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喷淋式脱硫塔脱硫特性的试验研究

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摘　要: 采用两种细度石灰石作为脱硫剂, 对喷淋式脱硫塔的脱硫特性进行了试验研究, 试验结果表明在一定烟气流速下, 脱硫效率随液气比的增大而增大; 在高烟气流速下, 脱硫效率随液气比的增大而增加的趋势更加显著。脱硫效率随着提高浆液的 pH 值而提高, 随入口烟气 SO_2 浓度增加而下降; 石灰石粒径越小, 其溶解性好, 有利于提高脱硫效率。结合吸收段阻力特性, 分析得到该装置的一个最佳工况点: 烟气流速 2.31 m/s, 循环浆液量 50 m^3/h, 浆池 pH 值 5.6～5.8 时, 脱硫效率为 93.9%。

关　键　词: 喷淋塔; 湿法烟气脱硫; 脱硫特性; 试验研究

中图分类号: TQ053.5; X701.3　　文献标识码: A

引　言

SO_2 由于对其环境的破坏性和对人类健康的危害性, 是当今人类面临的主要大气污染物之一。工业用能和电力行业中的燃煤是产生 SO_2 最主要的人为来源[1~2]。SO_2 污染已成为我国经济可持续发展的一个重要制约因素[3~4]。在众多 SO_2 排放控制技术中, 湿法烟气脱硫技术目前已经成为我国燃煤电站控制 SO_2 排放的主要技术, 其中钙基喷淋塔在国内电厂应用最为普遍[5~6]。我国目前的湿法烟气脱硫技术基本由国外引进, 昂贵的投资和运行费用成为制约国内脱硫技术进一步发展的因素[7]。研究和开发具有自主知识产权的新型烟气脱硫技术是我国控制和解决 SO_2 污染的重要手段。本研究以此为目的对典型喷淋式湿法烟气脱硫装置进行了深入研究, 以期掌握关键参数, 为喷淋式湿法脱硫工艺的设计和优化运行提供参考数据。

1　试验装置及系统

试验装置由吸收塔本体、送引风系统、浆液系统、氧化系统、石膏沉降系统以及测试系统组成。吸收塔的高度为 8.9 m, 截面为正方形(0.49 m×0.49 m)。分别在塔内距浆池液面 4、5.5、7、7.5 m 4 层高度各布置一个雾化喷嘴。这样布置可通过调整不同标高的喷嘴开启组合, 对不同液气比、不同液滴停留时间的试验工况开展试验研究。喷嘴型号为 HHSJ-90210 异型压力式雾化喷嘴, 垂直向下布置。塔内烟气和浆液为逆流布置, 试验装置及试验系统如图 1 所示。

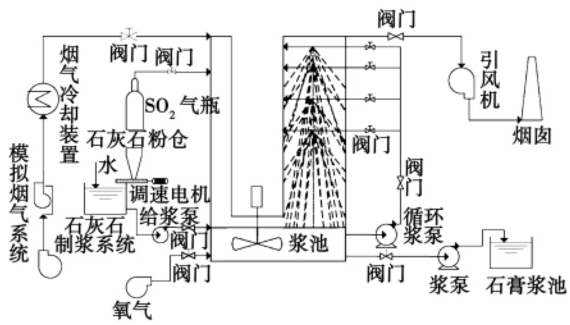

图 1　试验装置及试验系统示意图
Fig. 1 Schematic drawing of the test device and system

2　试验内容和试验工况

试验以石灰石作为脱硫剂, 分别产自重庆和广西桂林, 平均粒度分别为 21.37 μm 的细粉和 6.55 μm 的超细粉, 其化学成分如表 1 所示, 两种石灰石的粒径分布分别见表 2 和表 3。

表 1　两种石灰石的成分分析和平均粒径
Tab. 1 Composition analysis and average particel diameter of two kinds of limestone

