

# 电厂送粉系统煤粉浓度测量的热探头方法研究

刘 磊, 周芳德

(西安交通大学 动力工程多相流国家重点实验室, 陕西 西安 710049)

**摘 要:** 煤粉浓度测量是气固两相流急待解决的问题之一。自行研制热探头测量系统, 研究了该系统测量煤粉浓度的可行性。考虑两相流中的热弛豫效应, 提出了修正雷诺数和努谢尔特数的计算式。研究结果表明, 应用修正雷诺数和努谢尔特数关联绕流热探头的试验数据, 气固两相流与单相气体流具有相同的换热关系式。基于这一规律性, 热探头测量方法可使煤粉浓度测量结果的相对偏差在±15%以内。

**关键词:** 气固两相流; 气力输送; 传热; 测量; 热探头

中图分类号: TK124

文献标识码: A

## 1 引 言

煤粉的完全燃烧具有提高能源利用率、降低污染物排放的双重意义, 燃烧过程的调控要求对送粉系统中的煤粉浓度实行在线监测。粉体与一次风的混合输送涉及多相流体力学。

热探头煤粉浓度测量方法因应燃烧过程流程控制的需求而提出, 其原理与热线热膜风速仪的测量原理类似, 即利用流动与换热的相关性测量流动参数。但是, 在具体的流动—换热关系上, 两相流与单相气体流存在差异。热线热膜风速仪并不是直接测量气流速度, 更确切地说它的热损耗取决于气体的质量通量。采用热探头测量煤粉浓度, 由于气固两相相间的热弛豫现象, 热探头的讯号既不会简单地依赖于煤粉浓度, 也不会简单地取决于流体的质量通量。本文作者对热探头测量方法进行研究, 为调控煤粉的燃烧过程提供实用新型监测技术。

## 2 热探头法测量原理

热探头煤粉浓度测量方法由热探头和温度传感器组成。热探头直径为 7 mm 的圆柱体, 温度传感器直径为 5 mm, 其结果如图 1 所示。温度传感器内

置两个热电阻, 热探头内置两个热电阻和一个功率为 10 W 的加热元件。温度传感器测量两相流体来流温度, 热探头与温度传感器组成桥式电路测量流体与热探头的温差。温度测量电路见图 2。

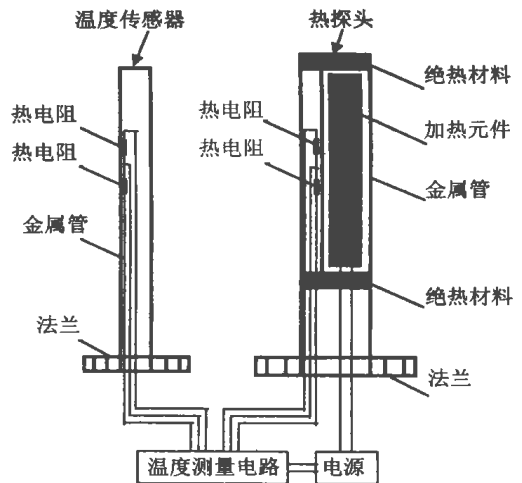


图 1 热探头结构示意图

热探头的加热元件以固定功率释放热量, 这一热量被两相流体吸收, 换热过程可看作由两部分组成: 其一是单相气体的换热, 其二是煤粉的加入而引起的换热变化。这两部分的迭加使气固两相流的流动—换热关系偏离单相气流的流动—换热关系。

电厂送粉系统中的气固两相流为稀相流, 固相的体积份额为千分之一数量级, 固相流速近似等于气相流速, 两相流体的质量通量可表示为:

$$G_m = \rho_g(1 + Z_s)V_g \quad (1)$$

式中:  $\rho_g$  为气体密度,  $V_g$  为气相流速,  $Z_s$  为煤粉浓度, 定义为

$$Z_s = m_s / m_g \quad (2)$$

式中:  $m_s$  与  $m_g$  分别为固相和气相的质量流量。在通常的气力输送条件下, 加热功率所引起的流体

收稿日期: 2002-01-11

基金项目: 国家重点基础研究规划基金资助项目(G1999022308)

