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微型燃气轮机冷热电联供系统变工况性能研究

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摘　要: 设计了以微型燃气轮机为核心的冷热电联供系统并建立了该系统变工况性能分析模型。结合具体算例, 对该联供系统在采用“以冷(热)定电”的模式下运行变工况时的热力性能进行了计算分析, 揭示了系统在不同调节方式下的变工况性能。结果表明, 回热度调节具有较宽的冷热负荷调节范围, 因此微型燃气轮机联供系统特别适用于冷热负荷变化大而系统内电负荷较稳定的场合。为使系统变工况时保持较高的性能, 当冷热负荷增加时应优先考虑发电功率调节, 其次采用回热度调节, 最后采取补燃量调节; 当冷热负荷减小时宜采用相反的调节顺序。研究结果将对微型燃气轮机冷热电联供系统的设计及运行提供有益的参考和指导。

关　键　词: 微型燃气轮机; 冷热电联供系统; 变工况性能

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引　言

分布式能量系统由于节能、环保、可增加用户电力可靠性等诸多优点, 在国内外得到了广泛的重视[1]。冷热电联供是分布式能量系统发展的一个重要方向。微型燃气轮机的排烟温度较高, 便于回收, 非常适合作为分布式冷热电联供系统的核心装置[2]。以微型燃气轮机为核心的联供系统可大量推广到建筑能源领域, 而建筑能源需求中的冷热需求会随气温的变化而变化, 因此冷热电联供系统一般为变工况运行[3]。目前, 分布式能量系统的冷热电联供系统在国内存在着“并网不能上网”的问题, 多采用“以冷(热)定电”的运行方式。因此本文重点研究了微型燃气轮机冷热电联供系统在这种运行方式下调节冷热负荷时系统的热力性能。

1　微型燃气轮机冷热电联供系统

1.1　联供系统组合方式

微型燃气轮机冷热电联供系统可采用多种组合形式, 本文提出了一种较为合理的组合方式。如图 1 所示, 微型燃气轮机透平排出烟气先进入回热器, 部分热量被回收用来发电, 然后进入余热锅炉生产饱和蒸汽。生产的蒸汽在夏季用来驱动溴化锂吸收式制冷机组制冷; 在冬季进入汽水换热器生产热水进行供热; 春秋季可以由汽水换热器生产生活热水。溴化锂制冷机组与汽水换热器采用并联, 增加了系统的冷热调节的灵活性。

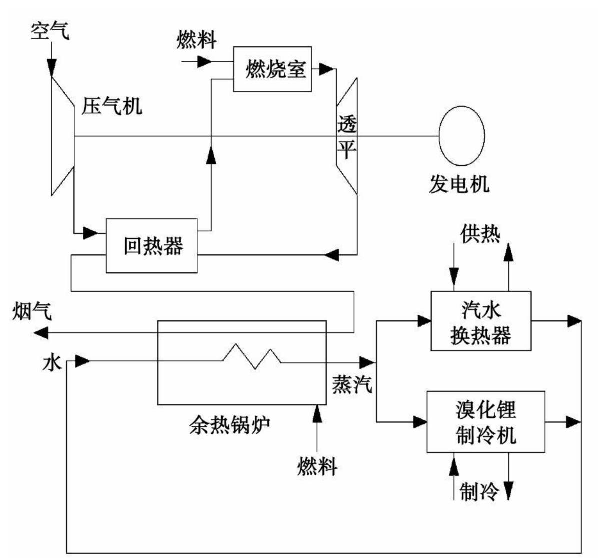

图 1　系统示意图

为提高冷热负荷调节范围, 采用可补燃的单压余热锅炉, 但根据需要采用补燃与不补燃两种工作状态。溴化锂吸收式制冷机利用废热制冷的同时可以避免使用对大气有破坏影响的氟利昂等制冷剂, 可起到保护环境的作用。微型燃气轮机采用了高效回热器额定功率下的排烟温度一般在 250 ℃左右, 当发电功率减小, 排烟温度将降低。例如本文所选微型燃气轮机发电功率由 100 kW 降到 30 kW 时, 排

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烟温度由 245 ℃降到 198 ℃。废烟气的温度在 250 ℃以下时适合作为单效溴化锂制冷机组的热源[5]，所以匹配单效蒸汽型溴化锂制冷机组。

