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压水堆核电机组二回路热力系统计算的研究

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摘 要：根据压水堆二回路机组的特点，给出了最简化压水堆二回路热力系统的概念，并通过待定蒸汽份额，编程循环迭代的方法完成了最简化系统的各级抽汽份额计算和正反热平衡计算，在此基础上，通过对核电系统附加项的详细分析，得出了在最简化系统上逐项添加附加项的精确快捷的核电机组原则性热力计算的方法。

关 键 词：压水堆；二回路；正反平衡；附加项
中图分类号：TK212　　文献标识码：A

1 前 言

压水堆二回路核电机组与常规的火电机组的热力系统有着明显的不同，使得常规火电机组的热力系统计算方法在这种机组的应用中存在着诸多困难。难点主要在两个方面：(1)系统中包含汽水分离器和采用新蒸汽和高压抽汽来加热的再热器，其疏水引入回热加热器，使得无法直接套用现行的各种原则性热力计算方法；(2)系统中包括排污扩容、管道渗漏工质、管道散热、门杆漏汽、轴封漏汽和小汽轮机等附加项，增加了热力计算的复杂性，正反平衡计算极易出错，且不容易查出错误。目前，比较成熟的常规火电机组热力系统分析计算方法有文献[1]的简捷法、文献[2]的矩阵法、文献[1]的等效热降法和文献[3]的循环函数法。基于这4种方法，文献[6～7]针对压水堆二回路热力系统进行了详细的经济性定量分析，而文献[4～5]分别应用矩阵分析法、线性单元分析法对压水堆二回路核电机组进行了整体分析计算，但矩阵分析法和线性单元分析法概念、方程较为抽象，与常规的原则性热力系统计算差别较大。因此，本文便从常规的原则性热力系统计算方法出发，针对压水堆二回路核电机组的特点，对核电机组热力计算的第一个难点通过待定再热器出口蒸汽份额 α_{rh} 的方法解决，而第二个难点，通过引入最简化系统的方法来处理。图1为一压水堆二回路核电机组的原则性热力系统简图，其中虚线部分为排污扩容和管道渗漏等附加项，去掉虚线部分，得到的即为最简化系统。

