热力工程

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无烟煤细颗粒在 300 MW CFB锅炉内停留时间分析

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摘 要: 通过分析我国首台引进型 300 MW CFB锅炉燃煤特性与结构特点, 研究了 CFB锅炉燃烧系统各部分的具体结构对无烟煤颗粒炉内停留时间的影响。探讨了在各分燃烧系统内停留时间的计算方法, 定量计算了 300 MW CFB锅炉 BMCR工况下细颗粒的炉膛内停留时间和燃尽时间。研究发现: 返料管内为还原性气氛, 无烟煤颗粒与高温物料在返料管内混合, 时间长达 2 min, 热解过程主要发生在该阶段, 这种结构极大地促进了无烟煤颗粒的着火和燃尽; 炉膛是煤燃烧的主要区域, 大颗粒主要在密相区流态化燃烧, 直至燃尽; 细颗粒燃烧主要发生在稀相区, 其在该锅炉炉膛稀相区的停留时间大于其燃烧所需时间; 具有一定的下倾角和凹槽的分离器入口烟道和排气中心筒底部缩口并偏置的绝热旋风分离器保证绝大部分的细颗粒返回炉膛, 确保细颗粒在炉膛的停留时间超过其燃尽时间; 以上结构形式是确保锅炉飞灰含碳量低的根本圆心, 这为更大容量 CFB锅炉的设计奠定理论基础。

关 键 词: 循环流化床锅炉; 无烟煤细颗粒; 停留时间
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引 言

我国煤炭资源丰富, 以燃煤电站为主的电源结构在未来较长时间内很难改变, 循环流化床 (Circulating Fluidized Bed, CFB)锅炉可以燃用高硫劣质燃料, 具有效率高, 炉内脱硫, 氮氧化物排放量低的优点, 近几十年得到广泛应用。大型化是 CFB锅炉发展的基本方向, 300 MW等级 CFB锅炉已经逐渐成为我国发电的主力炉型[1]。

由于无烟煤挥发分低, 着火和燃尽非常困难, CFB锅炉在燃用无烟煤时普遍存在飞灰含碳量高等问题[2], 造成锅炉效率低, 但某引进型 300 MW CFB锅炉飞灰可燃物含量在 2.75%, 大大低于国内燃烧无烟煤的中小型 CFB锅炉[3]。燃煤颗粒的燃尽程度与其在 CFB锅炉内停留时间密切相关。本研究通过分析该锅炉燃煤特性与锅炉结构, 研究了 CFB锅炉各燃烧系统具体结构对无烟煤颗粒炉内停留时间的影响, 找出无烟煤颗粒在各分燃烧系统内停留时间的计算方法, 计算了 300 MW CFB锅炉 BMCR工况下细颗粒的炉内停留时间, 发现了该类型锅炉飞灰含碳量低的理论原因, 为指导同类型以及未来 600 MW CFB锅炉的设计和运行提供理论支持。

1 燃用的无烟煤特性

我国首台 300 MW CFB锅炉采用法国 ALSTOM公司技术, 安装在中国四川某电站[4]。设计燃用芙蓉无烟煤, 运行中主要燃用当地的劣质无烟煤, 设计煤种及实际使用煤种如表 1所示。

表 1 煤质特性

	设计煤种	校核煤种	实际使用煤种
M_t/%	7.69	9.5	
A_{ar}/%	35.27	38.01	50左右
C_{ar}/%	49.2	44.20	38左右
H_{ar}/%	2.09	1.94	
O_{ar}/%	1.65	1.57	
N_{ar}/%	0.56	0.48	
$S_{t,ar}$/%	3.54	4.3	2.8左右
V_{daf}/%	14.99	16.39	6~9
$Q_{net,ar}$/kJ·kg^{-1}	18 495	17 040	12 000~14 000
K_{km}	4.06	4.82	

芙蓉无烟煤属晚二叠纪乐平煤系, 其硫分高达 3.88%, 有机硫比例较少而硫铁矿硫较多。具有碳化程度高、挥发份低、析出时间长、结构致密、煤质脆、细颗粒含量大等特点, 着火和燃尽非常困难[5]。