1.2 联供系统变工况调节方法

“并网不能上网”的情况下采用“以冷(热)定电”的运行方式,若微型燃气轮机发出电量供应系统内的用电负荷不足时,不足电量可由电网补充,但多余电量不能上网,所以微型燃气轮机的发电功率根据冷热负荷调节时,可以自由的降低,但增大要受到系统内用电负荷的限制。此外系统供冷(热)功率还可以通过调节微型燃气轮机回热度与余热锅炉补燃量两种方式实现。

1.3 联供系统变工况性能计算方法

微型燃气轮机采用变转速运行,部分功率下的最佳转速采用经验公式[7]:

$$n=0.739+0.521N-0.446N^2+0.186N^3 \quad (1)$$

式中:n—转速;N—功率。上标“°”—折合参数。

考虑流量及转速对压气机及透平特性的影响,压气机及透平特性曲线根据文献[7]解析特性曲线计算;考虑烟气成份与温度对烟气物性的影响。

回热器变工况特性计算使用下式:

$$\sigma=\sigma_0/[\sigma_0+(1-\sigma)(G/G_0)^{0.2}] \quad (2)$$

式中:σ—回热度;G—流量。下标“0”—额定工况下的值。

余热锅炉变工况过程中,换热面积是不变的,所以主要考虑换热系数的变化。烟气侧的对流换热系数 a_g 对换热系数的影响最大,其比值可简化为下式[8]:

$$\frac{a_g}{a_{g0}}=\left(\frac{G_g}{G_{g0}}\right)^m\times\left(\frac{T_g}{T_{g0}}\right)^n \quad (m=0.6,\ n=0.6) \quad (3)$$

式中:a_g、a_{g0}—烟气侧在变工况与额定工况下对流换热系数;T_g、T_{g0}—烟气在变工况与额定工况下进出口平均温度;G_g、G_{g0}—在变工况与额定工况下烟气流量。余热锅炉的补燃情况用补燃率 b 表示,补燃率定义为:

$$b=\frac{f_2}{f_1}\times 100\% \quad (4)$$

式中:f_1—微型燃气轮机燃料量;f_2—余热锅炉补燃燃料量。

单效蒸汽型溴化锂制冷机制冷量调节一般采用加热蒸汽量与溶液循环量组合调节的方法,在制冷量变化时蒸汽消耗率变化较小,为简化计算,全部工况热力系数 COP 均取 0.7。

联产的优势在于利用发电产生的余热供冷与供热,所以很有必要分析能量用于发电的情况,可用系统发电效率 η_e 来分析:

$$\eta_e=\frac{W}{f\times H} \quad (5)$$

式中:W—微型燃气轮机发电功率;f—系统内微型燃气轮机与余热锅炉总的燃料用量;H—燃料低位发热值。

总能利用效率 η_z 可以从数量上反映联产系统能量的利用程度,其表达式为:

$$\eta_z=\frac{W+Q_c\times COP+Q_h}{f\times H} \quad (6)$$

式中:Q_h—用于供热的热量;Q_c—用于制冷的热量;COP—制冷机热力系数。

分析能量利用程度考虑数量的同时还应考虑其品位,可采用火用效率 η_y 来分析。

$$\eta_y=\frac{W+A_c\times Q_c\times COP+A_h\times Q_h}{f\times H} \quad (7)$$

式中:A_c—制冷量的卡诺循环效率;A_h—供热量的卡诺循环效率。分母采用燃料低位热值,而不是输入火用,主要是二者相差不大,而且这样便于使火用效率与总能利用效率相对应[9]。事实上冷火用与热火用是不等价的,但目前还没有更为合理且得到公认的实用的评价指标。

1.4 联供系统参数说明

本文所选联供系统微型燃气轮机额定工况基本参数:发电功率 100 kW,压比 3.8,回热度为 0.9,压气机效率 0.78,透平效率 0.80,透平进口温度 900 ℃;余热锅炉生产 0.098 MPa 饱和蒸汽,回水温度是 85 ℃,额定工况点接近点温差为 7 ℃,节点温差 10 ℃;溴化锂制冷机制冷功率选取为 200 kW[6],冷媒水进口温度 12 ℃,出口温度 7 ℃;汽水换热器生产供暖热水出口温度 70 ℃,回水 50 ℃,压力 0.2 MPa;燃料为 CH_4;环境平均温度夏季取 30 ℃,冬季取 0 ℃。

