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低浓度 CTAC 减阻流体流动性能试验研究

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摘　要: 通过对 CTAC 溶液的减阻性能的测量, 得到了 CTAC 溶液的减阻性能随伴随盐浓度变化的特性。研究结果表明, 即使对同种减阻方式, 减阻也存在极限和优选。同时, 应用激光相位多普勒测速仪进行减阻流体的湍流特性试验研究, 得到了 50 种工况下流体的速度脉动曲线。研究还发现, 减阻流体的横向和轴向速度脉动及雷诺应力明显小于牛顿流体; 减阻流体的轴向和横向速度脉动之间的关联被明显抑制。

关　键　词: 减阻流体; 湍流结构; 表面活性剂溶液; 相位多普勒测速仪

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1　前　言

1948 年, Toms[1] 发现在湍流内流的有机溶液中, 溶解少量的聚甲基丙烯酸甲酯, 其阻力大幅下降。这种现象后来被称为 Toms 效应或减阻效应。减阻效应使添加减阻剂后的流体在传送过程中的阻力大幅减小; 同时由于减阻流体的传热性能变差, 减少了沿程散热损失。因此减阻流体在区域制冷、供暖等系统中具有广阔的工业应用前景。以往减阻添加剂的研究主要集中在高分子聚合物上, 但其易机械降解的缺点使之在工业应用中受到制约。近年来, 表面活性剂由于具有良好的机械、化学、光和热稳定性, 而受到人们日益广泛的关注; 且其溶液减阻效应的产生、消失是可逆的, 因而具有较大的工业应用前景。

表面活性剂的加入使溶液变成了非牛顿流体, 溶液的性质发生了较大变化。对减阻流体减阻机理的研究, 对有效控制和利用减阻效应有很大的理论和实用价值。近年来, 国外对减阻流体的研究十分活跃[2~3], 主要集中在减阻流体的流动方面。国内也相继开展了这方面的工作, 如: 上海交通大学等对温度、浓度、配比变化对氯化十六烷基三甲基季铵盐(Cetyltrimethyl Ammonium Chloride, CTAC)减阻流体的减阻性能的影响进行试验研究, 同时对流体的速度场进行了初步的探讨, 认为在主流方向上存在低频周期运动[4]。由于其工作主要集中在中高浓度的 CTAC 溶液(如 170×10^{-6} 和 800×10^{-6}), 而试验证明低浓度的 CTAC 溶液也是可以取得令人满意的减阻效果, 而且更经济[5]。本试验在二维流道中对稀 CTAC 溶液的减阻性能随伴盐——水杨酸钠(NaSal)的浓度变化情况进行更细致的试验研究; 并用相位多普勒测速仪(Phase Doppler Anemometry, PDA)测量二维流道中减阻流体的速度曲线, 以进一步的探索减阻流体的流动结构。

2　试验装置与过程

本试验台采用开放式闭路循环系统, 见图 1。

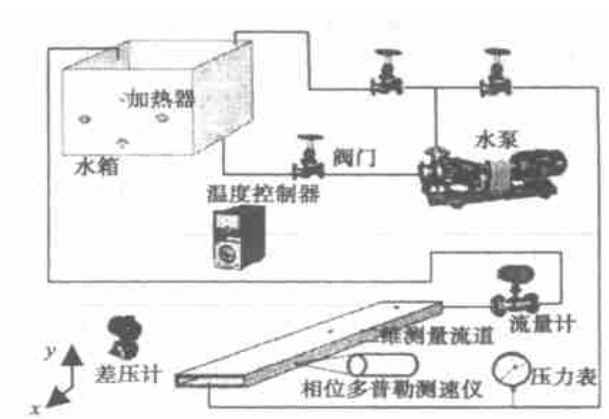

图 1　试验台系统图

透明有机玻璃流道作为测试段, 其横断面为 20 mm× 250 mm 的矩形, 目的在于保证流道的长宽比大于 10, 以模拟二维流场。试验中差压变送器(CECC－530)的精度为 0.5%, 取压孔相距 2.98 m; 涡轮流量传感器(LWGY－80A)精度为 0.5%, 分度号为 Pt100 热电阻温度传感器测量温度, 其精度可

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以达到±0.1 ℃。

距入口 3.6 m 处的速度分布应用 PDA 系统进行测量，该系统由氩离子激光器、光学探头、DualPDA 信号处理器等部件组成。光学探头固定在坐标架上，坐标架可以在 3 个方向上运动，定位精度可达 0.025 mm，这样就能够测量垂直于主流流动方向（即 y 方向）上的运动结构。信号的获取采用的是后向接收方式。