石灰石产地	CaO /%	MgO /%	Al_2O_3 /%	Fe_2O_3 /%	酸不溶物/%	平均粒径/μm
广西桂林	52.76	0.00057	0.08064	0.3344	2.19	6.55
重庆	45.53	2.47	0.16	0.13	5.38	21.37

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表 2　重庆石灰石的粒径分布

Tab. 2 Particle diameter distribution of Chong-qing-originated limestone

粒径/μm	累加百分含量/%
5.47	0
7.41	0.99
10.1	2.3
12.33	5.42
14.96	9.3
18.26	15.43
22.53	25.4
28.18	41.02
35.65	62.77
46.07	85.16
61.19	100

表 3　广西桂林石灰石的粒径分布

Tab. 3 Particle diameter distribution of Guilin-originated (Guangxi Province) limestone

粒径/μm	累加百分含量/%
2.0	0
2.8	2.13
4.0	8.04
5.04	18.7
6.35	28.63
8.0	40.73
10.08	55.77
12.7	69.85
16.0	85.63
20.2	96.43
25.4	99.8
32.0	100

试验内容包括逆流喷淋塔吸收段阻力和工艺参数(喷淋密度、烟气流速、氧化浆池 pH 值、烟气入口 SO_2 浓度和石灰石粒径等)对脱硫效率的影响。试验参数范围如表 4 所示,其中烟气流量均为标准状态下流量。

表 4　试验参数范围

Tab. 4 Scope of test parameters

	喷液量 /$m^3 \cdot h^{-1}$	烟气量 /$m^3 \cdot h^{-1}$	循环浆池 pH 值	入口烟气 SO_2 浓度/$mg \cdot m^{-3}$
喷淋塔(逆流)	30 ~ 50	2 000 ~ 4 000	5.4 ~ 6.0	5 140 ~ 8 570

脱硫效率可由下式计算得到[8]:

$$\eta_{SO_2} = \frac{C_{SO_2,in} - C_{SO_2,out}}{C_{SO_2,in}} \times 100\%$$

式中: $C_{SO_2,in}$、$C_{SO_2,out}$—脱硫前后烟气中的 SO_2 折算浓度(烟气的过量空气系数 α 取 1.2),mg/m^3。

对于脱硫工艺,烟气流量和循环浆液量是两个主要的工艺参数。烟气流量的变化通过调节送风机出口阀门开度来实现;循环浆液流量与喷淋层数相对应,通过调整喷淋层数来改变总的循环浆液流量大小。

3　试验结果与分析

3.1　吸收段阻力特性

图 2 为不同液气比对吸收区阻力的影响。由图可见,吸收区阻力随液气比的增加而增大,低烟气流速时,两者近似呈线性关系,阻力的递增幅度大于喷淋密度的递增幅度。其主要原因是:在相同烟气流速下,影响吸收区阻力的主要因素为喷淋密度和液滴初始速度,随喷淋密度增加,液滴初始速度增大,对阻力的影响相应增大,故高烟气流速时关系曲线偏离线性,且吸收区阻力的增加幅度大于喷淋密度的增加幅度。

