编 者 按: 本文曾在美国机械工程师协会燃气轮机年会"ASME Turbo Expo 2007"上宣读, 并被推荐在ASME会刊《Journal of Engineering for Gas Turbines and Power (JEGTP)》March, 2008上发表。

年会审阅人船用燃气轮机分会主席, 美国费城海军水面舰船中心威廉. 范泰先生认为:"该文对于间冷循环应用的许多实际问题进行了探讨……, 它会在未来多年内影响一些人在船用燃气轮机上的决策: 如究竟是用间冷回热循环或是间冷循环?"

本刊征得ASME的同意, 特此转发本文的译文, 以飨读者。

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IC循环船用燃气轮机的可行性研究

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摘 要: 从总体上分析了不同典型燃气轮机循环参数下采用间冷循环(IC)所能获得的性能。在此基础上, 针对一台大功率简单循环船用燃气轮机(MGT-33)开展了将其派生为一型间冷循环船用燃气轮机的研究, 前提是原发动机燃气发生器的通流部分和结构绝大部分保持不变, 以继承原机的可靠性。研究表明, 采用间冷循环后, 在结构改动最小和保持整机紧凑性的前提下, 燃气轮机的总体性能仍有明显的提高, 功率增加约34%, 效率提高约4.1%, 具有工程实施价值。

关 键 词: 船用燃气轮机; IC循环

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符号说明

P—压力; SFC—油耗率;
T—温度; Ga—流量;
ΔP—压力损失; η—效率;
PR_{LPC}—低压压气机压比; ξ—压力损失系数, $\xi=\Delta P/P$;
PR_{HPC}—高压压气机压比; ε—间冷度, $\varepsilon=(T_2-T_{22})/(T_2-T_{cool})$;
PR—总压比; η_e—循环效率;
TIT—燃气初温; SP—比功;
Ne—功率; LHV—燃料热值

下 标:
in—入口; LPT—低压涡轮;
LPC—低压压气机; PT—动力涡轮;
IC—间冷器; ID—中间扩压器;
HPC—高压压气机; ex—排气管;
CC—燃烧室; cool—冷却剂;
HPT—高压涡轮; 0、1、2、3等—计算截面(如图2所示)。

引 言

自20世纪80年代末以来, 随着各国对于水面船舶主动力装置的功率需求不断提高, 大功率船用燃气轮机(25 MW以上)成为各国研发的主流, 如表1所示。

表1 大功率船用燃气轮机研发情况(至2005年)[1]

	样机投入运行年份	ISO条件下最大出力(马力)	热效率	耗油率 /kg·(kW·h)$^{-1}$	压比	空气流量 /kg·s^{-1}	制造公司
LM2500	1969	33 600	0.372	0.227	19.3	70.4	GE
FT8	1990	36 860	0.389	0.217	18.8	83.3	P&W
UGT-25000	1993	42 400	0.381	0.221	21	87.6	Zorya-Mashproekt
WR-21	1997	33 850	0.421	0.200	16.2	73.1	RR
LM2500+	1998	40 500	0.391	0.215	22.2	85.8	GE
MT-30	2001	48 275	0.398	0.212	24	116.7	RR

注: 数据取自2005 GTW Handbook.

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由图 1 可见近 15 年来大功率船用燃气轮机的性能发展趋势：单机功率逐渐增长，其最大功率约为 36 MW（50 000 马力，ISO 条件下）；效率也逐步提高，简单循环效率达到 40％，复杂循环效率达到 42％。