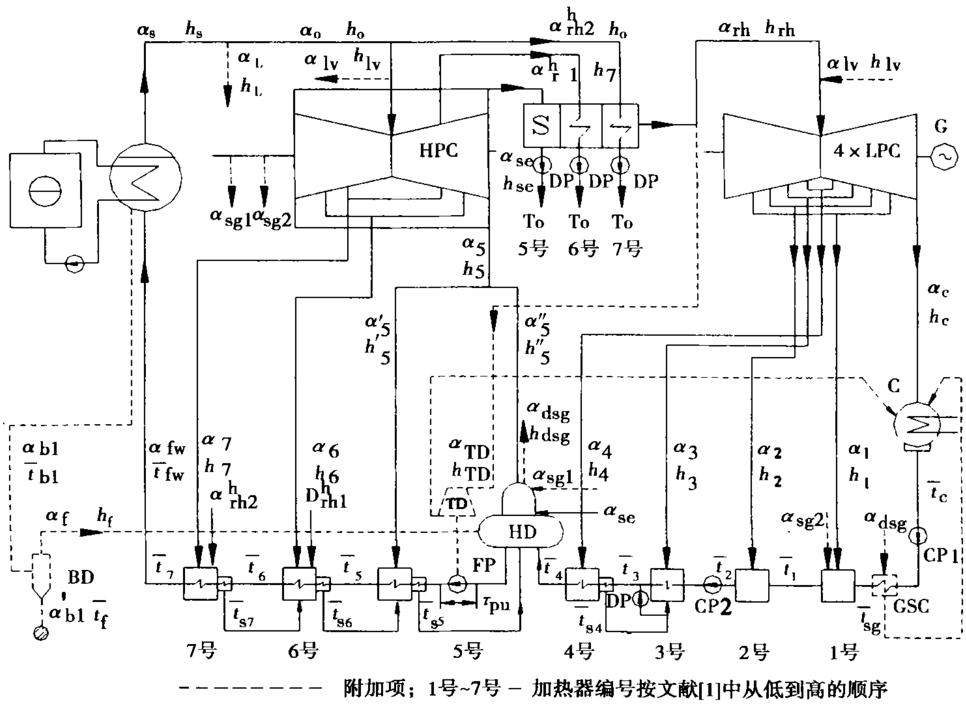

图1 压水堆二回路原则性热力系统图

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2　最简化核电热力系统计算

2.1　各级抽汽份额的计算

首先取再热器的出口份额 α_{rh} 作为参变量(取汽轮机装置总的进汽量为 1 即 $\alpha_0=1$)。先从汽水分离器和再热器的计算开始(见图 2),求得分离器疏水份额、再热器所用蒸汽份额与 α_{rh} 的关系。

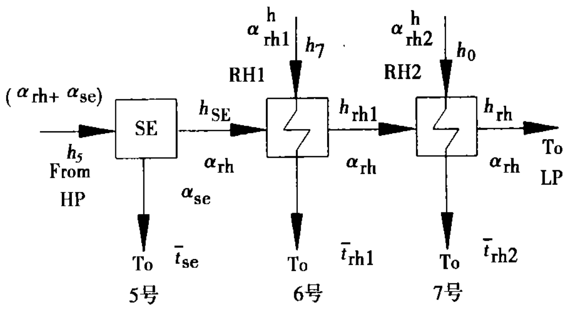

图 2　汽水分离器再热器系统图

由分离器、再热器的热平衡方程式可得:

$$\alpha_{se}=\frac{(h_{se}-h_5)}{h_5-\bar{t}_{se}}\alpha_{rh} \quad (1)$$

$$\alpha^h_{rh1}=\frac{h_{rh1}-h_{se}}{h_7-\bar{t}_{rh1}}\alpha_{rh} \quad (2)$$

$$\alpha^h_{rh2}=\frac{h_{rh}-h_{rh1}}{h_0-\bar{t}_{rh2}}\alpha_{rh} \quad (3)$$

式中:h_{se}— 已知的汽水分离器出口蒸汽焓值,kJ/kg;

h_5— 已知的汽水分离器入口蒸汽焓值,kJ/kg;

$\bar{t}_{se}$— 已知的汽水分离器分离疏水焓值,kJ/kg;

h_{rh1}— 已知的一级再热 RH1 出口蒸汽焓值,kJ/kg;

h_7— 已知的一级再热 RH1 加热汽源蒸汽焓值,kJ/kg;

$\bar{t}_{rh1}$— 已知的一级再热 RH1 疏水焓值,kJ/kg;

h_{rh}— 已知的二级再热 RH2 出口蒸汽焓,kJ/kg;

h_0— 已知的二级再热 RH2 加热汽源蒸汽焓,kJ/kg;

$\bar{t}_{rh2}$— 已知的二级再热 RH2 疏水焓,kJ/kg。

然后按照文献[1] 中介绍的简捷算法,确定各级抽汽的 τ_i、q_i 和 γ_i,并进行高压缸回热系统计算,求得用 α_{rh} 表示的高压缸各抽汽份额 α_i 的表达式。接着根据质量平衡方程,在再热器出口得到一个关于 α_{rh} 的方程,α_{rh} 的值可通过解此方程得出。但在编程计算时,解此方程应采用设迭代初值,通过循环迭代的方法解出 α_{rh} 的值。求出 α_{rh} 的值后,将 α_{rh} 的值代入式(1)~式(3),即可求出 α_{se}、α^h_{rh1}、α^h_{rh2}、α_i 的值。再进行余下的低压缸的回热系统计算,确定各级抽汽份额,然后类似于常规火电机组的原则性计算,对排汽份额进行正反平衡计算,以保证汽轮机的物质平衡。