2 联供系统变工况性能分析

本文只对系统夏季供冷与冬季供热的典型情况进行分析。

2.1 夏季供冷情况

图 2 给出了通过增加微型燃气轮机发电功率提高制冷功率时系统热力性能变化的情况。由图可见随着发电功率增加,制冷功率增加速度略有提高;3 种效率接近平行增大,且增大速率逐渐减缓。由图可见发电功率低时系统性能较差。

图 3 给出了额定发电功率下减小回热度提高制

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冷量时系统性能的变化。由图可见回热度与制冷功率接近直线关系，回热度减小时 η_z 呈直线缓慢提高，考虑能量的数量，对于能量的利用是有利的；η_y 与 η_e 随着回热度变小而降低，且降低速率逐渐减缓，考虑能量的品位，对能量的利用是不利的。

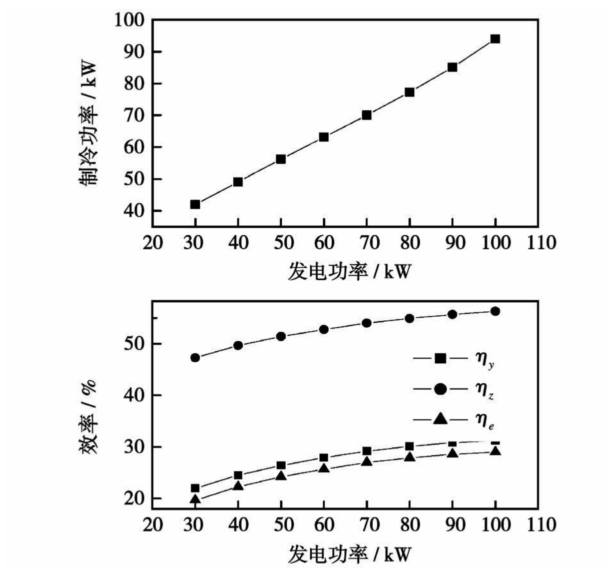

图 2　发电功率调节

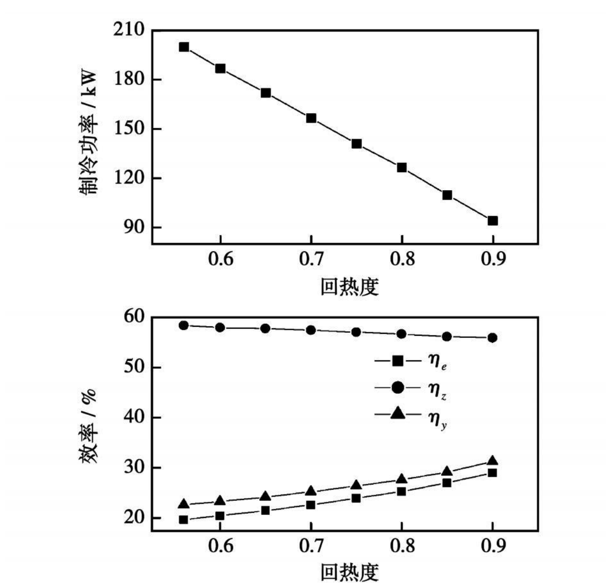

图 3　回热度调节

额定发电功率时增加补燃量使制冷功率增加的情况如图 4 所示。制冷功率随补燃率提高呈直线上升。由于随着补燃量的提高，余热锅炉的排烟温度明显提高，通过计算发现当补燃率达到 80%时，排烟温度提高近 60 ℃，所以系统的 3 种效率均出现降低，由图可见降低速度逐渐减慢。

回热度调节与补燃量调节系统性能变化的对比如图 5 所示。可见 3 种效率回热度调节均比补燃量调节高（图中回热度调节的变量标有下标 h，补燃量调节标有下标 b）。所以提高制冷量时应该优先进行回热度调节，相反，减小制冷量时优先进行补燃量调节。