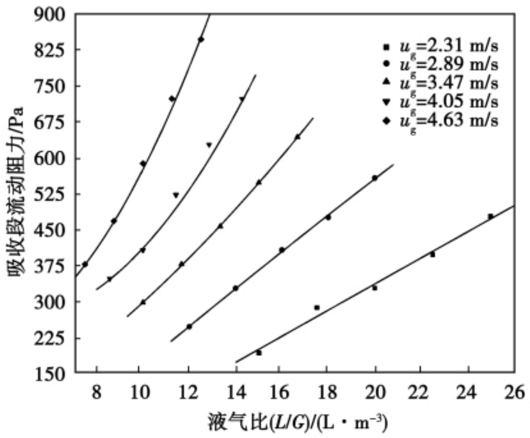


图 2　液气比对吸收区阻力的影响

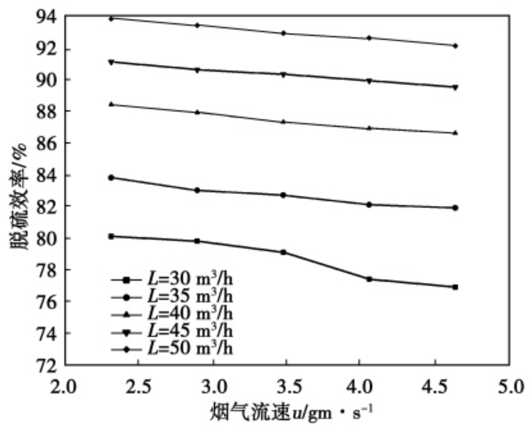
Fig. 2 Influence of the liquid-gas ratio on the drag force in the absorption zone

3.2　工艺参数对脱硫效率的影响

3.2.1　烟气流速和循环浆液量对脱硫效率的影响

烟气流速对脱硫效率的影响如图 3 所示。可见,脱硫效率随着烟气流速的增大缓慢下降,高喷液量下减小的趋势略为缓慢。在循环浆液量为 45

m^3/h 时，当烟气流速由 2.31 m/s 提高到 4.63 m/s 时，流速提高了一倍，对应的液气比（L/G）由 18 L/m^3 下降至 11.25 L/m^3，下降了 37.5%，而脱硫效率由 92.3% 下降至 89.7%，仅下降了 2.82%，远小于烟气量的增加幅度。由此可见，烟气流量增大，单位体积吸收液吸收的 SO_2 量增大，即提高烟气流速时，SO_2 吸收的传质效果增强。其主要原因是由于随着烟气流速的提高，吸收液液滴受到的表面曳力增大，液滴在塔内的下降速度减小，液滴在塔内停留时间增长，塔内持液量增加，传质面积增大；另外，烟气流速提高，烟气与液滴的相对速度增大，气液两相的湍流强度增大，决定传质阻力的气液两相界面的静止膜厚度减小[9]，传质阻力减小，总传质系数增大。由于吸收液的吸收能力与吸收浆液量的多少有关，因此单方面提高烟气量，在吸收浆液量较小的情况下会产生脱硫效率降低的“假相”。



（入口烟气 SO_2 浓度 $C_{SO_2,in}$ = 6 000 ~ 6 570 mg/m^3，浆液 pH = 5.6 – 5.8）

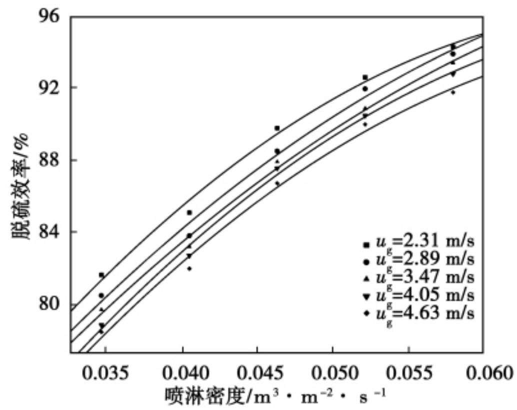
图 3　烟气流速对脱硫效率的影响

Fig. 3 Influence of the flue gas flow speed on the desulfurization efficiency

循环浆液量增大即塔内单位截面的喷淋密度增加，喷淋密度对脱硫效率的影响如图 4 所示。可见，在烟气流速不变、吸收塔截面不变的情况下，脱硫效率随着循环浆液量的增加而增大。这是由于随着喷淋密度的增加，气液接触面积增加，总的传质反应速率加快，所以脱硫效率增大。

