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不同粒度煤粉的表面结构与燃烧特性研究

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摘　要：制备了 4种不同粒度的平三煤和大友煤煤粉，分别采用低温饱和氮气吸附的方法和热天平研究了煤粉的表面结构特性和煤粉的燃烧特性。实验结果表明：随着煤粉粒度的减小，煤粉的孔隙结构发生变化，比表面积和孔容积均增大，表面结构复杂，致使分形维数增大，有利于煤粉颗粒的燃烧，因此，平三煤的着火温度降低了 14 ℃，表观活化能均降低了 12.3 kJ/mol，燃尽率提高了 9.81%，大友煤的燃烧特性变化规律相似。此外，煤粉颗粒的分形维数还能在一定程度上表述煤粉的燃烧特性，因此，分形维数可为煤粉燃烧特性的评价提供一种新的途径。

关　键　词：煤粉；粒度；表面结构；分形维数；燃烧特性
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引　言

粒度是煤粉最基本的物理参数，它对煤粉的表面和孔隙结构有重要影响[1]；煤粉的表面是发生化学反应的场所，孔隙结构是反应介质和反应产物扩散的通道，因此，研究煤粉粒度对表面结构与燃烧特性的影响具有重要意义[2]。

本研究利用分形维数表述不同粒度煤粉的表面结构，并通过分形维数来揭示煤粉粒度对燃烧特性的影响。

1　实验部分

1.1　实验样品的制备

实验煤样是将平三煤和大友煤在磨煤机中研磨不同时间，分别得到 4种不同粒度的煤粉。期间未对煤粉进行筛分处理，以保证实验数据能真实反映煤质特性。煤粉平均粒度是利用英国 Malvern公司生产的 MAM5004型激光粒度分析仪测量得到。相关样品的元素分析、工业分析和平均粒度如表 1所示。

表 1　煤样的元素分析、工业分析和粒度

煤样	元素分析 /%					工业分析 /%				平均粒度 d/μm			
	C_{ad}	H_{ad}	O_{ad}	N_{ad}	S_{ad}	M_{ad}	V_{ad}	A_{ad}	FC_{ad}				
平三	58.75	3.66	7.88	1.05	1.59	3.27	26.46	23.80	46.47	34.75	38.11	43.29	46.11
大友	50.78	3.50	9.54	0.94	0.56	3.80	26.40	30.88	38.92	26.72	31.24	39.64	54.05

1.2　实验设备和实验条件

不同粒度煤粉的表面结构特性是用美国 Micromeritics公司生产的 ASPA2000型比表面积及孔径分布分析仪测定，利用 N_2 作为吸附质，在 77 K温度下做等温吸附测量。在比表面积计算中，通常选用相对压力在 0.05～0.3范围内的若干个吸附量数据，根据 BET方程回归得到。孔容积和孔面积按 BJH法，通过相对压力和吸附量计算得到，具体过程参见文献 [3]。采用德国 NETZSCH－STA409C型热天平研究不同粒度煤粉的燃烧特性，实验升温速率分别为 10、20和 30 ℃/min，从常温升至1 100 ℃，载气是模拟空气（氧气和氮气比例为 1∶4），模拟空气的流量是 100 ml/min。

2　实验结果及讨论

2.1　煤粉的表面结构特性

图 1是不同粒度的平三煤和大友煤煤粉的累积

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孔容积分布。由图可知，对同一种煤而言，随着煤粉粒度的减小，累积孔容积的总体变化趋势是增加；但平三煤煤粉粒度由 46.11 μm减小至 43.29 μm时，累积孔容积的增加非常有限；大友煤煤粉粒度由 39.64 μm减小至 31.24 μm时，累积的孔容积变化也很小。从图 1还可看出，随着孔径的变小，所有粒度的平三煤和大友煤煤粉累积孔容积增长趋势变缓；在孔径 50 nm或 41 nm处，不同粒度的平三煤和大友煤煤粉分别出现拐点，这是由于部分中孔碎裂成小孔，数量逐渐减少而引起累积孔容积增加缓慢；但当孔径小于 3 nm时，孔容积增加的趋势变得明显，表明小孔的数量开始剧增，这与任庚坡等人研究不同粒度煤粉的表面结构时得到的结论相似[4]。

