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环境温度对湿空气透平(HAT)循环性能的影响

赵丽凤,肖云汉,张世铮
(中国科学院 工程热物理研究所,北京　100080)

摘　要:在建立 HAT 循环中各部件的变工况模型的基础上分析了 HAT 循环变工况性能,并同简单间冷循环进行了比较。结果指出,HAT 循环具有良好的变工况性能。

关　键　词:湿空气透平循环;变工况;性能分析

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符号说明

a_e— 常系数	G— 流量
h— 比焓	L— 水流量
n— 转速	m, s, b— 常数
N— 功率	P— 压力
T— 温度	X— 速比
x— 含湿量	π— 压比
η— 效率	

上　标

˙— 比折合参数	d— 设计点

下　标

o— 设计点	opt— 最佳点
a— 环境	f— 燃料
c— 压气机	T— 透平
w— 水	

1　引言

燃气轮机经常在偏离工况(变工况)的情况下工作,原因是:首先,燃气轮机负荷的变化,是导致机组在变工况下工作的一个重要原因;其次,大气状态参数的变化,使燃气轮机偏离设计工况,成为导致燃气轮机在变工况下工作的另一个重要因素;最后,当部件性能变化后燃气轮机也在变工况下工作。因此,需要考察其变工况性能。

本文研究的 HAT 循环包括压气机、燃烧室、透平、间冷器、后冷器、湿化器、回热器和热水器等部件,每个部件都有自己的特性,它们又通过流量、压力、转速等物理参数形成相互联系与制约的状况。通过研究系统的变工况性能,掌握各个部件之间相互联系与制约的规律,才能在设计时正确选取燃气轮机的方案和参数。HAT 循环流程图如图 1 所示。此流程为 HAT 循环最高效率流程之一[1]。要进行系统的变工况计算,首先要建立各部件的变工况特性模型。

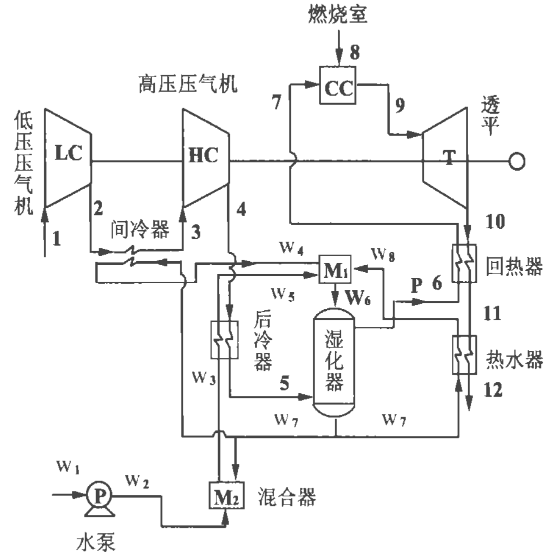

图 1　HAT 循环流程图

2　变工况特性模型

2.1　压气机

变工况计算采用文献[2]介绍的压气机特性关系式。

为推出形式上简单的解析解,该文献中各式采用比折合参数(定义为折合参数与其设计值之比,用该变量符号上方加“.”表示)作为变量形式。压比和效率与流量、转速的比折合参数之间的关系为:

$$\dot{\pi}_c = c_1(\dot{n}_c)\,\dot{G}_c^2 + c_2(\dot{n}_c)\,\dot{G}_c + c_3(\dot{n}_c) \quad (1)$$

$$\dot{\eta}_c = \left[1 - c_4(1 - \dot{n}_c)^2\right](\dot{n}_c/\dot{G}_c)(2 - \dot{n}_c/\dot{G}_c) \quad (2)$$

式中 $c_i(\dot{n})$ 的表达式为:

$$c_1 = \dot{n}_c/\left[b(1 - m/\dot{n}_c) + \dot{n}_c(\dot{n}_c - m)^2\right] \quad (3)$$