作者简介: 刘磊(1967—), 男, 安徽利辛人, 西安交通大学副教授。

温度的变化可忽略。热探头浓度测量法并不测量混合流体的温升, 而是通过测量气固两相流体横掠热探头(圆柱管)的换热系数  $h_m$ , 以确定煤粉浓度。如果气、固两相间可瞬时达到热平衡, 即热弛豫时间为零, 则对于一定物性和粒径的气固两相流, 换热系数

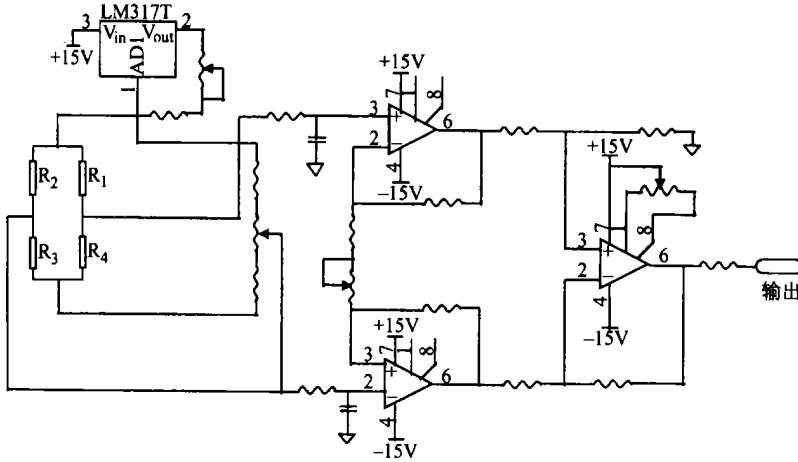


图 2 温度测量电路

$h_m$  只取决于两相流体质量流量  $G_m$

$$h_m = f(G_m) \tag{3}$$

但是, 气固两相流的相间传过程存在固有的热弛豫现象, 即热弛豫时间并不为零。因此, 换热系数不能表示成两相质量流量的简单函数, 而必须表示成如下形式

$$h_m = f(V_g, Z_s) \tag{4}$$

式(4)可进一步整理成准则关系式, 在已知气体流速的条件下, 可依据传热准则关系式确定煤粉浓度。

### 3 试验装置

在常温常压条件下, 以煤粉—空气两相流模拟一次风与煤粉的混合流动, 试验装置见图 3。空气流量由孔板测量, 煤粉流量由螺杆式给粉机的电机转速控制。粉体与空气通过负压混合器混合, 在试验段中形成气固两相流。试验段为内径 75 mm 的水平直管。煤粉的粒径由筛选法测定, 平均粒径为  $65 \mu\text{m}$ 。煤的密度为  $1220 \text{ kg/m}^3$ , 导热系数为  $0.26 \text{ W/(m}\cdot\text{C)}$ , 比热容为  $960 \text{ J/(kg}\cdot\text{C)}$ 。

### 4 换热系数

热探头为均匀壁温的加热圆柱管, 对流换热满足

$$Q = h_m A_D (T_D - T_\infty) \tag{5}$$

式中:  $Q$  为热探头加热功率,  $A_D$  为热探头换热面积,  $T_D$  为热探头温度,  $T_\infty$  为来流温度。图 4 是气固两相流体平均对流换热系数与气体流速的关系, 对应于相同的空气流速, 煤粉浓度  $Z_s$  增大则换热系数  $h_m$  增大。显然, 煤粉的加入使换热系数与空气流速的关系偏离单纯空气流绕流圆柱管换热的基本数据。