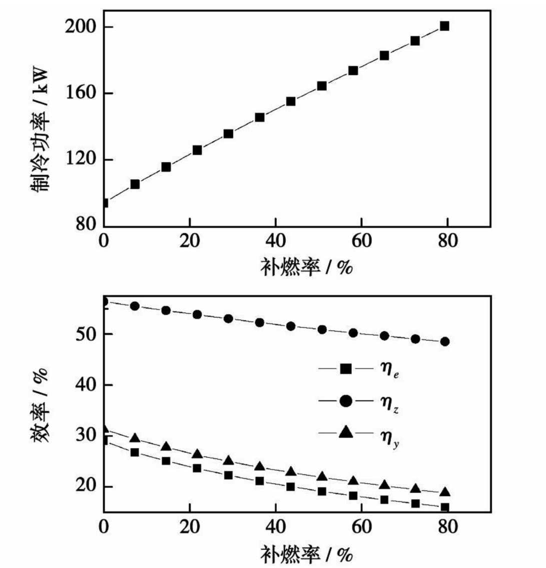

图 4　补燃量调节

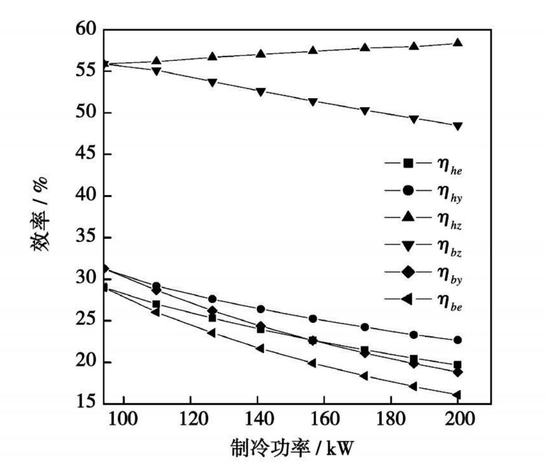

图 5　回热度调节与补燃量调节的对比

图 6 给出了全部制冷功率范围内系统的性能变化情况。图中用区间 1 表示发电功率调节，用区间 2 表示回热度调节。

图 7 反映的是在发电功率受限制时（以最大允许发电功率为 70 kW 为例）系统的性能随供冷量的变化。变化趋势与图 4 相近，但是系统性能在最大发电功率右侧下降幅度很大。可见较小的发电功率下承担大的制冷功率系统的性能变差。

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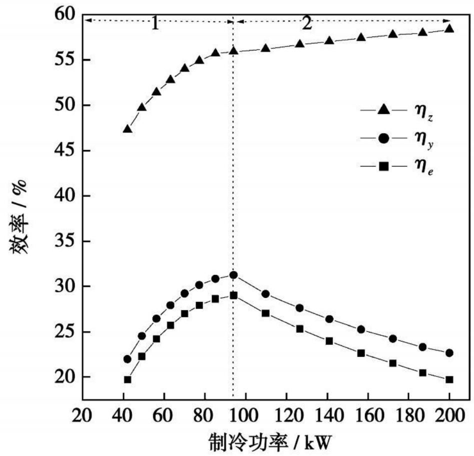

图 6　系统性能随供冷量的变化

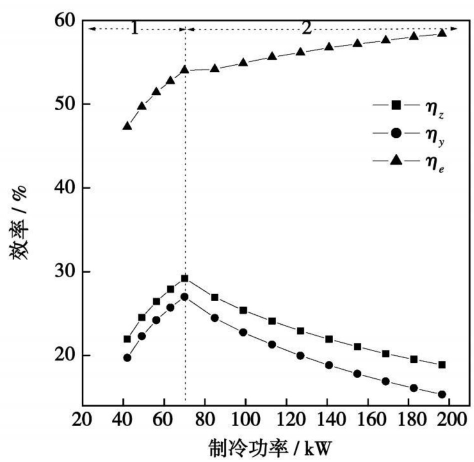

图 7　供冷时发电受限系统性能的变化

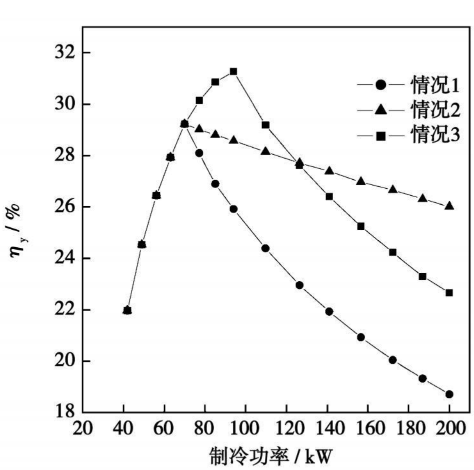

图 8　增加电空调系统性能的改善

当系统制冷功率大而发电功率受限制时，如果增加一些小功率电空调（$COP=5$），作为用电负荷把超发的电用来制冷，系统性能可得到改善，如图 8 所示，情况 1 是发电功率受到限制，情况 2 是增加了小功率电空调，情况 3 是发电功率不受限制。