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作者简介:赵丽凤(1972-),女,辽宁鞍山人,中科院工程热物理研究所,助理研究员。

$$c_2 = (b - 2m\dot{n}_c^2)/[b(1 - m/\dot{n}_c) + \dot{n}_c(\dot{n}_c - m)^2] \tag{4}$$

$$c_3 = -(bm\dot{n}_c - m^2\dot{n}_c^3)/[b(1 - m/\dot{n}_c) + \dot{n}_c(\dot{n}_c - m)^2] \tag{5}$$

为了保证各等转速线上$(\dot{n}_c^2, \dot{n}_c^2)$点均落在该曲线的右半支，$m$ 和 s 的取值还应满足：

$$\sqrt[3]{b} \geqslant 2m/3 \tag{6}$$

对于压气机效率特性，如取 $c_4 = 0.3$，$m = 1.06$，$b = 0.36$时的压气机流量特性和效率特性曲线图与常见的特性图是很相近的，说明上述所采用的解析解有其典型性。

2.2　透平

为了简化计算，可用弗吕盖尔公式近似地表达透平的流量性能。即：

$$\frac{G_T}{G_{T0}} = \sqrt{\frac{T_{30}^*}{T_3^*}}\sqrt{1 - 0.4\frac{\Delta n}{n_0}}\sqrt{\frac{P_3^{*2} - P_4^2}{P_{30}^{*2} - P_{40}^2}} \tag{7}$$

上式中透平排气压力 $P_4 = P_{40}$，并计及转速变化对流量的影响。

上式是根据斯托陀拉（A. Stodola）在电站汽轮机实验的基础上演化得到的，它适用于亚临界流动、级数多和转速不变的透平。而燃气轮机的级数一般比较少，相当多的转速还在变化，因而用弗吕盖尔公式来表达燃气透平的流量性能是近似的。

透平变工况时，透平效率随速比 $X_a = u/C_a$ 变化的规律近似于抛物线，其典型方程为：

$$\eta_T/\eta_{Tmax} = X_a/X_{aopt}(2 - X_a/X_{aopt}) \tag{8}$$

式中：$X_a = u/C_a$

$$C_a = \sqrt{2h_{TS}} = \sqrt{2k/(k-1)RT_3^*(1 - \delta^{(k-1)/k})} \tag{9}$$

式(8)只是定性估算公式，不能满足定量分析的需要，文献[3]给出了更为合适的透平效率变工况通用模型框架。

$$\frac{\eta_T}{\eta_{Tmax}} = \frac{n}{n_0}\sqrt{\frac{h_{TSmax}}{h_{TS}}\left[a_e - (a_e - 1)\frac{n}{n_0}\sqrt{\frac{h_{TSmax}}{h_{TS}}}\right]} \tag{10}$$

$$\frac{\eta_T}{\eta_{Tmax}} = \frac{n}{n_0}\sqrt{\frac{T_{30}^*}{T_3^*}}\sqrt{\frac{1-\delta_{opt}^\gamma}{1-\delta^\gamma}}\left[a_e(a_e - 1)\frac{n}{n_0}\sqrt{\frac{T_{30}^*}{T_3^*}}\sqrt{\frac{1-\delta_{opt}^\gamma}{1-\delta^\gamma}}\right] \tag{11}$$

式中：$\gamma = (k-1)/k$

$$a_e = f_3(\mu) = f_3[(\Delta C_u/u)_0] \tag{12}$$

式(10)和式(11)是以最佳工况点为基准的，若设计工况是最高效率时，则 $\eta_{Tmax} = \eta_{T0}$，$h_{TSmax} = h_{TS0}$，$\delta_{opt} = \delta_0$；若设计工况非最佳点时，又只知最佳点一个参数时，可利用式(10)或式(11)求出另一个参数。

