新能源动力技术

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新型低热损失微燃烧器原型的实验研究

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摘 要: 试验研究了一种降低微燃烧器热损失的新方式, 其原理是通过多孔壁面均匀进气来预热未燃混合气, 同时降低壁面温度, 从而有效降低燃烧器热损失。结果表明: 采用燃烧器周向供给富燃料混合气, 端面中心供给空气的组合进气方式, 可以在微燃烧器内形成稳定的管状预混合火焰, 火焰呈蓝色, 燃烧稳定。当火焰温度达到 1 100 ℃以上时, 燃烧器内壁的温度低于 500 ℃, 外壁面温度在 150 ℃左右, 微燃烧器的侧壁面热损失率约为 6%, 对于强化微燃烧器的火焰稳定性效果显著。

关 键 词: 微燃烧器; 微尺度火焰; 热损失; 多孔介质

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引 言

目前毫瓦级到瓦级的电源在军事、航空航天、传感器、微/小型日用电子产品、便携式仪器和办公设备等方面需求广泛。已有的独立电源包括传统一次性化学电池、高性能锂/镍氢充电电池等, 高效率的微型燃料电池也在快速发展中。与它们相比, 基于燃烧的微动力/发电系统直接燃烧炭氢燃料, 具有更高的能量密度。其原理是利用微型热机和微型发电机将微燃烧器内产生的热能转换为电能, 或者通过温差热电和热光伏直接转换产生电能。目前国内外开发的微动力/发电系统特征尺寸从几毫米到几十毫米, 输出功率范围为毫瓦到瓦的量级。由于尺度效应和热损失严重, 现有的微动力/发电系统发电效率还比较低, 系统原型试验发电效率在 1.0%左右[1~3]。

微燃烧器的热损失率与 S/V(表面积/体积)和外壁面温度成正比, 微燃烧器的S/V 比常规尺度下要大 2~3 个数量级, 热损失的增加导致火焰不稳定、熄火、热效率降低等[1,4]。此外, 高的壁面温度也是微燃烧器热损失增加的主要原因, 由于 *Bi* 数小, 微尺度下燃烧室壁面温度接近火焰温度。现有一些采用再热的方法降低微燃烧器热损失的研究报道, 如MIT 最近开发的微透平燃烧器采用了回热通道技术[5], 瑞士面包圈(Swiss-roll)结构的微燃烧器采用了缠绕通道超焓技术与催化燃烧结合的方法[6]。

本文提出一种新的降低微燃烧器壁面热损失的方法, 即微燃烧室壁面采用多孔材料, 改变通常的局部喷入可燃气方式为壁面均匀进气, 冷物料与燃烧器的散热方向相反, 由多孔介质壁面进入的未燃气被预热的同时也有效地降低壁面温度, 并进行了试验, 可望减少微燃烧器的热损失, 提高燃烧稳定性。

1 工作原理

图 1 为低热损微燃烧器的工作原理示意图。低温未燃混合气在穿过多孔壁面时, 与多孔壁面进行高效换热, 混合气被预热, 多孔壁面被冷却, 火焰向燃烧室内壁面传递热量(Q), 大部分被预热的未燃混合气带回燃烧室, 因此, 壁面热损失 $Q_{损失}$ 仅占 Q 很小比例, 从而有效降低热损失。其次, 在壁面附近形成一层很薄的未燃气膜将多孔壁面与火焰面隔开, 由于未燃气膜内气流速度与热量传递方向相反, 可有效隔断高温气流与多孔壁面之间的对流换热, 使得火焰向壁面的传热量 Q 减少。