2.2　冬季供热情况

供热量一般要比供冷量大很多，超出回热度调节范围可继续采用补燃调节。当供热功率增加时系统性能变化趋势与供冷时相似，如图 9 所示。图中用区间 1 表示发电功率调节，用区间 2 表示回热度调节，用区间 3 表示回热度调节后继续采用补燃量调节。由于热量的火用值与冷量火用值相比要高很多（A_c 为 0.082 1，A_h 值为 0.204），所以系统火用效率与制冷时相比要高。由图可见通过回热度调节，热电比可由 1.3 达到 5.3，可见微型燃气轮机通过回热度调节实现的调节范围是很宽的。

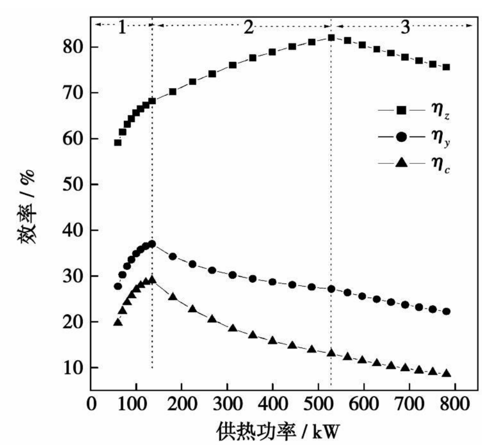

图 9　系统性能随供热量的变化

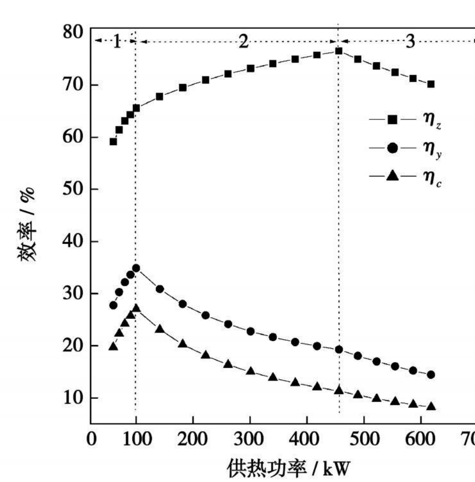

图 10　供热时发电受限系统性能的变化

图 10 为在发电功率受限制时（以最大允许发电功率为 70 kW 为例）系统的性能变化。与图 9 相比，变化趋势相似，但在热负荷较大时系统性能要明显降低。发电功率降低，系统发电效率降低，能量用于

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供热的份额增加, 通过回热度调节实现的热电比调节范围增大, 例如在 70 kW 时通过调节回热度, 热电比可由1.4 达到6.5。

3 结 论

本文结合具体算例对微型燃气轮机冷热电联供系统变工况运行时的性能进行了计算分析, 主要得出以下结论:

(1) 冷(热)负荷调节的 3 种方式中, 增加微型燃气轮机发电功率, 系统的 3 种效率均提高; 减小微型燃气轮机回热度, 系统发电效率与火用效率降低, 系统总能利用效率提高; 增加余热锅炉补燃量, 则 3 种效率均降低。

(2) 当系统冷(热)负荷增加时应该最先采取增加发电功率的方法, 其次考虑采用减小回热度, 最后采用增加补燃量; 当系统冷(热)负荷减小时最先考虑减少补燃量, 其次考虑增加回热度, 最后考虑减小发电功率。

(3) 微型燃气轮机冷热电联供系统有较宽的冷(热)调节范围, 微型燃气轮机发电功率对联供系统的性能有重要影响。微型燃气轮机冷热电联供系统适用于冷热负荷变化大而系统内有较稳定的电能负荷的场合。

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(编辑 滨)

新技术新工艺

管线收集 RB211 燃气轮机排气的余热用来发电

据《Gas Turbine World》2008 年 5～6 月号报道, Ormat 技术公司正在利用自动化蒸气涡轮装置对 5 个以上 RB211 压缩机站进行翻新改造。这些装置以燃气轮机排气热量运转, 用来生产电力。

Ormat 拥有并运行这些“回收能量生产”装置。RB211 燃气轮机基本负荷额定输出功率为 29.5 MW, 质量流量为 94.1 kg/s, 排气温度为 492 ℃。