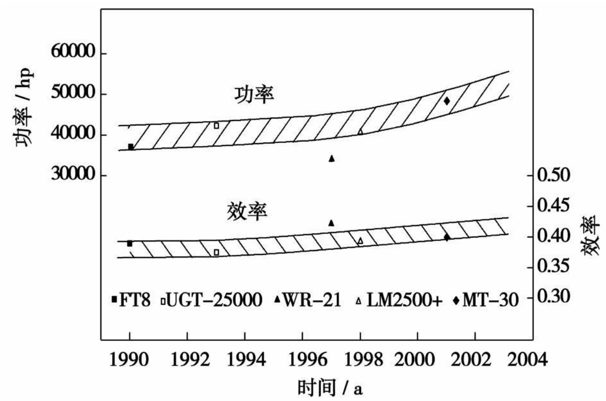

图 1　大功率船用燃气轮机功率、效率的变化趋势

可以认为 30～36 MW（40 000～50 000 马力）的船用燃气轮机可以满足未来 10～15 年内各国对于大中型水面船舶大功率燃气轮机主动力装置的需求。

船用燃气轮机性能的提高有两种途径：一是传统的简单循环，用提高压比、燃气初温和改进部件效率实现新的目标，这方面 LM2500＋是一个代表；二是采用复杂循环，通过循环的改进实现更高的性能，这方面采用间冷回热复杂循环的 WR-21 是代表。

本文将探讨在现有发动机的基础上，最大程度地保持核心部件不变，仅用较简单的间冷循环（IC）来发展大功率船用燃气轮机的可能性。

1　间冷循环分析

首先，定量地考察间冷循环燃气轮机的性能及主要循环参数间的关系。发动机由一个双轴燃气发生器（带间冷器）和一个动力涡轮组成，如图 2 所示，所假定的部件性能参数列于表 2 中。

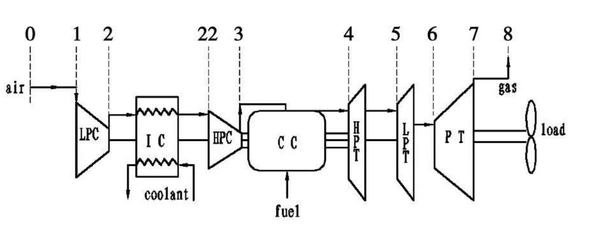

图 2　IC 循环的原理图

表 2　计算条件

	数　值		数　值
P_0/MPa	0.1013	η_{CC}	0.99
T_0/ ℃	15	η_{HPT}^{*}	0.87
T_{cool}/ ℃	20	η_{LPT}^{*}	0.89
ΔP_{in}/ Pa	980	η_{PT}	0.92
ΔP_{ex}/ Pa	3 920	ξ_{IC}	0.05
PR_{LPC}/ PR_{HPC}	1	ξ_{CC}	0.05
η_{LPC}	0.88	ξ_{ID}	0.01
η_{HPC}	0.90	LHV/kJ·kg^{-1}	42 700

注：以 1 200 ℃为基准，初温每提高（降低）100 ℃，涡轮效率降低（提高）1.25％。

在不同的总压比（PR＝12～42）、不同的燃气初温（TIT＝1 100～1 400 ℃）和不同的间冷度（ε＝0～0.85）下[2]，对发动机总体性能的计算结果曲线如图 3～图 6 所示。