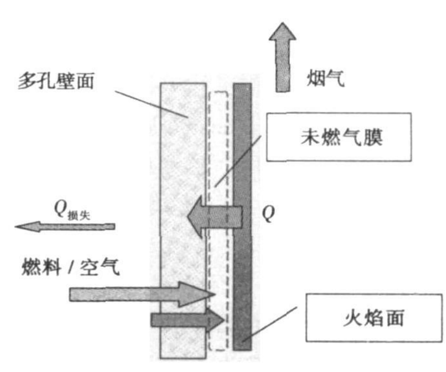

图 1 低热损微燃烧技术原理示意图

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2 实验装置

为了验证多孔壁面微燃烧器热损失降低和稳定燃烧强化原理，本文设计了圆柱型多孔壁面均匀进气微燃烧器并进行了燃烧实验。实验系统简图如图 2 所示，甲烷和空气分别经减压阀后，由质量流量计计量和混合后进入燃烧器，实验工况需要的燃料和空气流量通过质量流量计控制，燃烧器壁面和燃烧室内的温度设有多个直径为 0.2 mm 的 K 型热电偶进行测量，Agilent 34970A 多通道数据采集模块进行温度数据采集。点火系统采用 13～15 kV 直流脉冲电点火，火焰形态采用数码相机直接拍照记录。

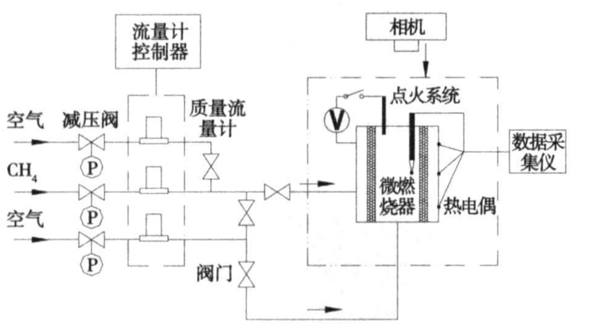


图 2 微尺度燃烧实验系统简图

图 3 为微燃烧器结构及热电偶布置位置图示，多孔壁面为内径为 10 mm 的多孔铜烧结材料，壁面厚度为 2.5 mm，高 19.5 mm，孔隙率为 37％。燃烧器外壁面材料为金属铝，分别在燃烧器端面和侧壁面开设进气口，侧面为 180° 对称布置两个进气口。燃烧器外壁面温度测量点为 T_1、T_2、T_3，出口截面多孔壁面内外温度（测点 T_b、T_a），多孔材料内壁面温度测量热电偶从燃烧室出口引入（测点 T_c、T_7、T_8、T_9），多孔壁面外壁面温度测量热电偶从进气侧引入（测点 T_4、T_5、T_6），燃烧室内温度场由可在轴向和径向移动的热电偶 T_0 进行测量。

