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气化半焦加压着火特性及燃烧稳定性研究

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摘　要: 在单炉膛双吊蓝加压热重分析仪上对气化半焦的加压着火特性和燃烧稳定性进行了较为系统的试验和理论研究, 考察了半焦种类、总压、氧浓度、粒径和加热速率等因素对半焦着火特性和燃烧稳定性的影响规律, 并以纯碳测试数据为基准, 提出了燃烧稳定性的判别指数 R_w。研究表明, 半焦的挥发份含量、固定碳含量以及孔结构是影响半焦着火温度的主要因素。随着总压和氧浓度的提高以及粒径的减小, 半焦的着火温度下降, 燃烧稳定性提高; 随着加热速率的增加, 半焦的着火温度明显上升。

关　键　词: 煤; 半焦; 着火特性; 燃烧稳定性; 加压燃烧; 增压流化床

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1　引　言

增压流化床联合循环(PFBC-CC)发电技术是一种世界公认的洁净煤发电技术。它具有发电净效率高、燃料适应性强、燃烧效率高、易于实现低 SO_2 和低 NO_x 排放、结构紧凑等优点[1~2]。第一代 PFBC-CC 技术的最大弱点是由于增压流化床的运行温度从防止结焦的角度考虑不宜超过 900 ℃, 从而限制了燃气透平的进口温度, 阻碍了燃气布雷登循环效率的进一步提高, 使 PFBC-CC 系统的发电净效率难以超过 42%[3]。

在第一代 PFBC-CC 技术基础上发展起来的第二代 PFBC－CC(2^{nd}-Generation PFBC-CC)技术或称先进 PFBC-CC(Advanced PFBC-CC)技术[4~6], 采用煤的部分气化及煤气前置燃烧方法, 将燃气轮机的入口温度提高到 1 100～1 300 ℃, 使联合循环效率有可能达到 45%～48%。半焦是第二代 PFBC-CC 系统中部分煤气化炉的气化产物。它被送至 PFB 炉内燃烧, 放出的能量部分转化为过热蒸汽的能量, 推动汽轮机发电, 燃烧产生的高温、高压烟气经煤气前置燃烧室升温后推动燃气轮机发电。

相对于煤炭而言, 气化半焦具有高灰份、低挥发份和低发热量等特点, 其着火特性和燃烧稳定性直接影响到 PFB 锅炉的点火过程和稳定运行。目前, 有关气化半焦加压燃烧特性的研究还十分薄弱, 近年来, 只有少数有关这方面研究的报导[7~9], 而且这些研究的对象均为惰性气氛下得到的慢速热解焦, 它们在理化性能上与气化半焦有较大差异。为探明气化半焦的加压燃烧特性, 本文在自行研制的加压热重分析仪上对气化半焦的着火特性和燃烧稳定性进行了较为系统的研究。

2　试验装置与方法

2.1　试验装置

试验在图 1 所示的加压热重分析仪上进行, 其主要组成部分包括记录天平、温控加热系统、承压炉膛、配气系统和数据采集与处理系统。该热重分析仪的主要特色是采用了单炉膛双吊蓝结构, 即在一个炉膛里放置两个吊蓝, 一个用于测量试样的失重过程, 另一个用于测量试样的温度变化。两个吊蓝放置在炉膛的相同高度, 确保两只吊蓝中的试样在基本完全一致的环境气氛和温度下反应, 以尽可能减少试验误差。

记录天平采用偏转型悬臂式结构, 使用电涡流位移传感器测量天平的偏转量, 记录天平的最大量程为 1 g, 精度为 0.1 mg。热重分析仪的炉膛由加热元件、耐火层和绝热层构成, 放置在下高压容器内。加热元件为一 Φ80 mm×5 mm 的双螺纹单端引线硅碳管, 最高使用温度 1 600 ℃。可控硅程序温控仪的加热速率可在 10～100 ℃/min 之间选择, 控温精度为 1 250±1 ℃。仪器最高工作压力为 1.6 MPa。