比表面积是表述煤粉表面特性和微孔结构的一个重要指标，是影响煤粉着火和燃尽的重要因素[5]。从表 2可知，平三煤和大友煤的比表面积变化规律相似，都是随着煤粉粒度减小，比表面积增大；相比之下，大友煤的比表面积的变化比平三煤大，这可能与煤的内部孔隙结构有关；煤粉细化的过程中，很多大孔和中孔碎裂成小孔使得内表面和粗糙度都有所增加，这为煤粉的着火提供了更多的接触面，有利于煤粉的着火[6]。

煤粉的孔隙结构和表面粗糙程度非常复杂，其内部孔隙表面积占颗粒总表面积的 95%左右，对煤粉的燃烧特性具有重要影响，但是传统的欧氏几何模型却很难准确描述其不规则的表面结构[7~8]。由于分形理论特别适于描述那些外形极不规则和支离破碎，但又存在着各自内在的自相似性的几何体，能定量准确地描述具有非线性特征和不规则粗糙表面的几何体的复杂程度[9]，故本研究利用分形维数来评价煤粉颗粒。煤粉颗粒的分形维数体现孔分布和孔表面的不规则性，而非单一的某些参数体现的某一方面的信息[10]。

本研究采用 FHH改进方法计算分形维数，计算式为[11]：

$$\lg V = C + (D-3)\lg[RT\lg(1/X)] \quad (1)$$

式中：C—常数；D—分形维数；R—气体常数，8.314 J/(mol·K)；T—热力学温度，K；V—气体吸附量；X—相对压力（$X = p/p_0$）。

表 2为不同粒度平三煤和大友煤的分形维数，随着粒度的减小，煤粉颗粒中含有更多的小孔，比表面积增大，孔隙结构更复杂，因此，平三煤和大友煤的分形维数也会增大。

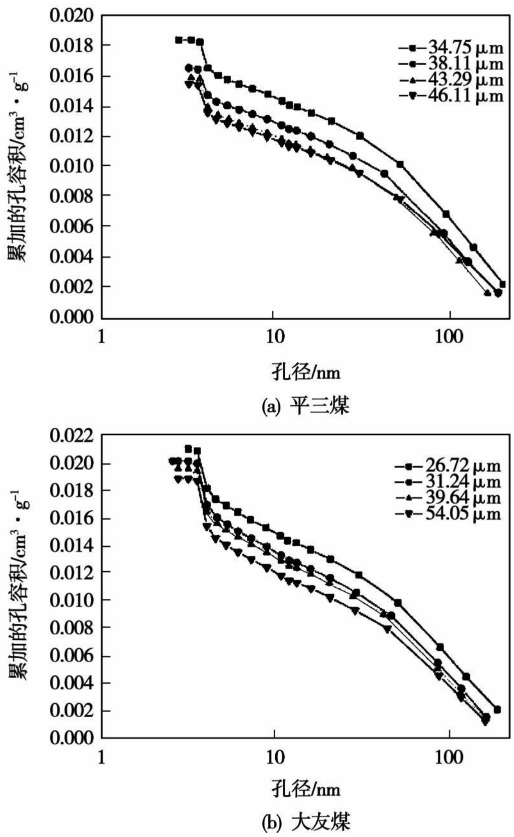

图 1 煤样的累积孔容积分布

表 2 煤样的 BET比表面积和分形维数

	平三				大友			
煤粉粒度 d/μm	34.75	38.11	43.29	46.11	26.72	31.24	39.64	54.05
比表面积 S/m²·g⁻¹	3.739 3	3.738 5	3.445 1	3.415 7	5.533 0	5.373 5	5.361 4	5.074 1
分形维数	2.562 0	2.561 4	2.561 1	2.527 2	2.552 8	2.552 5	2.551 8	2.546 1