2.3　燃烧室

燃烧室性能指标中与变工况性能密切有关的是燃烧室效率、压力损失和熄火极限，效率和压力损失影响到系统的性能参数，而熄火极限主要影响到系统的运行范围。由于燃烧室效率和压力损失在变工况情况下的变化只能通过实验来得到，而且它们的变化范围都不大，所以在变工况计算时可以认为燃烧室效率和压力损失是不变的。

2.4　换热器

换热器的变工况计算采用了简化方法，认为各个换热器的传热系数和换热面积不变，换热温差采用对数平均温差。

间冷器

$$\Delta T_{ln} = \frac{(t_2 - t_{w4}) - (t_3 - t_{w7})}{\ln\frac{(t_2 - t_{w4})}{(t_3 - t_{w7})}} \tag{13}$$

后冷器

$$\Delta T_{ln} = \frac{(t_4 - t_{w5}) - (t_5 - t_{w3})}{\ln\frac{(t_4 - t_{w5})}{(t_5 - t_{w3})}} \tag{14}$$

回热器

$$\Delta T_{ln} = \frac{(t_{10} - t_7) - (t_{11} - t_6)}{\ln\frac{(t_{10} - t_7)}{(t_{11} - t_6)}} \tag{15}$$

热水器

$$\Delta T_{ln} = \frac{(t_{11} - t_{w8}) - (t_{12} - t_{w7})}{\ln\frac{(t_{11} - t_{w8})}{(t_{12} - t_{w7})}} \tag{16}$$

2.5　湿化器

湿化器中换热量 $Q = AU \cdot \Delta T_{ln}$，对数平均温差

$$\Delta T_{ln} = \frac{(t_{w6} - t_6) - (t_{w7} - t_5)}{\ln\frac{(t_{w6} - t_6)}{(t_{w7} - t_5)}} \tag{17}$$

$$AU = AU^d \cdot \left(\frac{G_a}{G_a^d}\right)^{1.03}\left(\frac{L_w}{L_w^d}\right)^{0.3} \tag{18}$$

2.6　其它部件

在 HAT 循环中，还有其它的一些部件和管道，它们对循环变工况性能的影响都反映在压力损失

上。在进行变工况计算时，这些压力损失系数同燃烧室压力损失系数一样可以视为不变[4]。

本文在计算时采用单轴系方案，系统转速不变，通过迭代求解，即可得到系统的变工况性能。

3　环境温度对简单间冷循环性能的影响

简单间冷循环流程图如图 2 所示，间冷器中用水冷却空气，水温不变时从间冷器出口的空气温度基本不变，即与进口空气温度和流量的变化基本无关。当水温变化时，间冷器出口空气温度则随水温而变，且两者的变化量基本相同，进行简单间冷循环变工况计算时，假定间冷器出口空气温度与冷却水温度之差保持 10 ℃不变。压气机、燃烧室和透平的变工况计算采用第二部分的部件模型。