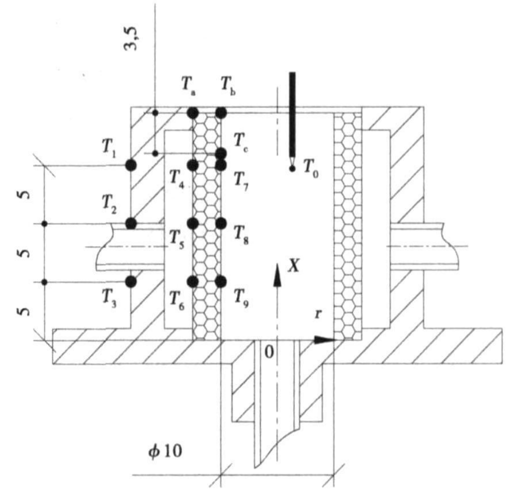


图 3 微燃烧器结构及热电偶布置位置

3 实验结果及讨论

3.1 进气方式对燃烧器内火焰形成的影响

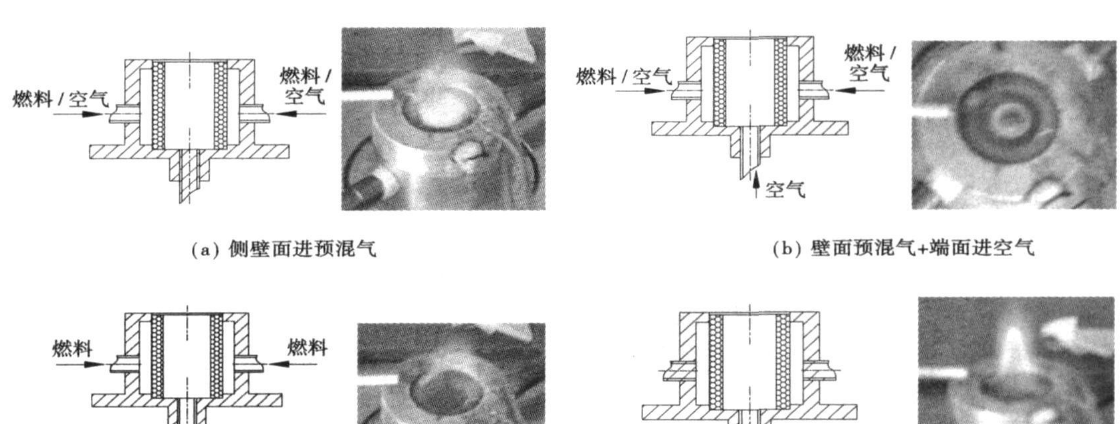


图 4 进气方式及对应火焰形态

为考察把通常的喷管局部喷入可燃气改为壁面均匀进气能否在微小的燃烧器内形成稳定的火焰，在总的燃料/空气混合气流量和燃料当量比一定的前提下(燃料: Q_{CH_4} = 97.6 ml/min; 空气: Q_{total} = 844 ml/min; 燃料当量比 ϕ = 1.1)，针对 4 种不同的组合进气方式，观察了微燃烧室内的火焰形态变化，实验结果如图 4 所示。图中(a)进气方式的火焰稳定在出口附近;(b)进气方式是部分空气从端面中心进入，富燃料混合气从多孔壁面进入，这种方式下火焰可以稳定在燃烧室内;(c)采用进气方式时，火焰在燃烧室外形成，燃烧室内无火焰;(d)进气方式，相当于传统进气方式，形成射流火焰大部分工况是在燃烧室外。上述结果表明，采用壁面均匀喷入预混合气有利于在燃烧室内形成稳定的火焰。

3.2　空气流量分配对火焰形成的影响

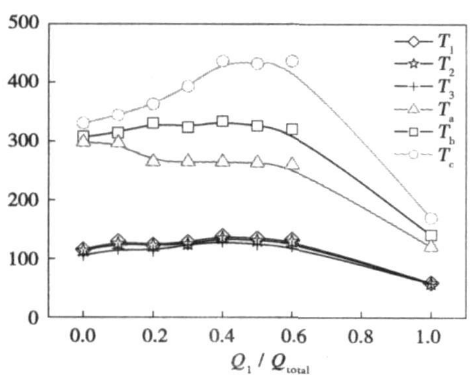
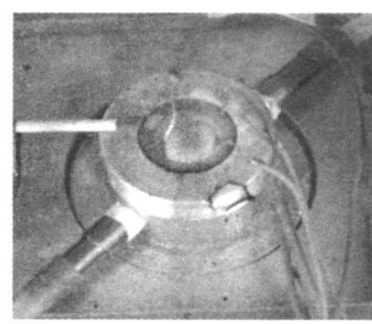


图 5　空气流量分配对燃烧过程的影响

采用侧面喷入预混合气、端面喷入空气的方式容易在微燃烧器内获得稳定火焰，但是，在总的预混合气流量和当量比不变的条件下(燃料: Q_{CH_4} = 97.6 ml/min; 空气: Q_{total} = 844 ml/min; 燃料当量比 ϕ = 1.1)，空气量的分配对燃烧器内的火焰形成有较大的影响。图 5 为不同空气分配比例时试验测试的微燃烧器不同测点处的温度变化情况。图中: Q_1 为端面空气流量; Q_{total} 为总空气流量，Q_1/Q_{total} = 0 对应进气方式见图 4(a); Q_1/Q_{total} = 1.0 对应进气方式见图 4(c)。由图可知，在 $0 < Q_1/Q_{total} \leq 0.6$ 范围内，随 Q_1/Q_{total} 的增加，f 点温度逐渐增大，表明火焰位置由空气出口向燃烧室内移动，火焰在燃烧室内趋向稳定。增加空气流量对稳定燃烧有利，其原因分析为端面中心射流可以在燃烧室内前部附近形成小的卷吸回流，使得火焰容易在燃烧室进口处稳定。过低的 Q_1/Q_{total} 值不能形成卷吸回流，火焰稳定效果差，而过高的 Q_1/Q_{total} 值使得多孔壁面进气混合气当量比增大，燃料与空气还需要在燃烧室小空间内进一步混合，也不容易形成稳定火焰，Q_1/Q_{total} = 0.3～0.6 时，火焰稳定效果较好。

