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低热值煤层气燃烧器的数值模拟

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摘　要:对一种低热值煤层气燃烧器进行了全尺寸的三维燃烧数值模拟研究,预测了燃烧器出口的流场、温度和组分分布情况,并考察了不同热负荷和不同喷口形式对燃烧器性能的影响。结果表明:该燃烧器具有较宽的负荷调节能力,渐缩喷口燃烧器燃烧温度最高且射流刚性好,50%~100%热负荷内渐扩喷口燃烧器燃烧性能最佳,25%热负荷下渐缩喷口燃烧器燃烧性能最佳。模拟结果对该燃烧器的进一步优化设计有一定的指导意义。

关　键　词:低热值;煤层气燃烧器;数值模拟;热负荷

中图分类号:TK229.1　　文献标识码:A

引　言

煤层气是一种存在于煤层及其围岩中以甲烷为主的混合气体,根据开发形式的不同可分为地面开发煤层气、煤矿井下抽放煤层气和报废矿井煤层气 3 种。煤矿井下抽放煤层气主要可燃成份是 CH_4,浓度在 30%~60%之间,其余则主要是 N_2 和 CO_2 等不可燃气体[1]。决定混合气体燃料燃烧特性的主要因素是可燃气体浓度和燃烧特性,因此用 CH_4 体积比为 30%的低热值混合气体来研究以上述气体为燃料的燃烧器是可行的。

工业上利用低热值燃气面临的一个主要问题是燃烧效率不理想[2],有必要采用预混合和旋流的燃烧方式。旋流燃烧器内部流场是复杂的三维流场,物理模型实验研究受实验条件的限制,无法对燃烧器的燃烧状况及流场得到全面的了解。随着湍流流动和燃烧模型的不断完善以及计算机技术的飞速发展,数值模拟逐渐成为研究燃烧器的燃烧、流动等问题的常用方法。本文建立燃烧器完整真实的三维几何结构,对旋流燃烧器在不同工况和不同喷口情况下进行了全尺寸的燃烧数值模拟研究,研究结果对燃烧器优化设计和工业应用有一定指导意义。

1　燃烧器的物理和数学模型

1.1　物理模型

图 1 是燃烧器结构简图。燃气分两股进入燃气分配管不同的腔室,空气通过风机送入等速蜗壳产生旋流后进入空气环腔。燃气从内、外腔室的数个小孔喷入空气环腔中,与旋转的空气流进行预混,然后通过喷口喷出进行燃烧。燃烧器热负荷(P_d)150 kW,燃料为混合燃气(CH_4 体积比为 30%,N_2 体积比 70%),燃气低位热值 10 772 kJ/m^3,过剩空气系数 1.05。

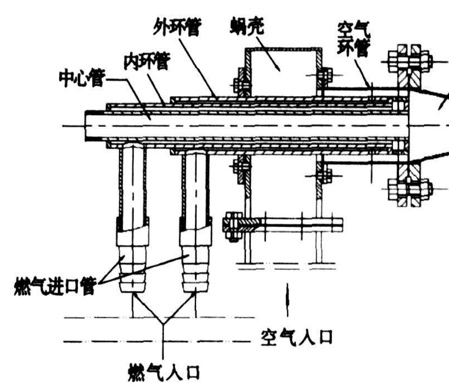

图 1　预混式旋流燃烧器结构

1.2　基本控制方程

连续性方程、动量方程、能量方程、气相组分方程以及 $k-\varepsilon$ 双方程在柱坐标中的统一形式如下[3~4]:

$$\frac{\partial}{\partial x}(\rho u\varphi)+\frac{\partial}{r\partial r}(r\rho v\varphi)+\frac{\partial}{r\partial\theta}(\rho w\varphi)$$
$$=\frac{\partial}{\partial x}\left(\Gamma_\varphi\frac{\partial\varphi}{\partial x}\right)+\frac{\partial}{r\partial r}\left(r\Gamma_\varphi\frac{\partial\varphi}{\partial r}\right)+\frac{\partial}{r\partial\theta}\left(\Gamma_\varphi\frac{1}{r}\frac{\partial\varphi}{\partial\theta}\right)+S_\varphi$$