3 性能试验结果分析讨论

3.1 性能试验原理

当流动处于充分发展紊流时，对牛顿流体和非牛顿流体，均用式(1)来计算平均壁面剪切应力，即

$$\tau_w = \frac{\Delta PHW}{2L(H+W)} \tag{1}$$

式中：τ_w 为壁面剪切应力；ΔP 为试验测得的差压；H 是流道高度；W 是流道宽度；L 是两个取压孔之间的距离。

无量纲阻力系数（Fanning 系数）由式(2)计算：

$$f = \frac{\tau_w}{\frac{1}{2}\rho U_b^2} \tag{2}$$

式中：f 为摩擦阻力系数；ρ 为溶剂的密度；由于本试验使用的 CTAC 溶液为极稀溶液，因此在进行数据处理时使用溶剂的物性参数；U_b 为主流速度。

文中涉及的 y^+ 为无量纲坐标，公式为：

$$y^+ = \frac{y \times u^*}{v} \tag{3}$$

$$u^* = (\tau_w/\rho)^{1/2} \tag{4}$$

式中：u^* 为剪切速度；y 为流道纵坐标（壁面处 $y=0$）；v 为溶剂运动粘度。

3.2 性能试验结果分析

图2 是试验得到的减阻流体性能曲线，图中符号含义为：C 表示CTAC；060 代表 CTAC 浓度为 60×10^{-6}；120 代表 CTAC：Nasal = 1 ∶2.0（摩尔比），其它符号与之类似。图中 Prandtl－karman 曲线和 Virk 曲线对应的公式分别为：

$$f = 0.073Re^{-0.25} \tag{5}$$

$$f = 0.58Re^{-0.58} \tag{6}$$

Prandtl－Karman 曲线描述的是在二维湍流中摩擦阻力系数随雷诺数变化的特性；Virk 曲线是减阻流体最大减阻曲线。其分别由 Prandtl－Karman 坐标下的式(7)和式(8)拟合而得。

$$f^{-1/2} = 4.0\log Ref^{1/2} - 0.4 \tag{7}$$

$$f^{-1/2} = 19.0\log Ref^{1/2} - 32.4 \tag{8}$$

$$DR\,\% = \frac{f_1 - f_2}{f_1} \times 100\% \tag{9}$$

式中：$DR\,\%$ 为减阻率；f_1 为牛顿流体的摩擦阻力系数；f_2 为减阻流体的摩擦阻力系数。

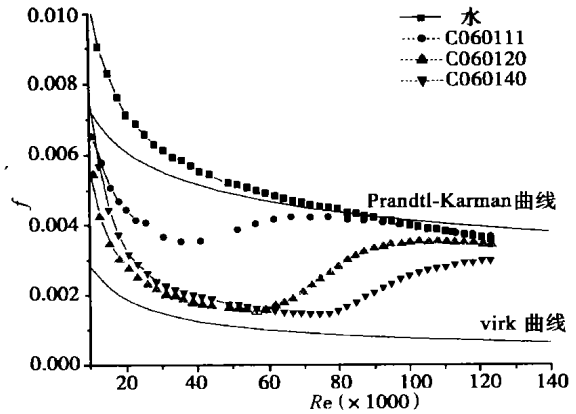


图 2 减阻流体减阻性能曲线

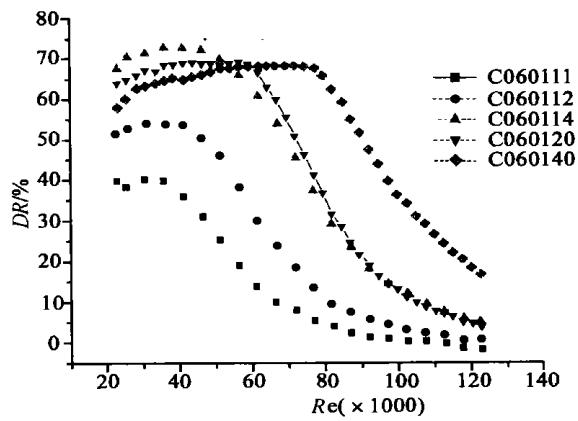


图 3 减阻率变化曲线

由于试验流道是三段有机玻璃管道由法兰连接而成，连接处过渡不光滑造成流道阻力增加。从图中可以看出系统存在一定偏差，但这对我们的研究影响不大。试验中，浓度及配比工况有近 50 种，为了便于得到规律性结论，本文选择典型的 7 组数据。