### 5 计算公式与测量结果

应用热探头测量煤粉浓度, 首先须建立相应的计算公式, 这就需要考虑影响传热过程的因素。煤粉单颗粒对流传热的能量方程为

$$m_s C_s \frac{dT_s}{dt} = Nu \pi d_s \lambda_g (T_g - T_s) \tag{6}$$

式中:  $C_s$  为固体颗粒的比热容,  $T_s$  为固体颗粒的温度,  $t$  为时间,  $\pi$  为圆周

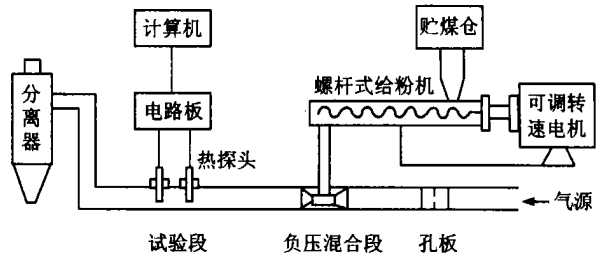


图 3 试验装置

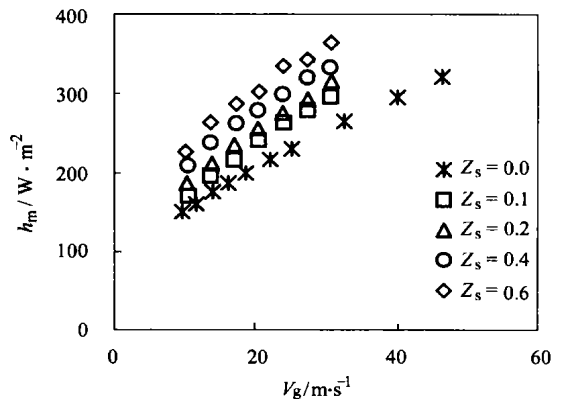


图 4 两相流绕流热探头的换热系数

率,  $d_s$  为固体颗粒的粒径,  $\lambda_g$  为气体的导热系数,  $T_g$  为气相温度。式(6)经变换可得

$$\frac{dT_s}{dt} = \frac{Nu_s}{2} \frac{12\lambda_g}{C_s \rho_s d_s^2} (T_g - T_s) \quad (7)$$

式中： $\rho_s$  为固体颗粒的密度， $Nu_s$  为固体颗粒的 Nusselt 数。 $Nu_s$  通常由 Ranz-Marshall 关系式计算<sup>[1]</sup>，对于两相速度近似相等的均相气固两相流， $Nu_s \approx 2$ 。定义为

$$\tau_T = \frac{2}{Nu_s} \frac{C_s \rho_s d_s^2}{12\lambda_g} \quad (8)$$

$\tau_T$  的量纲为时间，称为颗粒的热弛豫时间，是气固两相间达到热平衡的特征时间。两相间能否及时达到热平衡影响气固两相流的热扩散效果，如果热弛豫时间大于流场的特征时间，则颗粒与气体间来不及达到热平衡；若热弛豫时间小于流场的特征时间，则颗粒与气体间可达到热平衡。气固两相混合流体绕热探头的流动，其流场的特征时间  $\tau_F$  可表示为

$$\tau_F = D / V_g \quad (9)$$

式中： $D$  为热探头直径。定义一准则数，用以描述颗粒对温度场变化的响应特性，该准则数为

$$N_T = \tau_T / \tau_F \quad (10)$$

分别定义气固两相流绕圆柱流动的 Reynolds 数  $Re_D$  和 Nusselt 数  $Nu_D$  为

$$Re_D = \frac{V_g \rho_g (1 + Z_s) D}{\mu_g} \quad (11)$$

$$Nu_D = \frac{h_m D}{\lambda_g (1 + Z_s (1 - e^{-N_T}))} \quad (12)$$

式中： $\mu_g$  为气体粘度。若  $Z_s = 0$ ，则式(11)与式(12)即是单相气体的准则数。气体绕均匀壁温加热圆柱管的常用传热关系式为<sup>[3]</sup>

$$Nu_D = (0.4Re_D^{0.5} + 0.06Re_D^{2/3}) Pr^{0.4} \left( \frac{\mu_{g\infty}}{\mu_{g0}} \right)^{0.25} \quad (13)$$