式中:φ—流动物理量;Γ_φ—有效扩散系数;S_φ—源项;x、r、θ—轴向、径向、周向坐标;u、v、w—x、r、θ 方向的速度;ρ—气体密度。当 $\varphi=u$、v、w、k、ε、f 和 h 时,分别对应于 x、r 和 θ 方向的动量方程、湍流动能方程、湍流动能耗散率方程、组分质量分数方程和能量方程。当 $\varphi=1$、$\Gamma_\varphi=0$ 时为连续方程。各方

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程中 Γ_φ 及 S_φ 的具体表达式参见文献[5]。

2 模型的求解

2.1 网格划分

图 2 为燃烧器部分网格划分图。该燃烧器结构较为复杂、结构不规则，截面尺寸变化较大，流动变化剧烈，对这些部位采用了非结构化网格，网格加密；喷口和燃烧区域采用结构化六面体网格，网格则随流动发展趋于平缓而逐渐变得稀疏。设定交界面将非结构化网格和结构化网格相连，总网格数约为 50 万个。燃烧器出口计算域为 Φ200 mm × 1 200 mm 的圆柱域，图中只部分给出。

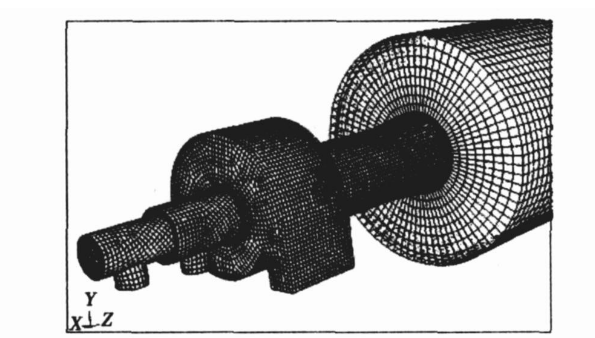


图 2 燃烧器部分网格

2.2 边界条件

空气、燃气进口设为速度入口边界，给定入口速度（见表 1）、组分质量分数、湍流度和水力直径；计算域出口设为压力出口边界，出口表压为零，给定出口湍流度和水力直径，其余设为壁面绝热边界条件。入口流体温度设为 300 K，求解初始温度为 1200 K。

表 1 空气、燃气进口速度 (m/s)

热负荷 P_d/%	燃气入口 I	燃气入口 II	空气入口
100	23.68	20.55	33.63
75	17.76	15.42	25.22
50	11.84	10.28	16.81
25	11.06	0	8.41

2.3 求解方法

采用带旋流修正的 Realizable $k-\varepsilon$ 模型[6~7]，模型常量为：$C_{1\varepsilon}=1.44$，$C_{2\varepsilon}=1.9$，$\sigma_k=1.0$，$\sigma_\varepsilon=1.2$。用标准的壁面函数和 SIMPLE 算法求解旋流燃烧器的强旋射流有限差分方程[8~9]；燃烧模型采用与容积反应有关的物质输运和通用有限速率化学反应，用 Magnussen 和 Hjertager 提出的涡耗散燃烧模型模拟反应与湍流的相互作用。

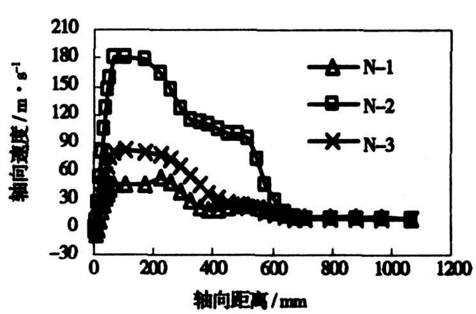
3 模拟结果及分析

燃烧器喷口有渐缩、渐扩以及缩放组合形式。本文研究的燃烧器是工业实际装置，喷口原型为渐缩口，为优化燃烧器结构，改善流动和燃烧，分别模拟了该燃烧器搭配 3 种不同形式喷口在 100%、75%、50%、25%热负荷下的热态运行情况。3 种喷口为渐扩口（Φ59 ~ Φ70）、渐缩口（Φ59 ~ Φ45）和平口（Φ59 ~ Φ59），依次记作 N－1、N－2 和 N－3 燃烧器。