2.2 煤粉的燃烧特性

着火温度是评价煤粉着火特性的重要参数，常用来表述煤粉着火的难易程度，本研究采用 TG—DTG法来确定煤粉的着火温度，结果如表 3所示。用热重反应后的焦炭残留物分析其灰分含量，根据质量守恒和灰平衡原理，利用式（2）计算焦炭的燃尽率（燃尽率是指已燃尽的可燃物质占可燃物质的百分含量，结果如表 3所示）：

$$X = (1 - A_0/A)/(1 - A_0) \quad (2)$$

式中：A_0—煤样的灰分，%；A—焦炭的灰分，%。

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表 3　煤样的燃烧特性指数

	平三				大友			
煤粉粒度 d/μm	34.75	38.11	43.29	46.11	26.72	31.24	39.64	54.05
着火温度 /℃	429	431	433	443	427	431	433	435
燃尽率 /%	99.84	95.57	94.76	90.03	99.33	97.64	96.10	88.61

活化能作为反应动力学一个重要指标, 常用来表述煤粉反应的难易程度。本研究采用 Dollimore法以及 Harcourt-Esson提出的速率常数来描述动力学参数[12~13], 避开了人们对阿累尼乌斯定理在非均相、不等温反应体系中是否适用的争议, 计算式为:

$$d\alpha/dt = CT^m f(\alpha) \tag{3}$$

式中: α—质量转化率; t—时间; C—常数; m—正数; T—热力学温度, K; f(α)—动力学机理函数。

热重分析过程中的质量转化率定义为:

$$\alpha = \frac{W_0 - W}{W_0 - W_\infty} \tag{4}$$

式中: W_0—样品开始反应时的质量; W—某一时刻样品的质量; W_∞—反应结束时样品的质量。

对式(3)两边取对数, 简化整理可得:

$$\lg[\beta \frac{d\alpha}{dT}] = \lg[Cf(\alpha)] + m\lg T \tag{5}$$

式中: β—升温速率。

根据不同升温速率 β的热重曲线, 质量转化率 α为某值时, 可得到不同升温速率 β对应的温度及 dα/dT, 由式(5)可拟合得到一条直线, 由直线斜率可得到 m。根据阿累尼乌斯定理和 Harcourt-Esson速率常数可得:

$$K(T) = CT^m = A\exp[-E/(RT)] \tag{6}$$

在温差 ΔT间隔不大的两个温度 T_1和 T_2之间的 E和 A应该相同, 因此可得:

$$E = m(\ln T_2 - \ln T_1)RT_1T_2/\Delta T \tag{7}$$

由式(7)可求得不同质量转化率 α对应的活化能, 再采用 Cumming等人提出的重量平均表观活化能(E_m)的概念来计算整个燃烧过程的总体表观活化能[14], 然后取不同升温速率的活化能平均值作为表观活化能, 结果如表 4所示。

表 4　煤样的燃烧特性指数

	平三				大友			
煤粉粒度 d/μm	34.75	38.11	43.29	46.11	26.72	31.24	39.64	54.05
表观活化能 E_1/kJ·mol⁻¹	174.4	175.3	190.5	192.1	178.9	192.3	196.4	200.9
表观活化能 E_2/kJ·mol⁻¹	153.9	156.7	162.6	170.2	163.4	170.1	179.5	181.2
表观活化能 E_3/kJ·mol⁻¹	142.7	143.8	145.2	145.6	150.7	156.0	160.8	167.2
表观活化能 E_4/kJ·mol⁻¹	157.0	158.6	166.1	169.3	161.0	172.8	178.9	183.1