2.2　正反平衡计算

求出循环内功 n_i、循环吸热量 q 和广义冷源损失量 q_n,继而求出正反平衡的实际循环效率。要保证正反平衡效率基本一致,关键是保证以上 3 个量计算公式的正确性,最简化系统的循环内功 n_i、循环吸热量 q、广义冷源损失量 q_n 的计算式分别为:

(1) 循环内功 n_i:

$$n_i=h_0+q_{rh}-h_c-\sum_{j=1}^{l}\alpha_j(h_j-h_c)-\sum_{j=l+1}^{m}\alpha_j(h_j+q_{rh}-h_c)-\alpha_{se}(h_{rh}-h_c)-\alpha^h_{rh1}(h_7+q_{rh}-h_c)-\alpha^h_{rh2}(h_0+q_{rh}-h_c)-\alpha_{fw}\cdot\tau_{pu} \quad (4)$$

式中:q_{rh}— 再热吸热量,kJ/kg;

h_0— 新蒸汽焓,kJ/kg;

h_c— 主汽机排汽焓,kJ/kg;

h_j— 各级抽汽焓,kJ/kg;

α_j— 各级抽汽份额;

α_c— 主汽机排汽份额;

α_{fw}— 主给水份额;

τ_{pu}— 给水泵焓升,kJ/kg。

需要说明的是,τ_{pu} 是 $\alpha_{fw}=1$ 时的给水泵焓升,若 $\alpha_{fw}>1$,则给水泵焓升为 $\alpha_{fw}\cdot\tau_{pu}$。

(2) 循环吸热量 q:

$$q=h_0-\bar{t}_{fw} \quad (5)$$

式中:$\bar{t}_{fw}$— 给水焓,kJ/kg

由于核电机组的再热热源来自于循环内的蒸汽,并没有吸收外部热量,因此循环吸热量中不含 q_{rh} 项。

(3) 广义冷源损失 q_n:

$$q_n=\alpha_c(h_c-\bar{t}_c) \quad (6)$$

式中:$\bar{t}_c$— 热井水焓,kJ/kg

以上 3 个量的计算式为最简化核电热力系统的计算式,若要考虑各种附加项,则仅需在程序中修改各抽汽份额和这 3 个量的计算式即可,因文章篇幅所限,下面主要说明一下附加项的引入对 n_i、q 和 q_n 3 个计算式的影响。

表 1　附加项的影响分析

	相关参数	流动状况	对 n_i、q 和 q_n 的影响量
排污扩容项	蒸发器排污份额 α_{bl}	进入排污水扩容器	使吸热量 q 的增加量为 $\alpha_{bl}(\bar{t}_{bl}-\bar{t}_{fw})$
	蒸发器排污水焓 $\bar{t}_{bl}$/kJ·kg^{-1}		
	扩容蒸汽份额 α_f	进入除氧器	
	扩容蒸汽焓 h_f/kJ·kg^{-1}		
	未扩容排污水份额 α'_{bl}	排放到地沟	使损失 q_n 的增加量为 $\alpha'_{bl}(\bar{t}_f-\bar{t}_c)$
	未扩容排污水焓 $\bar{t}_f$/kJ·kg^{-1}		
管道渗漏工质项	管道渗漏工质份额 α_1	渗漏出系统	使损失 q_n 的增加量为 $\alpha_1(h_s-\bar{t}_c)$
	管道渗漏工质焓 h_s/kJ·kg^{-1}		
管道散热项	散热前蒸汽焓值 h_s/kJ·kg^{-1}		使损失 q_n 的增加量为 $\alpha_0(h_s-h_o)$
	散热后蒸汽焓值 h_0/kJ·kg^{-1}		
门杆漏汽项	门杆漏汽份额 α_{lv}	由主汽阀、调节汽阀漏入低压缸前的再热蒸汽管内	使作功 n_i 的减少量为 $\alpha_{lv}q_{rh}$
轴封漏汽项	第一级轴封漏汽份额 α_{sg1}	引入除氧器	使作功 n_i 的减少量为 $\alpha_{sg1}(h_{sg1}+q_{rh}-h_c)$
	第一级轴封漏汽焓 h_{sg1}/kJ·kg^{-1}		
	第二级轴封漏汽份额 α_{sg2}	引入 1 号低压加热器	使作功 n_i 的减少量为 $\alpha_{sg2}(h_{sg2}+q_{rh}-h_c)$
	第二级轴封漏汽焓 h_{sg2}/kJ·kg^{-1}		
	除氧器供轴封用汽份额 α_{dsg}	进入轴封系统后，最终排入轴封冷却器	使损失 q_n 的增加量为 $\alpha_{dsg}(\bar{t}_{sg}-\bar{t}_c)$
	除氧器供轴封用汽焓 h_{dsg}/kJ·kg^{-1}		
小汽轮机项	小汽机耗汽份额 α_{ST}	由再热器出口引出，小汽机排汽进入凝汽器	使作功 n_i 的减少量为 $\alpha_{ST}(h_c^{ST}-h_c)$
	小汽机进汽焓 h_{rh}/kJ·kg^{-1}		
	小汽机排汽焓 h_c^{ST}/kJ·kg^{-1}		使损失 q_n 的增加量为 $\alpha_{ST}(h_c^{ST}-\bar{t}_c)$
	给水泵焓升 τ_{pu}/kJ·kg^{-1}		