国内外学者对无烟煤的燃烧研究表明[6~8], 无烟煤在流化床中的燃烧受化学动力学和扩散阻力共

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同控制。CFB锅炉大多数燃用 0~8 mm的宽筛分煤粒。其中小于 0.5 mm的煤粒占 25% ~30%,有的甚至更高。另外粗颗粒煤在燃烧时经一级、二级破碎和磨损也会产生一部分细颗粒焦炭,细颗粒焦炭一般小于 50~100 μm,部分细颗粒由于随颗粒团运动而被分离器捕集,其余部分则逃离分离器,其燃尽所需时间小于在炉膛内的停留时间,难以被燃尽,这构成锅炉飞灰可燃物的主要来源[9]。

2 引进型 300 MW CFB锅炉的结构特点

该锅炉为亚临界自然循环汽包炉,单炉膛、平衡通风、露天布置。锅炉的结构总体示意图如图 1所示[9~10]。采用相对较高的床温(约 890 ℃)、高循环倍率运行方式。

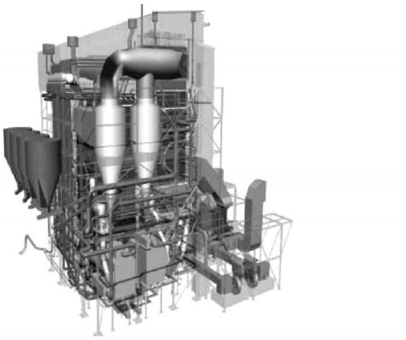

图 1　300 MW CFB锅炉总体示意图

2.1 炉膛

锅炉采用膜式水冷壁结构,底部采用裤衩管设计,将布风板一分为二,在裤衩腿内墙布置上下两排二次风喷口,外墙布置一排二次风口。每个裤腿的燃烧室有相对独立的给料系统、空气供给系统和排渣系统,如图 2所示。

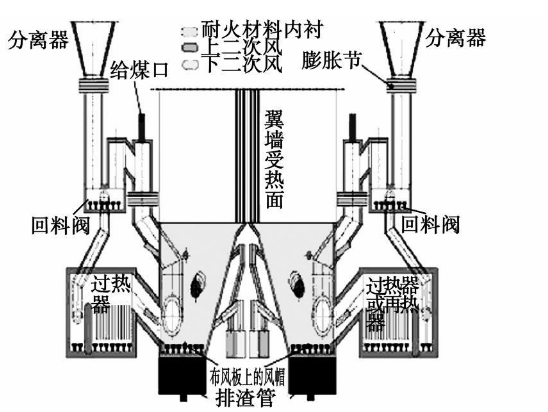

图 2　炉膛底部结构示意图

2.2 分离器

该锅炉设有 4个直径为 Φ8.7 m的高温绝热旋风分离器,分别布置于炉膛的两侧。每个分离器下布置 1个回料阀和 1个外置式换热器。回料阀一侧与炉膛前后墙的返料口相连,其上有石灰石和燃煤加料口,另一侧与外置床换热器相连。分离器分离下来的循环物料,分别进入回料阀和外置床换热器,再分别以高温物料和低温物料的状态返回炉膛。

2.3 外置床换热器及回料阀

锅炉设有 4个外置换热器(EHE),内布置低温、中温过热器以及高温再热器。通过调节外置床换热器灰控制阀(锥形阀)开度调节返料量、调节炉膛温度和再热蒸汽出口温度。

3 无烟煤细颗粒在 CFB锅炉内的停留时间

无烟煤颗粒在 CFB锅炉内的停留时间的计算是一个非常复杂的问题,它取决于锅炉结构以及运行工况等因素,并且受燃烧、传热的制约。由于燃煤颗粒在 CFB锅炉内的燃烧与颗粒的停留时间和运动轨迹有关,而精确地确定某个颗粒的这些参数是不可能的。现在可以采用数值计算的方法模拟颗粒的运动[8],由于计算量大,目前还不能广泛使用。

在引进型 300 MW CFB锅炉中,燃煤颗粒依次流经返料管、炉膛密相区、炉膛稀相区、旋风分离器入口烟道和旋风分离器。下面分别分析燃煤颗粒在各段的停留时间。

3.1 返料管阶段

该锅炉采用返料器给煤,燃煤入口在旋风分离器的返料管上,无烟煤颗粒与 900 ℃的高温循环灰混合,沿直径为 1.42 m,长约 20 m的返料管缓慢流进炉膛。这种结构减少了炉膛开口,有利于无烟煤颗粒预热。在 BMCR工况,锅炉循环倍率为 33.6[10],返料管内的高温灰流量高达 4 600 t/h,煤量与灰量之比约为 1∶25,混合时间长达 2 min。