3.2.2　液气比对脱硫效率的影响

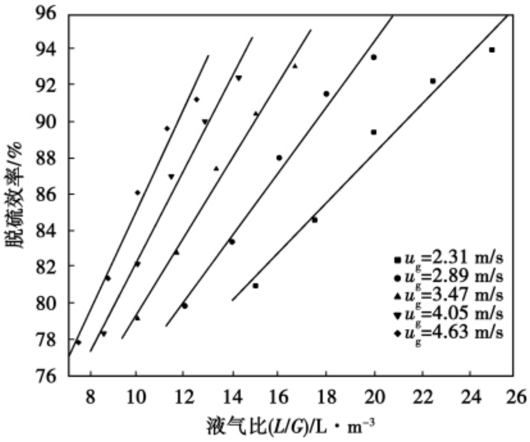
综合烟气流速和循环浆液对脱硫效率的影响，可以得到液气比对脱硫效率的影响，如图 5 所示。可见在一定烟气流速下，脱硫效率随着液气比的增大而增大。而且在高烟气流速下，脱硫效率随液气比的增加而增大的趋势更加显著。在处理相同的烟气量条件下，提高液气比，即增加了塔内的浆液喷淋密度，提高了吸收区的传质面积；同时，也增加了可用于吸收 SO_2 的总碱度，即增强因子增大，所以脱硫效率增加。



（入口烟气 SO_2 浓度 $C_{SO_2,in}$ = 6 000 ~ 6 570 mg/m^3，浆液 pH = 5.6 – 5.8）

图 4　喷淋密度对脱硫效率的影响

Fig. 4 Influence of the sprinkling density on the desulfurization efficiency



（入口烟气 SO_2 浓度 $C_{SO_2,in}$ = 6 000 ~ 6 570 mg/m^3，浆液 pH = 5.6 – 5.8）

图 5　液气比对脱硫效率的影响

Fig. 5 Influence of the liquid-gas ratio on the desulfurization efficiency

虽然提高液气比可提高脱硫效率，但液气比增大，将导致循环浆液量增大，循环泵功耗是影响脱硫成本的一个重要因素，在脱硫系统总耗能中，循环泵的能耗所占的比例高达 50% 左右。液气比的大小

是评价脱硫系统经济性的重要参数，设计时应尽量采用较小的液气比。从图 5 可明显看出，如果获得相同的脱硫效率，高烟气流速所需的液气比较小。换言之，流速提高可降低所需的液气比。如烟气流速为 2.31 m/s，液气比为 20 的脱硫效率为 89.5%，而当烟气流速提高至 4.63 m/s，液气比为 12.86 的脱硫效率为 89.7%。取得相同的脱硫效率而液气比降低了 35.7%。而烟气流速的提高又将带来系统吸收段阻力的增加，如何找到两者之间的最优值是确定最佳运行工况的关键。

3.2.3　浆池 pH 值对脱硫效率的影响

喷淋塔氧化浆池 pH 值对脱硫效率的影响如图 6 所示。由图可见，脱硫效率随着浆液 pH 值的提高而提高，pH 值较低时，对脱硫效率的影响较大，当 pH 值增至 5.6 以上时，再进一步提高 pH 值，对脱硫效率的影响相对较小。

pH 值影响脱硫效率的主要原因是: pH 值增大，吸收液碱度增大，同时，循环浆液中的固体石灰石含量增大，当吸收 SO_2 时，由于石灰石溶解，液相中消耗的碱度及时得到补充，以上两方面因素使化学吸收增强因子增大，总传质系数增大。高 pH 值运行的缺点是石灰石利用率低，运行成本提高; 此外，易造成吸收塔结垢，综合考虑脱硫效率、石灰石利用率和系统防垢等因素，适宜的 pH 值范围为 5.6～5.8。