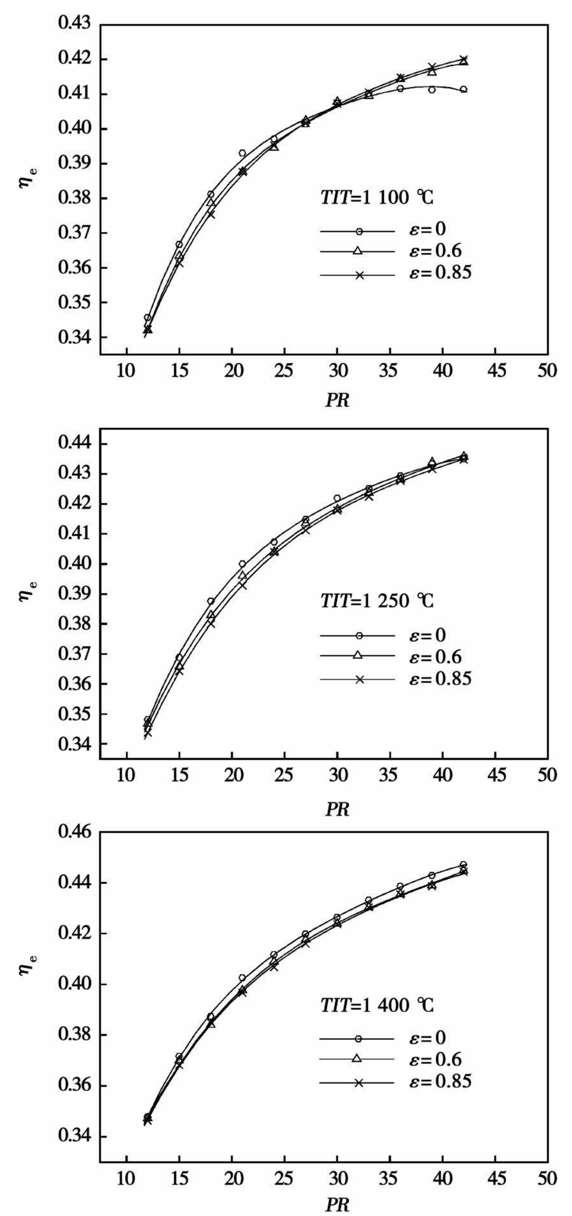

图 3　间冷对发动机效率的影响

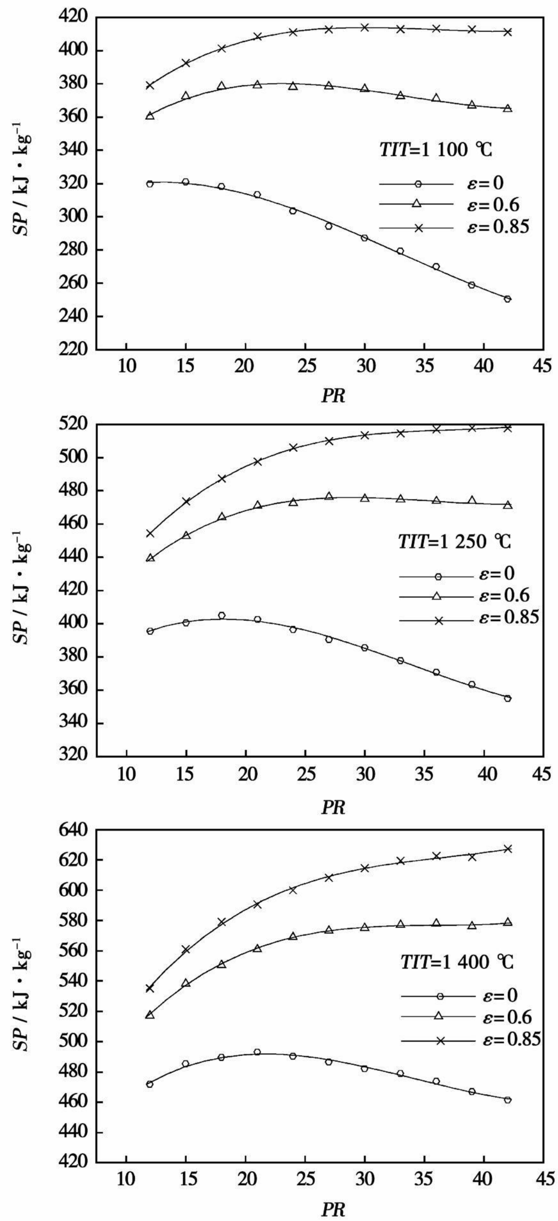

图 4 间冷对发动机比功的影响

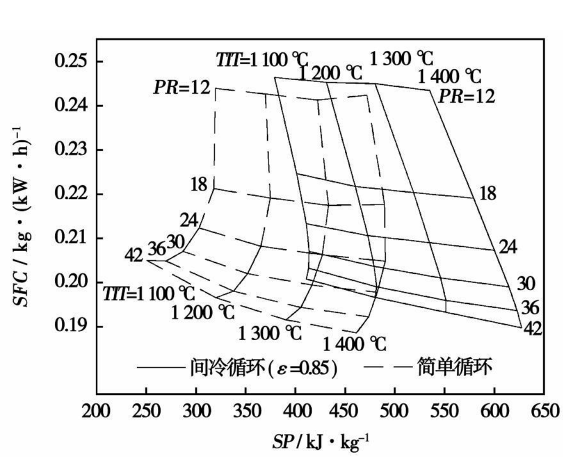

图 5 不同循环的总性能图线

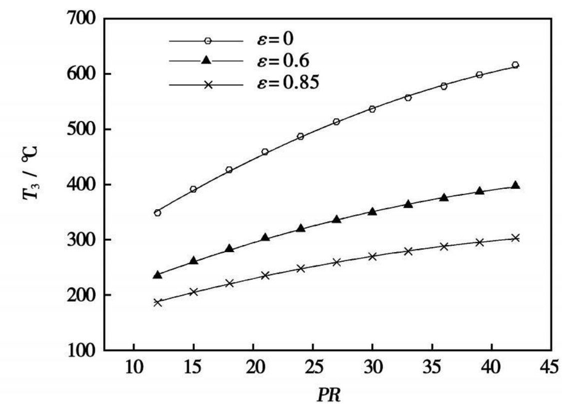

图 6 间冷对于压气机出口温度的影响

(1) 从图 3 中可见采用间冷对发动机效率的影响,在现代船用燃气轮机的参数下(燃气初温在 1 300 ℃左右,压比 20~25),采用间冷对发动机热效率的影响甚微,而且随着间冷度增加,效率略有下降。这是因为采用间冷后,虽减少了压气机的耗功,增加了有效输出功率,但是压气机出口温度降低。为使燃气达到预定的初温值就需要更多的燃料消耗,只有在高压比下,压气机耗功减少的影响会超过由于间冷导致燃料增加的影响,这时其效率会高于简单循环效率。

(2) 图 4 表示间冷对发动机比功的影响,显然,采用间冷使燃气轮机的比功有大幅增加,间冷度越大,比功越大,同时相应于最大比功的压比值也大大增高。在现代船用燃气轮机的参数下,采用间冷后比功可提高 22%~30%。

(3) 图 5 将简单循环和间冷循环的总性能图线叠在一起,可以清晰地看出,采用间冷后,无论是相应最大比功的压比值或是相应于最佳效率的的压比值均大大地增加。