3.2 炉膛阶段

该 CFB属高速流化床,由于底部床料的加速效应和大颗粒从底部循环回送,存在着底部的密相区和上部的稀相区,两者以下二次风口的中心线为界。在布风板和下二次风口之间的区域基本上处于鼓泡流化床和湍流流化床状态,而在上二次风口以上逐步过渡到快速流化床状态。

3.2.1 密相区

在密相区,燃煤颗粒受从底部布风板垂直向上的一次风吹动,从布风板处开始上升直到两相界面

处,此时的运行风速小于某些颗粒的终端沉降速度,这些颗粒开始进行炉内返混,密相区固体颗粒浓度很大且颗粒在其内部进行强烈的紊流,粗颗粒煤粒大部分的燃烧是在密相区内完成的。

该锅炉返料管入炉标高为9.4 m,截面为椭圆,垂直方向尺寸为1.98 m;而下二次风口标高为10.1 m,截面为椭圆,垂直方向尺寸0.566 m。两者标高大致相同,可以认为从返料管来焦炭粒子进入锅炉的区域是密相区和稀相区的过渡区,大颗粒在密相区循环运动,大部分细颗粒进入稀相区,细颗粒在密相区的停留时间较短,可忽略。

3.2.2 稀相区

无烟煤析出挥发份后形成焦碳颗粒,细焦碳颗粒在稀相区的运动主要在炉膛的中心区域,细颗粒一次通过稀相区的时间为[12~15]:

$$\tau_b = \frac{H_{bed}}{u_f - u_{slip}} \tag{1}$$

式中:τ_b—颗粒飞出时间,s;H_{bed}通常为炉膛高度,本锅炉为下二次风口中心线至炉膛出口中心线高度,H_{bed}=29 m;u_f—炉膛烟气速度,m/s;u_{slip}—颗粒的滑移速度,m/s。取颗粒的滑移速度为其终端速度(颗粒的滑移速度实际上并不等于颗粒的终端速度u_t,但如取颗粒的终端速度为其滑移速度则计算精度较好[15]):

$$u_{slip} \approx u_t = 0.153\frac{g^{0.71} d_c^{1.14} (\rho_p - \rho_f)^{0.7}}{\rho_f^{0.29} \mu^{0.43}} \tag{2}$$

式中:d_c—颗粒直径,μm;ρ_p—颗粒密度,取1 600 kg/m³;ρ_f—气体密度,890 ℃时为0.301 kg/m³;μ—气体运动粘度,890 ℃时为46.7×10^{-6} Pa·s;g—重力加速度,计算结果如图3所示。

3.3 旋风分离器及入口烟道

在BECR工况时分离器的烟气入口温度高达835 ℃,超过无烟煤颗粒的着火温度,文献[10]测出口温度为940 ℃,未燃尽的细焦炭颗粒在分离器内有一定程度的再燃。

从炉膛逃逸出来的细颗粒被捕捉回送炉膛燃烧,决定了细颗粒在燃烧室的总停留时间和燃烧时间。该CFB锅炉采用了独特的分离器入口烟道,具有一定的下倾角和凹槽,对烟气流动具有导流和加速作用,还有一定的预分离作用。烟道长约11 m,BECR工况时入口烟速达到10.5 m/s。

旋风分离器为高温绝热方式,直径为8.7 m,由圆形筒体和锥形筒体组成,整体高约19.2 m,出口中心筒偏置。烟气携带飞灰颗粒沿旋风分离器切线方向进入,绕旋风分离器中心线向下作旋转运动,到达锥筒底部区域后开始折向上方运动,从出口中心筒流出,绝大部分飞灰颗粒沿锥筒内壁面向下旋转运动,进入返料管。这种结构增加了颗粒在分离器内的运动线路,延长了细颗粒在分离器内的停留时间,提高了分离效率,该分离器的临界分离粒径达到为40~70 μm,较传统分离器的临界分离粒径90~100 μm低30~50 μm[4]。