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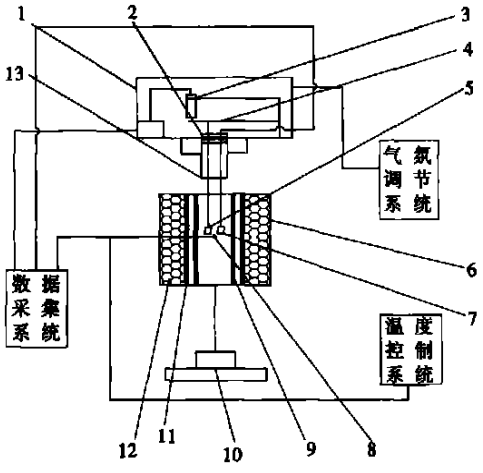

1-上高压容器; 2-迷宫密封; 3-电涡流位移传感器; 4-弹簧片; 5-吊蓝; 6-下高压容器; 7-双铂铑热电偶; 8-镍铬-镍硅热电偶; 9-硅碳管; 10-电动推杆; 11-刚玉管; 12-保温材料; 13-金属软管

图 1 加压热重分析仪结构简图

2.2 试验样品

试验用气化半焦的工业分析和元素分析结果如表 1 所示。其中, 焦样 1 和焦样 2 为一种动力煤在喷动流化床煤气发生炉内气化时的二旋和返料器处半焦, 焦样 3、焦样 4 和焦样 5 分别为另一种煤在流化床煤气炉内气化时的炉内半焦、一旋处半焦和炉渣。

表 1 试样工业分析和元素分析(空干基)

试样	工业分析/%				元素分析/%				
	M	A	V	FC	C	H	N	S	O
焦样 1	6.67	48.04	5.92	39.37	43.16	0.07	0.36	1.09	0.61
焦样 2	2.75	64.39	4.33	28.53	31.53	0.12	0.28	0.68	0.25
焦样 3	2.69	37.69	2.45	57.17	57.93	0.12	0.64	0.36	0.57
焦样 4	2.83	35.24	1.98	59.95	—	—	—	—	—
焦样 5	0.76	61.73	2.37	35.14	36.26	0.13	0.34	0.26	0.52

2.3 试验条件

(1) 试验压力: 0.1 MPa, 0.5 MPa, 0.7 MPa, 1.0 MPa

(2) 试样粒径: 0~0.2 mm, 0.3~0.45 mm, 0.45~1 mm, 1~2 mm

(3) 气氛氧浓度: 21%, 34.26%, 43.28%, 84.2%

(4) 加热速率: 10 ℃/min, 20 ℃/min, 30 ℃/min

(5) 试样质量: ~90 mg

3 试验结果及分析

3.1 着火温度和燃烧稳定性判别方法

本文采用 TG-DTG 法[10] 确定半焦的着火温度 T_i, 并以纯碳的测试数据为基准[11], 引入半焦燃烧稳定性判别指数 R_w 对半焦的燃烧稳定性进行比较, R_w 的定义如下:

$$R_w = \frac{655}{T_i} \times \frac{763}{T_{max}} \times \frac{(dW/dt)_{max}}{0.005\ 82} = 8.587\ 5 \times 10^7 \times \frac{(dW/dt)_{max}}{T_i T_{max}} \quad (1)$$

式中: 655— 碳粉的着火温度, ℃;

763— 碳粉最高燃烧速率峰所对应的温度, ℃;

0.005 82— 碳粉的最大燃烧失重速率, s^{-1};

T_i— 半焦着火温度, ℃;

T_{max}— 半焦最大燃烧失重速率对应的温度, ℃;

$(dW/dt)_{max}$— 半焦燃烧最大失重速率, s^{-1}。

着火温度 T_i 反映了半焦的着火性能或半焦燃烧反应活化能的高低, 其数值越小, 表明该半焦的着火越容易; 最大燃烧失重速率 $(dW/dt)_{max}$ 及其对应温度 T_{max} 反映了半焦着火后的后续燃烧情况, $(dW/dt)_{max}$ 值越大, T_{max} 值越小, 说明半焦着火后的燃烧速度越快, 燃烧稳定性越强。指数 R_w 综合反映了半焦的燃烧特性, R_w 值越大, 表明半焦的燃烧稳定性越好。