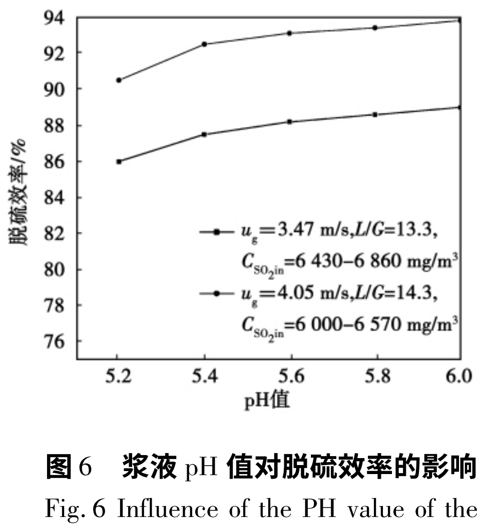


图 6　浆液 pH 值对脱硫效率的影响

Fig. 6 Influence of the PH value of the slurry on the desulfurization efficiency

结合图 2 液气比对吸收段气相阻力的影响，还可以看出，当液气比一定时，烟气流速大于 2.89 m/s 时，随着烟气流速的增加，脱硫效率虽然会增加但吸收段阻力会大幅提高，因此在烟气流速大于 2.89 m/s 的工况点运行系统经济性较差。比较烟气流速为 2.31 和 2.89 m/s 的工况点，发现在烟气流速为 2.31 m/s，循环浆液量为 50 m^3/h(液气比为 25 L/m^3)，浆池的 pH 值为 5.6～5.8 时，脱硫效率可达到 93.9%，此时吸收段阻力为 480 Pa，为该装置的一个最佳工况点。

3.2.4　入口烟气 SO_2 浓度对脱硫效率的影响

在烟气流速 $u_g = 4.05$ m/s，$L/G = 16.7$ L/m^3，入口烟气 SO_2 浓度 $C_{SO_2,in} = 6\ 000 \sim 8\ 000$ mg/m^3 时，喷淋塔系统脱硫效率随 SO_2 浓度的变化如图 7 所示。由图可见，脱硫效率随入口烟气 SO_2 浓度增加而下降。在较低的浓度范围内，入口烟气 SO_2 浓度对脱硫效率影响不大。但当 SO_2 浓度高至一定值后，由于液相中的碱性物质被迅速消耗掉，化学吸收增强因子减小，传质阻力增大，所以脱硫效率下降。从物料衡算可知，在吸收浆液 pH 值为 5.6 时，单位吸收液吸收的 SO_2 量小于 0.005 2 mol/L 时，烟气 SO_2 浓度基本不影响脱硫效率，若再进一步提高单位吸收液的脱硫负荷，脱硫效率下降。

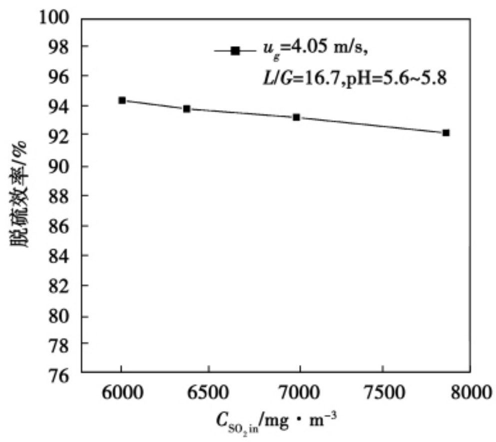


图 7　脱硫效率随入口烟气 SO_2 浓度的变化

Fig. 7 Change of the desulfurization efficiency with the SO_2 concentration of the flue gas at the inlet

3.2.5　石灰石颗粒细度对脱硫效率的影响

试验采用的石灰石吸收剂分别产自重庆和广西桂林，在成分百分比中钙含量非常接近，而两者的粒径分布显著不同。脱硫效率与石灰石粒径的关系如图 8 所示。可见，石灰石粒径大小对脱硫效率具有一定的影响作用。石灰石粒径越小，溶解性能越好，可降低由于其溶解慢造成的液侧传质阻力大的问题，提高液固之间的总传质系数[10]，使得石灰石利用率提高，系统的脱硫效率提高。

