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多孔介质往复流动燃烧的一维数值模拟

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摘 要: 建立了往复流动多孔介质燃烧器的一维数学模型; 在该系统中, 可燃预混气周期性换向, 分别从两端流入燃烧器。假定气相与固相处于局部热平衡状态, 考虑了辐射换热的影响。采用有限容积法求解, 通过大量数值计算研究了主要工况参数, 如半周期、流速、当量比、热损失、多孔介质衰减系数及其热容对该燃烧系统温度分布和反应特性的影响。计算结果与实验结果在定性上吻合良好。

关 键 词: 多孔介质; 往复流动; 超绝热燃烧

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1 引 言

在经历了 20 世纪 70 年代的能源危机和几次重大的城市环境污染事故之后, 西方学者开始研究一种新型的燃烧技术, 即预混合气体的超绝热燃烧技术, 来降低排放、提高燃烧效率和燃烧器整体的热效率[1]。所谓超绝热燃烧技术, 就是将预混合气体通入到装有多孔介质的燃烧器中燃烧, 由于多孔介质具有很好的导热和辐射性能, 燃烧释放的热量除了被尾气带走, 还可以被传输至上游预热气体(热反馈), 这样就有可能产生比绝热燃烧还要高的温度。实验表明, 这种燃烧机制大大拓宽了低热值燃料的可燃极限, 在较低当量比条件下, 燃烧所排放出的污染物浓度也达到非常理想的水平[1]。

为了更进一步地拓宽燃烧极限, 人们又提出了往复流动超绝热燃烧技术, 即将燃气在一定的时间间隔(半周期)内, 依次分别从燃烧器两端通入, 混合气体不停地流过上个半周期的火焰的下游区域, 吸收由多孔介质储存的上个半周期的尾气余热, 从而提高了燃烧器的蓄热能力。实验的结果表明, 与单向流动燃烧相比, 往复流动燃烧的可燃极限较低, 甚至可以达到当量比 0.026 的水平[2~3]。

文献[4] 报道了我们对多孔介质往复流动燃烧器的实验研究结果, 本文主要是想通过数值模拟来分析研究往复超绝热燃烧系统的燃烧特性。

2 数值模拟

2.1 问题描述

实验设备如图 1 所示[4]。燃烧器中填充有 264 mm 长的多孔介质(中间为 20 mm 的空气段, 点火装置安装在此处)。在燃烧器两端, 安装有换热器。整个燃烧器外壁都采用了良好的绝热措施, 其热损失不会超过燃气热值的 10%。实验中, 通过控制管路上的两组四个阀门交替开关来实现气流的换向。燃烧气是甲烷和空气的均匀混合物。

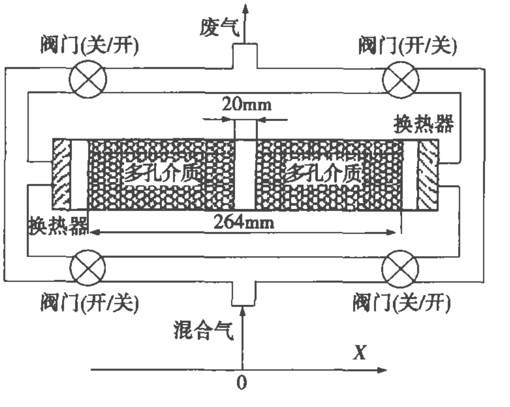

图 1 往复流动燃烧装置

2.2 控制方程

模拟区域选为长 2 l 的多孔介质区域(中间的空气段对燃烧影响不大), 气体和固体的热物性参数都是随温度变化的, 它们均取自于文献[5~8]。简化起见, 研究中作了如下假设:

(1) 与气体相比, 多孔介质有着良好的导热性能和辐射能力, 而且整个燃烧室绝热良好, 故可将此

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问题简化为一个一维的问题;

(2) 固相和气相间存在着局部热平衡,即在任何一处它们的温度相等;

(3) 多孔介质为光学厚介质;