4 细颗粒无烟煤燃烧所需时间

无烟煤颗粒燃烧所需时间包括由环境温度加热至着火点温度所需时间和由着火至燃尽所需时间组成。无烟煤颗粒的着火点温度一般取为400 ℃,该锅炉在返料管内已经把无烟煤颗粒加热到超过其着火点温度,大焦炭颗粒在CFB锅炉内循环直至燃尽,需要计算的主要是分离器不能扑捉的细焦炭颗粒在炉膛内的燃尽时间。

对于小颗粒煤焦,为扩散对燃烧速度影响较小,其燃烧由表面反应控制,燃烧速度为化学反应速度。CFB锅炉内温度比较均匀,在BECR工况,基本在890~1 050 ℃,通常认为煤焦颗粒温度等于炉膛温度,氧气浓度按炉膛内平均值计算,细颗粒的燃尽时间τ_c的经验式为[6]:

$$\tau_c = \frac{\rho_p \cdot d_c}{0.032\, k_0 T_{bed} \exp(-E/RT_{bed})\, C_{O_2}} \tag{3}$$

式中:τ_c—燃尽时间;k_0—频率因子,取598 m/(s·K);E—活化能,无烟煤的活化能很高,取149 200 J/mol;T_{bed}为炉膛温度,K;C_{O_2}—氧浓度,CFB锅炉炉膛氧浓度一般在在5~8 mol/m³之间,取6.25 mol/m³;R=8.314 J/(mol·K),计算结果如图3所示。

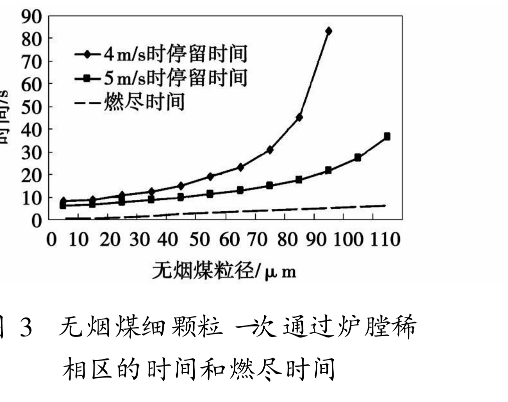

图3　无烟煤细颗粒一次通过炉膛稀相区的时间和燃尽时间

5 计算结果与分析

5.1 返料管

经计算，在 BMCR工况，高温循环灰和燃煤颗粒在混合时间长达 2 min，远大于无烟煤颗粒着火所需的预热时间[8]，煤中绝大部分挥发份已经析出，燃煤颗粒基本转化为焦炭。返料器内虽然有返料风和松动风，但数量较少，在返料管内氧浓度很低，为还原性气氛，可以认为无烟煤颗粒在返料管内发生热解过程，同时焦炭颗粒温度已经超过着火温度，这大大促进了无烟煤颗粒在炉膛内的着火和燃尽。

5.2 炉 膛

根据燃用无烟煤的运行经验，在保证炉内一定温度水平的前提下，煤粉停留时间 2 s以上，就可以保证煤粉的充分燃烧[16]。由图 3可知，颗粒燃尽所需时间和一次通过炉膛时的停留时间均随颗粒径的增加而增长，随炉膛烟风速度的增加，停留时间减少。无烟煤颗粒在该锅炉炉膛稀相区的停留时间大于其燃烧所需时间，能够保证飞出炉膛的煤焦绝大部分燃尽。

5.3 旋风分离器及入口烟道

旋风分离器入口烟道呈斗状，下倾，长约 11 m，入口烟气流速 10.5 m/s[10]，认为颗粒速度与烟气速度一致，停留时间 1 s。

旋风分离器内流动十分复杂，颗粒流速和运动轨迹很难确定，入口烟气有向下动量来抗拒热浮力和引风机吸力，使烟气能最大程度到达分离器底部区域，烟气沿分离器内壁运动的时间大大延长；细颗粒在离心力的作用下在分离器内壁富集，有团聚现象发生，减少了二次扬析；分离器出口中心筒末端带偏置大小头，减少分离器内负压区的作用半径，使细颗粒在分离器内的停留时间较传统结构约高出 7倍[16]。

6 结 论

（1）对燃用挥发分含量低，灰分大的无烟煤的 CFB锅炉来说，炉膛结构一定要满足颗粒特别是细颗粒在炉中停留的时间大于其燃尽时间，本研究的引进型 300 MW CFB锅炉在这方面是非常成功的，根据实际测量，其飞灰可燃物含量在 2.75%[11]，低于国内燃烧无烟煤的中小型 CFB锅炉。