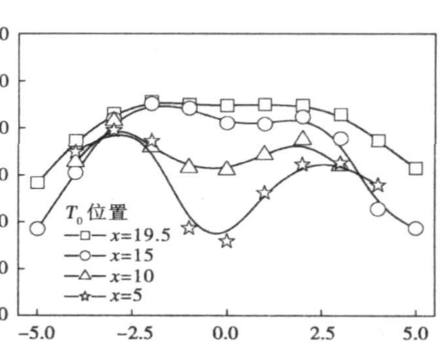
3.3　微燃烧器内的火焰结构及燃烧特性

图 6 为拍摄的微燃烧器内火焰形态，其特征为圆柱面蓝色火焰，微燃烧器内形成稳定火焰时的温度分布如图 7 所示。火焰面位置(即高温区)位于 r = 2.5～3.5 mm，在壁面附近存在较大的温度梯度，火焰面温度显著高于壁面附近测点的温度。由图 7 可见，火焰在燃烧器整个轴向长度存在，如在 x = 5 mm 位置，即在靠近前端面附近火焰已经形成，很好地利用了燃烧室空间组织燃烧。由于所形成的柱面火焰结构使得燃烧室多孔介质壁表面附近都形成了均匀的燃烧区域，因而在同样的燃烧器体积下，采用本文提出的火焰组织方式得到的火焰面积比通常的射流火焰要增大几乎 1 个数量级(柱面侧面积/圆截面面积)，因而新型多孔介质微燃烧器的热负荷可以大大提高。



实验工况: 燃料 134 ml/min; 空气 1 279 ml/min; ϕ = 1.0; Q_1/Q_{total} = 0.3

图 6　微燃烧室内火焰形状



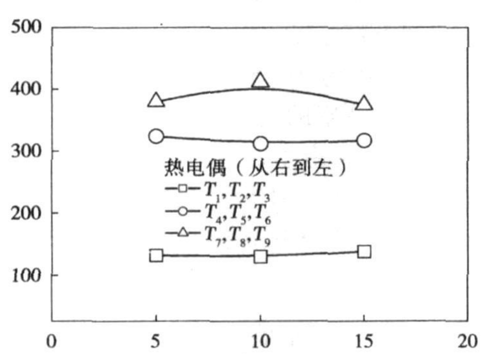
实验工况: 燃料 134 ml/min; 空气 1 279 ml/min; ϕ = 1.0; Q_1/Q_{total} = 0.3

图 7　微小燃烧室内温度分布

另一方面, 在相同的混合气流量时, 多孔壁面均匀进气使得预混合气的流速减小, 相应延长燃烧反应区内反应物的停留时间; 再者, 未燃混合气穿过多孔壁面时, 被燃烧器向环境的散热预热, 缩短了燃烧反应开始所需的预热时间。上述几个原因都强化了微燃烧器内的稳定燃烧。

3.4　微燃烧器的热损失

本节重点讨论新型微燃烧器的热损失情况, 图 8 是燃烧室(多孔材料)内、外壁面和燃烧器外壁面温度分布的测量值。在燃烧室出口烟气温度高于 1 100 ℃时(如图 7 所示), 多孔材料内壁面温度为 400 ℃左右, 多孔材料外壁面温度在 300 ℃左右, 而燃烧器的外壁面温度在 150 ℃左右, 图 5 中多个工况下燃烧外壁面 T_1、T_2 和 T_3 也均低于 150 ℃, 说明采用多孔壁面喷入未燃气有效地降低了燃烧器壁面温度。与其它微燃烧器相比较, 采用回热微透平燃烧器出口烟气温度在 800 ℃左右时, 其燃烧室外壁面温度高于 600 ℃[5], 如果不采用回热结构, 燃烧器外壁面温度几乎接近火焰温度[2], 而本文提出的多孔壁面微燃烧器, 在考虑外壁面辐射换热和自然对流换热时由试验值计算得到的侧壁面热损失率约为 6%。