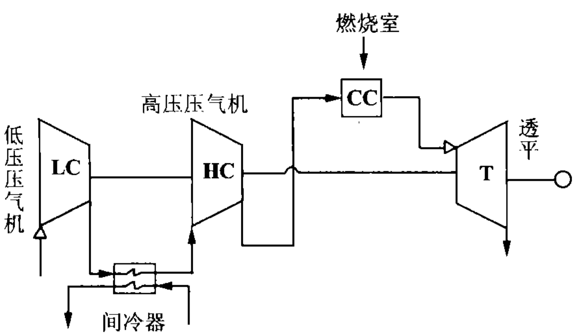

图 2　简单间冷循环流程图

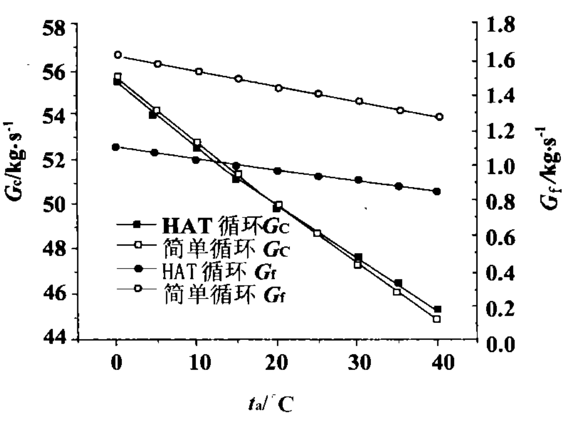

图 3　环境温度对空气和燃料流量的影响

计算结果如图 3 和图 4 所示。图 3 为空气流量和燃料流量随环境温度的变化，环境温度升高时，空气密度下降，导致压气机吸入的空气流量减少。由于透平前温保持不变，环境温度升高，空气流量的减少直接导致了燃料流量的减少。

图4 为循环效率和循环功率随环境温度的变化，环境温度变化则循环温比发生变化，对循环效率有较大的影响。环境温度升高时，温比下降，则循环效率随之迅速下降，当环境温度从 0 ℃升高到 40 ℃时，循环效率下降了 10.67%（相对值），约降低了 4 个百分点。由于环境温度升高时，空气流量和燃料流量都减少，则透平流量减少，导致了循环功率的下降，当环境温度从 0 ℃升高到 40 ℃时，循环功率下降了 29.8%（相对值）。

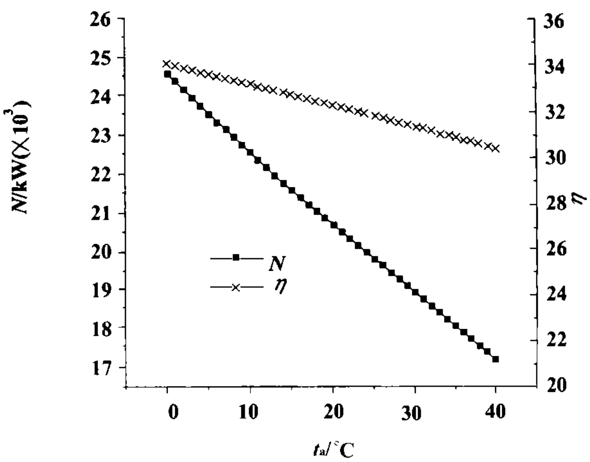

图 4　环境温度对功率和效率的影响

4　环境温度变化对 HAT 循环性能的影响

在各个部件的变工况模型的基础上，对 HAT 循环的变工况性能进行了计算和分析。表 1 给出了设计点参数。

表 1　HAT 循环设计点参数

	$P\times10^{-5}$ / Pa	t/ ℃	G/ kg·s^{-1}
1	1.013 25	20.0	49.93
2	3.361 4	155.6	49.93
3	3.294 17	80.0	49.93
4	8.910 8	210.5	49.93
5	8.732 58	80.5	49.93
6	8.645 26	119.0	55.11
7	8.472 35	739.1	55.11
9	8.218 18	1 300	56.07
10	1.005 03	763.9	56.07
11	1.033 93	158.8	56.07
12	1.013 25	75.5	56.07
w_1	29.119 25	20.0	5.174
w_2	29.119 25	20.0	5.174
w_3	29.119 25	46.3	12.277
w_4	29.119 25	172.9	12.277
w_5	29.119 25	138.6	12.372
w_6	29.119 25	153.1	39.191
w_7	29.119 25	65.5	34.017
w_8	29.119 25	148.9	14.542

HAT 循环空气流量随环境温度的变化情况同简单间冷循环相似，如图 3 所示。

图 3 还给出环境温度对 HAT 循环燃料流量的

影响，随着环境温度的升高，燃料流量降低。透平前温一定，影响燃料流量的主要因素是空气流量、空气含湿量及空气温度。随着环境温度的升高，空气流量降低而温度升高，空气含湿量增加，而空气含湿量的影响较小。因此，随着环境温度的升高，燃料流量减少。