通过试验可以看出，纯 CTAC 溶液没有减阻现象发生，当 CTAC 与 NaSal 之摩尔比达到 1 ∶1.1 时，溶液具有减阻特性，减阻率随着 NaSal 的添加比例增大而增大。临界雷诺数（即减阻现象开始消失时的雷诺数）同样随着 NaSal 的增加而增大，这使减阻流体在更广的流动范围里保持减阻特性，对于减阻现象的控制具有积极的意义。但是通过研究我们发现，添加 NaSal 并不会使减阻率持续增加，当减阻率达到某一最大值后，继续增加 NaSal 的浓度反而使之减小，如图 3 所示。从图中可以看出，当雷诺数为

35 000 时, 随着配比由 1 ∶1.1 增加到 1 ∶1.4, 减阻率随之增大到最大值。而配比更高的溶液(图中的 C060120 和 C060140)减阻率不再增加反而减小; 该两种溶液达到最大减阻率时的雷诺数明显增大, 但溶液的最大减阻率数值几乎不变。这说明即使对同一种减阻流体, 减阻性能也存在极限和优选。

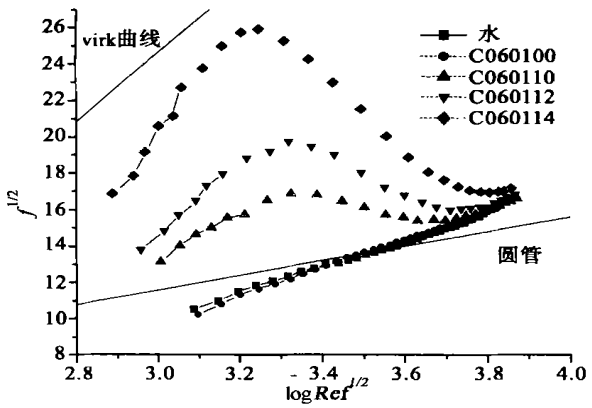


图 4(a)　减阻率随配比增加而增大

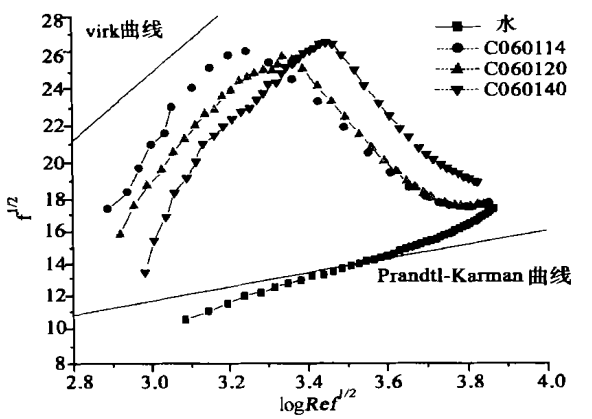


图 4(b)　减阻率随配比增加而减小

研究表明, 减阻流体的阻力特性曲线介于 Prandtl—Karmen 曲线和 Virk 最大减阻曲线之间, 减阻区(减阻流体处于完全减阻状态)和过减阻区(超过临界雷诺数, 减阻开始消失的区域)十分明显, 如图 4 所示。随着配比的增加, 减阻流体的减阻性能变化趋势发生改变。在配比达到 1 ∶1.4 之后, 减阻曲线变化趋势由上下移动转变为左右平移, 这可能是由于溶液中 CTAC 的胶束结构发生了变化, 具有减阻效果的棒状胶束结构更加稳定造成的[6]。