(4) 气体的导热和辐射相对于多孔介质来说可以忽略掉;

(5) 将化学反应简化为单步总体反应,即:

$$CH_4 + 2\varphi^{-1}(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 2(\varphi^{-1} - 1)O_2 + 2\varphi^{-1}(3.76N_2)$$

各组分的生成率:

$$W_i = M_i(v''_i - v'_i)C_{\mathrm{fuel}}C_{O_2}A_r e^{-E/(RT)}$$

基于上述假设,控制方程简化为:

(1) 状态方程:

$$\rho = p/RT$$

(2) 连续方程:

$$\varepsilon \frac{\partial \rho_g}{\partial t} + \frac{\partial}{\partial x}(\rho_g v) = 0$$

其中:ε— 孔隙率。

(3) 动量方程:

$$\varepsilon \frac{\partial}{\partial t}(\rho_g v) + \frac{\partial}{\partial x}(\rho_g v v) = -\frac{\partial p}{\partial x} + \mu \frac{\partial^2 v}{\partial x^2}$$

(4) 能量方程:

$$(1-\varepsilon)\frac{\partial}{\partial t}(c_s\rho_s T) + \varepsilon\frac{\partial}{\partial t}(c_g\rho_g T) + \frac{\partial}{\partial x}(c_g\rho_g T v) = \frac{\partial^2}{\partial x^2}(k_{\mathrm{eff}}T) - \frac{\partial}{\partial x}\left(\sum_i h_i J_i\right) + \varepsilon\Delta H W_{CH_4} - \beta(T - T_0)$$

假设多孔介质为光学极厚介质,其辐射传输热可由 Rosseland 模型来近似描述[9]:

$$q_x(x) = -\frac{16}{3}\frac{\sigma T^3}{\alpha}\frac{\mathrm{d}T}{\mathrm{d}x}$$

由于上述形式有着与热传导项相似的表达,故能量方程中的有效导热系数 $k_{\mathrm{eff}} = k_e + k_r$;其中,$k_r = \frac{16}{3}\frac{\sigma T^3}{\alpha}$;α是衰减系数($m^{-1}$);σ是斯蒂芬波尔兹曼常数 5.672×10^{-8} W/(m^2·K);k_e 是气体和固体的等效导热系数,其计算方法见文献[10]。

$\beta(T - T_0)$ 表征壁面热损失,单位截面积瞬时的热损失可由下式求得:

$$H_{\mathrm{loss}} = \int_{-l}^{l}\beta(T(x) - T_0)\mathrm{d}x$$

则,$H_{\mathrm{loss}}A = \eta Y_{CH_4}\dot{m}\Delta H$。

为了以后讨论方便,规定热损失所占进口热值的百分比 η 是一定的,这样就需要根据热损失百分比求出随时间变化的热损失系数 β,则在数值模拟中,令:

$$\beta = \frac{\eta Y_{CH_4}\dot{m}\Delta H}{A\sum_{i=1}^{n}(T(i) - T_0)\delta x}$$

(5) 组分方程:

$$\varepsilon\frac{\partial}{\partial t}(\rho_g Y_i) + \frac{\partial}{\partial x}(\rho_g v Y_i) = -\frac{\partial}{\partial x}J_i + \varepsilon W_i$$

2.3　边界条件

计算域取为长 $2l$ 的多孔介质区域,中间的空气段暂不考虑。边界条件简化为:

进口:$T = T_0 = 298$ K,$Y_{CH_4} = Y_{CH_4,\mathrm{in}}$,$Y_{O_2} = Y_{O_2,\mathrm{in}}$,$v = v_{\mathrm{in}}$;

出口:$\frac{\partial T}{\partial x} = 0$,$\frac{\partial Y_{CH_4}}{\partial x} = 0$,$\frac{\partial Y_{O_2}}{\partial x} = 0$,$\frac{\partial v}{\partial x} = 0$,

