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恒热流时污垢对管内对流换热过程热力学性能影响的分析

吴双应, 曾丹苓, 李友荣
(重庆大学 动力工程学院, 重庆 400044)

摘 要: 基于热力学第一二定律, 在恒热流工况下分析了污垢对管内对流换热过程热力学性能的影响, 提出了一项在恒热流工况下反映污垢对管内对流换热过程热力学性能影响的指标——无因次熵产相对增加数; 讨论了管内流体雷诺数(无污垢时)和无因次热流密度等参数对无因次熵产相对增加数的影响。研究结果表明, 该指标不仅能反映污垢对管内传热过程的影响, 而且能反映污垢对管内流动过程的影响, 而由污垢层导热所引起的熵产在管内传热过程总的熵产中占有重要的地位。同时, 还把结果与恒壁温时的有关结果进行了比较。

关 键 词: 恒热流; 对流换热; 污垢; 热力学性能

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1 前言

管内受迫对流换热过程广泛存在于化工、动力、制冷等工程技术领域的各种换热设备中, 据调查, 在工程上 90% 以上的换热设备都存在着不同程度上的污垢问题。由于污垢是热的不良导体, 一旦换热面上有了污垢, 便增加了流体与传热面之间的传热热阻, 降低了换热设备的传热性能; 另一方面, 污垢层还会减小管道的流通截面积, 在流量维持恒定的情况下, 必然导致流体流速的增大, 有时污垢还常使流道表面的粗糙度增加, 这些都会引起换热设备流动阻力的增大。因此, 污垢的存在会给换热设备带来一系列的经济损失, 从而成为换热设备设计、运行维护要考虑的一个重要方面, 而定量地分析污垢对传热和流阻性能的影响就显得尤其重要。过去研究污垢对传热性能的影响, 一般采用污垢系数、洁净系数和冗余面积等方法[1], 而污垢对流阻的影响还没有引起人们的足够重视。总之, 现有的研究大多孤立地研究污垢对传热或流动的影响, 而忽略了污垢同时对传热和流动造成的影响, 从而无法将传热的减弱效果与流阻的增大效果有机地结合起来; 同时现有的研究不能反映污垢对传热和流动过程造成的能量质的损失, 而以热力学第二定律为基础的熵产分析法从能量质的分析角度, 可综合地分析和评价污垢对传热和流阻性能的影响。文献[2~8]在恒热流或恒壁温这两种工况下, 曾对管内对流换热过程的熵产进行了大量的研究, 并讨论了有关参数对其不可逆性能的影响, 以上的研究对管内对流换热过程热量传递和流体流动的性能进行综合和定量的评价具有重要的意义。不过应当指出的是, 上述的研究忽略了在工程上被认为是影响换热设备传热和流动过程的重要因素之一——污垢, 而正确分析和处理污垢对管内传热和流动的不可逆损失的影响在节能工作日益受到重视的今天显得十分必要。于是, 本文作者利用热力学第一、二定律和熵产分析原理, 在恒热流工况下探讨污垢对管内对流换热过程性能的影响, 从而为定量分析污垢对传热和流阻性能的影响提供有效途径, 有关恒壁温工况下的分析由于篇幅限制则另文报道。

2 未考虑污垢时管内对流换热过程的熵产分析

考虑如图 1 所示的内径为 d_i 的管内受迫对流换热过程, 假定管内流动与传热过程均处于充分发展区, 且为稳态, 物性为常数。管内流体进口温度为 T_{fi}, 质量流量为 G, 平均流速为 u_m, 管长为 L, 且壁面热流密度 q_w 恒定。若不计轴向导热及散热损失的影响, 则对长为 dx 的控制体, 由能量平衡得:

$$\frac{\mathrm{d}T_f}{\mathrm{d}x}=\frac{4q_w}{\rho C_p u_m d_i} \tag{1}$$

式中, ρ、C_p 分别为流体密度和比热, T_f 为流体温度。

利用边界条件 $x=0$, $T_f=T_{fi}$ 积分上式得:

$$T_f=T_{fi}+\frac{4q_w}{\alpha_m}St\cdot\frac{x}{d_i} \tag{2}$$

式中, α_m 为管内平均对流换热系数; St 为斯坦顿数,

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作者简介: 吴双应(1968-), 男, 安徽桐城人, 重庆大学动力工程学院副教授.