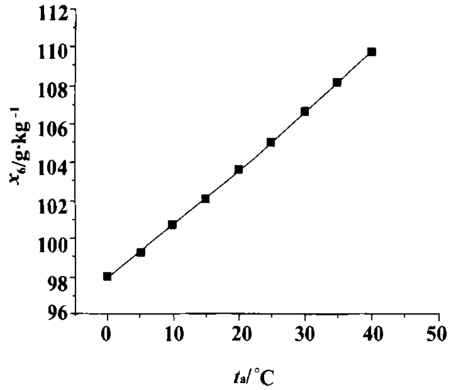

图 5　环境温度对含湿量的影响

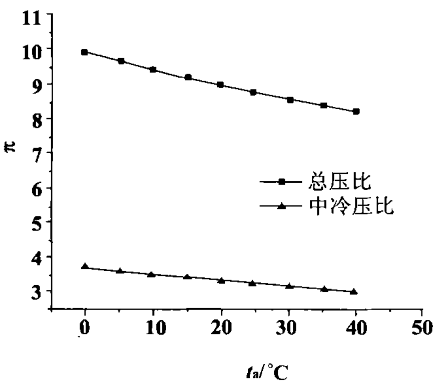

图 6　环境温度对循环压比的影响

环境温度对空气含湿量的影响如图 5 所示。随着环境温度的升高，含湿量迅速增加。

随着环境温度的升高，循环的总压比降低，循环间冷压比也随之降低，如图 6 所示。

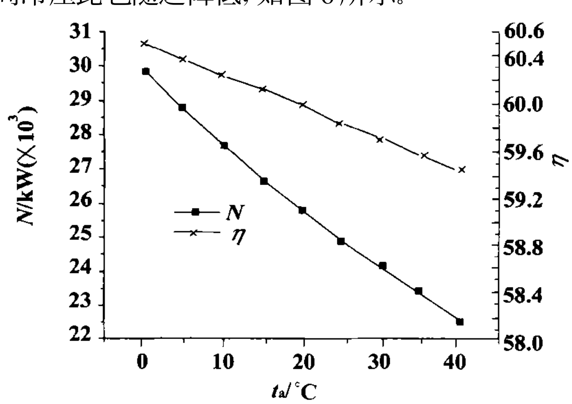

图 7　环境温度对功率和效率的影响

环境温度变化时温比随之改变，所以对循环效率有比较大的影响。随着环境温度的升高，温比下降，循环效率降低，但由于空气含湿量随着环境温度的升高而增加，一定程度上减缓了功的下降趋势，从而也减缓了循环效率的下降趋势。当环境温度从 0 ℃升高到 40 ℃时，循环效率下降了 1.74%（相对值），约降低了 1 个百分点，如图 7 所示。

环境温度对循环功率的影响如图 7 所示。由于环境温度升高时，空气流量和燃料流量都减少，则透平流量减少，导致了循环功率的下降；然而由于湿化器出口空气含湿量随着环境温度的升高而增加。减缓了功率的下降趋势。当环境温度从 0 ℃升高到 40 ℃时，循环功率下降了 24.3%（相对值）。

HAT 循环的变工况性能同简单间冷循环相比具有一定的稳定性，随着环境温度的升高，两种循环的空气流量、循环总压比和燃料流量都迅速减少，而效率和功率的变化趋势则有所不同。环境温度变化相同时，HAT 循环效率仅仅变化 1 个百分点，而简单间冷循环变化 4 个百分点左右，HAT 循环功率变化 24.3%（相对值），简单间冷循环变化 29.3%（相对值）。

5　结论

在部件变工况特性模型的基础上，研究了 HAT 循环变工况特性并与简单间冷循环的变工况性能进行了比较，结果表明 HAT 循环对于环境温度的变化没有简单间冷循环敏感，环境温度变化相同的范围，HAT 循环效率下降了 1.74%（相对值），约降低了 1 个百分点，而简单间冷循环效率下降了 10.67%，变化 4 个百分点左右，HAT 循环功率变化 24.3%，简单间冷循环变化 29.3%。之所以有这样大的差别主要是由于 HAT 循环中关键部件—湿化器的存在。当环境温度升高时，低压压气机流量减少、排气温度升高，则间冷器和后冷器间冷却水的排水温度和流量都随之变化，引起湿化器出口空气含湿量随着环境温度升高而增加，一定程度上减缓了功率的减小趋势，也减缓了循环效率的减小趋势，因此 HAT 循环具有较好的变工况性能。