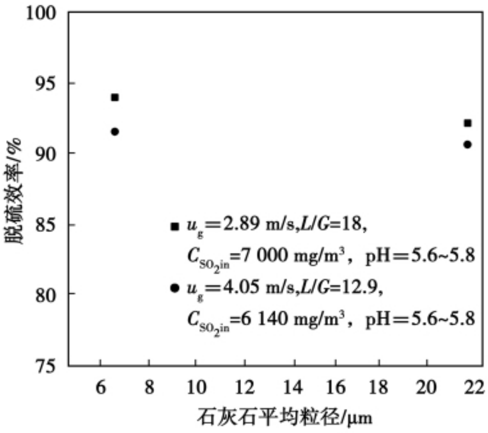


图8　脱硫效率与石灰石粒径的关系

Fig. 8 Relationship between the desulfurization efficiency and the particle diameter of limestone

4　结　论

(1) 在一定烟气流速下,脱硫效率随着液气比的增大而增大。而且在高烟气流速下,脱硫效率随液气比的增加而增大的趋势更加显著。

(2) 系统脱硫效率随着浆液 pH 值的提高而提高;脱硫效率随入口烟气 SO_2 浓度增加而下降;石灰石粒径越小,其溶解性能越好,石灰石利用率提高,系统的脱硫效率提高。

(3) 结合吸收段阻力特性,分析得到该装置的一个最佳工况点:烟气流速 2.31 m/s,循环浆液量 50 m^3/h(液气比为 25 L/m^3),浆池的 pH 值为 5.6 ~5.8 时,脱硫效率可达到 93.9%,此时吸收段阻力为 480 Pa。

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wall Tubes [刊,汉] ZHAO Zhi-yuan, XU Hong, LIN Zhen-xian (College of Energy Source and Power Engineering, North China University of Electric Power, Beijing, China, Post Code: 102206) //Journal of Engineering for Thermal Energy & Power. -2011, 26(5). -593~598

To obtain the circumferential temperature distribution and the internal wall surface oxide film growth characteristics of the waterwall tubes of a boiler, through conducting a study of its heat transfer process, the authors established a numerical model for predicting the temperature distribution on the tubes with an internal wall surface oxide film. On the basis of the heat flux densities measured from the tubular heat flux equipment items, a calculation was performed according to the actual operating condition of the waterwall tubes in a power plant. It has been found that when the circumferential angle is 120 degrees, the temperatures and thicknesses of oxide films at various interfaces are smallest. When the circumferential angle is 0 degree, the temperatures and thicknesses of oxide films at various interfaces are biggest. Compared with the actual operating data, they correspond very well, indicating that to use the method in question to predict the thickness of an oxide film and temperatures at various interfaces of the tube wall is feasible. **Key words:** waterwall, oxide film, growth, prediction, new method

一种中空离心式喷嘴流场特性的研究 = Study of the Flow Field Characteristics of a Hollow Centrifugal Type Nozzle [刊,汉] QIU Qing-gang, LIU Li-na, YIN Xiao-qi (College of Energy Source and Power, Dalian University of Science and Technology, Dalian, China, Post Code: 116000) //Journal of Engineering for Thermal Energy & Power. -2011, 26(5). -599~603

