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分离式热管小螺旋管蒸发段换热特性的实验研究

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摘　要: 将小螺旋管应用于分离式热管的蒸发段。通过采用玻璃管和不锈钢管模拟分离式热管的蒸发段, 对不同充液率和热流密度下, 小螺旋管管内流体的流动与换热特性进行了实验研究。通过可视化实验观察小螺旋管蒸发段管内流型, 初步分析热流密度和充液率对流型转换的影响, 讨论壁温分布与管内两相流流型的关系。提出螺旋管内的脉冲震荡和二次回流使得管内流体的紊动强化, 从而使平均换热系数和临界热流密度得以提高, 不会产生壁温飞升, 具有较好安全性的结论。

关　键　词: 分离式热管; 小螺旋管; 平均换热系数; 临界热流密度

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符号表

B— 螺旋管管圈节距, mm	h— 换热系数, kW/(m^2·K)
d— 螺旋管内径, mm	v— 运动粘度, m^2/s
D— 螺旋管曲率直径, mm	π— 圆周率
Ds— 螺旋管斜向曲率直径, mm	ρ— 密度, kg/m^3
f— 脉冲频率, 1/s	L— 螺旋管长度, mm
N— 螺旋管管圈数,	q— 热流密度, kW/m^2
Q— 传热量, kW	R— 充液率
下　标	
l— 液相	v— 汽相
准则数	
Bo— 邦德数	Nu— 努谢特数
Pr— 普朗特数	Re— 雷诺数
Wo— 脉冲频率无因次数	

1　引言

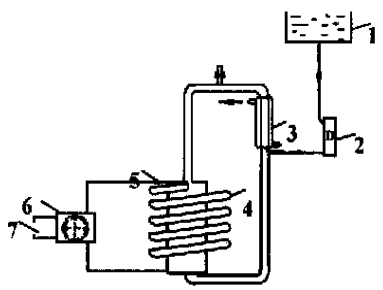
目前, 分离式热管换热器在我国已处于工程应用阶段, 并取得了良好的效果。然而鉴于换热现象的复杂性, 用纯理论分析求解管内换热系数难以实现, 多数文献都只在一定范围内进行实验以获得经验关系式[1]。

由于螺旋管具有许多优于直管的换热特性和结构特征, 所以在许多工程领域得到了广泛应用。螺旋管内的两相流传热特性研究, 同样是通过实验研究, 整理出换热系数的实验关系式[2]。

2　实验装置与实验方法

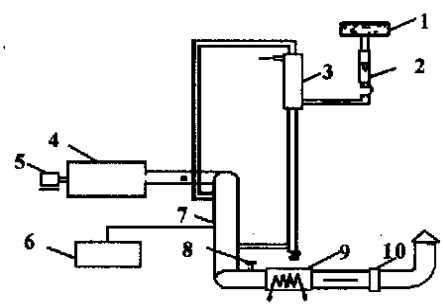
2.1　可视化实验

可视化实验装置如图 1 所示。蒸发段螺旋管一共有四圈。其内径为 4 mm。采用电阻丝加热器来加热, 高位水槽来水用于冷却冷凝段。通过摄像机观察记录小螺旋管内工质的流动情况。在不同的充液率情况下改变输入功率, 观察管内流型的变化。定义充液率 R 为充液量与总容积之比。



1— 高位水槽; 2— 转子流量计; 3— 冷凝段; 4— 蒸发段; 5— 加热器; 6— 调压器; 7— 电源

图 1　可视化实验装置示意图



1— 高位水槽; 2— 流量计; 3— 冷凝段; 4— 燃烧炉; 5— 燃烧器; 6— 数据采集系统; 7— 蒸发段; 8— 孔板流量计; 9— 水冷器; 10— 烟气流量调节阀

图 2　实验装置示意图

2.2　换热特性实验

实验装置如图 2 所示。通过轻柴油在燃烧炉内燃烧产生的烟气来加热蒸发段, 调节燃油喷枪的压力和烟气通道上的阀门开启大小来改变烟气流量, 烟气流量用孔板流量计测量。分离式热管冷凝段焊有水夹套, 用高位水槽来的冷却水吸收热量。管壁温度用 Φ0.2 mm 的镍铬－镍硅热电偶测量(图 3)。烟气进口温度用 Φ 3 mm 的镍铬－镍硅铠装热电偶测量。