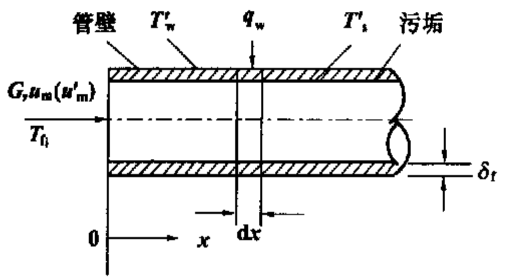

图1　管内受迫对流换热过程

$St = \alpha_m/(\rho C_p u_m)$。

又由 $q_w = \alpha_m(T_w - T_f)$ 得管壁温度 T_w 为:

$$T_w = T_f + q_w/\alpha_m \tag{3}$$

假定流体为不可压缩流体或理想气体,则对如图1所示的控制体,其温差对流传热引起的熵产 $d\Delta S_{\Delta T}$ 和粘性流动阻力引起的熵产 $d\Delta S_{\Delta P}$ 分别为[2]:

$$\frac{d\Delta S_{\Delta T}}{dx} = GC_p\left(\frac{1}{T_f} - \frac{1}{T_w}\right)\frac{dT_f}{dx} \tag{4}$$

$$\frac{d\Delta S_{\Delta P}}{dx} = \frac{G}{\rho T_f}\left(-\frac{dP}{dx}\right) \tag{5}$$

将式(2)、(3)代入式(4)、(5)并由 $x = 0 \sim L$ 积分得由温差传热引起的总熵产 $\Delta S_{\Delta T}$ 和由粘性流动引起的总熵产 $\Delta S_{\Delta P}$ 分别为:

$$\Delta S_{\Delta T} = GC_p[\ln(1 + N_q/Nu) - \ln(1 + \frac{1}{Nu/N_q + 4StN_L})] \tag{6}$$

$$\Delta S_{\Delta P} = \frac{GC_p f Re^3}{8N_{qw}}[\ln(1 + \frac{4N_qN_L}{RePr})] \tag{7}$$

式中,f 为管内流体流动的摩擦阻力系数,$f = 2d_i(-dP/dx)/(\rho u_m^2)$;$Nu$ 为努谢尔特数;$N_q = (q_w d_i)/(\lambda T_{fi})$ 为无因次热流密度;$N_{qw} = q_w/[\mu^3/(\rho^2 d_i^3)]$ 为无因次量;Re 为管内流体雷诺数;$N_L = L/d_i$ 为无因次特征尺寸;其中,μ 为管内流体的动力粘度;λ 为流体的导热系数。

定义无因次熵产数 N_s 为:

$$N_s = \frac{\Delta S}{GC_p} = \frac{\Delta S_{\Delta T} + \Delta S_{\Delta P}}{GC_p} \tag{8}$$

3　考虑污垢时管内对流换热过程的熵产分析

仍然取图1所示的管内对流换热过程作为研究对象,但这时管内壁存在一层厚为 δ_f 的污垢层。用上标"′"表示考虑污垢时的有关物理量。为分析问题方便起见,假定污垢处于稳定状态,污垢均匀分布在管内壁,且不考虑污垢表面粗糙度的影响,污垢表面温度为 T_s',此时的管壁温度为 T_w'。为比较起见,管壁热流密度仍保持恒定为 q_w;流体质量流量和入口温度仍然为 G 和 T_{fi};其它假定条件同不考虑污垢时的情况。于是,可得结垢后的流体平均流速 u_m' 与结垢前的平均流速 u_m 之间的关系为:

$$u_m' = (d_i/d)^2 u_m \tag{9}$$

其中,$d = d_i - 2\delta_f$。

考虑到工程上很多流动处于紊流,作者即以紊流为例来进行分析和研究,对层流情况其研究方法同紊流。对紊流,结垢后的管内流体努谢尔特数 Nu' 和流动阻力系数 f' 分别为:

$$Nu' = 0.023(Re')^{0.8}Pr^{0.4}, \quad f' = 0.184(Re')^{-0.2}$$

于是可得结垢前后的对流换热系数和流动阻力系数的关系为:

$$\alpha_m' = (d_i/d)^{1.8}\alpha_m \tag{10}$$

$$f' = (Re/Re')^{0.2}f = (d/d_i)^{0.2}f \tag{11}$$

又由式(1)可看出,由于结垢前后管壁热流密度 q_w 和流体质量流量 G 保持不变,则考虑污垢时的流体温度 T_f' 的变化与不考虑污垢时流体温度 T_f 的变化相同,即

$$T_f' = T_f = T_{fi} + \frac{4q_w}{\alpha_m}St \cdot \frac{x}{d_i} \tag{12}$$

又由 $q_w \pi d_i = \alpha_m' \pi d(T_s' - T_f')$ 得:

$$T_s' - T_f' = \frac{q_w d_i}{\alpha_m d'} = \left(\frac{d}{d_i}\right)^{0.8} \cdot \frac{q_w}{\alpha_m} \tag{13}$$

对于如图1所示的微元体由温差对流换热和粘性流动引起的熵产仍然可采用式(4)、(5)计算,只是把其中的 T_w 和 T_f 改为 T_s' 和 T_f',并用 dP'/dx 代替 dP/dx 即可。把式(12)、(13)代入该微元体熵产计算式并进行积分得到考虑污垢时温差对流换热熵产 $\Delta S_{\Delta T}'$ 和粘性流动的熵产 $\Delta S_{\Delta P}'$ 分别为:

$$\Delta S_{\Delta T}' = GC_p\{\ln[1 + \frac{N_q}{Nu}(\frac{d}{d_i})^{0.8}] - \ln[1 + \frac{1}{(d/d_i)^{-0.8}(Nu/N_q + 4StN_L)}]\} \tag{14}$$

$$\Delta S_{\Delta P}' = \frac{GC_p f Re^3}{8N_{qw}} \cdot (\frac{d_i}{d})^{4.8} \cdot \ln[1 + \frac{4N_qN_L}{RePr}] \tag{15}$$

由于污垢的存在,将使原有的传热过程增加了污垢的导热过程,因此,通过污垢层的导热过程将使传热过程的不可逆损失增加,故在计算此时的管内传热过程的熵产时,还需要考虑由污垢层导热引起的熵产 $\Delta S_f'$。微元体污垢层导热引起的熵产 $d\Delta S_f'$ 为:

$$\frac{d\Delta S_f'}{dx} = GC_p\left(\frac{1}{T_s' - T_w'}\right)\frac{dT_f'}{dx} \tag{16}$$

又由污垢层的导热过程得：

$$T_w' - T_s' = \frac{q_w d_i \ln(d_i/d)}{2\lambda_f} \qquad (17)$$

式中，λ_f 为污垢的导热系数。

把式(12)、(13)、(17)代入式(16)并积分得：

$$\Delta S_f' = GC_p\left\{\ln\left[1+\frac{4StN_L}{Nu/N_q+(d/d_i)^{0.8}}\right] - \ln\left[1+\frac{4StN_L}{Nu/N_q+(d/d_i)^{0.8}+Nu(N_\lambda/2)\ln(d_i/d)}\right]\right\} \qquad (18)$$

式中，$N_\lambda = \lambda/\lambda_f$，为流体与污垢层的导热系数之比。

此时无因次熵产数 N_s' 为：

$$N_s' = \frac{\Delta S'}{GC_p} = \frac{\Delta S_{\Delta T}' + \Delta S_{\Delta P}' + \Delta S_f'}{GC_p} \qquad (19)$$