4　激光试验结果分析

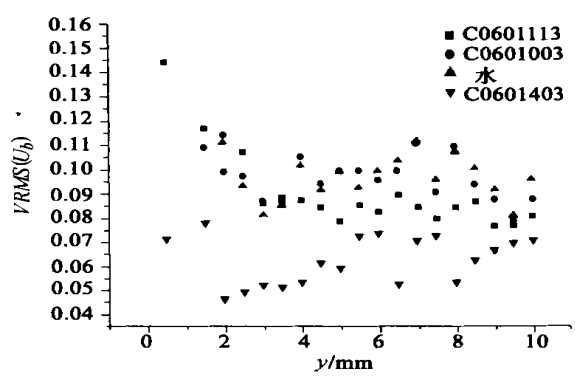
通过对 NaSal 对 CTAC 减阻性能影响的分析, 得到伴随盐对减阻流体减阻性能影响的规律。为了进一步了解减阻的机理, 本研究应用 PDA 对减阻流体的流动结构进行测量。激光测试试验的流动工况见表 1。所选工况能够覆盖所有的减阻特征点, 这些研究点包括: 最大减阻率点, 临界雷诺数点, 过减阻区中点, 减阻特性即将完全消失的点[7]。为了便于讨论, 我们在原溶液符号之后加上工况代号为 C0601203 是溶液 C060120 处于雷诺数为 61613 的工况代号, 此时流体减阻率为 67%, 正好处于临界雷诺数点。

表 1　激光试验工况

工况代号	流量/$m^3 \cdot h^{-1}$	雷诺数 *Re*
1	9	23 105
2	16.2	41 589
3	24	61 613
4	30	77 016
5	40	102 688

4.1　减阻流体的速度脉动曲线

通过对处于不同减阻状态的流体的横向速度脉动分析, 可以看到: 处于最大减阻状态的 C0601403, 其横向速度脉动明显小于其它溶液; 无减阻效果的 C0601003 溶液, 其横向速度脉动则基本与水一致, 见图 5。这说明减阻流体的横向速度脉动受到抑制。随着雷诺数的加大, 某些溶液, 如 C0601113, 已处于过减阻区, 但是仍然具有微弱的减阻性能, 其速度脉动也相应小于水。这可能是由于尽管 CTAC 减阻流体的剪切诱导结构在较大的剪切力作用下受到破坏, 但是溶液中仍然有由棒状胶束构成的网状结构存在, 从而抑制了其横向速度脉动。

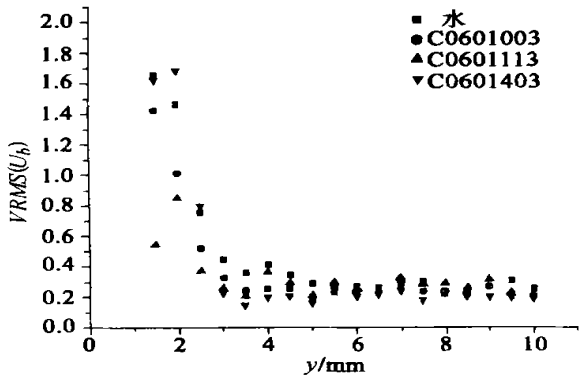


VRMS 为 *y* 方向速度脉动的均方根

图 5　横向速度脉动图

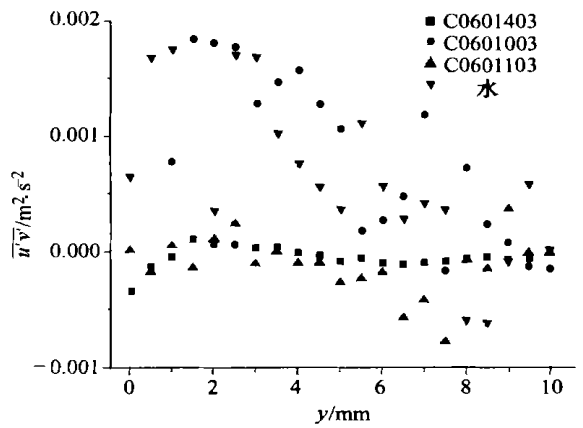
与横向速度脉动不同, 减阻流体的轴向速度脉动形状与牛顿流体基本相似, 在壁面附近($y^+ < 80$)存在峰值, 越接近湍流核心区, 速度脉动越小, 如图

6 所示。与横向速度脉动相同的是减阻流体的减阻率越大, 其轴向速度脉动越小, 即速度脉动受抑制的程度越大。



URMS 为 *x* 方向速度脉动的均方根

图 6 横向速度脉动图



$u'v'$ 为速度脉动的相关量

图 7 雷诺应力分布

4.2 减阻流体的雷诺应力分布

通过研究发现, 处于减阻状态的 C0601403 和 C0601103 两种减阻流体的交叉动量数值非常小, 尤其是 C0601403, 几乎是一条等于 0 的直线, 而减阻率稍小的 C0601103 则是在 0 的上下摆动, 其均值等于 0, 如图 7 所示。这表明在减阻流体中, 流体主流流动方向和垂直于主流流动方向的速度脉动之间几乎没有关联, 或者说这种联系已经被最大可能的抑制。