注: E_1、E_2和 E_3分别是升温速率为 10、20和 30 ℃/min时的表观活化能, E_4是取不同升温速率活化能的平均值。

2.3　运用分形维数对煤粉燃烧特性进行评价

煤粉的分形维数作为煤粉表面结构特性的一个重要物性参数, 对比表 2和表 3数据可以发现, 煤粉的分形维数与燃烧特性存在着明显的依存关系, 因此, 有必要运用分形维数对煤粉的燃烧特性进行评价。图 2是煤样的分形维数与燃烧特性的关系图。

随着分形维数的增加, 煤粉的表面结构变得复杂, 煤粉的比表面积和孔容积呈增大趋势, 为氧气与煤粉表面之间的反应提供了更多的接触机会, 同时扩大了反应产物与反应介质的通道, 有利于煤粉的着火, 因此, 煤粉着火温度和表观活化能将呈降低趋势, 煤粉更容易燃尽。从图 2可以明显看出, 煤粉分形维数与煤粉燃烧特性之间存在这种规律, 这与周俊虎等人研究精细水煤浆的颗粒分形特征对燃烧特性的影响规律相似[15]。从图 2还发现: 平三煤分形维数从 2.5611上升至 2.5620时, 着火温度、表观活化能和燃尽率有一个阶跃, 大友煤分形维数从 2.5518上升至 2.5528时, 着火温度、表观活化能和燃尽率变化规律相似, 这是由于煤粉粒度减小时, 部分中孔和大孔碎裂成小孔, 还有部分盲孔被打开, 导致小孔数量剧增, 从而对煤粉的着火温度、表观活化能和燃尽率产生重要影响。

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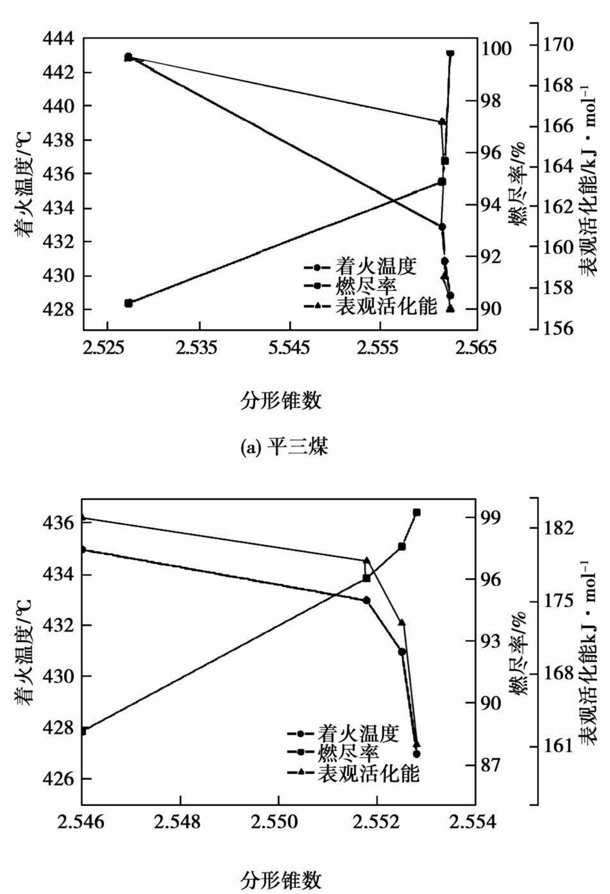

(a) 平三煤

(b) 大友煤

图 2 煤样的分形维数与燃烧特性的关系

3 结 论

（1）随着平三煤和大友煤煤粉粒度的减小，煤粉的着火温度和表观活化能降低，燃尽率提高，这主要是煤粉粒度的减小，孔隙结构变得更加复杂，比表面积和孔容积增大，为氧气与煤粉颗粒之间的反应提供了更多的接触面，反应介质和反应产物扩散的通道也更多。