由上述分析可知，污垢的存在会影响到管内传热和流动的不可逆性，考虑到恒热流工况下结垢前后总的传热量没有发生变化(而在恒壁温时传热量会发生变化)，于是提出在恒热流工况下污垢对管内对流换热过程性能影响的指标，即无因次熵产相对增加数 η 为：

$$\eta = \frac{N_s' - N_s}{N_s} = \frac{\Delta S_{\Delta T}' + \Delta S_{\Delta P}' + \Delta S_f'}{\Delta S_{\Delta T} + \Delta S_{\Delta P}} - 1 \qquad (20)$$

最后一点需要说明的是，在恒壁温工况下，笔者曾提出单位传热量的熵增率这一指标来反映污垢对管内对流换热过程性能的影响，很显然，如用该指标来评价恒热流工况下污垢对管内对流换热过程性能的影响，则得到的结果与式(20)的结果一致；反之，如用无因次熵产相对增加数来评价恒壁温工况下污垢对管内对流换热过程性能的影响，则得到的结果不尽合理；这两个指标的本质区别在于是否考虑了污垢对传热量的影响，在恒热流工况下由于传热量不变，这时如提单位传热量的熵增率就没有多大的意义了。

4　计算结果分析与讨论

以管内流体为水为例，由文献[8]，取水的污垢系数 R_f 为 0.000 176(m^2·K)/W，水垢的导热系数 λ_f 为 2 W/(m·K)，则水垢的厚度 δ 为 0.352 mm。取管长 L 为 3 000 mm，管内径 d_i 为 45 mm，流体的进口温度 T_{fi} 为 298 K，计算过程流体物性假定取流体进口温度下的物性，计算结果如下。

如图 2 给出了无因次熵产相对增加数 η 随管内流体雷诺数(无污垢时)Re 的变化关系曲线。从图中可看出，随着 Re 的增大，η 先增大后减小，即存在一雷诺数使 η 达到最大，此时污垢的影响最大，且对应最大 η 值时的 Re 值随无因次热流密度 N_q 的增大而增大；同时，在所计算的雷诺数范围内皆有 η 大于零，这表明由于污垢的存在，使得管内传热和流动过程的不可逆性增加，且与恒壁温工况相比，不仅污垢的影响更大，而且在恒壁温工况下污垢的影响随着雷诺数的增大而单调递增。

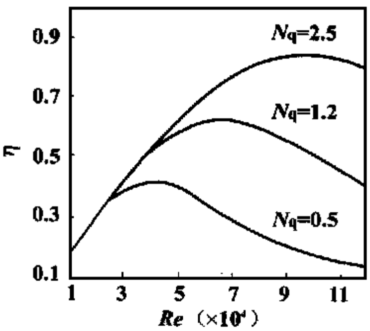

图 2　η 随 Re 的变化关系曲线

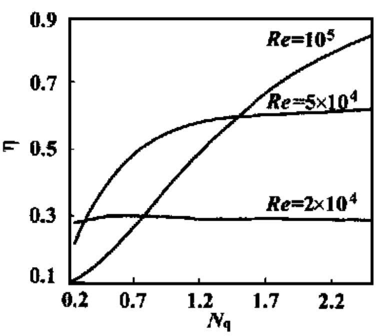

图 3　η 随 N_q 的变化关系曲线

图 3 为无因次熵产相对增加数 η 随无因次热流密度 N_q 的变化关系曲线。从图中可看出，随着 N_q 的增大，η 一般单调递增，即污垢的影响随 N_q 的增大一般变得越来越大，但在 Re 较小时，变化趋势不很明显；且在 N_q 较小时，η 随 Re 的增大而减小。