水和无减阻效应的 C0601003 溶液则不同, 可以明显看到, 在壁面附近($y^+ \approx 90$), 存在一个交叉动量的峰值。目前人们普遍认为, 减阻流体的雷诺应力被抑制是减阻发生的直接原因。通过研究我们发现, 在壁面附近, 减阻流体的雷诺应力与水具有最大差别。

5 结论

通过对 50 种工况 CTAC 流动性能的试验, 主要得出以下两个结论:

(1) 在一定条件下, NaSal 的增加使 CTAC 溶液的减阻能力显著提高, 但是减阻率的增加存在极限。当达到同浓度 CTAC 溶液的最大减阻能力后, NaSal 的增加不再使溶液的减阻能力增大, 而只是使减阻流体的最大减阻率点平移及临界雷诺数增大。试验结果表明, 对同种减阻流体, 减阻存在极限和优选。

(2) 处于最大减阻状态的溶液, 其横向速度脉动和主流方向速度脉动均明显小于牛顿流体; 减阻流体的主流方向速度脉动和横向速度脉动之间的关联被抑制, 其雷诺应力与牛顿流体相比, 显著降低而且两者主要在壁面附近($y^+ \approx 90$)存在最大的差别。

致谢: 本试验得到上海交通大学动力机械与工程教育部重点实验室的大力协助和支持; 感谢罗次申、金浩、巩斌老师在试验中给予的指导和帮助。

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(辉 编辑)

of measuring pulverized coal concentration by the system was investigated. In consideration of the thermal relaxation effect in two-phase flows a calculation formula is proposed based on a revised Reynolds number and Nusselt number. The test data obtained by using the above two revised numbers to correlate the gas-solid two-phase flow round the thermal probes have shown that the gas-solid two-phase flow and single-phase one have an identical heat exchange relation. On the basis of this mechanism the thermal probe measurement method has made it possible to keep the relative deviation of pulverized-coal concentration measurement results within ±15%. **Key words**: gas-solid two-phase flow, pneumatic transport, heat transfer, measurement, thermal probe

射流对高温空气燃烧过程中 NO_x 生成的影响= **The Influence of Jet Flows on NOx Generation during a High-temperature Air Combustion Process** [刊, 汉] / WANG Jie-teng QI Hai-ying, LI Yu-hong, YOU Chang-fu (Institute of Thermal Energy Engineering under the Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —575 ~ 579

Presented are the NOx generation mechanism during a fuel combustion process and various influencing factors. In addition, in connection with the specific features of high-temperature air combustion (HiTAC) and the basic theory of jet flows the authors have investigated the influence of an entrainment of fuel and air jet flows on NOx generation rate occurring at the HiTAC mode. The results of the investigation may provide a theoretical basis for the selection of a rational design and operating parameters as well as for the attainment of super-low NOx emissions and sizable energy-savings when operating at the HiTAC mode. Furthermore, they can also promote the industrial application and popularization of this advanced HiTAC technology in China. **Key words**: jet flow, high-temperature air combustion, NOx emissions

声空化场下浸没在多孔介质中水平圆管传热的实验研究= **Experimental Research on the Heat Transfer in a Horizontal Circular Tube Immersed in a Porous Medium under the Action of an Acoustic Cavitation Field** [刊, 汉] / ZHOU Ding-wei, LIU Deng-ying, HU Xue-gong, ZHANG Zheng-fang (Institute of Engineering Thermophysics under the Chinese Academy of Sciences, Beijing, China, Post Code: 100080) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —580 ~ 584

With the outside portion of a horizontal circular tube being packed by solid granules acetone is used to serve as a working medium. Under this condition an experimental research has been performed to identify the influence of various parameters on the single-phase convection and boiling heat transfer, including boiling hysteresis, in the above-cited tube immersed in a porous medium. Such parameters include the intensity and distance of acoustic cavitation, granule diameter, height of a porous layer, fluid subcooling, etc. **Key words**: acoustic cavitation, porous medium, boiling heat transfer, hysteresis

低浓度 CTAC 减阻流体流动性能试验研究= **Experimental Investigation of the Flow Properties of a Low-concentration CTAC (Cetyl Trimethyl Ammonium Chloride) Drag Reducing Fluid** [刊, 汉] / XU Peng, WANG De-zhong, HU Li-guang, ZHOU Hao-jun (Institute of Mechanical and Power Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —585 ~ 588