3.2 各种因素对气化半焦着火温度和燃烧稳定性的影响

3.2.1 半焦种类的影响

5 种半焦在 0.1 MPa 和 0.7 MPa 压力下的着火温度如表 2 所示。

表 2 5 种半焦的着火温度 (℃)

	焦样 1	焦样 2	焦样 3	焦样 4	焦样 5
总压: 0.1 MPa	497	554	565	511	580
总压: 0.7 MPa	433	465	504	446	516

半焦的挥发份含量、固定碳含量以及孔结构是影响半焦着火温度的主要因素。对于由同一种煤得到的半焦, 固定碳含量越高, 其着火温度越低。如焦样 1 和焦样 2, 它们是由同一种煤在相同的气化条件下制得的, 焦样 2 在炉内的停留时间相对较长, 因而其固定碳含量较低, 相应地其着火温度比焦样 1 高。本文作者认为, 产生这一结果的主要原因是: 煤

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颗粒在流化床内燃烧和气化的过程中会逐渐形成一个灰壳, 灰份含量越高, 灰壳越厚。灰壳的存在阻碍了氧分子向未反应碳粒表面的扩散, 使得灰壳内所包裹的未燃尽炭粒表面的氧浓度降低。灰壳越厚, 氧分子的扩散阻力越大。此外, 灰壳层越厚, 环境气氛与未燃尽炭粒之间的传热热阻越大, 使得炭粒和环境气氛间的温差增大。

焦样 5 的着火温度最高, 这与该种半焦的形成条件有关。焦样 5 是从灰熔聚流化床气化炉中排出的炉渣。在灰熔聚流化床气化炉中存在一射流高温区, 它使含碳量较低的颗粒软化, 碰撞后互相粘结长大, 最后排出炉内[12], 因此炉渣的含碳量较低。而且, 灰团在高温下软化后, 其孔结构遭到破坏, 孔隙率降低, 导致其着火温度进一步升高。

3.2.2　总压的影响

焦样 2 和焦样 3 的着火温度和燃烧稳定性指数 R_w 随压力的变化趋势分别如图 2 和图 3 所示。由图 2 可见, 半焦的着火温度随压力的增加明显下降, 但下降趋势随压力的增加而减缓。随着总压的提高, 氧分压线性增加, 因而碳的氧化反应速率增加, 单位时间内释放出更多的热量, 使炭粒的升温速率提高, 着火温度明显下降; 随着压力的进一步提高, 虽然环境氧分压增加了, 但由于氧的扩散系数与氧分压成反比, 因而导致较高压力下着火温度受压力的影响相对减小, 着火温度的下降相对变缓。

由图 3 可见, 在 0.7 MPa 以前, 随着压力的升高, 半焦燃烧稳定性显著增强; 0.7 MPa 以后, 燃烧稳定性几乎不再随压力发生变化。

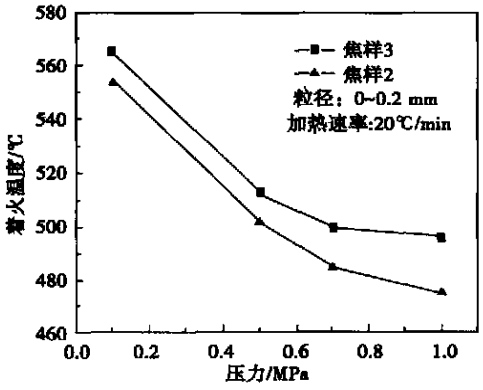

图 2　压力对半焦着火温度的影响

3.2.3　试样粒径的影响

对焦样 3 和焦样 4 在 4 组粒度范围内进行了加压燃烧特性试验。两种焦样的着火温度和燃烧稳定性指数 R_w 随粒径的变化曲线分别如图 4 和图 5 所示。

可以看出, 在不同的压力下, 两种半焦的着火温度随粒径的增大均有缓慢升高趋势。其原因在于, 小粒径半焦有较大的比表面积, 因而单位质量碳的氧化反应速率较大, 着火温度下降。