实验工况: 燃料 134 ml/min; 空气 1 279 ml/min; $\phi = 1.0$; $Q_1/Q_{total} = 0.3$

图 8　微燃烧器的温度分布实测值

4　结　论

(1) 实验表明, 采用多孔壁面均匀进气的方式组织微/小空间内燃烧, 可以显著降低微燃烧器的壁面热损失。

(2) 多孔壁面进气对改善微燃烧器的燃烧特性有利, 较好的火焰组织方式是壁面喷入预混合气, 端面喷入部分空气。

(3) 柱型多孔壁面微燃烧器内形成的火焰为蓝色管状, 壁面附近的温度梯度大, 壁面温度远低于火焰温度。当燃烧室内火焰温度超过 1 100 ℃时, 燃烧器外壁面为 150 ℃左右, 微燃烧器的热损失率约为 6%。

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tion-control Algorithm[刊，汉]/LI Hui-min, HE Yong (College of Mechanical Engineering, Donghua University, Shanghai, Post Code: 200051), ZENG Sheng (Chemical Machinery Research Institute, Zhejiang University, Hangzhou, Post Code: 310027)//Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —78～82

A kind of supporting structure for the on-line regulation of rotor shaft position, namely, an electromagnetic auxiliary support, was introduced by the authors. An on-line regulation of the rotor shaft position in space can be conducted by controlling the current in an electromagnetic actuator coil, and the out-of-alignment between rotor system shaftings, eliminated. The additional vibration caused by the out-of-alignment is considered as a kind of interference. An identification and control of the out-of-alignment can be automatically realized under the condition of a running rotor by adopting a self-searching optimal control algorithm and feedforward control algorithm with self-learning functions. Finally, an experimental verification and comparison was performed in a single-disk symmetrical rotor-bearing system. The experimental results show that both control methods have a relatively good correction ability for the out-of-alignment between shaftings. Moreover, for the out-of-alignment self-searching optimal controller, there is no need to establish an accurate mathematical model expression for an out-of-alignment system and the demands to displacement sensors are not high but a relatively long searching time is required. The out-of-alignment feedforward self-learning controller is also exempt from the need to establish an accurate mathematical model. It takes a relatively short search time, but puts forward comparatively high demands to displacement sensors. **Key words**: electromagnetic bearing, out-of-alignment, feedforward control, self-searching optimal control

轴颈偏斜对径向滑动轴承静态性能的影响＝**Effect of Journal Deflection on the Static Performance of Radial Sliding Bearings**[刊，汉]/WANG Xiao-hong, ZHOU Da-yuan, SHI Yu-quan, et al (No. 703 Research Institute of China Shipbuilding Industry Corporation, Harbin, China, Post Code: 150036)//Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —83～87

The effect of journal deflection on the static performance of radial sliding bearings was studied, and an oil film thickness expression derived in the case of journal deflection. During the calculation the temperature variation has been taken into account. Reynolds Equation, energy equation and temperature-viscosity equation have been simultaneously solved. The authors have calculated the pressure and temperature distribution on the bearing at different deflection angles and oblique orientations as well as the static performance of the bearing at different eccentricities and deflection angles. It has been shown that when the journal is being deflected, the distribution of oil film thickness, pressure and temperature changes significantly and the minimum oil film thickness appears at the ends. In the meantime, the maximum oil film pressure and temperature all tend to move to the bearing ends and exercise a relatively conspicuous influence on the static performance of the bearing. With an increase of the deflection angle the oil film reaction force will increase, but the drag coefficient, decrease. The law governing the influence of oil leakage at bearing ends reveals itself as different at different bearing eccentricities. **Key words**: journal deflection, radial sliding bearing, temperature variation, energy equation, static performance

新型低热损失微燃烧器原型的实验研究＝**Experimental Study of a Novel Miniature-burner Prototype with a Low Heat Loss**[刊，汉]/JIANG Li-qiao (Department of Thermal Science and Energy Source, China State University of Science and Technology, Hefei, Post Code: 230026), ZHAO Dai-qing, WANG Xiao-han, YANG Wei-bin (Chinese Academy of Sciences Guangzhou Institute of Energy Conversion, Guangzhou, Post Code: 510640)//Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —88～91

