文章编号: 1001－2060(2005)01－0022－05

压电陶瓷激励影响燃气燃烧器性能的实验研究

赵　宏, 杨治国, 娄慧娟
(北京航空航天大学 能源与动力工程学院, 北京 100083)

摘　要: 应用热线风速仪和 TESTO360 烟气分析仪分别对压电陶瓷激励下燃气燃烧器冷、热态情况进行了测量, 主要考察了压电陶瓷激励频率、幅值对掺混区域速度场、燃烧器出口 NO_x 生成量和温度分布的影响。实验结果表明, 各种频率的压电陶瓷激励对助燃风流动及其与天然气的掺混都有一定效果, 但千赫兹量级的激励频率的激励效果更为明显一些, 且激励造成的时均速度变化程度要弱于湍流度变化。压电陶瓷激励下, 燃烧器 NO_x 生成量和燃烧温度均有所提高, 表明燃烧更趋完全。

关　键　词: 压电陶瓷; 扩散燃烧; 低污染; 主动流动控制

中图分类号: TK16　　文献标识码: A

1　前　言

大气中的 NO_x 对人体的健康及环境有极大的危害, 因此, 世界各国对 NO_x 的排放均有严格的限制。燃料燃烧过程中所产生的 NO_x 由 NO、NO 和 NO 组成, 但是在一般的情况下 NO 占绝大部分(≥90%～95%)。火焰中 NO_x 的形成主要有 3 种机理: 热力型、燃料型和快速型。燃烧固体燃料时 NO_x 的排放量取决于燃料型机理, 而燃烧气体和低含氮量的液体燃料时 NO_x 的形成量取决于热力型机理。燃烧过程中快速型 NO_x 的形成量随燃料成分和燃料条件的不同而在 150～200 mg/kg 的范围内波动。因此, 对于燃烧气体燃料的燃烧过程而言, 抑制热力型 NO_x 的生成是减少燃烧烟气中 NO_x 排放量的主要途径。

抑制温度型 NO_x 的核心是降低燃烧温度、改变当量比和减少烟气在高温区停留时间, 这些都可以通过主动控制燃气、空气和烟气之间的流动混合来实现, 也为主动流动控制[5～7]领域所研究的压电陶瓷激励(Piezoceramic Cantilever Actuator)提供了调控对象。因此, 在中国石油化工有限责任公司的资助下, 我们应用压电陶瓷激励器对小型单级旋流燃烧器的助燃风进行了激励, 考察各种参数的压电陶瓷激励对燃烧器出口冷流流场、燃烧温度、NO_x 生成的影响及相关机理。

2　实验设备

实验在低污染燃烧实验台完成, 该实验台由气路、激励器、小型燃烧器和测量控制系统 4 部分构成(见图 1)。

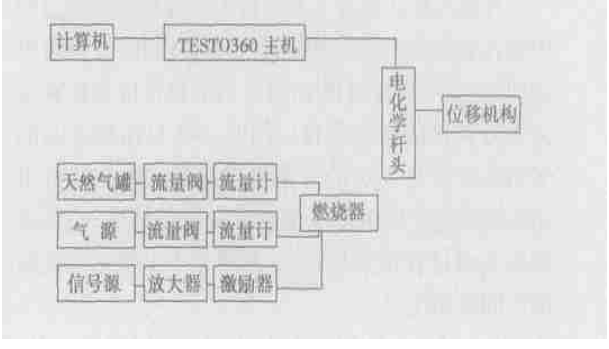


图 1　压电陶瓷激励调控燃烧机理实验台

(1) 气路提供冷、热流实验所需天然气和助燃风: 由低压暂冲气源、输气管路、稳压罐和法兰等组成助燃风气路, 由气罐、减压阀和微调流量阀等组成天然气供给回路。低压暂冲气源额定压力为 810.6 kPa, 容积 500 m^3。稳压罐体积 0.5 m^3, 不锈钢材料制造。