（2）分形维数能表述孔隙结构的复杂程度，还可用来评价煤粉的燃烧特性。平三煤的分形维数由 2.5272升至 2.5620，着火温度由 443 ℃降至 429 ℃，表观活化能由 169.3 kJ/mol降至 157.0 kJ/mol，燃尽率由 90.03%升至 99.84%；大友煤的规律与平三煤类似。因此，可以通过改变煤粉粒度，改善煤粉的表面结构，提高煤粉的燃尽率，改善煤粉的燃烧特性。

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bine-based cogeneration system is compared with the coal-fired and gas-fired boiler system, NOx emissions are not reduced remarkably, but other emissions are lowered conspicuously. The gas turbine system features a definite edge in comparison with the coal-fired and gas-fired boiler system and will enjoy bright prospects in case a rational design is ensured. Key words: gas turbine, heat and power cogeneration, boiler, performance comparison

有无后冷器的微燃气轮机 HAT循环性能比较 = A Comparison of the HAT (Humid Air Turbine) Cycle Performance of a Micro Gas Turbine With and Without an Aftercooler[刊, 汉] / WANG Bo, ZHANG Shi-jie, XIAO Yun-han, et al (Key Laboratory on Advanced Energy and Power Engineering Thermophysics Research Institute, Chinese Academy of Sciences, Beijing, China, Post Code: 100190) // Journal of Engineering for Thermal Energy & Power. — 2010, 25 (1). —39 ~42

Compared was the performance of a 80 kW micro gas turbine recuperative cycle after its conversion to a HAT (humid air turbine) cycle with and without an aftercooler. The needed increase in the heat exchanger area is given. The research results show that for the gas turbine under investigation, both the conversion efficiencies and power outputs of the HAT cycle system with and without an aftercooler are nearly the same. Compared with the HAT cycle having an aftercooler, the cycle without an aftercooler is equipped with a humidifier of a greater height and volume. The total heat exchange area (sum of the heat exchange areas of the aftercooler, humidifier and economizer), however, becomes smaller in the absence of the aftercooler. This means that the total investment will be lower, and the configuration of the HAT cycle system more simple, thus making the system more compact and its control easier. Key words: HAT (humid air turbine) cycle, micro gas turbine, aftercooler

新型矩形翼纵向涡发生器流动与换热实验研究 = Experimental Study of the Flow and Heat Exchange in a Longitudinal Vortex Generator With a New Type of Rectangular Wing[刊, 汉] / MIN Chun-hua, QI Cheng-ying, XIE Shang-qun, et al (College of Energy Source and Environment Engineering, Hebei Polytechnical University, Tianjin, China, Post Code: 300401) // Journal of Engineering for Thermal Energy & Power. — 2010, 25 (1). —43 ~46

With a small rectangular auxiliary wing being affixed at one side of the rectangular wing, called a combination wing, a new type of rectangular wing longitudinal vortex generator is formed. Under the condition of the pressure loss being identical, the flow and heat exchange characteristics of the combination-wing longitudinal vortex generator and the original rectangular wing one in the rectangular passage were compared through experiments. The test results show that for the original rectangular wing, the optimum attack angle is 45 degrees. Compared with the rectangular wing, the combination one has a heat exchange conspicuously intensified with a reduced resistance coefficient. Especially when the auxiliary wing is installed at the upstream of the rectangular wing, there emerges a more conspicuous effectiveness in intensifying the heat exchange and reducing the resistance coefficient. In the range of the present study, the flow and heat exchange effectiveness will be optimum when the attack angle of the auxiliary wing is set at 30 degrees. Key words: longitudinal vortex generator, rectangular passage, intensified heat transfer, pressure loss, combination wing, rectangular wing

不同粒度煤粉的表面结构与燃烧特性研究 = Study of the Surface Structure and Combustion Characteristics of Pulverized Coal in Various Particle Sizes[刊, 汉] / XU Yuan-gang, ZHANG Cheng, XIA Ji, et al (National Key Laboratory on Coal Combustion, Central China University of Science and Technology, Wuhan, China, Post Code: 430074) // Journal of Engineering for Thermal Energy & Power. — 2010, 25 (1). —47 ~50