Ormat 的闭路余热回收系统以排气热量运转, 使不可燃、不可冻结的传热流体气化, 驱动小型涡轮发电机, 然后循环通过空气冷却的冷凝器, 以便被重新使用。

增压的有机蒸气涡轮驱动简易的 1 800 r/min 的涡轮发电机, 生产 5.5 MW 电力。

额定值: 余热能量回收装置的功率从燃气轮机 50% 负荷时的 3 100 kW 变化到 100% 负荷时的 5 500 kW。

费用: 装置(承包供应和安装)总费用非正式的估计约为 1 100 万美元。

年收入: 假设平均输出功率为 4 300 kW, 并且每千瓦小时价格为 0.06 美元, 则每年收入估计为 220 万美元。

(吉桂明 供稿)

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负荷结构对冷热电联供系统优化配置的影响＝**Influence of Load composition on the Optimized Configuration of a Combined Cooling, Heating and Power（CCHP）Cogeneration System**[刊，汉]/LI Zhao-zhen, SHI Yu-mei, HUANG Xing-hua（College of Mechanical and Power Engineering, Shanghai Jiaotong University, Shanghai, Post Code: 200240）//Journal of Engineering for Thermal Energy & Power.－2008, 23(6).－606～610

Being a factor specific to the optimization of a cogeneration system, load composition exercises a major influence on the configuration mechanism of the system in question. The research in this regard will be certainly beneficial to the proper popularization of this technology in China. The authors have established a nonlinear integrated optimization model of mixed integer type for the cogeneration system featuring a simultaneous supply of cooling, heating and electrical power. Several specific cases were calculated at different load proportions based on the loads actually measured from a hotel. The influence of heating/electric power ratio and cooling/electric power ratio on the optimal capacity of various equipment items was examined by making use of a sensitivity analysis. The results of the study show that at different load make-ups, the optimal capacity of the equipment items and its variation tendency undergo significant changes. It is difficult for the currently prevalent operating modes, namely heating production determination on the basis of electric power generation or electric power generation determination on the basis of heating requirements, to decide the optimal capacity of a gas turbine. The optimal capacity of an absorption type refrigerator is also influenced by various load settings. The optimal capacity of a boiler and an electric refrigerator may be approximately determined respectively and separately by heating/electric power ratio and cooling/electric power ratio. The research results can serve as a reference for the popularization of the cogeneration system (simultaneous supply of heating, cooling and electric power) in various climatic regions. **Key words**: combined supply of cooling, heating and electric power, load ratio, sensitivity analysis, configuration optimization, gas turbine

联合循环机组在线性能试验软件开发与应用＝**Development and Application of an On-line Performance Test Software for Combined Cycle Units**[刊，汉]/GAO Jian-qiang, FAN Xiao-ying, ZHAO Jun-you（College of Energy Source and Power Engineering, North China University of Electric Power, Baoding, China, Post Code: 071003）//Journal of Engineering for Thermal Energy & Power.－2008, 23(6).－611～614

On the basis of the real-time data acquired by a distributed control system (DCS), given were all the process parameters necessary for an on-line performance test along with the description of a method for calculating the main thermodynamic performance indexes of a combined cycle unit, namely, its gross power output and total heat rate etc. Based on an integrated modular model software (IMMS) and by adopting a modular modeling method, an on-line model for calculating the thermodynamic performance indexes was established. Moreover, through an user interface program, the calculated results were real-time displayed. The software in question has been applied in the plant-level supervisory information system (SIS) of a 395 MW gas-steam combined cycle unit in a power plant. The results show that the software can meet the requirement for an on-site real-time monitoring, thus facilitating relevant operating personnel to timely grasp and analyze the operation cost-effectiveness of the unit. **Key words**: combined cycle, performance calculation, on-line model, condition monitoring

微型燃气轮机冷热电联供系统变工况性能研究＝**A Study of the Off-design Performance of a Micro Gas Turbine-based Combined Cooling, Heating and Power（CCHP）Cogenration System**[刊，汉]/HE Bin-bin, YANG Yong-ping, DUAN Li-qiang（Beijing City Key Laboratory on Safe and Clean Utilization of Energy Sources and Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control, College of Energy Source and Power Engineering, North China University of Electric Power, Beijing, China, Post Code: 102206）//Journal of Engineering for Thermal Energy & Power.－2008, 23(6).－615～619