(2) 小型燃烧器是小型单级单喷嘴燃烧器, 采用碳钢材料制造, 助燃风采用侧向进气方式, 额定天然气流量为 0.8 m^3/h。

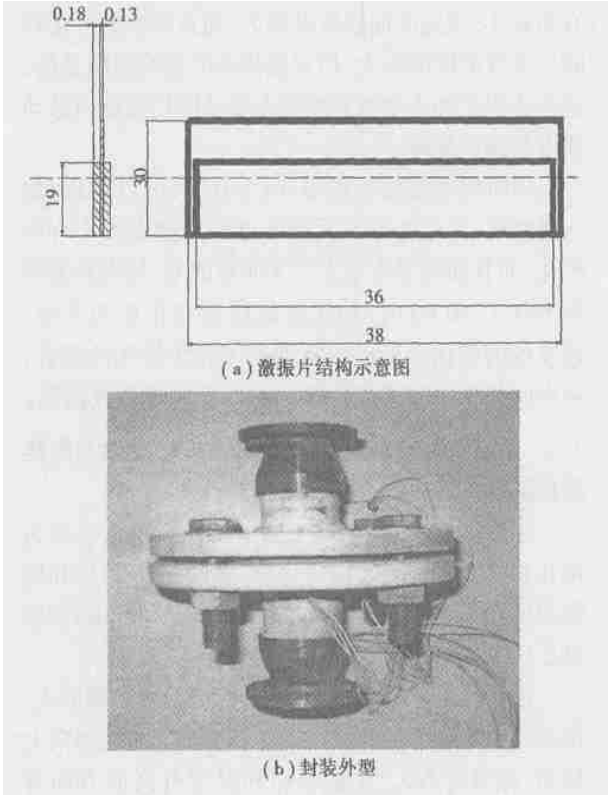
(3) 测量控制系统由流量计、热线风速仪(BD－2)、采集卡(PCL－818HG)、计算机、信号发生器(XD2A)、功率放大器(SA－750A)和 TESTO360 烟气

收稿日期: 2004－05－11;　修订日期: 2004－08－05
基金项目: 航空基础科学基金资助项目(02B51002)
作者简介: 赵　宏(1970－), 男, 辽宁北镇人, 北京航空航天大学副教授, 博士后.

分析仪组成, 分别完成冷热流状态下的流量计量调节、冷流速度测量、温度测量、烟气 NO_X 成份测量与分析功能。

烟气分析仪为德国德图公司的 TESTO360 型自动烟气成份分析仪。TESTO360 自动烟气成份分析仪可以自动测量环境参数、烟气参数和烟气成份, 如环境温度和压力, 燃气温度和压力, 燃气中的氧气、一氧化氮、二氧化氮、一氧化碳和二氧化碳等成份的浓度, 而且, 数据测量输出的滞后时间不到 20 s, 可实现实验的准实时测量。测量数据由与其联接的计算机自动采集存储。

(4) 悬臂梁式压电陶瓷激励器, 由 4 个激振片组成, 每个激振片由一块矩形的不锈钢片, 两面各粘有一块压电陶瓷片组成(见图 2(a)), 自由端最大振幅为 1 mm。将 4 片激振片夹于两块环形胶木中, 调整两两相对的两个激振片的相位差 180°, 利用环氧树脂将压电陶瓷片粘牢, 然后放于助燃气通道内, 封装后外型如图 2(b)所示。