2.4　初始条件和求解

求解时借助 CFD 软件包 Fluent,为了模拟点火过程,初始状态和开始阶段的燃烧浓度较大(当量比 0.5),且初始时刻将燃烧器中间区域(4 cm 长)设置为高温(1 100 K),待燃烧稳定后,燃料浓度变为正常。在换向时,为了保证收敛的稳定,进口速度在短时间内(根据流速的不同,在 0.2~0.4 s 间)逐渐变小,此半周期结束;另一半周期开始后,进口速度变为正常进口速度。

3　结果和讨论

计算的结果与实验取得了相同的趋势,但是温度场的最高温度较实验为高。其主要原因并非计算中部分工况没有考虑热损失,而是计算采用了单步反应模型[11]。

3.1　燃烧器温度场在一个周期内的变化

往复流动燃烧器内的温度场、组分场等的分布在正、反两个半周期相对应的时刻里是以燃烧器的中间点为基准对称的,本文中只介绍正向流动的半个周期里燃烧器内各变量的变化情况。换向前的处理,如前所述,是经过一段短暂的时间(本工况经过 0.2 s),将进口流速降为较小的流速(本工况为 0.07 m/s)。图2表示了正向(从左向右)半个周期内组分场、温度场、反应率的分布及变化。

图2(a)是正向流动开始时,即逆向流动的最后状态。此时,进口流速已经减小为 0.07 m/s,反应率已有所下降。换向后,原来的出口变为进口,在此进口附近处,受到尾气预热的燃料迅速反应,形成一个