由图5 可见, 半焦的燃烧稳定性在粒径 0.3 ~ 0.45 mm的范围内最好, 此粒径范围以上的半焦的燃烧稳定性均有所降低, 总体而言, 粒径对半焦燃烧稳定性的影响不大。

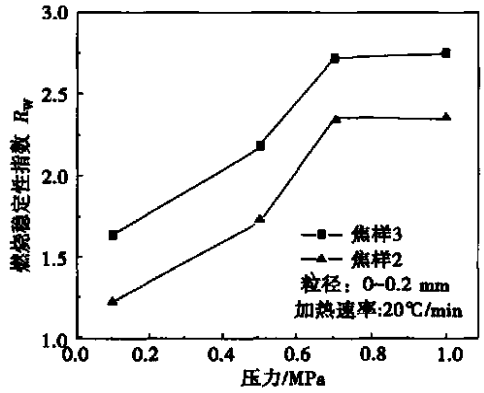

图 3　压力对半焦燃烧稳定性的影响

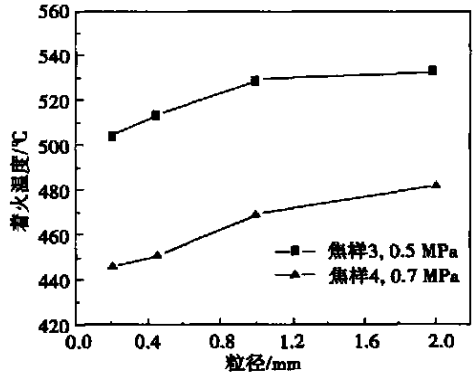

图 4　粒径对半焦着火温度的影响

3.2.4　氧浓度的影响

图 6 和图 7 分别为焦样 1 和焦样 3 的着火温度和燃烧稳定性指数 R_w 随氧浓度的变化曲线。由图 6 可见, 半焦的着火温度随氧浓度的增加而下降, 而当氧浓度高于 45% 以后, 氧浓度对着火温度的影响趋于减小。在总压一定的条件下, 氧浓度的提高意味着氧分压的增加, 因而导致半焦的氧化反应速度提高, 着火温度下降。但同样由于氧的扩散系数与

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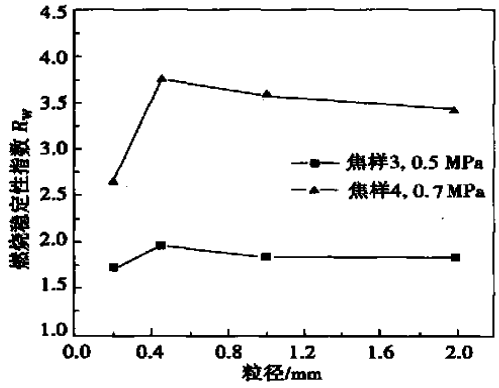