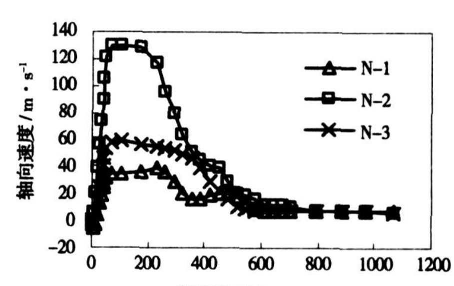
3.1 流场分析

3.1.1 中心轴线轴向速度分布

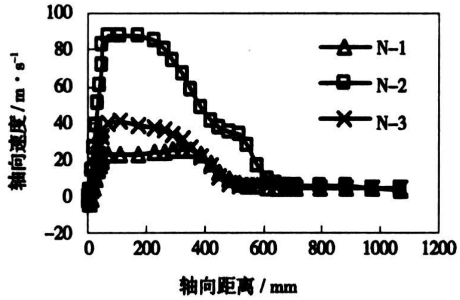
燃烧器的旋转射流特性是燃烧稳定性、燃烧效率的重要影响因素。图 3 是不同热负荷下燃烧器出口的中心轴线轴向速度分布图（坐标圆点位于燃烧器喷口出口中心处，以下分析同）。图中表明：3 种燃烧器在负荷调节比为 4∶1 情况下，50 mm 范围内均有逆向速度分布，且逆向速度大小随负荷降低相应减小。逆向速度的产生，说明出现了中心回流区[10]，对燃料迅速着火燃烧十分有利。50% ~ 100%热负荷范围内，相同热负荷下，N－1 燃烧器逆向速度最大，N－3 燃烧器次之，N－2 燃烧器最小；而 25%热负荷下，N－2 燃烧器逆向速度最大，表明低负荷情况下渐缩喷口燃烧器能更有效地产生中心回流区。



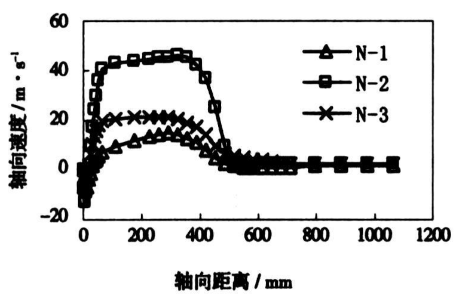
(a) 100% 热负荷



(b) 75% 热负荷



(c) 50% 热负荷



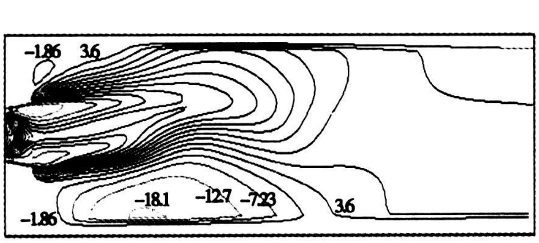
(d) 25% 热负荷

图 3　中心轴线轴向速度分布

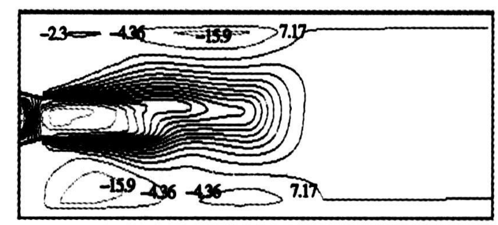
100％热负荷下射流速度在 900 mm 左右衰减到 10 m/s；75％和 50％热负荷下射流速度在 600 mm 处衰减到 10 m/s；25％热负荷时射流速度在 500 mm 处就已衰减到 10 m/s 以下。同一负荷条件下均是渐缩喷口燃烧器射流刚性最好，速度绝对值大，衰减慢。渐扩喷口燃烧器由于喷口出口截面的面积的逐渐加大，射流扩展较快，引起相应轴向速度减小，射流衰减最快。

3.1.2　外回流区分布

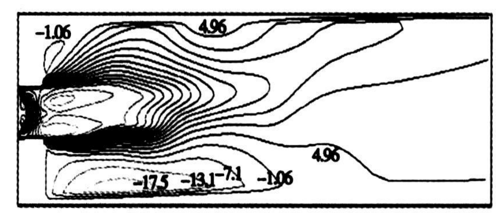
外回流区具有较强的卷吸外界高温烟气的作用，有利于加快燃气和空气升温速度和混合，保持着火稳定和提高燃烧效率。图 4 是 100％和 25％热负荷条件下 3 种燃烧器的热态轴截面轴向速度等值线分布。