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用螺旋管出口处的绝热段温度近似代替管内蒸汽温度。热管总容积为2 150 cm^3。蒸发段由三根并联的不锈钢螺旋管组成。结构见图 3, 具体尺寸见表 1。螺旋管用 Φ6× 1 的直管弯制而成。曲率直径可用式(1)计算。螺旋管长度 $L = \pi DN$, 用不锈钢垫片来保证螺旋管管圈的节距 B。

$$D = \left(\sum_{i=1}^{N} \sqrt{(D_S^2 - (B/2)^2)} \right) / N \qquad (1)$$

在实验范围内, 热平衡计算得出热损不超过 5%。充液率分别为 11%、13%、16%、18%。

表 1 螺旋管几何尺寸

序号	d/D	L/ mm	B/ mm	N	D/ mm	D_s/ mm
1	0.062	3 631	2	18	64.2	64.212
2	0.049	4 132	2	16	82.2	82.201
3	0.040	4 092	2	13	100.2	100.21

3 实验结果与分析

3.1 管内工质的流动特性分析

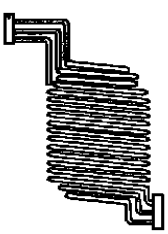

图 3 热电偶布置示意图

根据可视化实验的观察, 随充液量与热流密度的不同, 从入口到出口依次可以观察到四种流型: 单相流、泡状流、柱塞状流、分层流。

在一定的热流密度下, 提高充液率, 单相液体对流向柱塞状流的转换位置以及柱塞状流向分层流的转换位置向上层管圈移动。若在一定的充液率下, 提高热流密度, 流型的转换位置则向下层管圈移动。由于管内产生的脉冲震荡, 使得流型的转换位置在一定的管长范围内波动。在各种情况下都可以观察到柱塞状流占据了绝大部分管圈。其中当 $R = 50\%$, $Q = 300$ W、400 W 时, 管内观察到泡状流。此时, 汽泡沿管圈呈单列分布在管圈顶部。当 $R < 50\%$ 时, 单相液体的对流先转换为柱塞状流。这是由于下层管圈在小充液率情况下, 由冷凝段回流的过冷液较少, 壁面的过热度足够大。使得汽泡的脱离直径可以充斥整个管腔产生柱塞状流。在大充液率、低热流密度时, 单相液体的对流会首先转换为泡状流。这是由于下层管圈中由冷凝段回流的过冷液较多, 壁面过热度较低, 使得汽泡脱离直径较小所致。随两相流沿管圈的上升, 汽泡周围存在的过热液层以及小汽泡的聚合使得汽泡迅速长大而充斥整个管腔而产生柱塞状流。而当 $R = 50\%$, $Q = 500$ W 时, 未能观察到泡状流。说明此时的壁面过热度较高, 使得汽泡的脱离直径大于管径。分层流是从柱塞状流转换而来, 发生在上层管圈的出口段。此时, 汽液两相混合物在脉冲震荡作用下, 将两相混合物爆发性地推向出口, 使得速度陡然增加, 导致汽液分层, 出现分层流, 但分层流不能稳定存在。根据实验观察, 在脉冲的上升过程中, 汽液两相速度较高。离心力足以使两相流体产生分层。下降时, 速度降低。流型又表现为柱塞状流。本实验范围内的 $Bo < 2$, 根据文献[3] 的结论, 认为表面张力对管内的流动和换热的影响显著。由于表面张力会将壁面处液体拉向管中央, 一方面有助于维持柱塞状流的存在; 另一方面也加速了壁面干涸。而脉冲震荡使得柱塞状流可以填补周向任一位置上的干涸点, 避免局部烧干的持续; 同时, 又强化了工质的紊动, 提高了换热系数。