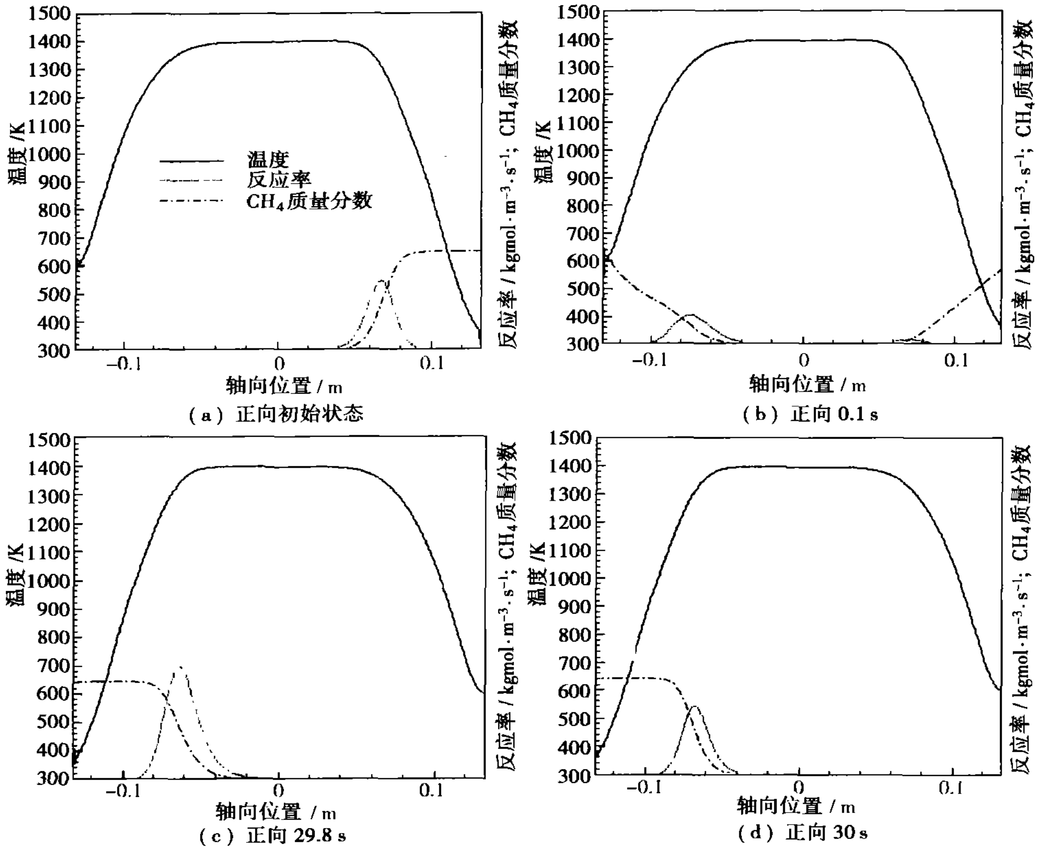

图 2 往复流动燃烧系统正向半周期内温度场、组分场、反应率分布图；工况：0.15 m/s，半周期 30 s，当量比 0.1，衰减系数 400 m^{-1}，无热损失（为了图片的简洁，图中没有标出反应率和组分的坐标轴）

反应区，而原反应区则由于没有燃料补偿，反应减弱，其状态如图 2(b) 所示。之后经过一段时间，正向反应区的反应率不断增大，直至达到其最大值，同时，反应区域也渐渐向下游漂移，而最高反应率则基本保持不变；逆向反应区迅速消失。图 2(c) 是正向流动 29.8 s 时，即减小流速前的燃烧状态。图 2(d) 是正向流动 30 s 时的燃烧状态；此时，由于流速的减小，反应率已下降。逆向半周期与此类似。

可以看到，在整个半周期内，温度场分布近似于梯形，出口温度始终在 360 K～600 K 间变化，而当量比为 0.1 的混合燃气，假设其可以全部反应，它放出的热量可以使气体（反应后气体）温度从 298 K 增加到 568 K。忽略进出口由于导热和辐射造成的热损失，可以认为，从换向开始到出口温度升为 568 K，这个过程燃烧所放出的热量大于对流作用带走的热量，这多余的热量被下游的多孔介质储存起来，将对下个周期的燃烧起决定作用。

3.2 半周期的影响

图 3 所示的是不同半周期下，正向进气速度减小前的温度分布及其反应率大小（以下各图均是此时刻的结果）。半周期的加大，使得反应区域随着时间飘移到离进口较远的地方，同时其上游温度下降剧烈；这种极限情况是反应器变为单向燃烧器，此时反应气体受到的预热将主要来源于热反馈的作用；由于燃烧区域上游温度被来气逐渐冷却，多孔介质蓄热对燃气的预热作用大大减弱；从定性的角度来分析，燃烧器热利用率将会明显降低，这一点也可从图中的出口温度看出来；半周期越大，出口温度越高，相同量的尾气带走的热量也就越多，储存在燃烧器中的反应热也就越少。由此，减小半周期，可提高燃烧器热利用率。但是，实际中，如果周期太小，就有可能使来流气体来不及到达高温区反应而使火焰最终熄灭。

半周期对最高温度的影响不大，这与实验的结论是一致的。

3.3 当量比的影响

当量比越大，单位质量预混合气体的热值也就越高。当量比对最高温度和高温区域宽窄有较大影响。当量比越大，其最高温度也越高，而高温区域也越宽，但是，出口温度也同时提高，逐渐减小当量比，其最高区域将逐渐变窄；当量比减小为 0.06 时，温度分布由梯形变为三角形，其高温区仅是一段圆弧，且正向和逆向的反应区域相当靠近，均在反应器中间一带；当量比低于 0.06 时，火焰将会熄灭，如图 4 所示。