(a) 激振片结构示意图

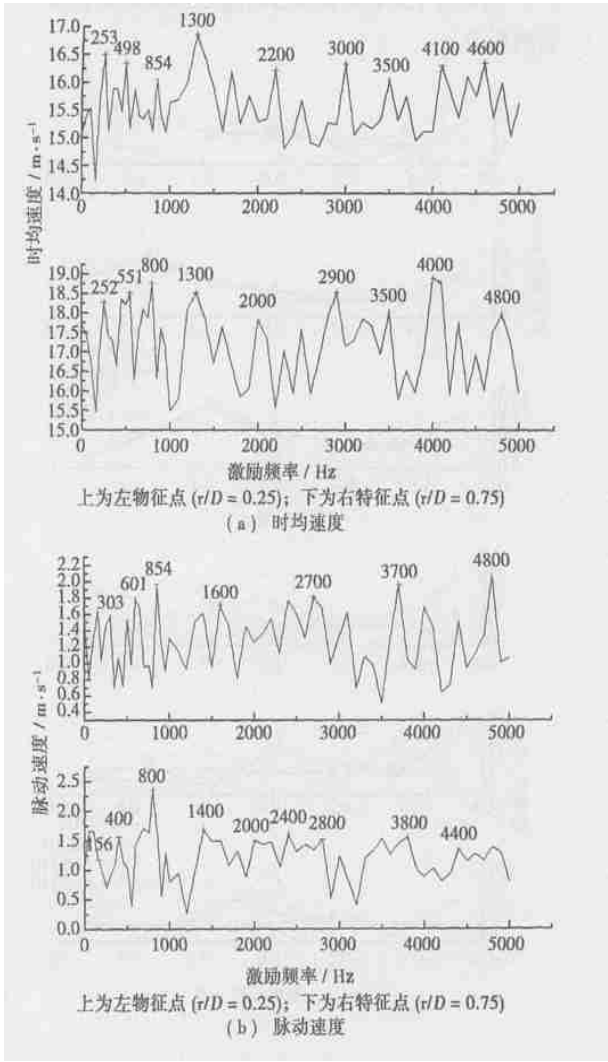
(b) 封装外型

图 2　悬臂梁式压电陶瓷激励器

3　实验结果与分析

实验分冷流和热流两个阶段进行。在冷流阶段, 主要测量燃烧器进口的悬臂梁式压电陶瓷激励参数变化对燃烧器内混合区域时均速度和湍流强度的影响; 热流阶段, 利用 TESTO360 进行测量, 考察悬臂梁式压电陶瓷激励对 NO_X 和燃烧温度的影响, 对悬臂梁式压电陶瓷激励改善燃烧器燃烧特性进行初步评估。

3.1　激励频率的选择



(a) 时均速度

(b) 脉动速度

图 3　燃烧器出口特征点速度随频率的变化

在激励器诸多参数中, 激励频率是核心参数之一, 其直接决定悬臂梁自由端涡脱落形成涡波的频率高低, 影响主流与涡波之间的耦合与发展和演化, 影响掺混区时均速度和湍流强度的分布规律, 对流动掺混非常重要, 是首先应考察的参数。实验中, 以燃烧器出口直径上两个半径中点处为特征点, 激励信号幅值保持 21 V 不变, 激励频率变化范围为 0 ~ 5 000Hz, 测量特征点处时均速度、脉动速度的变化,

验证激励频率对速度分布的影响(见图 3)。由实验结果可以看出,对于本燃烧器和配风条件(余气系数 $\alpha=1.1$),在 4 700 Hz, 2 100 Hz, 802 Hz 的激励频率下(对应的 S_t 数分别为 17.33, 7.74 和 2.95),时均速度和脉动速度较无激励(0 Hz)时变化明显,表明该频率对应的涡波与附面层中的 *T-S* 波和剪切层中的 *T-H* 波耦合效果最好,可作为后续详细测量的参考。

3.2 冷态下,压电陶瓷激励对掺混区横截面速度分布的影响

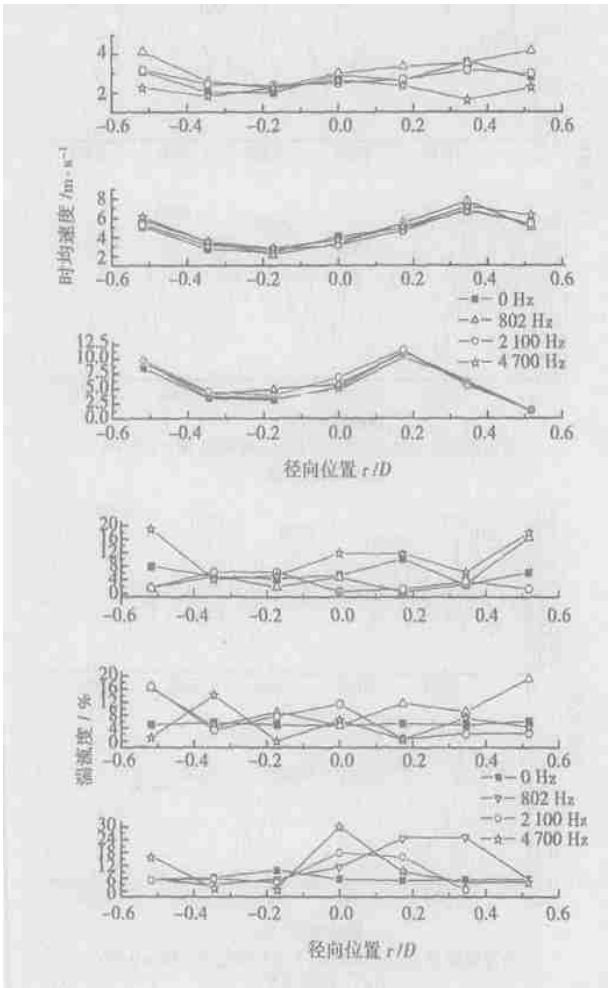


图 4 掺混区各截面时均速度和湍流度径向分布
(截面位置从上到下依次为 $x/D=0, 3, 6$)