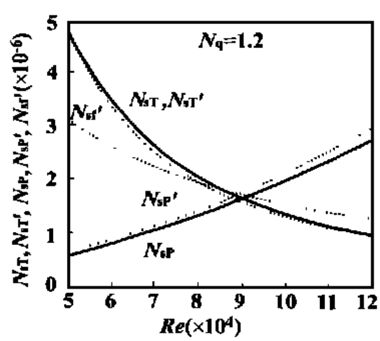

图 4　N_{sT}, N_{sT}', N_{sP}, N_{sP}' 和 N_{sf}' 随 Re 的变化关系曲线

图 4 给出了结垢前后由温差对流换热引起的无因次熵产数 N_{sT}、N_{sT}'；管内流动过程引起的无因次熵产数 N_{sP}、N_{sP}'；以及由污垢层的导热引起的无因次熵产数 N_{sf}' 随管内流体雷诺数的变化关系曲线。从图中可看出，由于污垢的存在，在管内流体质量流量保持不变的情况下，使得由流动过程引起的无因次熵产数增大，即 N_{sP}' 大于 N_{sP}，且随 Re 的增大，其差异越来越大；同时由于污垢的存在，会使温差对流换热引起的无因次熵产数减小，但减小的幅度不大；而污垢层导热引起的无因次熵产数 N_{sf}' 随 Re 增大而单调递减(而在恒壁温时则单调递

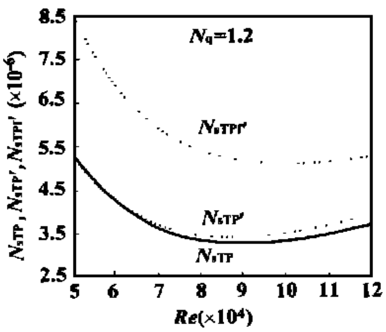

图 5　N_{sTP}, N_{sTP}' 和 N_{sTPf}' 随 Re 的变化关系曲线

增)，且 N_{sf}' 值位于 N_{sP}、N_{sP}' 和 N_{sT}、N_{sT}' 之间。另外，从图中还可看出，在一般的雷诺数范围内，由流动过程引起的无因次熵产数 N_{sP}、N_{sP}' 与由温差对流换热引起的无因次熵产数 N_{sT}、N_{sT}' 和由污垢层的导热引起的无因次熵产数 N_{sf}' 相比不能忽略，特别是在 Re 较大时，而这一点与恒壁温工况时的情况截然不同（恒壁温时由流动引起的熵产可忽略不计）。

图 5 给出了考虑污垢前后总的无因次熵产数 N_{sTP}（为 N_{sT} 与 N_{sP} 之和）、N_{sTP}'（为 N_{sT}' 与 N_{sP}' 之和）和 N_{sTPf}'（为 N_{sT}'、N_{sP}' 与 N_{sf}' 之和）与雷诺数 Re 的变化关系曲线。从图中可看出，如不考虑污垢层导热引起的熵产，则污垢对管内由温差对流换热和流动引起的总熵产的影响不是很大，即 N_{sTP}' 略大于 N_{sTP}（但在恒壁温时单位传热量的温差对流换热和流动的总熵产则会由于污垢的存在而变小），而在考虑了污垢层的导热熵产后，则总的无因次熵产数 N_{sTPf}' 要比无污垢时的总熵产数大很多，可见，污垢层导热引起的熵产在管内传热过程的总熵产中占有重要地位（这一点与恒壁温工况时相似）。另外，从图中还可看出，考虑污垢前后总的无因次熵产数 N_{sTP}、N_{sTP}' 和 N_{sTPf}' 都随 Re 的增大，先减小后增大，即存在一 Re 使考虑污垢前后总的无因次熵产数最小，而在恒壁温工况时考虑污垢前后单位传热量总的熵产随 Re 的增大缓慢递增。

5　结论

在恒热流工况下分析了污垢对管内对流换热过程热力学性能的影响，通过以上分析，可得到下列结论：(1)存在一雷诺数使无因次熵产相对增加数达到最大，即此时污垢的影响最大；且在一般的雷诺数范围内，无因次熵产相对增加数随无因次热流密度的增大而单调递增；(2)在质量流量不变的情况下，污垢的存在使管内温差对流换热过程的熵产减小，但减小幅度不大；使管内流动过程的熵产增大，且增大的幅度要大于温差对流换热熵产减小的幅度；(3)污垢层的导热引起的无因次熵产数随雷诺数的增大而单调递减，且在管内传热过程的总熵产中占有重要地位；由于污垢层导热过程的存在，使得管内传热过程的无因次熵产相对增加数达到 10%～85%；(4)在恒热流工况下，污垢对管内对流换热过程热力学性能的影响在很多方面不同于恒壁温工况。