表 2　额定工况基本参数表

已知	数量	已知	数量
汽机装置进汽份额 α_0	1.000000	新蒸汽焓 h_0/kJ·kg^{-1}	2776
给水份额 α_{fw}	1.020408	给水焓 $\bar{t}_{fw}$/kJ·kg^{-1}	964
蒸发器产汽份额 α_s	1.010204	蒸发器出口焓 h_s/kJ·kg^{-1}	2780.565
小汽机耗汽份额 α_{ST}	0.018760	小汽机入口焓 h_{rh}/kJ·kg^{-1}	2972
全厂汽水损失份额 α_1	0.010204	小汽机出口焓 h_c^{ST}/kJ·kg^{-1}	2327
门杆漏汽份额 α_{lv}	0.001000	给水泵焓升 τ_{pu}/kJ·kg^{-1}	11.8582
排污份额 α_{bl}	0.010204	蒸发器排污水焓 $\bar{t}_{bl}$/kJ·kg^{-1}	1235.749
除氧器供轴封用汽份额 α_{dsg}	0.001400	轴加入口蒸汽焓 h_{dsg}/kJ·kg^{-1}	2760
第一级轴封漏汽份额 α_{sg1}	0.002500	第一级轴封漏汽焓 h_{sg1}/kJ·kg^{-1}	2495
第二级轴封漏汽份额 α_{sg2}	0.000700	第二级轴封漏汽焓 h_{sg2}/kJ·kg^{-1}	2250
主汽机机械效率 η_m	0.992	反应堆效率 η_{nr}	0.99
发电机效率 η_g	0.989	蒸汽发生器效率 η_s	0.985

表 3　各加热器进出口焓及 τ_i、q_i 和 γ_i

加热器名称	抽汽压力	抽汽焓	进口疏水焓	出口疏水焓	出口水/汽焓	进口水/汽焓	τ_i	q_i	γ_i
1	0.0173	2428	—	—	234.5	121.4	113.1	2306.6	—
2	0.0576	2568	—	—	349.9	234.5	115.4	2333.5	—
3	0.19	2730	606.3	—	467.5	349.9	117.6	2380.1	256.4
4	0.43	2852	—	606.3	586.6	467.5	119.1	2245.7	—
5	1	2531	757	—	737	586.6	150.4	1944.4	170.4
6	1.76	2608	871	757	851	737	114	1851	114
7	2.84	2676	—	871	964	851	113	1805	—
SE	1	2531	—	758.7	2756	2531	225	1772.3	—
RH1	2.84	2676	—	984	2856	2756	100	1692	—
RH2	5.82	2776	—	1207	2972	2856	116	1569	—