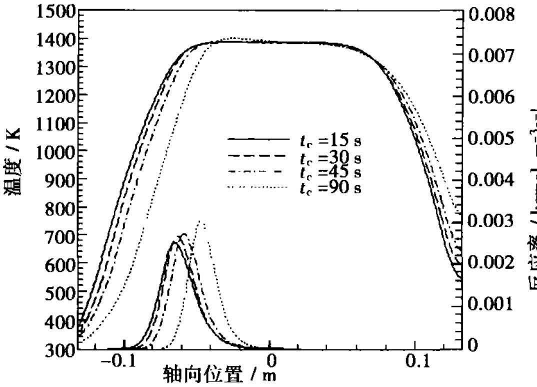

图 3　不同半周期时温度场和反应率分布

流速 0.15 m/s, 当量比 0.1, 衰减系数 400 m^{-1}, 无热损失

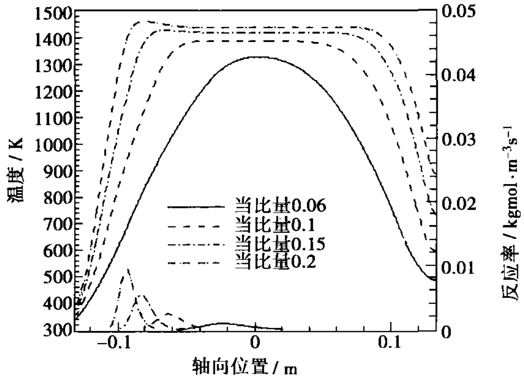

图 4　不同当量比时的温度分布及其反应率比较

流速 0.15 m/s, 半周期 30 s, 衰减系数 400 m^{-1}, 无热损失

3.4　流速的影响

图5 所示的是不同流速下燃烧室温度场、反应率的比较。可以看到, 最高温度和高温区域都随流速的增加而变大, 但是反应区却越来越靠近进口。这是因为流速增大, 其出口温度也增加了, 相应的, 刚刚换向后, 它的反应区也越来越靠近进口。

3.5　热损失的影响

图6 所示的是考虑壁面热损失后, 正向进气速度减小前的温度分布及其反应率大小。可以看到, 随着热损失所占进口热值比例的不断变大, 正反向的反应区域不断靠近, 从而其反应放出的热不断集中, 才能维持火焰的自维持状态。当热损失占到进口热值的 70% 时, 正、反向的高温区重合成了一个点, 继续增大热损失, 此最高温度将持续下降, 直至熄灭。但是热损失对最高温度并没有太大影响, 较大的热损失只是稍微降低了燃烧的最高温度。