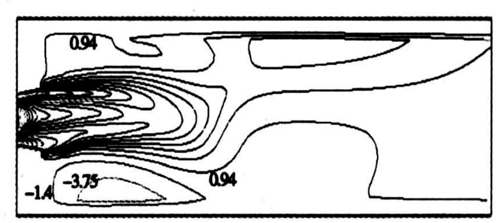
(a) N-1燃烧器(100% 热负荷)



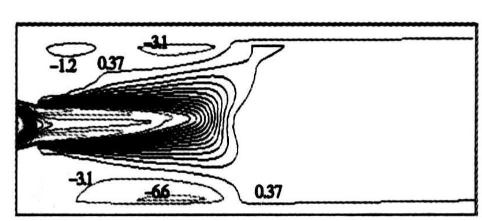
(b) N-2燃烧器(100%热负荷)



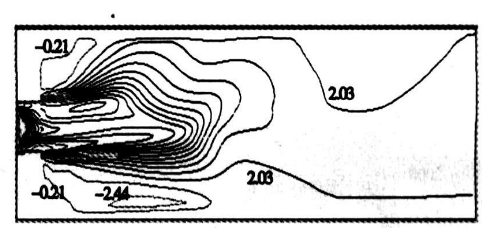
(c) N-3燃烧器(100%热负荷)



(d) N-1燃烧器(25%热负荷)



(e) N-2燃烧器(25%热负荷)



(f) N-3燃烧器(25%热负荷)

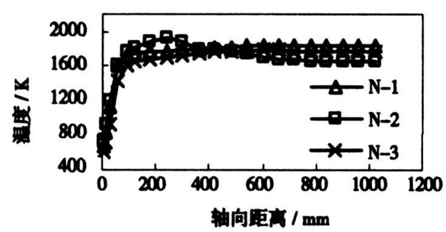
图 4　轴向速度等值线分布

模拟结果表明：3 种燃烧器都能形成稳定的外回流区，高负荷情况下 N－1 燃烧器的外回流区逆向速度最大，N－2 燃烧器最小；低负荷情况下 N－2 燃烧器外回流区逆向速度最大且外回流区比例最大。外回流区沿中心轴分布不对称，下半部回流区面积大于上半部，这是由于蜗壳使空气产生强烈旋

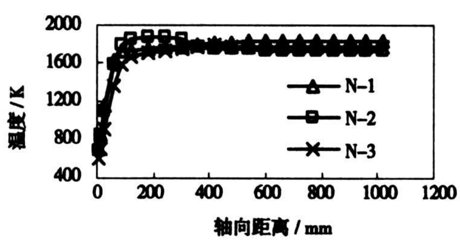
转，受空气旋转射流动量的作用，下半部主流的径向、轴向逆压梯度大于上半部所致。随着负荷的降低，外回流区比例逐渐降低，N－1 燃烧器降低相对最为明显，原因是渐扩口导致低负荷时的气流径向、轴向速度下降更显著，旋转射流的轴向和径向逆压梯度衰减较大引起回流区变小更加明显。

3.2　温度分布

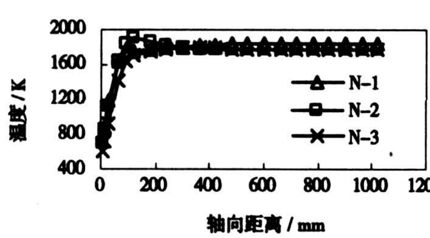
燃烧器出口温度分布能判断该燃烧器的燃烧状况。沿燃烧器出口依次取 21 个截面，按质量加权平均求得每个截面的平均温度，得到不同热负荷时的燃烧器出口温度分布如图 5 所示。