3 附加项的影响分析

对于具体情况不同现场的各种压水堆二回路核电机组，一般来说其最简化系统是一样的，均可采用上述最简化系统的计算方法，不同的二回路机组主要区别在各种附加项上，在保证编程计算的最简化系统正反平衡相等的基础上，仅需考虑各附加项对各级抽汽份额、循环内功、循环吸热量和广义冷源损失各量的影响即可，在加入附加项的影响时，编程计算的修改是十分方便的。在编程计算时，各种附加项总体归纳起来主要包括连续排污项、管道渗漏工质项、管道散热项、门杆漏汽项、轴封漏汽项和小汽轮机项等。附加项的引入应逐一进行，并仔细检查 α_i、n_i、q 和 q_n 这几个公式。要保证正反平衡效率一致，关键是保证 α_i、n_i、q 和 q_n 各量的计算公式的正确性。附加项对 α_i 的影响，可在程序中相应的 α_i 计算式中修改，而表 1 汇总了各附加项对 n_i、q 和 q_n 3 个量的计算式的影响分析。

通过表 1 的分析，最终可得到引入上述各种附加项后，n_i、q 和 q_n 3 个量的计算式变成下列形式：

(1) 循环内功：

$$n_i = n_{i(4)} - \alpha_{lv} q_{rh} - \alpha_{sg1}(h_{sg1} + q_{rh} - h_c) - \alpha_{sg2}(h_{sg2} + q_{rh} - h_c) - \alpha_{ST}(h_c^{ST} - h_c) \quad (7)$$

式中：$n_{i(4)}$ 为式(4) 计算出的循环内功，kJ/kg

(2) 循环吸热量：

$$q = q_{(5)} + \alpha_{bl}(\bar{t}_{bl} - \bar{t}_{fw}) \quad (8)$$

式中：$q_{(5)}$ 为式(5) 计算出的循环吸热量，kJ/kg

(3) 广义冷源损失：

$$q_n = q_{n(6)} + \alpha'_{bl}(\bar{t}_f - \bar{t}_c) + \alpha_l(h_s - \bar{t}_c) + \alpha_0(h_s - h_o) + \alpha_{dsg}(\bar{t}_{sg} - \bar{t}_c) + \alpha_{TD}(h_c^{TD} - \bar{t}_c) \quad (9)$$

式中：$q_{n(6)}$ 为式(6) 计算出的广义冷源损失，kJ/kg

应用式 7 ~ 式 9 就可确定引入各附加项的全系统的 n_i、q 和 q_n，从而可得出正反平衡的循环效率，以及其它经济性指标。

4 算例分析

俄罗斯 1 000 MW 带 K－1000－60/1500 型汽轮机装置的核电机组的已知额定工况参数如表 2。

根据表 2 和表 3 的已知参数，可按式 4 ~ 式 6 求得最简化系统的 n_i、q、q_n、正平衡循环效率 η_{ip} 和反平衡循环效率 η_{ic}，根据表 1 的附加项分析，按式 7 ~ 式 9 可求得带附加项的全系统的 n_i、q、q_n、正平衡循环效率 η_{ip} 和反平衡循环效率 η_{ic}，其结果见表 4。

表 4 计算结果

最简化系统计算结果		带附加项的全系统计算结果	
指标	结果	指标	结果
n_i/kJ·kg^{-1}	617.657	n_i/kJ·kg^{-1}	605.324 9
q/kJ·kg^{-1}	1 816.565	q/kJ·kg^{-1}	1 837.874
q_n/kJ·kg^{-1}	1 812	q_n/kJ·kg^{-1}	1 232.549 46
η_{ip}	0.340 87	η_{ip}	0.329 36
η_{ic}	0.340 87	η_{ic}	0.329 36