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spray technique both the steam humidification activation and spray-water humidification activation can contribute to an enhancement of desulfurization efficiency. However, the spray-water activation is much more effective than steam activation. Moreover, there will be an enhancement in desulfurization efficiency in case of an increase in Ca/S ratio and a decrease in saturation approach temperature, SO_2 concentration and flue gas speed. As regards desulfurization by spray-water humidification activation the desulfurizer droplets play a by far greater role in desulfurization than the desulfurizer moisture sorbent. **Key words**: desulfurization, humidification activation, experimental investigation

油焦浆、水焦浆燃烧特性的试验研究＝**An Experimental Study of the Combustion Characteristics of Oil-coke Slurry and Water-coke Slurry** [刊, 汉] / XIONG Yuan-quan, SHEN Xiang-lin (Thermal Energy Engineering Research Institute under the Southeastern University, Nanjing, China, Post Code: 210096), ZHENG Shou-zhong (materials Bureau of National Electric Power Co., Beijing, China, Post Code: 100016) //Journal of Engineering for Thermal Energy &Power. — 2001, 16(5). —494～496

Under low-speed heating conditions the combustion characteristics of oil-coke slurry (mixture of petrol-coke powder and heavy oil) and water-coke slurry (mixture of petrol-coke powder and water) were studied through the use of a thermogravimetric analytical method. These combustion characteristics are compared with those of petrol-coke and pulverized coal. Furthermore, the above results were analyzed from the perspective of a work mechanism. **Key words**: oil-coke slurry, water-coke slurry, combustion characteristics, thermogravimetric analytical method

利用电厂粉煤灰再生劣化抗燃油的试验研究＝**An Experimental Study on the Utilization of Power Plant Pulverized Coal Ash for Regeneration of Deteriorated Fire-resistant Oils** [刊, 汉] / LI Zhi (Testing Research Institute of Guangdong Electric Power Industrial Bureau, Guangzhou, China, Post Code: 510600) //Journal of Engineering for Thermal Energy &Power. — 2001, 16(5). —497～498

A contrast analysis was conducted of pulverized coal ash and several kinds of commonly used adsorbent. Optimum technological conditions were explored through an orthogonal test of regeneration by the use of a contact method. Moreover, a quality contrast analysis has also been performed of the fire-resistant oil prior to and after the regeneration. **Key words**: pulverized coal ash, regeneration, fire-resistant oil, test

气动系统中管路的二维粘性流场计算＝**Calculation of a Two-dimensional Viscous Flow Field in the Pipe of a Pneumatic System** [刊, 汉] / BAO Gang, LI Yu-jun, LI Jun, WANG Zu-wen (Pneumatic Technology Center under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —499～502

With the help of an algorithm SIMPLE a two-dimensional viscous flow field was calculated with respect to a pipe, which has its two ends fitted with a throttle orifice. This is performed for facilitating an in-depth study of pipe flow characteristics in a pneumatic system and the law of variation of various parameters. A stagnation pressure and stagnation temperature were set at the pipe inlet. On the basis of the pipe geometric characteristics and flow features a calculation zone has been divided into five domains with corresponding domain algorithm being given. The results of numerical calculation indicate that the algorithms provided can clearly reflect the flow characteristics in the pipe and the variation trend of relevant parameters. With the method under discussion it is possible to calculate not only the flow field within the pipe but also the flow field of the jet flow zone at the end of the pipe. **Key words**: algorithm SIMPLE, pipe, pneumatic system, sub-domain algorithm