By making use of the VOF (volume of fluid) method and realizable $k-\varepsilon$ turbulent flow model, the authors conducted a numerical simulation of the gas-liquid two-phase flow in a hollow centrifugal type nozzle and compared the simulation results with the test data. Both were in good agreement. The simulation results show that the pressure inside the swirling flow chamber will decrease with a decrease of its radius and a low pressure zone exists in a range of 1/3 of the radius around the center. The existence of such a low pressure zone will result in suction to the air outside the nozzle, forming an air core. The bigger the radius of the air core, the thinner the liquid film. There exists a relatively high dynamic pressure in the area greater than 1/3 of the radius. This will cause the liquid film to extend its sprinkling in the area. If the liquid phase volumetric fraction at the outlet of the nozzle equals to 1, the more remote from the nozzle, the smaller the liquid phase volumetric fraction. The outlet speed will increase with an increase of the inlet pressure. The direction of the outlet speed and the fluid trajectory chart inside the nozzle show that the fluid flows out of the nozzle in a rotating state. **Key words:** VOF (volume of fluid), centrifugal type nozzle, two-phase flow, pressure distribution, air core, velocity flow field

喷淋式脱硫塔脱硫特性的试验研究 = Experimental study of the Desulfurization Characteristics of a Sprinkling Type Desulfurization Tower [刊,汉] FANG Li-jun (Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control, North China University of Electric Power, Baoding, China, Post Code:

071003) //Journal of Engineering for Thermal Energy & Power. -2011,26(5). -604~608

With limesone at two finenesses serving as the desulfurization agent, experimentally studied were the desulfurization characteristics of a sprinkling type desulfurization tower. The test results show that at a definite flue gas flow speed, the desulfurization efficiency will increase with an increase of the liquid-gas ratio. At a high flue gas flow speed, the tendency increasing the desulfurization efficiency with the liquid-gas ratio will be even more remarkable. The desulfurization efficiency will also increase with an increase of the pH value of the slurry and decrease with an increase of the SO_2 concentration of the flue gas at the inlet. The smaller the particle diameter of the limestone, the better the dissolvability, more favorable to improving the desulfurization efficiency. In combination with the drag force characteristics in the absorption section, an optimal operating point of the device was obtained from an analysis. When the flue gas flow speed is 2.31 m/s, the circulating slurry flow rate is 50 m^3/h and the PH value in the slurry pool ranges from 5.6 to 5.8, the desulfurization efficiency hits 93.9%. **Key words:** sprinkling tower, wet-method flue gas desulfurization, desulfurization characteristics, experimental study

污水污泥的燃烧特性及动力学研究 = Combustion Characteristics and Dynamic Study of Sewage Water and Sludge [刊,汉] HE Yan-feng, ZUO Jian-kun, LI Shui-qing, YAO Qiang (Department of Thermal Energy Engineering, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy & Power. -2011,26(5). -609~614

By making use of the thermogravimetric method, studied were the combustion characteristics and dynamic regularities of four kinds of sewage water and sludge present in Chengdu City, Sichuan Province. It has been found that the combustion process of sewage water and sludge can be divided into three stages: water content separation stage, volatile content separation stage and fixed carbon combustion stage. For the main volatile content separation stage, a two-stage reaction model was used to obtain the combustion reaction of four kinds of sludge, which can not be described purely by using a single stage reaction. The activation energy at the low and high temperature stage was 36.65~67.34 kJ/mol and 50.47~84.51 kJ/mol respectively. The test and calculation value of the sludge transformation rate had a very high degree of fitting with their correlation coefficient being more than 0.998. The ignition temperature of the sludge ranged from 496.35 to 512.85 K, being relatively low and easy to ignite and burn. The comprehensive combustion characteristic index of the four kinds of sludge was $(2.75\text{-}9.31) \times 10^{-10}$ $mg^2/(K^3 \cdot min^2)$, far below that of a coal, showing that the comprehensive combustion performance of the sludge is not very high. **Key words:** sewage water and sludge, combustion characteristics, comprehensive combustion characteristic index, thermogravimetric analysis, dynamics

太阳能平板空气集热器内部流动与传热分析 = Numerical Study of the Flow and Heat Transfer Inside a Solar Energy Flat-plate-based Air Heat Accumulator [刊,汉] HU Jian-jun, SUN Xi-shan (Department of Architectural Environment and Equipment Engineering, Yanshan University, Qinhuangdao, China, Post Code: 066004),