(4) 图 6 表示间冷对于压气机出口温度的影响,这意味着进入高温涡轮叶片的冷却空气温度降低,在保持高温涡轮叶片金属表面温度不变时可允许适度提高燃气初温。此外,高压转子在压气机折合转速相同时,其物理转速也将明显减小,使其工作应力明显减小。

综上所述,在现代船用燃气轮机的参数下,采用间冷可明显增大比功,提高发动机的输出功率,间冷度越大,有效输出功率越大。采用间冷时对热效率的影响则较微弱,间冷度越大,循环效率越低,但总的来说效率变化的幅值较小。

以上是间冷循环作简单分析的结果。当把一台现有发动机作为发展为间冷循环燃气轮机的母型机

而进行实际研究时，会发现一些有利于效率提高的因素，诸如燃气初温的适度提升、重新匹配后某些部件工作点效率的提高、折合转速的变化等，使得在明显提高发动机功率的同时其热效率也获得提升。

2　间冷循环方案实例

决定选取一型发动机（MGT-33）作母型机进行发展为 IC 循环的研究，以确定该方案的技术可行性。MGT-33 简单循环燃气轮机的主要性能如表 3 所示。

表 3　MGT-33 燃气轮机 ISO 条件下的性能

	数　值
功率 Ne/kW	28 500
热效率 η_e/%	37
空气流量 Ga/$kg \cdot s^{-1}$	90
燃气初温 TIT/K	1 543
总压比 PR	22.2