恒热流时污垢对管内对流换热过程热力学性能影响的分析＝**An Analysis of the Effect of Fouling on the Thermodynamic Performance of Convection Heat Exchange Process in a Tube under Constant Heat Flux Conditions** [刊, 汉] / WU Suang-yin, ZENG Dan-ling, LI You-rong (Power Engineering Institute under the Chongqing University, Chongqing, China, Post Code: 400044) //Journal of Engineering for Thermal Energy &Power. — 2001, 16(5). —

503～506

On the basis of the first and second laws of thermodynamics and under constant heat flux conditions an analysis was conducted of the influence of fouling on the thermodynamic performance of convection heat exchange process in a tube. A criterion for evaluating such an influence is put forward, the so-called relative increment number of dimensionless entropy generation. Also discussed is the effect of parameters such as in-tube fluid Reynolds number (in the absence of fouling) and dimensionless heat flux density on the above-mentioned increment number. The results of the study indicate that the above criterion reflects not only the effect of fouling on the in-tube heat transfer process but also the effect of fouling on the in-tube flow process. It is noted that the entropy generation caused by the fouling layer heat conduction plays an important role in the total entropy generation of the in-tube heat transfer process. In addition, the study results have been compared with those of a tube with constant wall temperature. **Key words**: constant heat flux, convection heat exchange, fouling, thermodynamic performance

先进汽轮机准三维设计方法研究与流型分析＝**A Study of the Quasi Three-dimensional Design Method for an Advanced Steam Turbine and an Analysis of Its Flow Patterns** [刊, 汉] / ZHANG Dong-yang, JIANG Hong-de (Institute of Engineering Thermophysics under the Chinese Academy of Sciences, Beijing, China, Post Code: 100080), LI Jiu-hua (Jiangxi Electric Power Testing Research Institute, Nanchong, Jiangxi Province, China, Post Code: 330006) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —507～509, 512

Presented is the development of a quasi three-dimensional design method for an advanced steam turbine. With a successfully modified 200 MW unit serving as an object of study the authors have performed the related analysis of its flow patterns. **Key words**: steam turbine, quasi three-dimensional design, flow pattern analysis

正交实验法在湿式烟气脱硫装置除水器实验中的应用＝**The Application of an Orthogonal Experimental Method in the Experimental Study of a Dehydrator for a Wet Flue Gas Desulfurization Unit** [刊, 汉] / QIU Zhong-zhu, ZHANG He-sheng, XU Ji-huan (Tongji University, Shanghai, China, Post Code: 200092) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —510～512

An orthogonal experimental method was employed to conduct the experimental study of the performance of a centrifugal dehydrator for a wet flue gas desulfurization unit. Through a variance analysis of the test data the effect of the various structural parameters of the dehydrator on water removal performance was ascertained along with an determination of the optimum structural parameters of the dehydrator. This had led to an optimum design of the latter. **Key words**: orthogonal experimental method, centrifugal dehydrator, dehydration performance, optimum design

大型油页岩循环床电站锅炉运行性能分析＝**Operating Performance Analysis of an Oil Shale-fired Circulating Fluidized Bed Boiler of the Highest Capacity Currently in Operation in China** [刊, 汉] / WANG Qing, HAO Zhijing, SUN Jian, et al (Power Engineering Department, Northeast Electric Power Institute, Jilin, China, Post Code: 132012) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —513～516

Presented are the design features, overall structure, operating performance and the test results of a 65 t/h oil shale-fired circulating fluidized bed boiler of low circulation ratio. The economic and social benefits of the power plant operating on oil shale were also analyzed. The test results show that the overall performance of the boiler has attained the advanced international level. **Key words**: oil shale, circulating fluidized bed, boiler, operation

汽轮机真空系统严密性试验的静态模拟计算＝**Static Simulation Calculation of the Air Tightness Test of a Steam Turbine Vacuum System** [刊, 汉] / LI Yong, DONG Yu-liang, YANG Shan-rang (Power Engineering Department, Northeast Electric Power Institute, Jilin, China, Post Code: 132012) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —517～519