压电陶瓷片自由端脱落的涡波在附面层内向下游传播的同时,不断地与附面层流动结构相互作用,引起助燃风管道内流动状态发生明显变化,进而影响掺混区内各截面时均速度和脉动速度之间的能量传递与转移,并造成横截面内径向分布的变化(见图 4 和图 5)。由图 4 可以看出:在流场上游(掺混开始区域),激励对时均速度和湍流强度的激励效果不明显,只是在个别位置的个别激励频率下时均速度有所改变;在流场的下游,声激励的加入对速度有了明显的影响,有无激励下速度对比较上游变化明显,且不同频率对不同截面的湍流度影响不同。另外,由图中可以看出:激励频率为 4 700 Hz 时时均速度总体的分布趋势小于无激励时的时均速度,由此可以推出此激励频率下的激励可以使掺混区域各截面的时均速度有不同程度的降低,而在其它频率下这个规律并不明显。

由燃烧器出口截面速度等值线分布(见图 5)可以看出:与时均速度径向分布相似,截面内等值线分布变化明显,比较密的区域减少,整体分布趋向均匀,说明出口截面的掺混已经很好。

3.3 压电陶瓷激励对掺混区轴向截面速度分布的影响

在轴向截面,压电陶瓷激励对时均速度和湍流度的分布影响也非常明显(见图 6 和图 7),具体表现为:沿中心线向下游方向上,有激励的时均速度值有所减小,湍流度曲线波动加大,而且频率的变化对时均速度的影响不大,但对湍流度的影响更明显些,这也体现了加入激励后能量主要从时均速度向脉动速度传递的规律。

由时均速度等值线分布(见图 7)可以发现:加入激励后,不但整个平面的各点时均速度大小有所变化,而且曲线分布也发生了明显改变,特别是激励频率在 4 700 Hz 时,轴线区域附近变化更为明显。速度场的变化会直接影响助燃风和天然气的混合,从而间接性影响燃烧过程的 NO_x 生成和温度高低。

3.4 压电陶瓷激励对燃烧器出口 NO_x 含量与燃烧温度的影响

热流实验中,在余气系数 $\alpha=1.1$,喷嘴形式为两孔和四孔条件下,考察燃烧器出口 NO_x 含量和燃烧温度随不同激励频率(0 Hz, 802 Hz, 4 700 Hz)激励电压(0 V、20 V 和 30 V)的变化情况(见图 8)。

由曲线发展趋势可以看出,对于两种喷嘴形式,都有:(1)随着电压的增大,温度和 NO_x 曲线都向上移动,即向着 NO_x 含量增加和温度升高的方向移动,表明扰动幅度增强导致掺混改善,燃烧趋向完全,NO_x 生成量增加;(2)随着频率的增大,温度和 NO_x 曲线都向上移动,即向着 NO_x 含量增加和温度升高的方向移动,但不是频率越高,NO_x 含量和温度就越高,表明激励频率的变化对 NO_x 的生成和温度的变化有一定的影响,也不是单调地增加或降低