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（辉　编辑）

热经济学研究的使命与任务＝**Mission and Assignments of Thermoeconomics Research** [刊, 汉] / WANG Jia-xu-an, WANG Qing-zhao, SONG Nai-hui (Power Engineering Department, North China Electric Power University, Beijing, China, Post Code: 102206)// Journal of Engineering for Thermal Energy &Power. — 2002, 17(2). —111～114
Two basic methods of thermodynamics analysis and its development are expounded along with a description of the fundamental character of exergy, explaining why the latter serves as the parameters of potential. The thermoeconomics-related thermodynamics basic research issues are explored, enunciating the influence of exergy law on thermoeconomics. The value-setting law of the thermoeconomics is described and some observations on its unified-direction development problems are presented. In conclusion, a brief account is given of some advances in the model building of ecological system network thermodynamics in connection with the ecology-balanced thermoeconomics. **Key words**: thermodynamics analysis, thermoeconomics, ecology system, model building

WNS 型燃油、燃气锅炉技术现状与发展方向＝**Present Situation and Direction of Development of Model WNS Oil/Gas-fired Boiler Technology** [刊, 汉] / WANG Huai-bin, MENG Li-li (Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy &Power. — 2002, 17(2). —115～117
An analysis and comparison is conducted of the construction of existing model WNS oil-fired and gas-fired boiler proper. On this basis the authors point out that the elimination of its back-burning furnace represents an improvement in the right direction for three-pass wetback boilers. On the other hand, central return-burning type of oil and gas-fired boilers pertain to a type of small and medium-sized oil and gas boilers worthy of popularization in the process of their development. Also discussed is the control system of the model WNS oil and gas-fired boilers. In the light of their specific features it is noted that a fully intellectualized control and remote-operated technical service system is their trend of future development. **Key words**: oil-fired boiler, gas-fired boiler, central return burning, direction of development

高温燃料电池一燃气轮机混合发电系统性能分析＝**Performance Analysis of a High-temperature Fuel Cell and Gas Turbine Hybrid Power Generation System** [刊, 汉] / ZHANG Hui-sheng, LIU Yong-wen, SU Ming, WENG Shi-lie (Power and Energy Source Engineering Institute under the Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy &Power. —2002, 17(2). —118～121
High-temperature fuel cell system features high-efficiency, environmental friendliness and enormous potential of exhaust gas waste-heat utilization. The combination of this system with a gas turbine to form a hybrid power plant can well be regarded as a very promising scheme of future distributed power generation. A brief description is given of the high-temperature fuel cell and the hybrid cycle system consisting of the fuel cell and a gas turbine. This is followed by a performance analysis of two typical hybrid systems (topping cycle and bottoming one). The above work can provide some informative materials and data for the development of the high-temperature fuel cell and gas turbine hybrid cycle system in China. **Key words**: molten carbonate fuel cell, solid oxide fuel cell, gas turbine, hybrid plant, distributed power generation