An experimental study has been conducted of a new method for reducing the heat loss of a miniature burner, the working principle of which lies in its preheating of unburned gas mixture by admitting gas uniformly through porous wall surfaces and in the meanwhile by reducing the temperature of the wall surfaces, thus effectively lowering the heat loss of the burner. The experimental results show that the adoption of a combined gas admission mode of supplying the burner with fuel-rich gas mixture in a circumferential direction and air from the central portion of end wall surfaces can contribute to the formation of a stable tubular premixed flame inside the miniature burner, the flame assuming a blue color and burning steadily. When the flame temperature reaches a level higher than 1100 ℃, the burner inner wall temperature will be lower

than 500 ℃, while the burner outer wall temperature will be around 150 ℃ and the heat loss from side walls of the burner, approximately 6%, thus significantly enhancing the flame stability of the burner. **Key words**: miniature burner, micro flame, heat loss, porous medium

黑液水煤浆燃烧试验研究＝**Experimental Study of Black-liquor Coal Slurry Combustion**[刊, 汉] / LAN Ze-quan (College of Safety Engineering, North China Institute of Science and Technology, Yanjiao, Post Code: 065201), CAO Xin-yu, LIU Jian-zhong, CHENG Jun (National Key Laboratory on Clean Utilization of Energy Source, Zhejiang University, Hangzhou, Post Code: 310027)//Journal of Engineering for Thermal Energy & Power. －2008, 23(1). －92～96

To investigate the feasibility and potential problems of the industrial application of the black-liquor coal slurry, a contrast study was conducted of the ignition, combustion, pollutant emissions and ash deposition characteristics of black-liquor slurry, raw coal for slurry preparation and normal slurry through the combustion tests on three different scales, i.e. thermobalance mechanism tests, 0.25 MW test furnace and 4 t/h industrial furnace. The results of the study show that when compared with raw coal, the black-liquor slurry has the following specific features due to the catalytic and combustion-promoting function of sodium: easy ignition, stable combustion, short combustion duration, a high burnout rate and low emissions of such pollutants as SO_2, NO_x and dust etc. As a result, the slurry in question is considered as a new type of clean fuel. On this basis, the authors have concluded that it is absolutely feasible to use the coal water slurry technology to dispose of and harness the papermaking black liquor. The industrial application of the black liquor slurry is associated with such potential problems as a relatively strong tendency for ash deposition and slag formation in furnaces. **Key words**: black liquid coal slurry, thermogravimetric analysis, combustion characteristics, industrial test

固体氧化物燃料电池输出电压前馈－反馈控制＝**A Feedforward-feedback Control Over the Output Voltage of a Solid Oxide Fuel Cell**[刊, 汉] / KANG Ying-wei, CAO Guang-yi, TU Heng-yong, et al (Fuel Cell Research Institute, Shanghai Jiaotong University, Shanghai, Post Code: 200240)//Journal of Engineering for Thermal Energy & Power. －2008, 23(1). －97～101

Based on the relationship among the static values of SOFC (solid oxide fuel cell) operational parameters, the operation of a SOFC at a constant output voltage was analyzed. The authors have noted that SOFC operation at a constant output voltage requires the fuel utilization rate to meet a definite restraint apart from keeping the output voltage constant. Furthermore, an output voltage controller was designed by adopting the feedforward-feedback control tactics, among which the feedforward controller was designed based on the relationship among the static values of SOFC operational parameters. In this process the key issue was the solution of a cubic equation by making use of Cardano's Formula. As a PI controller, the feedback controller was designed by adopting a frequency-response method after the linearization of the SOFC model. The simulation results show that the feedforward-feedback control presented by the authors boasts a better dynamic performance than the single feedback control, and can fully meet the requirement for an operation at a constant output voltage when the load changes are within its normal range. **Key words**: solid oxide fuel cell (SOFC), automatic control technology, output voltage control, feedforward-feedback control tactics