2.1　确定从 MGT-33 燃气轮机发展到 CGT-IC 循环燃气轮机的主要原则

（1）在 ISO 条件下，CGT-IC 与母型机的燃气初温相同或增加不超过 30 ℃；

（2）在 ISO 条件下，CGT-IC 低压压气机的折合转速与母型机相同；

（3）最大程度地继承母型机燃气发生器的通流部分；

（4）高低压涡轮叶片的冷却结构不作变动，高压涡轮动叶不作任何改动；

（5）最大程度地继承母型机部件的可靠性。

这些原则的贯彻实施，为改型后发动机的功率和热效率的提高提供了基本前提，并在母型机燃气发生器结构变动最小和通流部分通用性最高的前提下，继承了高可靠性。

经优化计算，获得循环性能如表 4 所示，MGT-33 和 CGT-IC 燃气轮机的示意图如图 7 所示。

表 4　CGT-IC 燃气轮机 ISO 条件下的性能

	方案 I	方案 II
功率 Ne/kW	36 400	38 200
热效率 η_e/%	38.1	38.5
空气流量 Ga/$kg \cdot s^{-1}$	89.6	89.6
燃气初温 TIT/K	1 543	1 572
总压比 PR	22.3	21.9

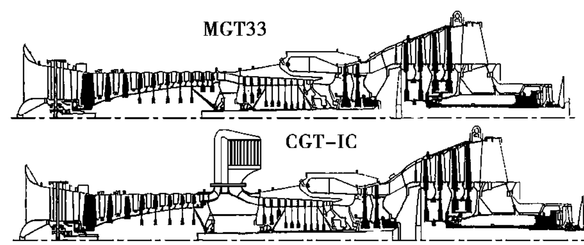

图 7　MGT-33 和 CGT-IC 燃气轮机示意图

2.2　方案（以方案 II 为例）的技术要点

2.2.1　压气机

低压压气机取掉末两级，并重新设计新末级导叶和校直叶片，使减级后的低压压气机的工作点在保持折合流量和折合转速不变的情况下，出口压力降低，平衡由于间冷造成的高压压气机入口折合流量降低的影响。调整后的低压压气机压比降低 19.1%，效率提高 1.82%。

高压压气机不变，匹配后的折合转速上升 6.2%，物理转速降低 11.5%，压比增高 20.5%，效率降低 1.4%。

2.2.2　中间冷却器

间冷器是大幅度提高功率的关键部件。由于在两个压气机之间增加了一个中间冷却器，空气在进入高压压气机前受到预冷而减少了高压压气机的功耗，有效地提高了发动机的功率。为实现高紧凑性、低流阻的中间冷却器，采用模块化结构，间冷度 0.85，间冷器的总压恢复系数为 0.95。

2.2.3　高、低压涡轮

鉴于母型机燃气初温较高，高压涡轮和低压涡轮叶片冷却结构复杂的特点，为了将技术风险降低到最小，高压涡轮和低压涡轮动叶的冷却结构保持不变。重新匹配后的高压涡轮虽因高压压气机耗功减小，使高压涡轮的膨胀比显著减少，但因圆周速度大幅下降，致使级载荷系数增加，导致涡轮效率下降 1.8%。

由于低压压气机拆除了末二级，低压涡轮膨胀比减少了 16.3%，效率提高 0.9%。还有，高压涡轮膨胀比减小及燃气初温升高，使进入低压涡轮的燃气温度增加 5.7%。

由于进入高、低压涡轮叶片的冷却空气温度显著降低，叶片金属表面温度仍不会超过母型机的相应值，加之高压转子的物理转速下降，导致离心力减小 21.7%。

2.2.4　动力涡轮

由于采用间冷及低压压气机拆除后两级,因此高、低压压气机的耗功减少,动力涡轮的入口温度增加9.2%,膨胀比提高36.2%,动力涡轮的输出功率显著增加,动力涡轮需重新设计。重新设计的动力涡轮效率提高了1%,使最终的功率增幅达到34%。由于动力涡轮的效率远高于高、低压涡轮的效率,因此把相当一部分的能量移至高效区膨胀做功,对整机效率的改善起了有效的作用。所以对IC循环而言,设计一个高效动力涡轮尤为重要。