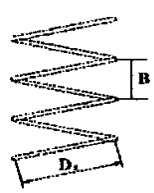

图 4 几何特性示意图

3.2 管内工质的换热特性分析

3.2.1 壁温分布特性

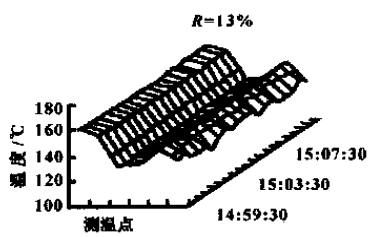

图 5 小螺旋管壁温分布示意图

图 5 给出充液率 $R = 13\%$ 和热流密度 $q = 27 \sim 29$ kW/m^2 时最外层管圈的壁温随时间变化的三维曲面。图 5 表明, 沿管圈上升, 壁温呈现明显跳跃。下层管圈温度可能高于其上一层管圈温度。这明显不同于常规的分离式热管蒸发段的壁温分布。结合可视化实验的观察结果, 显然是柱塞状流占据了这部分管圈。笔者认为, 在壁面发生干涸前, 由于柱塞状汽泡区的液膜换热强于液相区的单相液体对流换热, 因此汽泡区温度较低, 液相区温度较高。壁面干涸后, 液柱区的温度较低, 柱塞状汽泡区的温度较高。柱塞状汽泡区的温度较高是由于汽泡和壁面之间的液膜蒸干所致。

3.2.2 管内换热特性

在汽泡区, 液膜蒸发后产生的干涸点被脉冲震荡和二次回流产生的液膜周向运动作用下带来的液体反复润湿, 能维持较高的局部换热系数。在液相区, 脉冲震荡和液体的二次回流也使得单相液体的紊动增强, 局部换热系数提高。因此, 蒸发段的平均

换热系数得到提高。可以认为, 当柱塞状汽泡区足够长, 它与壁面间的液膜在脉冲震荡和液膜周向运动的作用下能不断得到补充时, 管内换热状况最好。

3.2.3　几何结构对临界热流密度的影响

若干涸壁面过长, 难以得到润湿时, 蒸发段产生持续的干涸。此时, 干涸壁面依靠汽体的对流换热, 换热系数开始降低。由图 6 可以看出, 当 $R = 11\%$, $q = 10 \sim 12$ kW/m^2 时, 由于汽泡区足够长, 柱塞状汽泡与壁面之间的薄液膜在脉冲震荡的作用下能充分得到补充, 因而管内换热系数达到最大。此时的热流密度即为临界热流密度。$q < 10$ kW/m^2 时, 汽泡所占管长太小, 液膜的对流传热尚不占主导地位。随热流密度的升高, 换热系数增加。$q > 12$ kW/m^2 时, 尽管此时的脉冲频率也随之提高, 但柱塞状汽泡所占管长逐渐增大, 使得液膜蒸发后的干涸点已不能得到迅速润湿, 换热系数开始降低。并且, 随充液率的增加, 临界热流密度推迟。当 $R = 18\%$, 临界热流密度约为 38 kW/m^2。尽管本次实验中蒸发段的管径小于文献[1] 中实验的管径($d = 21$ mm), 但临界热流密度已大于其实验所得($q_{cr} = 30$ kW/m^2), 说明螺旋管与垂直管相比, 临界热流密度明显提高。这与文献[2] 的结果一致。考虑到干涸壁面的液体补充事实上是通过脉冲震荡和二次回流导致的液膜周向运动完成, 可以认为这二者的共同作用是临界热流密度得以推迟的主要因素。由于实验中难以维持烟气热量的稳定输入, 未能观察到 $R = 13\%$ 时的临界热流密度。由图 6 可见, 管壁发生干涸后与干涸前的换热系数可以相比较, 说明螺旋管使得蒸汽的紊动强化, 管内换热系数也相当高, 不会发生壁温飞升。实验范围内的管壁温度最高不会超过 400 ℃, 因此安全性较好。由上所述, 此种分离式热管换热器的最佳工作范围应在临界热流密度左右。