式中：下标 0 表示加热圆管处流体的平均物性， $\infty$  表示均匀来流的物性， $Pr$  为气体的 Prandtl 数。由于加热功率小，流体的温升可忽略，近似认为

$$\mu_{g\infty} = \mu_{g0}$$

气体绕均匀壁温加热圆柱管的换热同样满足幂律关系式， $Reynolds$  数在 4 000 ~ 40 000 范围内，常用的幂律关系式为<sup>[3]</sup>

$$Nu_D = 0.174Re_D^{0.618} \quad (14)$$

图 5 是不同煤粉浓度下  $Nu_D$  与  $Re_D$  的关系，试验数据与式(13)和式(14)基本吻合，表明在稀相条件下，只要在 Reynolds 数和 Nusselt 数中恰当考虑气固两相流的影响因素，两相流绕均匀壁温加热圆柱管的准则关系式与单相气体的准则关系式基本相

同。利用这一规律性，应用单相气体即可标定出热探头煤粉浓度测量的特性曲线。对于图中的试验数据，如下幂律关系式可更好地关联气固两相流绕热探头对流换热的试验数据

$$Nu_D = 0.56Re_D^{0.51} \quad (15)$$

若已知气体流速，可由式(15)迭带算出煤粉浓度。图 6 是以式(15)作为计算公式，热探头法对煤粉浓度测量结果与实际值的比较，测量偏差在  $\pm 15\%$  以内。

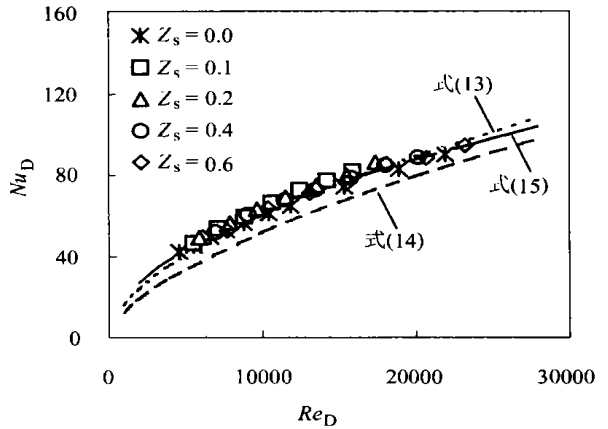


图 5 热探头换热准则关系式

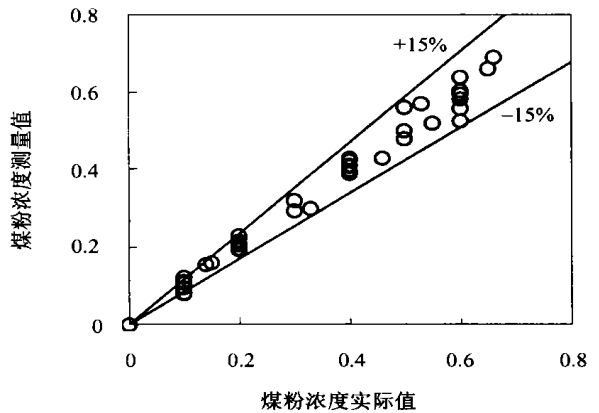


图 6 煤粉浓度测量值与实际值比较

## 6 结论

本文提出了热探头煤粉浓度测量方法，其基本原理是气固两相流绕圆柱流动时换热系数与流动参数具有相关性。对应于相同的气相流速，煤粉浓度增大则换热系数增大。考虑气固两相流中的热弛豫效应，提出了修正 Reynolds 数和 Nusselt 数，以修正 Reynolds 数和 Nusselt 数关联气固两相流绕热探头的试验数据，可得到与单相气体相同的换热准则关系

射流对高温空气燃烧过程中  $\text{NO}_x$  生成的影响

王皆腾, 祁海鹰, 李宇红, 由长福

(清华大学 热能工程研究所, 北京 100084)