Through the measurement of the drag reducing properties of a CTAC (cetyl trimethyl ammonium chloride) solution obtained were the characteristics of variation of these properties with the change in salt concentration. The results of an investigation indicate that even for one and the same drag reduction mode there exists a limiting value and an optimized selection for drag reduction. Meanwhile, a laser phase Doppler anemometer was employed to investigate the turbulent flow characteristics of a drag reducing fluid and, as a result, speed pulse curves were obtained for 50 kinds of operating conditions. It has also been discovered through the investigation that the transverse and axial speed pulses as well as Reynolds stress of the drag reducing fluid are markedly smaller than those of a Newtonian fluid. The correlation between the axial

and transverse speed pulsation of the drag reducing fluid has been conspicuously suppressed. **Key words**: drag-reducing fluid, turbulence structure, surfactant solution, phase Doppler anemometer

220 t/h 电站燃油炉改烧水煤浆炉内传热及排放特性的试验＝**Heat Transfer and Emission Characteristics Tests of a 220 t/h Oil-fired Utility Boiler Retrofitted for Firing Coal-water Slurry** [刊, 汉] / WANG Ling, ZHAO Xiang, CAO Xin-yu, HUANG Zhen-yu, et al (Institute of Thermal Energy Engineering under the Zhejiang University, Hangzhou, China, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —589 ~591

Heat transfer performance and pollutant emissions were measured and tested for an oil-fired 220 t/h utility boiler being retrofitted to fire coal-water slurry, a new type of clean fuel as a replacement for oil. Measurements were taken of the temperature field, flame emissivity, superheater tube wall temperature, exhaust gas temperature and composition. These data represent some special features of coal-water slurry combustion and may serve as reference data during the design and retrofitting of a boiler for firing coal-water slurry. **Key words**: coal-water slurry, flame emissivity, pollutant emission, boiler

高硫石油焦燃烧污染物排放特性的试验研究＝**Experimental Investigation on Pollutant Emission Characteristics Resulting from the Burning of Petroleum Coke with a High Sulfur Content** [刊, 汉] / YUAN Gui-cheng, LIU Wu-biao, ZHANG Chun-lin, LIU De-chang (National Key Laboratory of Coal Combustion under the Huazhong University of Science & Technology, Wuhan, China, Post Code: 430074) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —592 ~594, 606

On a hot-state test rig a desufurization test was conducted for the burning of high-sulfur petroleum coke. On this basis discussed was the influence of such factors as combustion temperature, calcium/sulfur ratio and excess oxygen content on SO_2 and NOx emissions. As a result, a theoretical and practical basis is provided for the industrial application of petroleum coke with a high sulfur content. **Key words**: petroleum coke with a high sulfur content, combustion test, SO_2 emissions, NOx emissions

无烟煤与贫煤混煤燃烧和 NO_x 排放特性的实验研究＝**Experimental Research on the Burning of Anthracite Mixed with Lean Coal and Its NOx Emission Characteristics** [刊, 汉] / FANG Li-jun, HUI Shi-en (Institute of Energy and Power Engineering under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049), GAO Zheng-yang, YAN Wei-ping (Department of Power Engineering, North China University of Electric Power, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —595 ~598

By using a thermobalance and a small-sized pulverized-coal combustion test rig an experimental study was conducted for a multitude of test items. The latter include the combustion characteristics of anthracite, lean coal and the blends of the above two coals in three different proportions, NOx generation mechanism at different combustion-air supply rates, and burn-out characteristics. Through the processing and analysis of the test data it is concluded that there exists some differente in combustion performance between the anthracite and lean coal with the performance of the blends of these two coals exhibiting intermediate characteristics. A proper selection of excess air factor can lead to a high-efficiency combustion of anthracite and lean coal blended in different ratios and to low NOx emissions. With respect to coals being blended in three different ratios a suitable range of excess-air factor values is proposed to attain a high-efficiency combustion and low pollutant emissions. This may serve as a guide for the cost-effective and clean operation of power plants firing the above coal blends. **Key words**: burning of anthracite mixed with lean coal, combustion characteristics, NO emissions, burn-out characteristics

1025 t/h“W”火焰锅炉燃烧特性试验研究＝**Experimental Study of the Combustion Characteristics of a 1025 t/h**