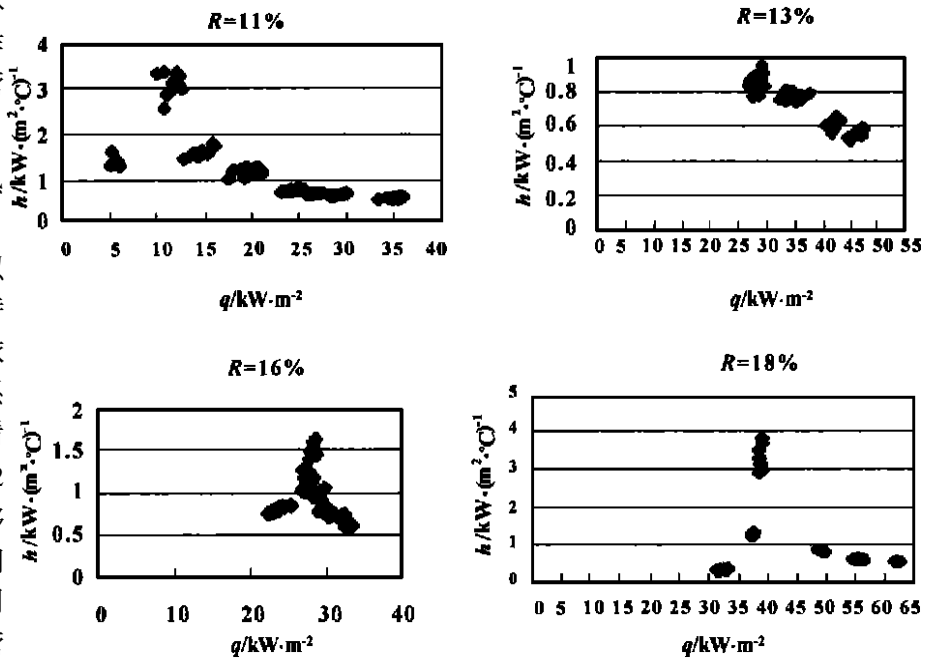

图 6　管内换热系数与热流密度的关系

3.2.4　准则关系式的建立

通过对上述影响管内换热的诸多因素的分析, 根据文献[3 ~ 5] 的结果, $Bo = d/\sqrt{\sigma/g(\rho_l - \rho_v)}$, $Wo = d\sqrt{2\pi f/v}$, $f = cq^n$, $c = 1.473 \times 10^{-6}$, $n = 1.075$。本文提出小螺旋管管内换热系数的无因次准则关系式为:

$$Nu = ARe_l^a Pr_l^b Bo^c Wo^d R^e \tag{2}$$

对上式进行多元线形回归可得:

管内换热的无因次准则关系式

$$Nu = 10^{-5.7602} Re_l^{3.5939} Pr_l^{-0.8809} Bo^{2.2350} Wo^{-4.1044} R^{-9.4881} \tag{3}$$

式中:

$Re_l = 221.397 \sim 1\,748.769$, $Pr_l = 0.890 \sim 2.711$, $Bo = 0.569\,1 \sim 1.558\,4$, $Wo = 977.431 \sim 1\,322.889$, $R = 11\% \sim 18\%$, $d/D = 0.040 \sim 0.062$, $q = 5 \sim 39$ kW/m^2, 工质为水。定性温度是螺旋管蒸发段进出口的平均温度, 定性尺寸是螺旋管内径。复相关系数为 0.969, Nu 数的平均偏离度为 18.83%。

管内干涸后换热的无因次准则关系式

$$Nu = 15.3188 Re_l^{-0.0373} Pr_l^{-2.9680} Bo^{1.6674} Wo^{-3.7535} R^{2.2973} \tag{4}$$

式中: $Re_l = 393.124 \sim 4\,694.202$, $Pr_l = 0.890 \sim 3.103$, $Bo = 0.564 \sim 1.721$, $Wo = 615.664 \sim 2\,043.846$, $R = 11\% \sim 18\%$, $d/D = 0.040 \sim 0.062$, $q = 10 \sim 62$ kW/m^2, 工质为水。定性温度是螺旋管蒸发段进出口的平均温度, 定性尺寸是螺旋管内径。复相关系数为 0.988, Nu 数的平均偏离度为

11.75%。

4 结论

本文在可视化实验的基础上，根据分离式热管小螺旋管蒸发段性能测试的数据，得出：

(1) 实验结果表明内径 4 mm 的小螺旋管管内的两相流以柱塞状流为主。表面张力和脉冲震荡对管内流动和换热的影响不可忽视。

(2) 分离式热管小螺旋管蒸发段也会产生脉冲震荡。脉冲震荡和二次回流使平均换热系数得以提高。由于在一定热流密度范围内，脉冲震荡和液膜的周向运动可以补充柱塞状汽泡区的液膜烧干，所以脉冲震荡和二次回流产生的液膜周向运动也是临界热流密度得以提高的主要因素。

