	56 200	52 300	48 200	47 300	45 400
热耗率(LHV)/kJ	12 702	12 855	13 093	13 483	13 573	13 747
效率/%	28.3	28.0	27.5	26.7	26.5	26.2
增益净出力/kW	13 600	13 300	13 200	12 800	12 500	12 000
热耗率(LHV)/kJ	3 661	3 809	4 262	4 415	4 410	4 405
效率/%	98.4	94.5	84.5	81.5	81.6	81.7

5 结 论

本文所讨论的循环具有如下共同特点:

(1) 增加功率。可使燃气轮机出力增加 10% ~ 25%。

(2) 降低热耗率。可使燃气机热耗降低 6% ~15%。

(3) 低排放。与简单循环燃气轮机相比,NO_x 排放量降低 15% ~50%。

(4) 每新增千瓦功率所需的投资低。

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(辉 编辑)

温度变化对燃气轮机叶片材料抗蚀性的影响

据《Теплоэнергетика》2005 年 8 月号报道,根据试验和计算结果,为了减少涡轮叶片的腐蚀,提出了有关燃气轮机运行的下列建议:

1. 尽可能保持不变的温度工况;

2. 在降低温度时尽可能更迅速地通过高温区域;

3. 在循环温度工况时要极限地限制温度变化的幅度;

4. 应该考虑到,任何循环温度工况都会导致比在同样范围温度均匀变化工况更大的腐蚀;

5. 可以根据在不变温度条件下的试验结果来选择在温度变化工况下工作的燃气轮机装置涡轮叶片的最耐腐蚀的材料。其依据是在等温试验下抗腐蚀性差的合金在温度变化下的抗蚀性必然也差。

(吉桂明 供稿)

炭黑与 NO 还原反应的研究综述= **An Overview of the Research on Reduction Reactions Involving Soot and NO** [刊, 汉] / XU Bin, XIE Guang-lu, FAN Wei-dong, et al (Institute of Mechanical & Power Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(1). —1 ~4, 9

Over the last three decades reduction reactions involving soot and NO have attracted the attention of environmental research workers worldwide. The authors have given an overview of the recent research progress on the above-mentioned reduction reactions with an emphasis on the reduction reaction mechanism of pure NO and soot. The experimental instruments nowadays being often used are discussed. Various kinds of reaction instrumentation can be employed for different ranges of reaction-temperature and the various products thus obtained as a result of the NO-soot reaction are also quite different. At low temperatures (less than 300 ℃) an adsorption reaction will mainly take place, while at high temperatures a reduction reaction occurs. Finally, a brief description is given of the impact of the different atmospheres and the presence of catalysts on reaction results. Different reaction atmospheres will have different impacts on NO-soot reactions. All substances, which promote the generation of an activated potential on a soot surface, can invariably be conducive to the progress of reactions. **Key words**: natural gas, soot, nitric oxide, desorption, surface base groups

氦气轮机装置的高温材料= **High-temperature Materials for Helium Gas Turbines** [刊, 汉] / JI Gui-ming, WANG Chong (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(1). — 5 ~9

Due to its operating features a helium gas turbine is constrained in its use of construction materials, which must cope with specific operating conditions, environmental and maintenance service factors. The key problems to be considered during material selection include: long creep life, high-temperature corrosion and radiation effects. Briefly described are the major candidate materials used for the parts and components, such as blades, discs, stators and shafting, of HTGR-GT (high-temperature gas cooled reactor - helium gas turbine) based power generation plants. It is noted that oriented crystallization and single crystal nickel-based alloys with protective coatings are the best candidate materials for turbine blades of currently prevalent operating parameters. As for the design scheme of a cooled disc, nickel-based super heat-resistant alloys are considered eligible materials. For use at temperatures below 600 ℃ alloy IN 718 can be selected with U720LI and MA6000 being destined for still higher temperatures. **Key words**: helium gas turbine unit, high-temperature alloy, turbine, blade, disc

微型燃气轮机回热器燃气腔结构优化= **Configuration Optimization of the Recuperator Gas-cavity of a Micro Gas Turbine** [刊, 汉] /ZHANG Dong-jie, WANG Qiu-wang, LUO Lai-qin, et al (State Key Laboratory of Multiphase Flows under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(1). —10 ~13

A numerical simulation was conducted for the gas-cavity flow field of the split-body type recuperator of a 100 kW micro gas turbine along with an analysis of the impact on the gas cavity by such factors as the use of different cone angles α at the gas inlet piping and different lengths L of protrusion into the cavity. The results of the simulation indicate that when $\alpha = 5^{\circ}$ and L = 370 mm, the resistance losses of the flow path as a whole and the uniformity of velocities at various gas outlets have been comprehensively evaluated as having achieved optimum values. **Key words**: distributed power generation, micro gas turbine, recuperator, configuration optimization