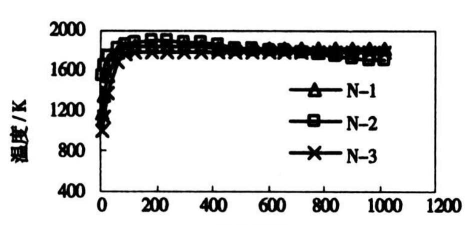
(a) 100% 热负荷



(b) 75% 热负荷



(c) 50% 热负荷



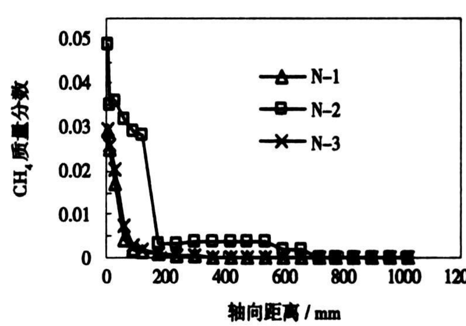
(d) 25% 热负荷

图 5　出口温度分布

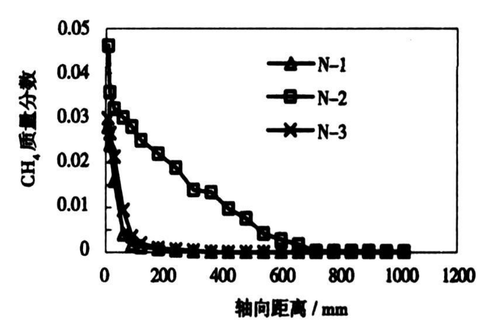
模拟预测显示：50% ~100%热负荷范围内，3 种燃烧器在距离燃烧器出口下游 50～100 mm 内均能着火燃烧，表现在此范围内的最高燃烧温度都达到 1 000 K以上。当热负荷降到 25%时，3 种燃烧器在燃烧器出口温度就在1 000 K左右，说明在喷口内就已经开始着火燃烧，原因是低负荷情况下，燃料量和空气量的减小引起整个燃气、空气混合物的流速下降，燃气和空气在喷口内的混合时间变长，而气体燃烧只要达到燃烧当量比便可迅速着火燃烧，所以着火距离反而提前。相同热负荷下，N－2 燃烧器所能达到的燃烧温度最高，原因是渐缩喷口燃烧器主流核心面积小，局部燃烧强度高。50% ~ 100%热负荷范围内，N－1 燃烧器高温区域比例最大，燃烧效率高；而 25%热负荷下，N－2 燃烧器高温区域比例相对最大。

3.3　组分分布

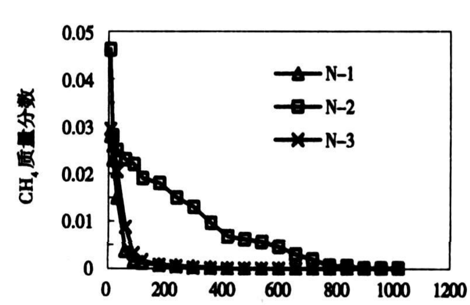
燃料质量分数沿出流方向降低预示着燃烧过程的进行，反映了燃烧效率的高低。沿燃烧器出口依次取21 个截面，按质量加权平均计算出每个截面的平均 CH_4 质量分数，得到不同负荷下燃烧器出口 CH_4 质量分数分布（见图6）。模拟结果表明：随着负



(a) 100% 热负荷



(b) 75% 热负荷



(c) 50% 热负荷

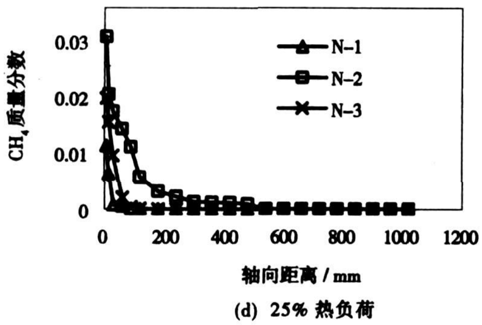


图 6　CH_4 质量分数分布

荷的降低，3 种燃烧器出口 CH_4 质量分数均呈下降趋势。在 50%～100% 热负荷范围内，N－1、N－3 燃烧器出口 CH_4 质量分数均小于 10^{-9}，N－2 燃烧器小于 2×10^{-4}；N－1 燃烧器出口 CH_4 质量分数相对最低，并且 CH_4 质量分数下降最快；N－2 燃烧器起点、出口的 CH_4 质量分数值都高于 N－1、N－3 燃烧器，CH_4 质量分数下降也最慢，说明 N－2 燃烧器燃尽距离最长，燃烧效率相对较低。25%热负荷时，N－1 和 N－3 燃烧器出口 CH_4 质量分数下降到 1×10^{-14} 和 2.97×10^{-11}，而 N－2 燃烧器出口 CH_4 质量分数下降到 3.6×10^{-15}，燃烧效率相对最高。燃烧效率由下式计算：