(3) 管壁发生干涸后，由于螺旋管使得蒸汽的紊动强化，管内换热系数也相当高。不会发生壁温飞升，所以安全性较好。其最佳工作范围应在临界热流密度左右。

(4) 由实验整理得出管壁干涸前后管内换热系数的无因次准数关系式均与实验数据吻合较好。

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喷射器一维设计理论的研究进展= **Recent Advances in the Study of One-dimensional Ejector Design Theory** [刊, 汉] / LIU Zhi-qiang, SHEN Sheng-qiang, LI Su-fen (Power Engineering Department, Dalian University of Science & Technology, Dalian, Liaoning Province, China, Post Code: 116024) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —229 ~ 232

This paper mainly focuses on the recent progress in the theoretical research on one-dimensional gas ejector design theory. Discussed are such a variety of topics as constant pressure mixing theory, constant area mixing theory as well as their experimental research results. The authors end the paper with a forecast of the future prospects of the above-mentioned ejectors. **Key words**: ejector, constant-pressure mixing theory, constant-area mixing theory

DG—1000/17.6—Ⅱb 型锅炉 NO_x 排放特性试验研究= **Experimental Study of NO_x Emission Characteristics of a Model DG-1000/17.6-Ⅱb Boiler** [刊, 汉] / ZHAO Xiang-qian, LI Wen-xue (Huaneng Shantou Power Plant, Shantou, Guangdong Province, China, Post Code: 515071) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —233 ~ 238

An analysis is performed of the emission characteristics of a model DG-1000/17.6-Ⅱb boiler at Huaneng Shantou Power Plant. Through a comprehensive combustion adjustment test compared were the various factors liable to have an influence on NO_x emission characteristics and fly-ash combustibles C_{fh}. The test results indicate that the above-mentioned boiler features low NO_x emissions but an excessively high amount of fly-ash combustibles C_{fh}. In view of this, some proposals have been put forward for the reduction of fly-ash combustibles C_{fh}. **Key words**: utility boiler, combustion adjustment, NO_x emissions

切向炉燃烧器区涡量分布的实验研究= **Experimental Investigation of Vorticity Distribution in the Burner Zone of a Tangentially Fired Boiler** [刊, 汉] / HE Bo-shu, CHEN Chang-he (National Key Laboratory of Coal Clean Combustion under the Tsinghua University, Beijing, China, Post Code: 100084), DIAO Yong-fa, XU Jin-yuan (Institute of Energy & Power Engineering under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —239 ~ 242

With the help of a six-sensor hot-wire probe the authors have measured for the first time the velocity and vorticity field in the burner zone of the cold model of a tangentially fired boiler. Presented are the parameters depicting turbulent flow characteristics, such as turbulent flow intensity, skewness factor and flatness factor, etc. The results of an experimental investigation indicate that there emerges a wall-attachment phenomenon as soon as the jet flow at the burner zone reaches its outlet. Furthermore, a high intensity of vorticity and turbulence can be observed near the wall surface. **Key words**: tangentially fired pulverized-coal boiler, vorticity, skewness factor, flatness factor

分离式热管小螺旋管蒸发段换热特性的实验研究= **Experimental Investigation of Heat Transfer Characteristics of Small Spiral-tube Evaporating Section in a Segregation-type Heat Pipe** [刊, 汉] / YI Jie, WANG Jing (Shanghai Jiaotong University, Shanghai, China, Post Code: 200030), ZHANG Hong, et al (Nanjing Chemical Engineering University, Nanjing, China, Post Code: 210009) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —243 ~ 246

Small-diameter spiral tubes were employed in the evaporating section of a segregation-type heat pipe. Through the use of a glass tube and stainless steel tube a simulation was conducted of the evaporating section of the above-mentioned heat pipe. Under the condition of different liquid-filling rates and heat flux densities an experimental investigation was undertaken of the fluid flow and heat exchange characteristics inside the small-diameter spiral tube. By way of a visualized test observed was the flow pattern inside the evaporating section of the spiral tube. A preliminary analysis was conducted of the influence of the heat flux density and liquid-filling rate on the transformation of flow pattern. A discussion of the relationship between wall temperature distribution and in-tube two-phase flow pattern has led to the following conclusion: the pulsation shock in the spiral tube and secondary return flow can bring about an intensified turbulence of the in-tube fluid. As a result, there emerged an enhancement of the average heat exchange factor and critical heat flux density as well as an

avoidance of abrupt rise in wall temperature, thus contributing to a relatively high operation safety. **Key words**: segregation type heat pipe, small-diameter spiral tube, average heat exchange factor, critical heat flux density