（2）对于该类型 CFB锅炉，在计算燃煤颗粒在炉内停留时间时，返料管、炉膛、旋风分离器及入口烟道都需要考虑。

（3）对于该类型 CFB锅炉，无烟煤颗粒和高温循环灰在返料管内混合时间长达 2 min，热解过程主要发生在该阶段，这种结构极大地促进了无烟煤颗粒的着火和燃尽。

（4）炉膛是煤燃烧的主要区域，大颗粒主要在密相区流态化燃烧，直至燃尽；细颗粒燃烧主要发生在稀相区。颗粒在炉膛高温区中的停留时间对其燃尽有重要影响。炉膛高度、炉膛烟气流速等对细颗粒煤焦在 CFB锅炉中的停留时间有重要影响。

（5）该锅炉采用大型高效绝热旋风分离器，分离器及入口烟道烟气温度高，颗粒停留时间长，未燃尽的细焦炭颗粒在分离器内有一定程度的再燃，旋风分离器及入口烟道是飞灰含碳量进一步降低的重要场所，因此停留时间应该计算到至旋风分离器的出口。

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conducted. In this connection, the vibration initiation and elimination process of the system and their mechanism were analyzed and the influence of the heating end temperature, cooling end temperature and recuperator on the system performance was also studied. The research results show that the hybrid type travelling-wave thermo-acoustic engine has a lower vibration initiation temperature than the pure loop type one. With an increase of the cooling end temperature, the vibration initiation temperature of the system will rise accordingly. The recuperator opening diameter has a relatively big influence on the system performance. In the present test, when the recuperator opening diameter was 0.8 mm, the system had a lowest vibration initiation temperature. During the test, a "secondary vibration initiation" phenomenon has also been found. Key words: thermo-acoustic engine, pure loop and hybrid type, vibration initiation, vibration elimination, recuperator

对 CFB燃烧/煤热解多联产工艺过程的开发 = Development of CFB (Circulating Fluidized Bed) Combustion/Coal Pyrolysis Multiple Cogeneration Processes[刊,汉] / LIANG Peng (College of Chemistry and Environment Engineering, Shandong University of Science and Technology, Qingdao, China, Post Code: 266510), QU Xuan, BI Ji-cheng (National Key Laboratory on Coal Transformation, Shanxi Coal Chemistry Research Institute, Chinese Academy of Sciences, Taiyuan, China, Post Code: 030001), WANG Zhi-feng (Ningbo Branch, Chinese Academy of Weapon Sciences, Ningbo, China, Post Code: 315103) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(3). —278~282

Self developed was an intermittent type solid heat carrier pyrolysis plant with a self-processing capacity of 1 kg coal. Furthermore, with bituminous coal of a high volatile content and quartz sand serving as the raw material and heat carrier respectively, a pyrolysis characteristics evaluation experiment was performed. It has been found that with an increase of the hybrid pyrolysis temperature, the gas productivity can somehow increase. When the pyrolysis temperature is higher than 560 ℃, the coal tar productivity can reach 9% to 11% by weight. Through a simulation of the low temperature dry distillation process in the front of the furnace and with Pingshi-originated coal of a high sulfur content serving as raw material, it has been found that the cycling ash exhibits a conspicuous role of sulfur fixation and the majority of gas-phase sulfur produced during the pyrolysis process is fixated in ash. In the meantime, in combination with the research achievements made in the earlier period by the laboratory and the ongoing multiple cogeneration pilot test, an exploratory study has been made of the solutions to the key technologies in the development of CFB combustion/coal pyrolysis multiple cogeneration processes, such as combination type U-shaped recycling device, control mode of the pressure in the reactor and establishment of the system equilibrium correlation etc. Key words: coal pyrolysis, combustion, multiple cogeneration, heat carrier, pyrolysis plant

无烟煤细颗粒在 300 MW CFB锅炉内停留时间分析 = An Analysis of the Residence Time of Anthracite Fine Particles in a 300 MW Circulating Fluidized Bed Boiler[刊,汉] / YANG Dong, XU Hong, CHEN Hai-ping, et al (Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control, North China University of Electric Power, Beijing, China, Post Code: 102206) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(3). —283~286