5 结 论

从以上的计算可发现，核电机组原则性热力系统计算与常规火电机组的计算仅在汽水分离器和再热器处有所差别，而使用这种逐渐增加复杂性的计算机编程的计算方法，不但计算精度高，即正反平衡的循环效率误差可保持小数点后十位以上，而且容易找出计算中的错误，节省计算时间。同时，各附加项的引入既可单独进行，也可通过比较引入某项附加项的前后，循环效率和其它热经济性指标的变化来进行热经济性的定量分析。另一方面，这种附加项添加法也可应用在常规火电机组的热力计算中，因此，相信这一方法会成为电力行业机组热力计算的一种有效的新方法。

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The vortex shedding condition of three rows of staggered circular cylinder with a same diameter was experimentally investigated. The cylinders being tested were made of acrylic glass cylinders with a diameter of 30mm. During the tests the two-phase gap-flow Reynolds number ranges from $2.0\times10^4\sim6.0\times10^4$ and the range of void fraction, from 0 - 0.3. By way of experimental analyses the Strouhal number of two-phase flows was determined in staggered tube bundles with different layout modes. The test results indicate that the Strouhal number of the two-phase flows decreases with an increase in the void fraction. The characteristic curves of Strouhal numbers are presented for the staggered tube bundles with a rotating regular-triangle layout. It is noted that Weaver curves of single-phase flows can be approximately used as discrimination criteria for the tube bundle vibrations induced by the vortex shedding in rotating-square arranged and regular-triangle arranged tube bundles in two-phase flows. **Key words**: gas-liquid two-phase flow, Strouhal number, staggered cylinder

汽—液相变过程的热力学分析＝**Thermodynamic Analysis of a Vapor-liquid Phase Transition Process** [刊, 汉] / ZENG Dan-ling, HUANG Shuang, WANG De-ming, et al (Power Engineering Institute under the Chongqing University, Chongqing, China, Post Code: 400044) // Journal of Engineering for Thermal Energy & Power. — 2004, 19 (1). —17～19

By applying a thermodynamic theory a thermodynamic analysis was conducted of the actual vapor-liquid phase transition process commonly encountered in engineering practice. The necessary thermodynamic conditions for realizing the above-mentioned process are discussed along with the laws governing the progress of the process and relevant influencing factors. The authors have focused on the study of boiling phase-transition process, and especially analyzed from a thermodynamic perspective the enhancement of convection heat-transfer factor due to the phase transition and also the related influencing factors. It is stressed that in a phase-transition process the chemical potential difference $\Delta\mu$ between the two coexisting phases serves as a major generalized thermodynamic driving force of the process. The heat exchange process has been realized under the joint action of $\Delta\mu$ and ΔT and in tandem with the convection movement of fluids. The introduction of the driving force $\Delta\mu$ makes the above process different from a single-phase convection heat exchange and this also constitutes a main cause leading to an intensification of the phase-transition heat exchange process. **Key words**: phase transition, superheated liquid, subcooled vapor, metastable state, chemical potential

冷却水流程数对凝汽器热力性能的影响＝**The Impact of the Number of Cooling-water Passes on the Thermodynamic Performance of a Steam Condenser** [刊, 汉] / WANG Guo-shan (Institute of Power & Mechanical Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030), JIN Chun-nan, CHEN Yu-xiang (No.703 Research Institute, Harbin, China Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —20～24

Power plant steam condensers can be designed as single-pass or two-pass ones. By using a self-developed computer program PPOC3.0, a software for the numerical simulation of condenser operation characteristics, the authors have simulated and analyzed the impact of the number of cooling water passes on the thermodynamic performance of power-plant steam condensers. The results of simulation and analysis indicate that a single-pass condenser offers a higher thermal load and smaller steam-side resistance. **Key words**: steam condenser, thermodynamic performance, flow pass, steam resistance, degree of subcooling

压水堆核电机组二回路热力系统计算的研究＝**A Study of the Thermodynamic System Calculations for the Secondary Circuit of a Pressurized Water Reactor** [刊, 汉] / YANG Yu-sen, YAN Jun-jie, LIU Li-cheng (National Key Lab of Power Engineering Multi-phase Flows under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049), SHEN Gou-sheng (Shenzhen Daya Bay Nuclear Power Station, Shenzhen, China, Post Code: 518124) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —25～28