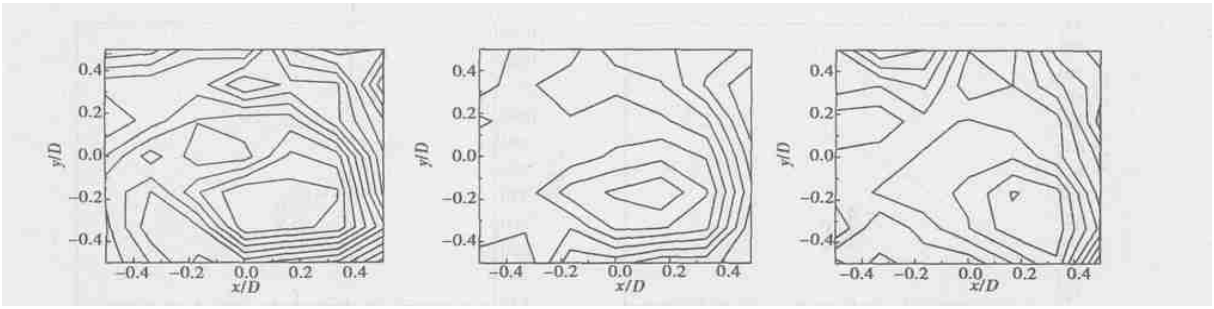


图 5　出口截面时均速度等值线分布(激励频率分别为 f=0, 802, 4 700 Hz)

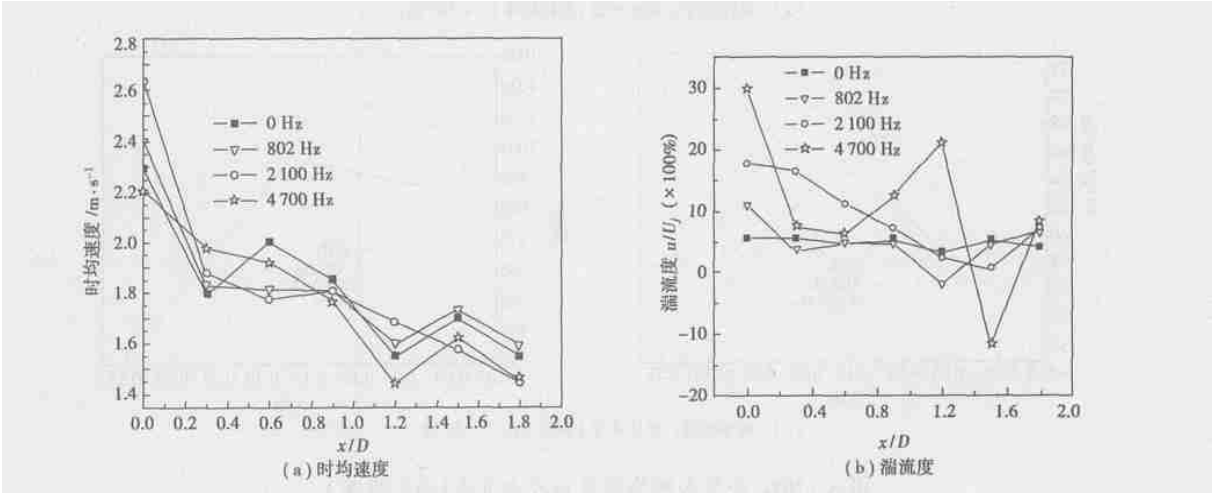


图 6　中心线上速度轴向分布

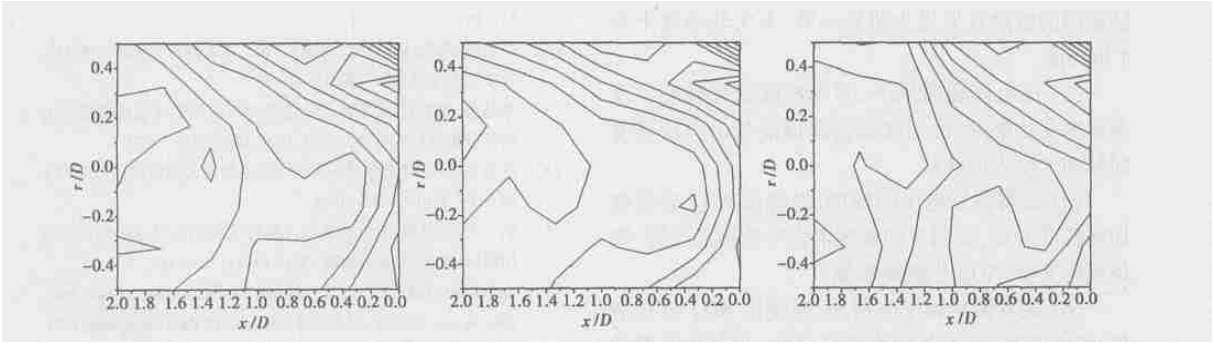


图 7　轴向截面时均速度等值线分布(激励频率 f=0, 802, 4 700 Hz)