2.2.5 低压转子临界转速

由于需要在母型机高、低压压气机之间引入间冷器,必然引起低压转子的轴向尺寸增加,这将改变低压转子的临界转速。低压压气机去掉末二级的原因之一也是为了减小由于引入间冷器对于低压转子轴向尺寸增加的影响,并控制发动机的总长。

2.2.6 燃烧室与燃油系统

采用间冷后,进入燃烧室的空气温度显著降低,而燃气初温不变,因此燃料加入量增加(相对于简单循环增加了28.3%),燃油泵、燃油喷嘴、燃烧室及燃油调节系统均需作相应调整或重新设计。

3 性能比较

CGT-IC燃气轮机的功率、油耗率性能曲线如图8所示。为了比较,也列出了母型机的性能和用MGT-33发展为CGT-ICR的计算性能。

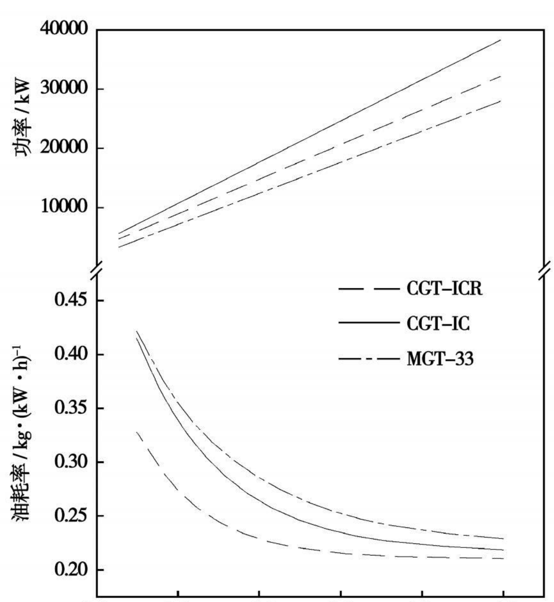

图8 不同循环功率、油耗率的性能曲线

IC循环的功率最大。由于单纯采用间冷技术避免了由于回热器所增加的高压压气机出口经回热器到燃烧室的管道压力损失和动力涡轮出口经回热器到大气的管道压力损失,使得IC循环在提高燃气轮机功率方面比ICR循环更具优势,压力损失的降低也在一定程度上弥补了没有回热在热效率方面的损失。

ICR循环效率最高。由于采用回热和动力涡轮进口导叶可变几何技术,使其不仅在设计点,而且在部分负荷时也具有较高的效率。

4 结 论

(1) 从一般的循环分析来看,采用间冷循环可使燃气轮机的比功明显增加,但其循环效率通常有较弱的负面影响。

(2) 对实际发动机进行的IC循环改造方案分析表明,在增大功率的同时提高其效率,因为有如下因素可以利用:高压转子的物理转速明显下降,其折合转速有适度调整的可能,其离心应力也显著减小;由于压气机出口空气温度明显降低,在保证高温涡轮叶片金属表面温度不高于规定值的前提下,燃气初温有上升的空间;由于燃气发生器的耗功减小,更多部分的能量转换是在效率更高的动力涡轮部分完成的;在燃气轮机重新匹配过程中,部分部件的效率、压比、膨胀比和温度等参数向有利方向变化。

分析结果表明,功率由28 500 kW增加至38 200 kW(ΔNe=34%),热效率由37%提高至38.5%($\Delta\eta_e$=4.1%),发动机总体性能提高的效果是显著的。