$$\eta=\frac{CH_{4i}-CH_{4o}}{CH_{4i}}\times100\%$$

式中 CH_{4i} 和 CH_{4o} 分别是燃烧器进口 CH_4 质量和出口烟气中的 CH_4 质量。统计计算可得：50%～100% 热负荷范围内，N－1、N－2 和 N－3 燃烧器的燃烧效率分别是 99.99%，99.8% 和 99.99%；25%热负荷时，3 种燃烧器的燃烧效率都达到 99.99%。

4 结　论

（1）燃烧器在 4∶1 负荷调节比范围内能稳定着火燃烧，燃烧效率达到 99.8%以上。

（2）在 50%～100%热负荷范围内，渐扩喷口燃烧器的中心、外回流区逆向速度大，燃烧高温区域比例大，燃烧效率高，燃尽距离短。

（3）渐缩喷口燃烧器燃烧温度最高，低负荷时中心、外回流区逆向速度大，燃烧效率高。

（4）渐缩喷口燃烧器射流刚性好，渐扩喷口燃烧器射流衰减最快。

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law of mechanical atomizing nozzles. But when the oil spray pressure is relatively low, the atomization mechanism will take a reverse course, i.e. the lower the oil spray pressure, the finer the atomized particles. From the foregoing it can be shown that the swirling steam-based mechanical atomized-oil sprayer can maximally improve the atomization quality under a low-load operating condition and has a relatively large turndown ratio with a steam consumption rate lower than that of an often-used pneumatic atomized-oil sprayer. **Key words**: supercharged boiler, oil sprayer, atomization characteristics, numerical simulation

基于粗糙集理论的火焰图像处理与状态识别 = **Flame Image Processing and Status Discrimination Based on Rough Sets Theory** [刊, 汉] /WU Guang-fu, LU Zhen-zhong (College of Energy Source and Environment under the Southeast University, Nanjing, China, Post Code: 210096)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —310 ~313, 321

A flame status discrimination method based on rough sets theory has been presented in the light of the main problems concerning the flame detection of an entire furnace. The method makes use of the classification principle in the rough sets theory to identify the high temperature zone of flame combustion. In combination with other flame image characteristic values, a knowledge decision-making system was employed based on the rough sets theory to set up flame-status discrimination rules and establish a basic model for the discrimination of entire furnace combustion status to make a judgement of the latter. As the decision-making table is of a simple attribute expression, it lends itself to be easily understood by operators and provides operation guidance for boiler combustion regulation. The on-site tests indicate that the characteristic magnitudes of flame images have a close bearing on the quality of combustion process. The processing based on the rough sets theory can lead to a higher effectiveness and the quantitative classification by adopting attribute sets should help realize a qualitative discrimination of the output values, thus resulting in a precise and reliable discrimination of the system status. **Key words**: rough set, image processing, status discrimination, flame detection, decision-making table

基于混沌理论的 PID 参数自整定锅炉汽包水位控制系统设计 = **Design of a Water Level Control System for the Drum of a PID Parameter and Self-tuning Boiler Based on Chaotic Theory** [刊, 汉] /LU Ning, JI Qiu-yun, XIA Zeng-gang (College of automation under the Harbin University of Science and Technology, Harbin, China, Post Code: 150080)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —314 ~316

The water level in a boiler drum is an important index for the safe and steady operation of an industrial steam boiler. Nowadays, for the water level control usually adopted are feed-forward cascade three-impulse controllers. The control effectiveness is heavily dependent on the proper selection of PID (proportional-integral-differential) parameters of the controller. However, the commonly used parameter-adjusting method involves complicated and tedious steps, resulting in a relatively low searching efficiency. Furthermore, the method is not always an optimized one and big oscillations and overshoots often occur to the control system. By making use of the ergodicity specific to the chaotic theory, one can improve the chaotic-searching optimization method based on Logistic mapping. Presented was a new chaotic PID-parameter optimization method by using one-dimensional iterative chaotic self-mapping which features infinite collapses in a finite region. The simulation results obtained by using the boiler drum models show that the relevant algorithm has a relatively high searching efficiency and accuracy, capable of realizing an optimized adjustment of PID parameters. **Key words**: drum water level, chaos, optimization, PID control