的关系; (3)无论在频率变化下, 还是在电压变化下, NO_x 和温度分布都呈现山峰状, 即: 燃烧器截面的半径中间位置温度和 NO_x 含量都比较高, 其原因可能是由于在半径中间位置, 空气与燃气的量比较接近化学恰当比, 所以中部区域温度比较高, 燃烧产物中温度型 NO_x 含量也比较高。

4　结　论

通过上述冷流和热流实验结果分析, 可以得到以下结论:

(1) 各种频率的压电陶瓷激励对助燃风流动及与天然气的掺混都有一定效果, 但千赫兹量级的激

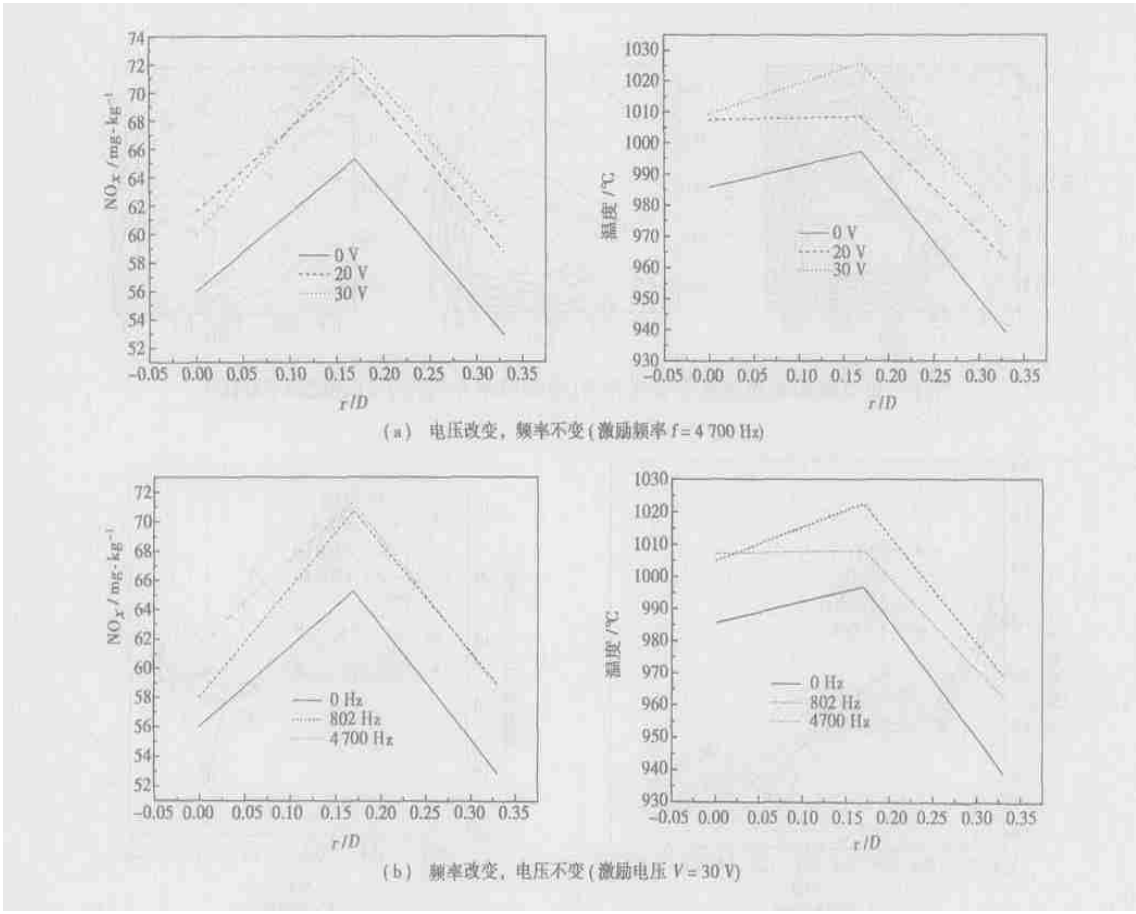


图 8 NO_X 含量和燃烧温度沿径向分布(两孔喷嘴)

励频率的激励效果更为明显一些，本实验条件下为 4 700 Hz。

(2) 压电陶瓷激励下，时均速度变化幅度不及湍流度变化幅度，说明激励会造成能量由时均速度向脉动速度方向转移。

(3) 随着激励电压的增加，燃烧器 NO_X 含量增加和温度升高，表明扰动幅度增强导致掺混改善，燃烧趋向完全，NO_X 生成量增加。

(4) 随着激励频率的增加，燃烧器 NO_X 含量增加、温度升高，但不是频率越高，NO_X 含量和温度就越高，表明激励频率的变化对 NO_X 的生成和温度的变化不是单调地增加或降低的关系。

参考文献：

[1] 赵果然，石艳君. 低 NO_X 燃烧技术综述[J]. 锅炉制造，2003(3)：15—16.