燃气轮机湿空气回注循环分析= **An Analysis of the Gas Turbine Humid-air Injected Cycle** [刊, 汉] /WEN Xue-you, LU Ben, LI Ming-jia (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(1). —14 ~18

A gas turbine humid-air injected cycle is discussed with the assertion that there are two kinds of injected cycle, namely, internal and external humid air injection. On the basis of a partial regenerative steam injected gas turbine (PRSTIG) cy-

cle analyzed is the impact of such parameters as turbine entry temperature, pressure ratio, injection ratio and regeneration ratio, etc on cycle efficiency and specific work. Through a comparison and discussion of the specific features of the two relevant cycles the authors have come to the conclusion that the humid air injected cycle makes it possible to enhance output power by 10% ~25%, reduce heat consumption rate by 6% ~15% and NO_X emissions by 15% ~50%. Moreover, the above-mentioned modification can be implemented on existing power plants. **Key words**: gas turbine, steam injected gas turbine, regenerative gas turbine, humid air cycle

火电机组轴封渗漏及利用系统的通用计算方法= **A General Method for Calculating the Shaft Seal Leakage and Utilization System of a Thermal Power Plant** [刊, 汉] /CHEN Hai-ping, YU Shu-mei, ZHANG Shu-fang (Power Engineering Department, North China University of Electric Power, Baoding, China, Post Code: 071003), SHI Wei-zhu (Beifang United Electric Power Co., Huhuohaote, Inner Mongolia, China, Post Code: 010020) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(1). — 19 ~21, 26

With the shaft seal leakage and utilization system of a thermal power plant serving as an object of study and on the basis of a comprehensive consideration of its system configuration and composition features deduced was a model of quantitative analytic calculations for the shaft seal leakage and utilization system. This model adopts a matrix-form expression with the presence of a one-to-one correspondence between the calculation model and the thermal system configuration. Its usage features simplicity and conciseness in calculations and high versatility. The model can be used for the analysis of power units of various types and different operating conditions, and is especially suited to serve as a computer processing-based mathematical model. In view of the above the model under discussion is of major theoretical significance for the realization of energy-savings and the reduction in energy consumption for thermal power plants. **Key words**: thermo-economics, shaft seal leakage and utilization system, general calculation method, thermal system, matrix

低温多效蒸馏海水淡水一发电联产系统经济性分析= **An Analysis of the Cost-effectiveness of a Cogeneration System for the Simultaneous Production of Electric Power and also Fresh Water by Low-temperature Multi-effect Distillation of Seawater** [刊, 汉] /SHEN Sheng-qiang, YANG Luo-peng (Department of Power Engineering, Dalian University of Science & Technology, Dalian, China, Post Code: 116024) //Journal of Engineering for Thermal Energy & Power. — 2006, 21(1). — 22 ~26

With respect to a cogeneration system for the simultaneous production of electric power and also fresh water by low-temperature multi-effect distillation of seawater the energy cost of water-making and the impact of extracted-steam heating on a steam turbine unit were calculated using an equivalent enthalpy drop theory. In conjunction with a q-γ-τ matrix equation constructed were a partial quantitative analytic matrix model and an equivalent enthalpy drop method-based steam-extraction efficiency matrix model featuring high versatility and precision as well as ease of sequencing. By employing the above matrix models it is possible to conveniently, rapidly and accurately calculate water-making power consumption rate and the variation of water-making fuel cost caused by a change in steam extraction pressure and steam heating temperature. The results of the calculation indicate that compared with the traditional performance index water-making ratio or gained output ratio (GOR) the use of water-making electric power consumption rate can more accurately evaluate the thermal performance of the water-electricity cogeneration system. The reduction of steam extraction pressure and steam heating temperature is favorable to lowering the water-making energy cost. However, the lower limit of steam extraction pressure and steam heating temperature should respectively meet the requirements of ejection factor of steam injector and compression ratio. The cogeneration system for the simultaneous production of electric power and also fresh water by low-temperature multi-effect distillation of seawater can effectively resolve the water shortage problem in northern China coastal areas, especially that of thermal power plants in those areas. **Key words**: equivalent enthalpy drop, cogeneration of water and electricity, low-temperature multi-effect distillation, seawater desalination

基于矢量分析的转子碰磨故障轴向定位方法= **Vector Analysis-based Axial Locating Method for Rotor Contact-rubbing Faults** [刊, 汉] /LI Lu-ping, ZOU Xin-yuan, JIN Feng-hua (Institute of Energy Source & Power Engi-