Four particle sizes of Pingsan-originated and Dayou-originated coal were prepared. The surface structure and combustion characteristics of the pulverized coal in different particle sizes were investigated by using respectively the

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low-temperature saturated nitrogen adsorption method and a thermobalance. The test results indicate that with a decrease of the particle size of the pulverized coal, a change will occur to the pore structure of the pulverized coal. Both the specific surface area and pore volume will increase, and the surface structure become complicated, thus leading to an increase of the fractal dimension and facilitating the combustion of pulverized coal particles. As a result, the ignition temperature of Pingsan-originated coal goes down by 14 ℃, the apparent activation energy decreases by 12.3 kJ/mol and the burnt-out rate rises by 9.81%. The variation law of the combustion characteristics of Dayou-originated coal is similar to that of Pingsan-originated coal. In addition, the fractal dimension of the pulverized coal particles may represent the combustion characteristics of the pulverized coal to a certain extent. Hence, the fractal dimension will provide a new approach for evaluating the combustion characteristics of the pulverized coal. Key words: pulverized coal, particle size, surface structure, fractal dimension, combustion characteristics

循环流化床中心二次风的设计及实验研究＝Design and Experimental Study of the Centrally-located Secondary Air of a Circulating Fluidized Bed[刊,汉] / SUN Shao-zeng, WANG Zheng-yang, DU Ming-kun, et al (College of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(1). —51~56

Described were two types of secondary air structure, i.e. horizontally arranged rod type and vertically arranged pillar type, both of which are located in the center of a furnace. On a cold-state circulating fluidized bed (CFB), the influence of the arrangement pattern, height and secondary air flow rate of the centered secondary air on the particle concentration distribution along the height direction inside the bed was studied and compared with that of the conventional wall-surface secondary air at the same height. It has been found that after the division of air into stages, the particle concentration below the staged secondary air increases with an increase of the secondary air flow rate. An increase in the secondary air height will be accompanied by the dense-phase zone at the bottom extending upwards. Among the secondary air arrangement patterns, the horizontal rod type secondary air arrangement pattern can make the concentration at the bottom attain a maximal value. A trajectory tracking of the jet flow shows that when the secondary air speed is high, the centrally located secondary air can be diffused to the wall-surface zones, but in the central area there is a lack of secondary air. This is unfavorable for the oxygen replenishment to the central area. The horizontal rod type centered secondary air jet flow, however, will swerve and deflect under the action of a lateral momentum when it enters into the bed and can form a relatively large diffusion area. The authors have also mentioned the problems meriting attention and requiring solutions when the centered secondary air is further applied in practical CFB boilers. Key words: circulating fluidized bed (CFB), centrally located secondary air, axial particle concentration distribution, diffusion of secondary air

非设计配风条件W火焰锅炉NOx排放特性分析＝An Analysis of the NO_x Emission Characteristics of a Boiler with a W-shaped Flame Under the Condition of an Off-design Air Distribution[刊,汉] / SUN Xiao-zhu, GAO Zheng-yang, SONG Wei, et al (College of Energy Source and Power Engineering, North China University of Electric Power, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(1). —57~60

The air distribution pattern is a key factor influencing the NO_x emissions in a pulverized coal combustion process. It is of major significance to study in depth the NO_x emission characteristics of a boiler with a W-shaped flame under the condition of an off-design air distribution. By using software CFX-TASCFLOW, a numerical simulation was conducted of a 300 MW plant with the above boiler in active service. The on-site operating data were used to verify the accuracy of the numerical simulation results at the base load condition. The in-furnace combustion was numerically simulated at 18 off-design air distribution operating conditions. The calculation and analysis results show that when the primary air ratio of the front and rear arch changes in a range of more than 5.6 and less than 6.5, the difference

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