[2] 卢啸风，郑先国. 天然气再燃低 NO_X 技术的冷模试验分析[J]. 重庆大学学报，2003，**26**(5)：40—45.

[3] 余战英，蒋宏利，谭厚章，等. 浓淡型双调风旋流燃烧器低 NO_X 特性分析[J]. 热能动力工程，1999，**14**(6)：455—457.

[4] 肖理生. 分级燃烧最佳一次风空气系数的实验研究[J]. 动力工程，2001，**21**(1)：1042—1045.

[5] 赵 宏，娄慧鹃. 合成射流流动特性实验研究及在燃烧中的应用探讨[J]. 航空动力学报，2004，**19**(4)：512—519.

[6] SANG SOO LEE，LIU J C T. Multiple large-scale coherent mode interation in a developing round jet[J]. **Journal of fluid mechanics** 1993，**248**：383—401.

[7] GUTMARK E，PARR T P，HANSON-PARR D M，*et al*. Active shear flow control for improved combusion[R]. Long Beach：American Institute of Aeronautics and Astronautics，1990.

[8] SADRI A M，CROOK A，WOOD N J. The use of piezoceramics for development of syntheric jet actators for active flow control[D]. UK：Manchester School of Engineering，1999.

non-uniform distribution of parameters. A pair of spiral vortex with an opposite direction of rotation was formed in a plenum. The results of calculation were compared with those of experiments. **Key words**: numerical simulation, flow field, steam extraction opening, steam turbine

汽轮机空心静叶去湿缝隙结构的研究=**A Study of the Moisture-removal Slot Structure in the Hollow Stationary Blades of a Steam Turbine** [刊, 汉] / WANG Xin-jun, GAO Tie-yu, XU Ting-xiang (National Key Laboratory on Multi-phase Flows in Power Engineering under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(1). —14 ~ 17

On a test rig of air and water-film two-phase flows an experimental research was conducted of the relationship between the geometric shapes and dimensions of a moisture removal slot on the one hand and the moisture removal efficiency of the slot on the other. As a result, obtained were the correlation curves of slot angles, widths and moisture removal efficiency. An analysis was performed of the suction process and mechanism of the moisture removal slot in a hollow stationary blade and the impact of the slot suction on the main flow field in a cascade passage discussed. The results of the analysis show that a small slot angle can enhance the moisture removal efficiency of the slot and there exists a range of slot widths, which contribute to a relatively low efficiency of moisture removal. Under the present test conditions the slot width associated with a relatively low efficiency of moisture removal is found to be 1.0 - 1.5 mm. Moreover, when the front-end edge of the slot inlet is machined to form a transition round angle with a 1 mm radius, it is possible to enhance the moisture removal efficiency of the slot by more than 5%. On this basis proposed are the basic design principle of a moisture removal slot and rational slot structure shape and dimensions for the hollow stationary blades. **Key words**: hollow stationary blade, moisture removal slot, structural design

焦炭流化床燃烧条件下氧化亚氮生成过程的实验研究=**Experimental Investigation of Nitrous Oxide Formation During the Combustion of Coke in a Fluidized Bed** [刊, 汉] / REN Wei, LU Jun-fu, ZHANG Jian-sheng, et al (Department of Thermal engineering, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(1). —18 ~ 21

On the test rig of a small-sized fluidized bed an experimental research was conducted of the formation of nitrous oxide during the combustion of anthracite coke. It has been found that the oxidation reaction of HCN during the combustion of the coke represents an avenue of conversion of coke nitrogen to N_2O. At the same time the multi-phase reaction of NO and coke surface is also a kind of generation path of N_2O. The separation-out of HCN is a result of the further devolatilization during the combustion of coke. On completion of the coke devolatilization process N_2O has originated from the gas-solid multi-phase reaction of NO and coke surface. **Key words**: coke combustion, nitrous oxide, formation path