图 5 粒径对半焦燃烧稳定性的影响

氧分压成反比的原因, 随着氧浓度的进一步提高, 氧浓度对着火温度的影响减小, 着火温度的下降变缓。

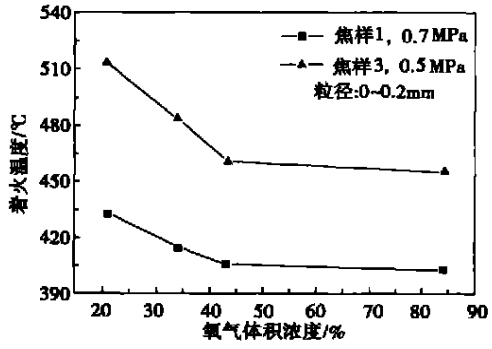

图 6 氧浓度对半焦着火温度的影响

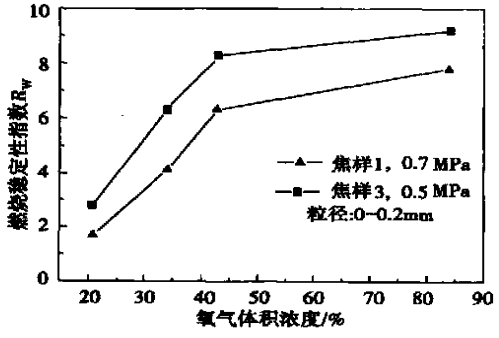

图 7 氧浓度对半焦燃烧稳定性的影响

随着氧浓度的增加, 半焦的燃烧稳定性指数 R_w 逐渐增加, 而当氧浓度高于 45%后, 氧浓度的影响趋于减小。

讨论了氧浓度在不同总压下对半焦着火特性的影响以后, 就有可能进一步认识系统总压对半焦燃烧特性的影响, 即弄清总压增加导致着火温度下降的原因是由于总压的提高, 还是由于氧分压的提高, 或者是两者共同作用的结果。

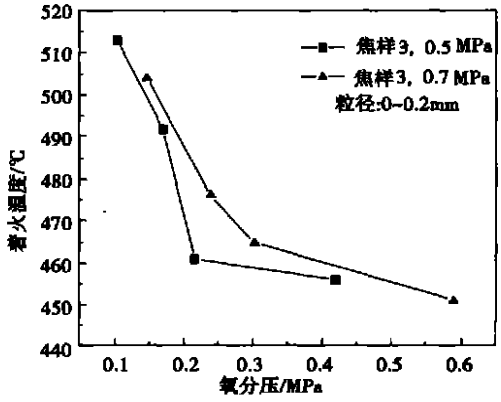

图 8 氧分压对半焦着火温度的影响

图 8 是以氧分压为横坐标整理试验数据后得到的曲线。由图 8 可以发现, 在不同的总压下, 若氧分压相同, 则着火温度相差很小, 在大多数情况下一般不超过 20~30 ℃。由此可以断定, 总压增加导致半焦着火温度下降的主要原因是由于氧分压的提高。

3.2.5 加热速率的影响

加热速率对焦样 1 和焦样 4 着火温度的影响如图 9 所示。从图 9 可以看出, 加热速率对半焦着火温度的影响比较明显, 增加加热速率会导致着火温度明显提高。其原因在于, 增大加热速率时, 环境气氛的温度增加速度较快, 但由于半焦外部灰层的影响, 半焦内部残碳的温升速率虽然也有所提高, 但其提高的幅度远远不如环境气氛, 因而增大加热速率导致了着火温度的升高。

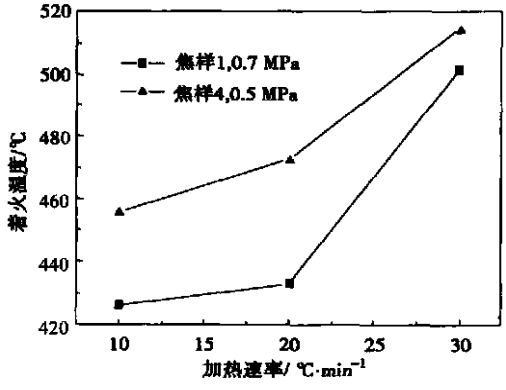

图 9 加热速率对半焦着火温度的影响

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4 结　论

(1) 半焦的挥发份含量和固定碳含量是影响半焦着火温度的主要因素。对于由同一种煤得到的半焦, 固定碳含量越高, 其着火温度越低。

(2) 半焦的着火温度随压力的增加明显下降, 但下降趋势随压力的增加而减缓, 总压增加导致半焦着火温度下降的主要原因是由于氧分压的提高。在0.7MPa 以前, 随着压力的升高, 半焦燃烧稳定性显著增强; 0.7MPa 以后, 燃烧稳定性几乎不再随压力发生变化。