(3) CGT-IC的主要优点是:母型机燃气发生器的核心部件结构变动最小,通流部分通用性最高,继承了高可靠性;规避了回热器及动力涡轮可调导叶等部件可靠性方面的技术难点,系统较简单,可明显缩短研发的周期,减少研发费用,又能在发动机总体性能上有所跃升;CGT-IC的性能介于ICR和简单循环之间,对于航空工业尚不发达的发展中国家来说,也许是一个可靠和现实的折中方案。

注:为了与原文保持一致,译文中的功率单位采用了kW、MW、hp或马力。

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(编辑 滨)

sponds with the case when the wake of the first-stage stationary blades is located in the middle of the second-stage stationary blade passage. **Key words**: axial clearance, clocking effect, directly-bowed stationary blade

对一种具有余热回收系统的 LNG 联合循环电站分析 = **An Analysis of LNG (Liquefied Natural Gas)-fired Combined Cycle Power Plants with a Waste Heat Recovery System**[刊,汉]/ SHI Xiao-jun, CHE De-fu, WANG Huan(National Key Laboratory on Multi-phase Flows in Power Engineering, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. – 2009, 24(1). – 47 ~ 52

Presented was a waste heat recovery system, which fully recovers two kinds of low-temperature waste heat in a LNG(Liquefied Natural Gas)-fired combined cycle power plant, i.e. the latent heat of the exhaust steam from a steam turbine and the vapor latent heat of flue gases from a waste heat recovery boiler. A thermodynamic analysis shows that relative to a 240 MW conventional combined cycle power plant, the net electric efficiency and exergy one of the system in question can increase by 1.6% and 2.84% respectively. The fuel utilization rate can hit 62.88%. This means that a heat quantity of 86.27 kJ/s can be recovered from each kilogram of the flue gases. Hot water at a mass flow rate of about 46.1 kg/s, with a temperature of 167.45 ℃ and a pressure of 0.84 MPa, can be extracted from the outlet of a low-pressure economizer, which can be fed into a waste heat utilization sub-system. A cost-effectiveness analysis indicates that the payback period of the investment for the heat recovery system is 0.117 years. All these features attest to an extremely strong attractiveness inherent to newly-built LNG-fired combined cycle power plants and the retrofitting of the existing ones. **Key words**: combined cycle, waste heat recovery, LNG (Liquefied Natural Gas), thermodynamic analysis, cost-effectiveness analysis

冷热电三联供燃气机热泵系统的㶲损功率分析 = **An Analysis of Exergy Loss Power for a Cooling-heating-power Cogeneration System**[刊,汉]/ FANG Zheng, YANG Zhao, CHEN Yi-guang (Thermal Energy Research Institute, Tianjin University, Tianjin, China, Post Code: 300072) // Journal of Engineering for Thermal Energy & Power. – 2009, 24(1). – 53 ~ 59

From the viewpoint of energy grade stepped utilization, a gas-turbine-driven heat pump system based on a cooling-heating-power cogeneration was analyzed, and a definition of systematic exergy loss power, proposed. In addition, the exergy loss power of the system in question at various condensation temperatures, evaporation temperatures and compressor rotating speeds was also analyzed. Herefrom, the authors have come to the following conclusion, which can provide definite guidance for the design of the system mentioned earlier: from the perspective of energy grade, an engine with a relatively high thermal efficiency should be chosen as far as possible to reduce the power generation capacity of the generator, and an operating mode to directly drive the water pump by an engine can be considered. Depending on the location of the south or north regions, the influence of condensation and evaporation temperatures on the system should be comprehensively taken into account. A heat exchanger with a relatively good heat exchange effectiveness should be selected to minimize the exergy loss power of the heat exchanger which produces and utilizes cooling and heating exergy. The rotating speed of the engine should not be set at an excessively high value. It is better to select an engine with an economic rotating speed. A gas-turbine-driven heat pump with a high rotating speed is not cost-effective. **Key words**: cooling-heating-power cogeneration, gas-turbine driven heat pump, exergy loss power