压电陶瓷激励影响燃气燃烧器性能的实验研究=**Experimental Study of the Impact of Piezoelectric Ceramics Excitation on the Performance of a Gas Combustor** [刊, 汉] / ZHAO Hong, YANG Zhi-guo, LOU Hui-juan (Energy and Power Engineering Institute under the Beijing Astronautics and Aeronautics University, Beijing, China, Post Code: 100083) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(1). —22 ~ 26

By using a hot wire anemometer and a TESTO 360 gas analyzer measurements were taken respectively of the cold and hot-state conditions of a gas combustor under the excitation of piezoelectric ceramics. Investigated mainly was the impact of piezoelectric-ceramic excitation frequency and amplitude magnitude on the velocity field of a mixing-dilution zone, the NO_X generation rate at the combustor outlet and the distribution of temperature. Test results indicate that the piezoelectric-ceramic excitation of various frequencies has a definite effect on the flow of combustion-assisting air and the mixing-

dilution of natural gas with the combustion-assisting air. However, the excitation effect of excitation frequency of KHz magnitude is somhow more pronounced and the time-averaged velocity variation caused by the excitation is weaker than the variation of turbulence. Under the excitation of the piezoelectric ceramics the NO_X generation rate of the combustor and the temperature of combustion have, to a certain extent, been enhanced, indicating a combustion process tending to be more complete. **Key words**: piezoelectric ceramics, diffusion combustion, low pollution, active flow control

不同催化剂对脱矿煤焦还原NO的催化能力比较= **A Comparison of the Catalytic Ability of Various Catalysts for the NO Reduction of Demineralized Coal Char** [刊, 汉] / TANG Hao, ZHONG Bei-jing (Department of Engineering Mechanics, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy &Power. — 2005, 20(1). —27~29, 68

Through tests an investigation was conducted of the catalytic action of the oxides of metals (K, Na, Cu, Fe, Ca) commonly encountered in coal ash for NO reduction of coal char. To compare the catalytic ability of these metal oxides for NO reduction reaction of coal char, the latter has been subjected to a demineralization treatment. The test was completed in a high-temperature sedimentation furnace. The pulverized coal and coal char used in the test have been derived from lignite of Shenfu. The test results indicate that the minerals in the coal ash possess catalytic function for the heterogeneous NO reduction of coal char. Under the test conditions the catalytic ability of different metal oxides for NO reduction of coal char assumes the following sequence: K> Na> Ca> Cu> Fe. The test results also indicate that test conditions (temperature, SR number) and the added quantity of catalysts will more or less influence the process of NO reduction. **Key words**: demineralized coal char, NO catalytic reduction, catalyst

相变换热适时动态过程数值模拟= **Numerical Simulation of a Transient Dynamic Process for Phase-transition Heat Exchange** [刊, 汉] / YAO Zhe-qing, YUAN Zhu-lin (Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology under the Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy &Power. — 2005, 20(1). —30~33

With a steam condenser serving as a physical model a dynamic model of transient distributed parameters was set up with divided zones and divided flow patterns. During the setting-up of the model some specific details have been taken into account, such as fluid transient physical-property parameters, liquid content in wet zones, flow pressure losses and tube-wall heat accumulation, etc, thereby markedly enhancing the accuracy and usage scope of the model. In the process of simulation a computer can on the basis of a refrigerant condition automatically check and select corresponding physical-property parameters from an established physical-property database. The model adopts an explicit-type equation group, which expedites resolution speed. With the help of the model it is possible to conduct the non-steady performance study of a condensation heat-exchange process, acquiring a time-dependent variation process, such as the cold and hot fluid temperature, pressure and condensation state, etc during a heat-exchange process. By way of an experimental verification it has been shown that the model under discussion features relatively high precision. **Key words**: condensation heat exchange, transient dynamic parameters, numerical simulation

基于现场数据与神经网络的热工对象动态建模= **Dynamic Modeling of a Thermotechnical Object on the Basis of On-site Data and a Neural Network** [刊, 汉] / ZHANG Xiao-tao, NI Wei-dou, LI Zheng, et al (Thermal Energy Department, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). —34~37

On the basis of a neural network one can set up a linear or nonlinear dynamic mathematical model for a thermotechnical