(3) 随着粒径的增大, 半焦的着火温度缓慢升高。半焦的燃烧稳定性在粒径为 0.3 ~ 0.45 mm 的范围内最好, 此粒径范围之外的半焦燃烧稳定性都有所降低。

(4) 随着氧浓度的增加, 半焦的着火温度下降, 燃烧稳定性指数 R_w 逐渐增加。当氧浓度高于 45% 以后, 氧浓度对着火温度和燃烧稳定性的影响趋于减小。

(5) 增加加热速率导致半焦的着火温度升高。

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(渠　源　编辑)

(上接第 144 页)

(2) 通过实验结果分析, 回归出了垂直波槽管管外膜状凝结条件下的管内对流换热、管外凝结换热及冷态条件下波槽管管内流动阻力系数的实验关联式, 以上经验公式可供实际应用参考。

(3) 在管径和壁厚一定的条件下, 波槽管的槽深和节距有一个最佳组合。

(4) 波槽管垂直布置时的换热效果不如水平布置时的好, 凝结换热设备中布置换热管时最好水平布置避免垂直布置; 若需要垂直布置时, 可考虑在一定位置上安装导流罩的方法来疏导凝液, 以达到换热设备小型化的目的。

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湿法烟气脱硫系统除雾器特性试验研究= **Experimental Investigation of the Characteristics of a Demister in a Wet Flue-gas Desulfurization System** [刊, 汉] / YANG Liu, WANG Shi-he (Department of Municipal Engineering, Southeastern University, Nanjing, China, Post Code: 210096), WANG Xiao-ming (Nanjing Research Institute of Electric Power and Environmental Protection, Nanjing, China, Post Code: 210096) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(2). —145 ~ 147

After an analysis of mist elimination principles and in connection with the different layouts of demisters the pressure drop and air flow speed of demistors were measured through numerous tests. Demisting efficiency was calculated with the use of a water balance method. The influence of air flow speed and layout modes of a demistor on its efficiency was analyzed, and the relationship between the air flow speed and pressure drop identified. The results of the above work can serve as a very useful guide and reference for the industrial appliction of the type of demistors under discussion. **Key words**: wet flue-gas desulfurization, demistor, mist elimination characteristics

多孔介质的热物性对往复流动下超绝热火焰的影响= **The Influence of the Thermophysical Properties of Porous Media on a Superadiabatic Flame under the Condition of Reciprocating Flows** [刊, 汉] / DU Li-ming (Dalian Institute of Chemical Physics under the Chinese Academy of Sciences, Dalian, China, Post Code: 116023), XIE Mao-zhao (Department of Power Engineering, Dalian University of Science &Technology, Dalian,, China, Post Code: 116024) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(2). —148 ~ 152

The heat transfer properties of a porous media combustor mainly depend on the thermophysical properties of a porous-media material. Based on the hypothesis of local thermal non-equilibrium between the solid and gas phases the authors have set up a two-dimensional mathematical model for porous-media superadiabatic combustion under the condition of reciprocating flows. The influence of the porous-media specific heat, heat conductivity, dissipation factor and volume heat-exchange factor, etc on temperature distribution and combustion rate was studied in order to provide a theoretical basis for the selection of porous-media materials and the optimized design of a reciprocating-flow porous-media superadiabatic combustor. **Key words**: porous media, superadiabatic combustion, reciprocating flow, thermophysical parameters

气化半焦加压着火特性及燃烧稳定性研究= **A Study of the Ignition Characteristics and Combustion Stability of Gasified Semi-char under an Elevated Pressure** [刊, 汉] / CHEN Xiao-ping, GU Xiao-bing, DUAN Yu-feng, et al (Education Ministry Key Laboratory of Clean Coal Power Generation and Combustion Technology under the Southeastern University, Nanjing, China, Post Code: 210096) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(2). —153 ~ 157