Through an analysis of the coal combustion characteristics and structural features of a 300 MW circulating fluidized bed (CFB) boiler first introduced by China, studied was the influence of the specific structures of various parts of the boiler combustion system on the in-furnace residence time of anthracite particles. The method for calculating the residence time in various combustion subsystems was explored, and the in-furnace residence time and burn-out duration of the fine particles in the 300 MW CFB boiler under the BMCR (boiler maximum continuous rating) operating condition were quantitatively calculated. It has been found that a reduction atmosphere predominates the space inside a recycling tube, and the anthracite particles and high temperature materials are mixed in the recycling tube, which lasts 2 minutes, during which the pyrolysis process mainly takes place. This type of structure can greatly promote the ignition and burn-out of anthracite particles. The furnace is considered as the main zone for coal combus-

tion and big particles are mainly burned in the dense phase zone until they are burned out The combustion of the fine particles mainly takes place in a sparse phase zone The residence time of the fine particles in the sparse phase zone of the boiler furnace is longer than that required by the combustion The adiabatic cyclone separator with its inlet gas duct having a certain downward inclination angle and a concave slot and with the bottom of the exhaust gas central shell being converged and offset can guarantee the majority of fine particles being returned to the furnace ensuring the residence time of fine particles in the furnace longer than their burn-out duration The above-mentioned structure constitutes the root cause for ensuring a low carbon content of the flying ash in the boiler thus laying a theoretical basis for the design of CFB boilers of greater capacity Key words: circulating fluidized bed boiler fine anthracite particle residence time

低浓度可燃废气作为辅助燃料在燃煤锅炉中的应用研究＝Applied Study of Low Concentration Combustible Waste Gases Serving as an Auxiliary Fuel in a Coal-fired Boiler[刊,汉] / DENG Lei WANG Yi-kun CHE De-fu (National Key Laboratory on Multi-phase Flows in Power Engineering Xi'an Jiaotong University Xi'an China Post Code: 710049) // Journal of Engineering for Thermal Energy & Power: — 2010 25(3). —287 ~ 291

A method for using low-concentration (0.1% to 1.0%) combustible waste gases in coal-fired boilers was presented Based on mass balancing heat balance and transfer the influence of the combustible waste gases on the boiler thermodynamic parameters was analyzed It has been found that when the low concentration combustible waste gases are fed into a coal-fired boiler as an auxiliary fuel there is no need to reconstruct the boiler system and its operation is hardly affected However it can effectively save coal recover the heat in the combustible waste gases and in the meantime reduce the emissions of the greenhouse gas methane With an increase of the volumetric concentration of the combustible waste gases the radiative heat exchange in the furnace will be slightly intensified but the heat exchange through convection heating surfaces will be weakened accordingly With a 600 MW boiler serving as an example after a hydrocarbon waste gas with a volumetric concentration of 1.0% has replaced the air for combustion the thermal efficiency of the boiler was enhanced by 0.5% and the coal consumption rate reduced by 25.4%. Key words: low concentration combustible waste gas auxiliary fuel coal-fired boiler thermodynamic parameter

基于 LS-SVM和单纯形的烟气含氧量软测量＝Soft Measurements of Flue-gas Oxygen Content Based on LS-SVM (Least Square Supportive Vector Machine) and a Simplex Algorithm [刊,汉] / LIU Chang-liang LI Shu-na (Automation College North China University of Electric Power Baoding China Post Code: 071003) // Journal of Engineering for Thermal Energy & Power: — 2010 25(3). —292 ~296

Flue gas oxygen content is an important factor influencing the combustion efficiency of a thermal power plant To measure the flue gas oxygen content in a thermal power plant is somewhat difficult as it is influenced by multiple factors A soft measurement model was established based on the easily measured secondary variables and by utilizing the mathematical relationship between the secondary variables and the process variables to be measured which present difficulties for measurement The appropriate secondary variables were chosen and a soft measurement model based on LS-SVM (Least Square Supportive Vector Machine) was presented for measuring the flue gas oxygen content of a thermal power plant A simplex optimum-seeking algorithm was applied in two parameter optimization problems of the least square supportive vector machine which have to be determined The model in question was forecasted and verified with on-site data The simulation results show that the method under discussion can measure relatively accurately the flue-gas oxygen content in a thermal power plant and is of major significance for realizing economic combustion in the thermal power plant Key words: LS-SVM (least square supportive vector machine), simplex algorithm flue gas oxygen content soft measurement optimization-seeking algorithm