环境温度对湿空气透平(HAT)循环性能的影响＝**The Effect of Ambient Temperature on the Performance of a Humid Air Turbine (HAT) Cycle Performance** [刊, 汉] / ZHAO Li-feng, XIAO Yun-han, ZHANG Shi-zheng (Institute of Engineering Thermophysics under the Chinese Academy of Sciences, Beijing, China, Post Code: 100080) // Journal of Engineering for Thermal Energy &Power. —2002, 17(2). —122～125
Based on the building of an off-design performance model for the various components in a humid air turbine (HAT) cycle the authors have analyzed the off-design performance of a HAT cycle, which was compared with that of a simple intercooling cycle. The results of the comparison show that the HAT cycle enjoys a good off-design performance. **Key words**: hu-

mid air turbine cycle, off-design operation, performance analysis

船用汽轮机带冠叶片动力特性研究＝**A Study of the Dynamic Characteristics of Marine Steam Turbine Shrouded Blades** [刊, 汉] / LI Jian-zhao, WEN Xue-you, LIN Zhi-hong (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036), YU Zeng-bo (Harbin Steam Turbine Co. Ltd., Harbin, China, Post Code: 150046) // Journal of Engineering for Thermal Energy & Power. —2002, 17(2). —126～128

With the help of a large-sized finite-element general program MSC/NASTRAN the dynamic characteristics of the shrouded blades of a steam turbine are studied and the treatment of boundary conditions, the "tenseness" between shrouds as well as the load-bearing conditions of the blades discussed. In addition, the analysis of a specific example is conducted to expound the above-cited points. **Key words**: steam turbine, shrouded blade, vibration, finite element

叉排圆柱阵列自由段及顶端对流传热研究＝**Research on the Convection Heat Transfer of the Free Section and Top of a Staggered Cylindrical Array** [刊, 汉] / DONG Hua (Environmental Engineering Department, Qingdao Institute of Architectural Engineering, Qingdao, China, Post Code: 266033), KARNI J (Department of Environmental Science &Energy Research, Weizmann Institute of Science, Rehovot, Israel, Post Code: 76100) // Journal of Engineering for Thermal Energy & Power. —2002, 17(2). —129～131

A staggered cylindrical array represents a major structural form of heat exchangers for a solar energy-based thermal power station. Various zones inside a heat exchanger have different heat-exchange features. The authors have studied the free end flow and heat exchange characteristics of the staggered cylindrical array and derived the fitting formula of non-dimensional heat-exchange thermal parameters of the free section and top end. The results of simulation through the use of a multi-zone and continuous model are in good agreement with test data. **Key words**: free section, top end, staggered cylindrical array, convection heat exchange

固体废弃物热解半焦特性的研究＝**A Study of the Pyrolytic Semicoke Characteristics of Solid Waste** [刊, 汉] / LI Ai-min, WANG Zhi (Shenyang Aeronautical Industrial Institute), LI Shui-qing, YAN Jian-hua, CEN Ke-fa (Zhejiang University, Hangzhou, China, Post Code: 310027)// Journal of Engineering for Thermal Energy & Power. —2002, 17(2). —132～138

Studied is the chemical composition and reaction activity of pyrolytic semicoke of solid waste. The property of the material itself and the final temperature of the pyrolysis will have a direct influence on the productivity of semicoke, the residual quantity of such elements as C, H, N and S in the semicoke as well as the reaction activity of CO_2. of the semicoke. Moreover, under identical conditions and on the basis of component ratio the algebraic sum of mixed material and that of single material are approximately equal. **Key words**: solid waste, pyrolysis. semicoke, rotating kiln, reaction activity

H_2O-O_2 自由基簇射结合化学吸收脱除烟气中的 NO_x＝**Removal of NO_x from Flue Gases by DC Corona H_2O-O_2 Radical Shower in Conjunction with Chemical Absorption** [刊, 汉] / LIN He, GAO Xiang, LUO Zhong-yang, CEN Ke-fa (Thermal Energy Engineering Institute under the Zhejiang University, Hangzhou, China, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(2). —139～142

A study is performed of the removal of NO_x from flue gases by DC corona H_2O-O_2 radical shower in conjunction with alkali solution (26% by weight of NaOH in water) scrubbing. The results of the study show that a steady streamer corona can be obtained by adjusting the flow rate of oxygen fed into nozzle electrodes. The vapor in the oxygen exercises an influence on the V-I characteristics of the corona discharge. Both HNO_2 and HNO_3 are simultaneously generated in a reactor