In the light of the specific features of the secondary circuit of a PWR (pressurized water reactor) nuclear power plant a conception is proposed of the most simplified thermodynamic system of a PWR secondary circuit. Through a method based

on the steam share to be determined and the iteration of programming cycles, calculations were performed of the shares of steam extracted at the various stages of the above system and of the positive and negative thermal balance. On this basis and after a detailed analysis of the supplementary items of the nuclear power system a basic thermodynamic-calculation method both straightforward and precise was developed for the nuclear power plant by way of adding consecutively each supplementary item to the most simplified nuclear power system. **Key words**: pressurized water reactor, secondary circuit, positive and negative balance, supplementary item

电厂热力系统能效分布矩阵方程式及其应用＝**Energy-efficiency Distribution Matrix Equation for a Power-plant Thermodynamic System and Its Applications** [刊,汉] / GUO Jiang-long, ZHANG Shu-fang, CHEN Hai-ping (Power Engineering Department, North China Electric Power University, Baoding, Heibei Province, China, Post Code: 071003), SONG Zhi-ping (Power Engineering Department, North China Electric Power University, Beijing, China, Post Code, 102206) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —29～32

The conception of a virtual thermodynamic system is proposed, which makes it possible to replace the actual complicated thermodynamic system by a virtual one through the use of a single main system featuring an invariant system configuration and thermo-economic indexes but changing parameters. On this basis an energy-efficiency distribution matrix equation was derived, which can be directly correlated with the thermodynamic system configuration. Moreover, the matrix elements, which characterize power plant thermo-economic indexes, can effectively overcome the defect of other currently popular thermo-economic matrix analysis method. The latter requires other simultaneous equations for solving the final thermo-economic indexes of the system. The matrix equation under discussion has the merits of versatility, high precision and ease of undergoing programming treatment. Exemplary calculations have attested to the effectiveness of the proposed method. **Key words**: thermo-economics, virtual thermodynamic system, energy-efficiency distribution matrix equation, thermodynamic system

重力对微槽平板热管传热性能的影响＝**The Influence of Gravitation on the Heat Transfer Performance of Micro-grooved Flat-plate Heat Pipes** [刊,汉] / FAN Chun-li, SUN Feng-rui (Institute of Marine & Power Engineering under the University of Naval Engineering, Wuhan, China, Post Code: 430033). QU Wei, MA Tong-ze (Institute of Engineering Thermophysics under the Chinese Academy of Sciences, Beijing, China, Post Code: 100080) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —33～37

A systematic study was conducted of the impact of gravitation on the heat transfer performance of micro-grooved flat-plate heat pipes along with an analysis of such influencing factors as operating temperatures and cooling modes, etc. Through contrast experiments it has been found that there exists a very marked influence of gravitation on the liquid-film axial distribution, while in the peripheral direction the influence is significant only when high liquid-charging rates are employed. The latter condition enables an inclination angle to exercise a relatively great influence on the heat transfer capacity of heat pipes. A more detailed study has shown that deep-grooved flat-plate heat pipes offer fairly good heat transfer performance, providing them with bright prospects of usage in the area of micro-space heat dissipation for cooling microelectronic devices. **Key words**: miniaturized heat pipe, electronic device, micro-grooved flat-plate heat pipe, micro groove, thin liquid film

HAT 循环饱和器传热传质过程及相似分析＝**The Heat and Mass Transfer of a HAT (Humid Air Turbine) Cycle Humidifier and Its Similarity Analysis** [刊,汉] / WU Wei-liang, CHEN Han-ping (Institute of Mechanical and Power Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —38～41, 44

With the humidifier of a humid air turbine (HAT) cycle serving as an objective of study similarity conditions are discussed during the conduct of experimental research. Under simplified conditions equations of control of multi-phase flows in the humidifier were established along with corresponding boundary conditions. These equations were subjected to a