低热值煤层气燃烧器的数值模拟 = **A Numerical Simulation of a Low-heat-value Coal-bed Gas Burner** [刊, 汉] /LUO Yu-dong, ZHANG Li, TANG Qiang, et al (College of Power Engineering under the Chongqing University, Chongqing, China, Post Code: 400030)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —

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A numerical simulation study of a full-scale three-dimensional combustion has been conducted of a low-heat-value coal-bed gas burner along with a forecast of flow fields, temperature and constituent distribution at the outlet of the burner. Investigated also was the impact of different thermal loads and nozzle patterns on the burner performance. The results of the study show that the burner has the ability to regulate a relatively wide range of loads with the converging nozzle burner having the highest combustion temperature and a good rigidity of jet flow. The diverging nozzle burner has the optimal combustion characteristics during the thermal loads ranging from 50% to 100% and the converging nozzle burner has the optimal combustion performance at 25% thermal load. The simulation results may serve as a helpful guide for furthering the optimized design of the burner. **Key words**: low heating value, coal-bed gas burner, numerical simulation, thermal load

熔池内 Li/SF_6 缓慢燃烧可行性的实验研究＝**An Experimental Study of the Feasibility of Li/SF_6 Slow Combustion in a Molten Pool Reactor** [刊, 汉] / LI Yan (Military Representative Office of the Naval Forces of Chinese PLA Resident at Harbin Turbine Works Co. Ltd., Harbin, China, Post Code: 150046), ZHANG Li-chao, ZHENG Hong-tao (College of Power and Energy Source under the Harbin Engineering University, Harbin, China, Post Code: 150001)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —322 ~325

On the basis of experiments an exploratory study has been conducted of the feasibility of Li/SF_6 slow combustion in a molten pool reactor. During the three experiments separately performed, through nozzles SF_6 gas was sprayed at a pressure difference of 0.06 MPa into an air-tight molten pool reactor of 430 ℃ initial temperature containing liquid-state metal lithium. A slow combustion reaction between SF_6 and liquid lithium was made to occur at the liquid surface. Through a control of the flow rate of SF_6 taking part in the combustion, a preset temperature has been attained in the reactor. The preset temperatures were 500 ℃, 565 ℃ and 780 ℃ respectively under which the reactor worked stably for a period of time. On the basis of the test data, an analysis was performed of the experimental phenomena. Effective measures were taken to avoid nozzle blockage during the experiments. Through the experiments it has been verified that the slow combustion of Li/ SF_6 occurring at the liquid surface in the air-tight molten pool reactor can be fully controlled. Under the regulation of the control system, the temperature can reach a preset one only after a single adjustment with the maximal temperature fluctuation being within a range of ±5 ℃ and the pressure value being totally dependent on the temperature in the reactor. **Key words**: lithium, SF_6, molten pool reaction, slow combustion

液一液雾化的射流特性与粒径分布＝**Liquid-liquid Atomized Jet-flow Characteristics and Particle Diameter Distribution** [刊, 汉] / LIANG Kun-feng, PENG Zheng-biao, YUAN Zu-lin, et al (College of Energy Source and Environment under the Southeast University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —326 ~331

The particle diameter distribution of liquid droplets is one of the key factors involved in the technology for making fluid ice from a liquid-liquid circulating fluidized bed. On a fluidized bed test device, by using a method combining high speed photography with image processing, a study has been conducted of the liquid-liquid single-hole atomized jet-flow at a low flowing speed and its impact on the distribution of particle diameters of liquid droplets. In this connection, a mathematico-statistical method was employed to analyze the change in jet flow length and the distribution of particle diameters of liquid droplets. It has been found from the analysis that a jet flow emerges when its speed is greater than 1.14 m/s and the fluctuations in the jet flow length at various flow speeds assume a random and non-periodic character. Moreover, with an increase of the jet flow speed the mean value and variance of the jet flow length show an overall variation tendency of "first increase and then decrease". With the jet flow speed being 6.58 m/s, which is a turning point, a spherical or