IC 循环船用燃气轮机的可行性研究 = **Feasibility Study of an IC (Intercooled Cycle) Marine Gas Turbine**[刊,汉]/ WEN Xue-you, XIAO Dong-ming (CSIC Harbin No.703 Research Institute, Harbin, China, Post Code: 150036)// Journal of Engineering for Thermal Energy & Power. – 2009, 24(1). – 60 ~ 64

The performance made available by the adoption of an intercooled cycle at different typical gas turbine cycle parameters

was analyzed in a comprehensive way. On this basis, a study was conducted of the conversion of a high power simple-cycle marine gas turbine (MGT-33) to an intercooled cycle one. The precondition of the conversion is to keep the majority of the flow path and structure of the original engine gas generator unchanged to inherit the reliability of the prototype machine. The results of the study indicate that after the adoption of the IC cycle, under the precondition of minimum structure modification and retaining the compactness of the whole machine, the overall performance of the gas turbine still secures a conspicuous enhancement, with its power output being increased by about 34% and the efficiency, enhanced by approximately 4.1%, thus demonstrating the merits of the relevant engineering modifications. **Key words**: marine gas turbine, IC (Intercooled Cycle) cycle

汽轮机热力性能考核指标的通用方程 = **A General Equation of Indexes for Appraising the Thermodynamic Performance of a Steam Turbine**[刊,汉]/ YAN Shun-lin, GUO Jia-lei (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(1). - 65 ~ 67

For the safe and cost-effective operation of a whole thermal power plant, it is of the utmost importance to grasp and know well the thermodynamic performance of steam turbine units. Currently, only a definition and basic calculation formulae of various indexes are given in the technical specification for thermodynamic performance tests of a steam turbine. If for different steam turbine units, calculation formulae are to be listed separately, a relatively poor generalization will result and this is not conducive to the development of general-purpose computer programs. On the basis of a long-time analysis and observation, a unified physical model of thermal power plants was established, and a general-purpose equation of indexes for appraising the thermodynamic performance of a steam turbine, proposed. This not only provides an underlying basis for preparing the calculation indexes of steam turbine thermodynamic tests, but also lays a foundation for a further refinement of the test specification. **Key words**: thermodynamic performance, indexes for appraisal, general equation

一种识别气液两相流流型的新方法 = **A New Approach for Identifying Gas-liquid Two-phase Flow Patterns** [刊,汉]/ ZHOU Yun-long, LI Hong-wei, YUAN Jun-wen (College of Energy Source and Mechanical Engineering, Northeast Dianli University, Jilin, China, Post Code: 132012)// Journal of Engineering for Thermal Energy & Power. - 2009, 24(1). - 68 ~ 72

In the light of the statistical characteristics of image grey-scale histograms, proposed was a new method for identifying gas-liquid two-phase flow patterns by combining an image processing with an ameliorated supportive vector machine. The method in question is to use a high-speed video camera to acquire an image of 7 typical flow patterns on a gas-liquid two-phase flow test rig. Through the image processing, the statistical characteristics of the image grey-scale histograms were extracted to form an eigenvector, which serves as a flow pattern specimen to perform a training for and identification of the ameliorated supportive vector machine. The test results show that the characteristics of the image grey-scale histograms can very well reflect the difference of various flow patterns. Compared with the original supportive vector machine, the ameliorated one provides a good classification performance, a short operation time and a network identification rate as high as 99.04%, thus providing a new effective approach for an on-line discrimination of flow patterns. **Key words**: flow pattern identification, image processing, statistical characteristics of grey-scale histograms, ameliorated supportive vector machine

直接空冷凝汽器单元样机流动和传热性能研究 = **A Study of the Flow and Heat Transfer Performance of a Direct Air-cooled Condenser Sample Unit**[刊,汉]/ SHI Lei (College of Civil Engineering, Beijing Jiaotong University, Beijing, China, Post Code: 100044), SHI Cheng (China Electric Power Engineering Consultant Group Corporation, Bei-