3.6　衰减系数的影响

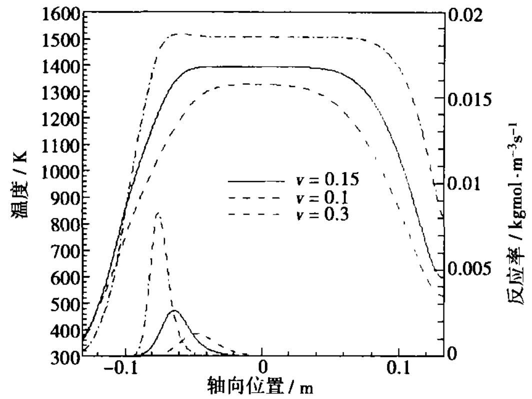

图 5　不同流速时温度场和反应率分布

半周期 30 s, 当量比 0.1, 衰减系数 400 m^{-1}, 无热损失

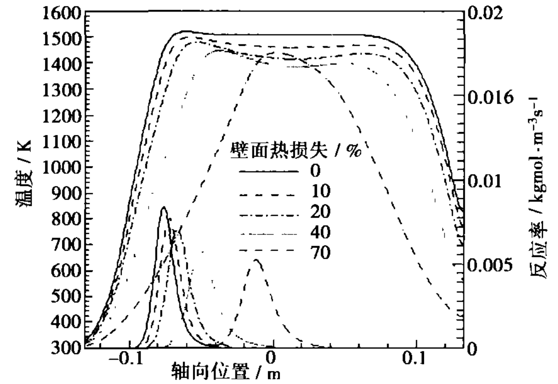

图 6　不同热损失时的温度分布及其反应率比较

流速 0.3 m/s, 当量比 0.1, 半周期 30 s, 衰减系数 400 m^{-1}, 无热损失

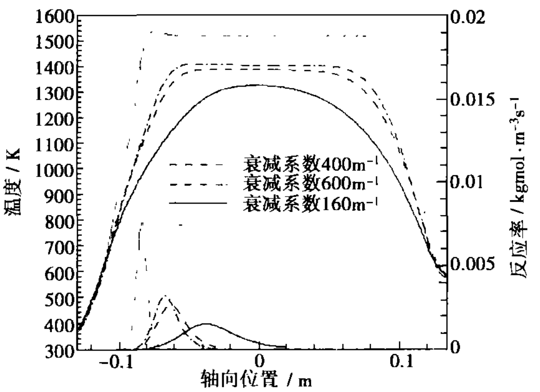

图 7　不同衰减系数时温度场和反应率分布

流速 0.15 m/s, 当量比 0.1, 半周期 30 s 无热损失

如前所述, 超绝热燃烧系统与普通燃烧器的主要不同于存在着由多孔介质的导热和辐射造成的热

反馈效应。反馈到上游的热量，以及由多孔介质储存的热量使得预混合气体得到预热，气体在未到达高温区域时即开始反应，其反应率的最大处也不在最高温度处。这是因为虽然最高温度处有着较高的温度，但是燃料在气体中的含量已大幅度下降，导致了反应率的下降，如图 2 所示；这和不加装多孔介质的燃烧器是不一样的。而且，随着衰减系数的增加，多孔介质的辐射换热能力下降，这一方面使得上游所得到的反馈热量有所减少，但另一方面反应区域向下游的散热量也降低了；结果与小的衰减系数情况相比，大衰减系数情况有较高的最高温度，反应区域也和最高温度区域较为接近，如图 7 所示。

大衰减系数情况下，由于反应区温升很快，使得其反应速率较大，火焰的相对移动速度也较小，其反应区域要更靠近入口，最高温度区域也更为宽阔。衰减系数减小时，辐射传热性能加强，但这也导致了反应区域热量的过多散失和反应区域变大，导致最高温度降低。为维持燃烧，正反两个反应区域只能越来越近。

3.7　多孔介质比热容的影响

多孔介质比热容越大，蓄热能力越强，超绝热效应也越强。如图 8 所示，其出口温度越低，反应区域也就越靠近上游。但是当多孔介质的比热容增加到一定程度时，大于原来的比热容两倍时，它对燃烧器温度场的分布将几乎不再有影响(如图 8 所示)。比热容的大小对最高温度没有什么影响。

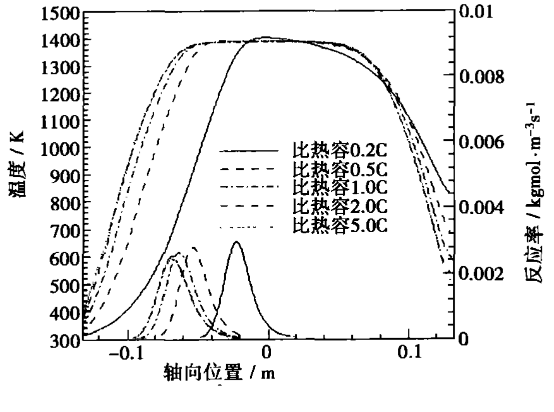

图 8　不同比热容时的温度分布及反应率比较

流速 0.15 m/s，当量比 0.1，半周期 30 s，衰减系数 400 m^{-1}，无热损失

4　结　论

建立了超绝热燃烧系统的数学模型并进行了模拟，计算结果得到了与实验相同的趋势。主要研究了燃烧行为在一个周期内的变化，以及主要工况参数，如半周期、当量比、流速、热损失、衰减系数和比热容对燃烧的影响。计算结果显示，温度场基本是梯形分布。当量比、流速对最高温度有明显影响，而多孔介质的比热容、往复周期、热损失则对温度分布影响较大。，值得注意的是，热损失对最高温度影响不大，即使非常小的当量比，也可以稳定燃烧。

目前的燃烧模型过于简单，导致计算的温度较实验要高，下一步的改进主要是放弃气固两相的热平衡假设，并引入更完善的辐射换热模型。

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lift-off. The lower the resonant frequency, the stronger the turbulence. At other frequency values the flame remains attached and has a shorter length with the shortest length appearing at 50% to 60% of duty cycle. The condition of piping connection can also influence the pulsating characteristics of the flame. Under resonant frequencies and with an increase in average Reynolds number the flame may lift off at a relatively high fuel-rich combustion-time share while under other frequencies the flame will remain attached all the time. **Key words**: combustion with a pulsating fuel feed, low NO_x combustion, flame characteristics, flame alternative structure.