A micro gas turbine-based combined cooling, heating and power (CCHP) cogeneration system has been designed and a model for analyzing the off-design performance of the system, established. In combination with specific calculation cases, an analytic computation has been performed of the thermodynamic performance of the system in question operating at an

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off-design condition under the mode of "determining power generation on the basis of heating (cooling) demand", thus revealing the off-design operating performance of the system under various regulating methods. It has been found that a recuperation adjustment can accommodate a relatively wide range of cooling and heating load regulation. Therefore, the micro gas turbine-based cogeneration system is particularly suitable for the occasion when the cooling and heating load undergoes a great change while the electric power load in the system is relatively stable. To keep a comparatively high performance of the system when operating at off-design conditions, in case of an increase of the cooling and heating load, the electric power regulation should be adopted as a first priority, followed by the recuperation regulation as a second choice and supplementary firing regulation as a last resort. When the cooling and heating load decreases, a reverse regulation order should be chosen. The research results can well provide useful reference and guidance for the design and operation of micro gas turbine-based CCHP cogeneration systems. **Key words**: micro gas turbine, cooling, heating and power cogeneration system, off-design performance

循环流化床旋直复合流化下的两相流动试验研究＝**Experimental Study of Two-phase Flows in a Circulating Fluidized Bed under a Rotating and Straight Compound Fluidization**[刊, 汉] / HAO Xiao-wen, (College of Automobile Engineering, Harbin Institute of Technology, Weihai, China, Post Code: 264209), MA Chun-yuan, ZHANG Li-qiang (College of Energy Source and Power Engineering, Shandong University, Jinan, China, Post Code: 250061), WANG Chun-bing (ZHONG-guang Nuclear Engineering Design Co. Ltd., Shenzhen, China, Post Code: 518124)// Journal of Engineering for Thermal Energy & Power. — 2008, 23(6). — 620 ~ 624

To increase in-tower blending and material concentration represents an approach for raising the flue gas desulfuration efficiency of a circulating fluidized bed. The authors have proposed a rotating and straight compound fluidization mode and measured gas-solid two-phase in-tower flow field by using a PDA (Phase Doppler Anemometer) measurement system. Obtained was a law governing the gas-solid two-phase flows in a desulfuration tower before and after axial rotating blades were installed in a Venturi throat. It has been found that the non-uniform air distribution as characterized by the rotating and straight compound fluidization mode can help increase the tangential speed in the tower, leading to an in-tower strong pulsation, good mixing and resulting in a higher in-tower particulate concentration and an increased inner circulation. In addition, a higher superficial speed can bring about a better comprehensive effectiveness of the compound fluidization. The experimental results can provide an underlying basis for the structural design and optimization of new technologies for flue gas desulfuration. **Key words**: circulating fluidized bed, compound fluidization, impulsive speed, inner cycle

串联型化工动力多联产系统主导因素与变工况特性＝**Leading Factors and Off-design Operating Characteristics of a Tandem Type Chemical-industry Power Polygeneration System**[刊, 汉] /FENG Jing, NI Wei-dou, LI Zheng (Thermal Energy Engineering Department, Tsinghua University, Beijing, China, Post Code: 100084)// Journal of Engineering for Thermal Energy & Power. — 2008, 23(6). —625 ~629

A polygeneration system having electric power as one of its main products, will, as a result, unavoidably face load variation problems during its operation. From the viewpoint of load variations to design a polygeneration system capable of meeting the requirement of an electric grid, the authors have through a detailed simulation analysis, come to emphasize two leading factors influencing the load variation capacity of a tandem type polygeneration system, namely, designed power-chemical production ratio and synthetic unit capacity surplus degree. In the form of a four-quadrant chart, shown was a relationship between the system design parameters and system product output on the one hand and the load variation capacity on the other. In addition, the characteristics of the system in question during a load variation were further analyzed, especially concerning the case when the fuel gas H_2/CO of the gas turbine increases with a decrease of the electric power load. **Key words**: polygeneration system, load variation, methanol synthesis, four-quadrant chart, leading factor

气液两相流垂直冲刷错列管束漩涡脱落特性的实验研究＝**Experimental Study of Vortex Shedding Characteristics of a Gas-liquid Two-phase Flow Vertically Sweeping Across a Staggered Tube Bundle**[刊, 汉] / ZHOU Yun-

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