**摘要:**总结了燃料燃烧过程中  $\text{NO}_x$  的生成机理和各种影响因素, 并结合高温空气燃烧(High Temperature Air Combustion-HiTAC)的特点和射流的基本原理, 研究了燃料和空气射流的卷吸作用对该燃烧方式  $\text{NO}_x$  生成量的影响。为选择合理的设计与运行参数, 实现该燃烧方式的超低  $\text{NO}_x$  排放和高效节能, 也为更好地在我国推广和应用这一先进技术提供理论基础。

**关键词:**射流; 高温空气燃烧;  $\text{NO}_x$  排放

中图分类号: TQ038.1 文献标识码: A

## 1 概述

众所周知, 在人类使用化石燃料的过程中会产生氮氧化物、烟炱和 CO 等污染物。氮氧化物包括  $\text{N}_2\text{O}$ 、NO、 $\text{NO}_2$ 、 $\text{N}_2\text{O}_3$ 、 $\text{N}_2\text{O}_4$ 、 $\text{N}_2\text{O}_5$  等多种成分, 其中 NO 和  $\text{NO}_2$  (总称为  $\text{NO}_x$ ) 对环境的危害最大。一般情况下,  $\text{NO}_2$  生成量不大, 约占总容积的 10%。 $\text{NO}_x$  的主要危害是在光的作用下形成光化学烟雾, 严重影响大气质量和危害人体健康; 还会形成酸雨, 影响农作物的生长, 造成很大的经济损失。因此, 控制燃烧过程的  $\text{NO}_x$  生成与排放一直是燃烧技术发展的关键之一。燃料的种类、燃料中氮化物的种类与含量、燃料和空气的化学当量比、燃烧温度、压力等都会影响  $\text{NO}_x$  的生成, 其中最主要的影响因素是燃烧温度

和反应物浓度。

对于工业炉窑, 炉膛出口的排烟温度一般都很高, 如炼钢炉, 在不回收余热的情况下, 其排烟温度高达 1 000  $^{\circ}\text{C}$  以上。为了更有效地利用能源, 常回收其一部分余热用于预热空气, 但通常随着空气预热温度的升高, 常规燃烧的火焰温度也随之升高, 生成的  $\text{NO}_x$  量急剧增加。这样虽然可以提高能量的利用效率, 但是对环境的危害增加了。近年来, 发达国家大都对  $\text{NO}_x$  的排放量有非常严格的法规限制。为了解决能量利用率和  $\text{NO}_x$  排放之间的矛盾, 对  $\text{NO}_x$  控制方面的研究也越来越多, 有很多种方法被应用到工程中, 主要有: 分段燃烧、烟气再循环、改善燃烧器、炉膛喷水、高温低氧燃烧等。概括这些方法的共同点都离不开降低氧浓度和最高燃烧温度这两个关键。在这些方法中以高温低氧燃烧(即高温空气燃烧)技术最具有优势和发展前景。

人们环保意识的普遍增强, 天然气和煤气等洁净燃料的大量使用, 正好为我国高温空气燃烧技术的推广应用提供了有利的条件。充分认识这项技术低  $\text{NO}_x$  排放的机理对于相关系统的设计和应用都具有重要的意义。高温空气燃烧技术之所以具有低  $\text{NO}_x$  排放的特点, 主要的原因就是燃料和空气喷嘴的特殊布置方式及其射流所造成的, 因此, 要想研究

收稿日期: 2002-04-04; 修订日期: 2002-07-17

作者简介: 王皆腾(1968—), 男, 山东嘉祥人, 清华大学硕士研究生。

式。这一规律不仅为热探头煤粉浓度测量方法提供了有力的计算公式, 同时表明可应用单相气体标定热探头的两相流特性曲线。以式(15)作为计算公式, 热探头方法对煤粉浓度的测量结果其偏差可在  $\pm 15\%$  以内。

## 参考文献:

[1] CROWE C T, SOMMERFELD M, TSUJI Y. Multiphase flows with

droplets and particles[M]. Boca Raton (U S A. Florida): CRC Press. 1998.