On a pressurized thermogravimetric analytical device of single-furnace and double sample bucket structure a relatively systematic experimental and theoretical study was conducted of the ignition characteristics and combustion stability of gasified semi-char under an elevated pressure. Investigated was the influence of various factors, such as the categories of semi-char, total pressure, oxygen concentration, particle diameter and heating rate, etc on the ignition characteristics and combustion stability of the above-mentioned semi-char. In addition, with the test data of pure carbon serving as a basic reference the authors have proposed index R_w for judging the degree of combustion stability. The results of the investigation indicate that the main factors which have an impact on the semi-char ignition temperature are: the volatile content of the semi-char, fixed carbon content and pore structure. With the increase in total pressure and oxygen concentration and a decrease in particle diameter the ignition temperature of the semi-char will decrease and the combustion stability increase. There will be a conspicuous rise in semi-char ignition temperature when the heating rate is increased. **Key**

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words: coal, semi-char, ignition characteristics, combustion stability, pressurized combustion, pressurized fluidized bed

基于 BP 神经网络的煤粉锅炉飞灰含碳量研究=**The Investigation of Carbon Content in Fly Ash for a BP Neural Network-based Pulverized Coal-fired Boiler** [刊, 汉] / ZHAO Xin-mu, LU Jun-fu, YUE Guang-xi (Department of Thermal Energy Engineering, Tsinghua University, Beijing, China, Post Code: 100084), WANG Cheng-liang (Laicheng Power Plant, Laiwu, Shandong Province, China, Post Code: 271100) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(2). —158 ~ 162

Carbon content in fly ash is a major index, which reflects the combustion efficiency of a pulverized coal-fired utility boiler. On the basis of a BP (inverse propagation of error) neural network method set up was a 11-23-1 type BP neural network model. In accordance with the specific features of a four-corner tangentially fired pulverized-coal utility boiler 11 parameters which can influence combustion have been selected to serve as input factors of the neural network. The parameters include: pulverized coal fineness, burner tilting angle, oxygen content in flue gas, parameters of 5 ranks of coal, operation combination of burner spray nozzles, etc. A training course was conducted for the established model and model parameters were obtained. The error predicted by using the model is less than 6% when compared with actual values. On this basis the authors have also proposed a simplified method for analyzing the carbon content in fly ash, which may be affected by a single parameter. This makes it possible to attain under certain conditions a concise and intuitive reflection of multi-dimensional non-linear law contained in the network. The results of the calculation and analysis indicate that the model-based method can effectively identify the mechanism of various parameters in influencing the carbon content in fly ash and may be employed to conduct the analysis, prediction and optimized regulation of carbon content in boiler fly ash. **Key words**: pulverized coal-fired boiler, BP neural network, carbon content in fly ash, single-parameter analysis

基于典型样本数据融合方法的锅炉制粉系统故障诊断=**Fault Diagnosis of a Boiler Milling System on the Basis of a Typical-swatch Data Fusion Method** [刊, 汉] / TIAN Liang, CHANG Tai-hua, ZENG De-liang, et al (North China University of Electric Power, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(2). —163 ~ 166

It is difficult for the evidence in a D-S evidence theory application to determine the distribution of target-mode confidence function. In the light of this problem the authors have proposed a typical swatch-based method for the acquisition of confidence function distribution. This method utilizes the Hamming distance between the evidence and the typical swatch of each target mode to construct the distribution of confidence function, thus meeting the definition of confidence function distribution and reducing its subjectivity. By using this data-fusion method in the fault diagnosis of a boiler milling system it is feasible to identify such pulverizer malfunctions and faults as pulverized coal self-ignition, pulverizer being full of coal and empty of coal, etc. As verified by historical data, the method under discussion can effectively recognize various types of faults and make an early prediction and diagnosis of ensuing malfunctions. **Key words**: evidence theory, typical swatch, fault diagnosis, coal milling system

应用模糊辨识方法对 DMFC 电堆的温度特性建模=**Temperature Characteristics-based Modeling of DMFC (Direct Methanol Fuel Cell) Stack by Using a Fuzzy Identification Method** [刊, 汉] / MIAO Qing, CAO Guang-yi, ZHU Xin-jian, et al (Fuel Cell Research Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(2). —167 ~ 169

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