"旋转型气—液雾化喷嘴"流量特性的实验研究＝**Experimental Investigation of the Flow Characteristics of a Swirl-type Gas-liquid Atomization Spray Nozzle** [刊，汉] / GONG Jing-song, FU Wei-biao (Department of Engineering Mechanics, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy &Power. — 2004, 19(4). — 376～379.

The atomization mechanism of various types of pneumatic spray nozzles was analyzed. On this basis proposed is an innovative atomization spray nozzle, the so-called swirl-type gas-liquid atomization spray nozzle. Its air-to-liquid mass flow rate ratio (ALR) during hot-state tests is 4% - 6% (atomized by compressed air). A systematic study was conducted of its flow factor with main attention being focused on the influence of nozzle structural parameters, ALR and liquid viscosity on the flow factor. Through experimental measurements and fitting a mathematical expression of the nozzle flow factor is obtained, which can serve as a guide for the spray nozzle design. **Key words**: spray nozzle, flow factor, air-to-liquid mass flow rate ratio.

惯性分离器内气固两相流雷诺应力数值模拟＝**Numerical Simulation of Reynolds Stresses of Gas-solid Two-phase Flows in an Inertial Separator** [刊，汉] / WANG Hai-gang, LIU Shi, JIANG Fan (Institute of Engineering Thermophysics under the Chinese Academy of Sciences, Beijing, China, Post Code: 100080) //Journal of Engineering for Thermal Energy &Power. — 2004, 19(4). — 380～383.

A detailed numerical study was conducted of the gas-solid inertial separation process in a circulating fluidized bed. A Reynolds stress model is used to serve as a turbulent flow model with the object of study being the gas-solid two-phase flow in a U-shaped separator. To truthfully describe the collision process between solid particles and a separator wall surface, a particle trajectory model was adopted to simulate solid particles. In addition to the introduction of the influence of the wall surface roughness, the diffusion action of the solid particles in turbulent flows and the mutual collision between particles have also been taken into account. The influence of different inlet speeds and quantity of separator dampers on particle separation efficiency and fluid pressure drop has been calculated through the use of simulations. The calculation results have given not only the structural features of the gas-solid two-phase flows in the separator, but also shown the relationship between the separator efficiency and pressure drop on the one hand and inlet main flow speeds and separator structural parameters on the other. **Key words**: Reynolds stress model, inertial separator, particle trajectory model.

多孔介质往复流动燃烧的一维数值模拟＝**One-dimensional Numerical Simulation of Reciprocating-flow Combustion in Porous Media** [刊，汉] / MA Shi-hu, XIE Mao-zhao, DENG Yang-bo (Power Engineering Department, Dalian University of Science &Technology, Dalian, China, Post Code: 116024) //Journal of Engineering for Thermal Energy &Power. — 2004, 19(4). — 384～388.

A one-dimensional mathematical model was set up to simulate the reciprocating-flow combustion in porous media. In this system combustible premixed gases change their direction periodically, and flow into a combustor from two ends. It is assumed that gas phase and solid phase exist in a state of local thermal equilibrium and the influence of radiation heat exchange has also been taken into account. A mathematical solution is obtained by using a finite volume scheme. By way of a huge quantity of numerical calculations investigated was the impact of major operating parameters on the temperature distribution and reaction characteristics of the combustion system. As for such parameters one can list: half cycle, flow speed, equivalence ratio, heat losses, attenuation factor of porous media and their heat capacity. The calculation results are qualitatively in fairly good agreement with experimental results. **Key words**: porous media, reciprocating, super adiabatic combustion.