石灰浆液雾化喷嘴及其特性研究＝**The Study of a Lime Slurry Atomization Nozzle and Its Characteristics** [刊, 汉] / WANG Nai-hua, GAO Xiang, LUO Zhong-yang, et al (Thermal Energy Engineering Research Institute under the Zhejiang University, Hangzhou, Zhejiang Province, China, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —247 ~ 249, 254

An experimental study was conducted of the atomization characteristics of a Y-shaped twin-fluid nozzle used for lime slurry atomization. An analysis was performed of the various factors liable to influence the atomization angle and the distribution of Sauter mean diameter (SMD) of the atomized spray drop. An empiric formula for predicting spray-drop average diameter has also been obtained. The results of the study indicate that the nozzle under investigation features low power consumption and high atomization effectiveness, making it especially suitable for flue gas desulfurization based on a semi-dry method. **Key words**: nozzle, atomization characteristics

可调式煤粉分配器冷态模化试验及理论分析＝**Cold Modeling Test and Theoretical Analysis of an Adjustable Pulverized-coal Distribution Device** [刊, 汉] / ZHOU Yun-long, GAO Shui-qiang (Power Engineering Department, Northeast Electric Power Institute, Jilin, Jilin Province, China, Post Code: 132012), SHI Hong-qi (Jilin Research Institute of Electric Power Science, Changchun, Jilin Province, China, Post Code: 130024) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —250 ~ 254

Proposed in this paper is a new type of adjustable pulverized-coal distribution device. Based on a theoretical analysis of the pulverized-coal distribution device the authors have conducted an in-depth experimental investigation. The investigation results have confirmed the feasibility of this new type of pulverized-coal distribution device, which regulates the combustion process of a boiler through a blade angle change of the distribution device. **Key words**: pulverized coal distribution device, experimental study

电站锅炉燃气脉冲除灰过程研究＝**A Study of Gas Pulsation-based Ash Removal Process in Utility Boilers** [刊, 汉] / FAN Wei-jun, SUN Wen-chao, WU Cheng-kang (Beijing Astronautics and Aeronautics University, Beijing, China, Post Code: 100083) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —255 ~ 258, 277

The burning of huge amount of inferior-quality unwashed coals in Chinese utility boilers has led to serious boiler ash-deposit and related fouling problems. The latter can result in a reduction of boiler thermal efficiency and cause the clogging of the boiler rear flue pass, thus affecting the normal operation of the boiler. The gas pulsation-based ash removal technology was developed by the combustion lab of a Mechanics Research Institute under the Chinese Academy of Sciences. Its use on 30-plus large-sized utility boilers has proved to be very effective. In the present paper the study results of the above-cited technology are reported. They cover a variety of aspects. These include the influence of furnace configuration and fuel on the flame propagation and pressure pulses, the measurement by the use of pressure sensors of the gas pulse pressure distribution at the outlet flow field, and the observation of gas pulse intensity and its action range. In addition, also touched upon were the vibration measurement of ash deposit plate with the help of a vibration sensor and the variation of vibration accelerations at various spatial locations. From the above one can readily gain a better understanding of the mechanism of the gas pulsation-based ash removal action. **Key words**: gas pulsation, explosive burning, soot blower

煤焦再燃过程中催化剂对 NO 还原的影响＝**The Effect of Catalysts on NO Reduction during the Reburning of Coal Chars** [刊, 汉] / ZHONG Bei-jing, SHI Wei-wei, FU Wei-biao (Engineering Mechanics Department, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —259 ~ 262, 274

With three kinds of coal char made from Xianglongtan lignite, Fulaerki lignite and Datong bituminous coal serving as reburning coals a study was conducted of the effect of these coal chars on the process of NO reduction in the reburning zone. Also analyzed was the effect of metallic oxides in the coal ash on the NO reduction. To study the catalytic action of