[2] WHITAKER S. Forced convection heat transfer correlations for flow in pipes, past flat plates, single cylinders, single spheres, and flow in packed beds and tube bundles[J]. *AIChE J* 1972, 18(2): 361-371.

[3] 杨世铭. 传热学[M]. 北京: 高等教育出版社, 1987.

(渠源 编辑)

**Revealing from the Law of Thermodynamics Its Connotation** [刊, 汉] / WANG Jia-xun, WANG Qing-zhao, ZHANG Xiao-dong (Power Engineering Department, North China University of Electric Power, Beijing, China, Post Code: 102206) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). — 561 ~ 564

The exposition and seeking of an implicit economic theory from many a law of physics can serve as a new approach for combining a thermodynamics analysis with an economic one. A specific analysis has been conducted of the economic theory of revealing its connotation from the first and second laws of thermodynamics. To this end, it is essential to clarify the existing misguidance of these two laws, especially the deep-seated misguidance of the second law. A further deepening of the understanding has been attained of the reasoning used by Georgescu Roegen in the statement "entropy law per se constitutes in substance the most cost-effective economic process among numerous laws". **Key words:** entropy, entropy law, new classic economics, ecological economics

**地源热泵运行经济性分析 = An Analysis of the Operating Cost-effectiveness of a Ground-source Heat Pump** [刊, 汉] / WANG Yong-biao, LI Bing-xi, JIANG Bao-cheng (Energy Science and Engineering School under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). — 565 ~ 567

In the light of the excessively low outdoor temperatures prevailing in Chinese northern frigid regions the authors have proposed a space heating system based on the use of ground-source heat pumps. There exist three driving modes for such pumps, namely, by electric motors, diesels and gas engines. In addition, there are three auxiliary heat supply sources, i. e., electric boilers, oil-fired ones and gas-fired ones. The authors have analyzed and compared the operating cost of various systems during a change of primary energy utilization rate and fuel price. The results of this comparison show that the operating cost of the driving modes by using gas engines, electric motors and diesel engines are respectively 6%, 40% and 57% higher than that of a central district heating system using boilers. **Key words:** ground-source heat pump, space heating, primary energy utilization rate, operation cost-effectiveness

**纳米流体强化导热系数机理初步分析 = A Preliminary Analysis of the Intensified Thermal-conductivity Mechanism of Nano-fluids** [刊, 汉] / LI Qiang, XUAN Yi-min (Power Engineering Institute under the Nanjing University of Science & Technology, Nanjing, China, Post Code: 210094) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). — 568 ~ 571, 584

The mechanism of an intensified thermal conductivity achieved through the use of nano-fluids is analyzed from the following two aspects, namely, a changed liquid structure due to the addition of nano-particles and the micro-motion of nano-fluids. The results of the analysis indicate that relative to the enhanced thermal conductivity effected by the addition in fluids of millimeter or micrometer-grade particles the enhanced thermal conductivity made possible by nano-fluids has come about mainly due to the micro-motion of the nano-particles. Through the measurement of the thermal conductivity of nano-fluids under various temperatures it has been verified that the micro-motion of the nano-particles represents a major factor contributing to the enhancement of thermal conductivity by the nano-fluids. **Key words:** nano-fluid, intensified heat transfer, thermal conductivity, micro-motion

**电厂送粉系统煤粉浓度测量的热探头方法研究 = Research on a Thermal Probe Method for the Measurement of Pulverized-coal Concentration in a Pulverized-coal Transport System of a Power Plant** [刊, 汉] / LIU Lei, ZHOU Fang-de (National Key Laboratory for Power Engineering Multi-phase Flows under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). — 572 ~ 575

The measurement of pulverized coal concentration represents one of the problems requiring an urgent solution in the area of gas-solid two-phase flows. The authors have developed a measuring system incorporating thermal probes. The feasibility

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  $\pm 15\%$ . **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  $\text{NO}_x$  生成的影响 = **The Influence of Jet Flows on  $\text{NO}_x$  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  $\text{NO}_x$  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  $\text{NO}_x$  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  $\text{NO}_x$  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,  $\text{NO}_x$  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