煤粉气流强迫点火特性试验研究= **Experimental Investigation of the Characteristics of Forced Ignition by Pulverized Coal-air Flows** [刊, 汉] / GU Zhong-zhu (Power Engineering Institute under the Nanjing Normal University, Nanjing, China, Post Code: 210042), WANG Zhi-bin (Jiangsu Provincial Electric Power Design Institute, Nanjing, China, Post Code: 210092), ZHANG Yong-lian (Education Ministry Key Laboratory of Clean Coal Combustion and Power Generation Technology under the Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). — 389 ~ 391.

On a small-sized combustion test rig for pulverized coal an experimental investigation was performed of the forced ignition characteristics of two types of pulverized coal-air flow under different conditions. The results of the investigation indicate that in case of igniting pulverized coal-air flows by torches there exists an optimum ignition speed corresponding to the minimum concentration of the pulverized coal. The pulverized coal-air flow ignition limit is mainly influenced by such parameters as initial temperature, ignition source temperature, coal rank and the fineness of the pulverized coal. The enhancement of the initial temperature of the pulverized coal-air flow, the ignition source temperature and the fineness of the pulverized coal can all widen the range of ignition. It is relatively easy to ignite coal with a high volatile content. Under the same conditions it is easier to ignite a straight pulverized coal-air flow than a swirling one. **Key words**: pulverized coal-air flow, ignition, ignition limit.

燃油烟管蒸汽锅炉热力设计优化数学模型的研究= **A Study of a Mathematical Model of Optimized Thermodynamic Design for an Oil-fired Smoke-tube Steam Boiler** [刊, 汉] / SONG Zheng-chang, GAO Jian-kang (College of Electro-mechanical Engineering under the China University of Mining Engineering, Xuzhou, China, Post Code: 211672) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). — 392 ~ 394, 432.

To optimize the thermodynamic design of an oil-fired smoke-tube steam boiler, optimized independent variables, relevant variables and objective functions were analyzed and determined on the basis of a thermal equipment optimization theory. In connection with a thermodynamic design process the intermediate variables in the objective functions were solved. The constraint conditions of optimization were determined and a complete mathematical model of optimization was set up. Furthermore, a computer program was prepared to solve the mathematical model. The results of optimization of a typical oil-fired smoke-tube boiler indicate that the optimization model and the computer program for mathematical solution are effective and practical for engineering applications. **Key words**: oil-fired boiler, thermodynamic design optimization, mathematical model, computer program.

湿法烟气脱硫系统中 ALS 式氧化装置性能的试验研究= **Experimental Study of the Performance of a ALS (Air Lance Assembly) Type Oxidation Device Used in a Wet Flue Gas Desulfurization System** [刊, 汉] / ZHU Qun-yi, QIAN Lin-feng, DU Qian, et al (College of Energy Science & Engineering under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(4). — 395 ~397.

An oxidation device composed of an agitator and air lance assembly (ALS) and installed in a wet flue-gas desulfurization system underwent a simulation by using an aeration type of stirring reactor. An experimental study was conducted of the influence on oxidation performance of the ALS type oxidation device exercised by such factors as the hole opening direction and hole diameter (0.5 -1.5 mm) of a sparger, stirring speed (150 - 350 r/min), apparent air velocity (0.8×10^3 ~5×10^3 m/s), etc. The results of the study indicate that the hole opening direction and the hole diameter of the sparger has a relatively small influence on the oxidation rate. With an increase in stirring speed and the apparent air velocity there will be an increase in oxidation speed. However, when the apparent air speed increased to a certain value, the oxidation rate increase tends to slow down. A theoretical analysis and calculation was conducted by using a two-film model. The calculation results are in relatively good agreement with test results. **Key words**: oxidation device of the air lance assembly type, oxidation performance.