文章编号: 1001－2060(2001)05－0491－03

增湿活化脱硫试验研究

吴树志, 赵长遂, 刘现卓

(东南大学 国家教育部洁净煤发电及燃烧技术重点实验室, 江苏 南京　210096)

摘　要: 在热态脱硫试验台上进行了喷水活化和蒸汽活化脱硫试验, 并研究了在不同钙硫比、饱和温距、SO_2 浓度和烟气速度下的脱硫性能。研究表明, 与单纯的吸收剂喷射技术相比, 蒸汽增湿活化和喷水增湿活化, 都可以提高脱硫效率, 但喷水活化效果比蒸汽活化效果好得多, 而且脱硫效率随钙硫比增加、饱和温距、SO_2 浓度及烟气速度的降低而升高; 在喷水增湿活脱硫中, 脱硫剂浆滴的脱硫作用远远大于脱硫剂吸湿脱硫作用。

关　键　词: 脱硫; 增湿活化; 试验研究

中图分类号: X511　　文献标识码: A

1　前言

SO_2 污染和酸雨沉降是影响大气质量的重要因素之一, 其对工业及民用设施的腐蚀, 对水陆生态环境的破坏和人体健康的影响, 已引起了人们的普遍关注。对现有燃煤锅炉进行脱硫环保改造是解决 SO_2 污染的根本途径。由于炉膛喷钙尾部增湿活化脱硫技术具有流程简单, 装置紧凑, 投资省, 成本低、脱硫效率中等的优点, 比较适合我国国情, 对现有中小锅炉的环保改造具有重要的应用意义。

在炉膛喷钙尾部增湿活化脱硫系统中, 增湿活化反应器是关键部分。炉膛内煅烧生成的脱硫剂生石灰中未充分利用的部分在反应器入口与喷入的水滴充分混合, 部分与水碰撞, 形成浆滴, 脱硫活性大大加强, 进一步吸收 SO_2, 脱硫效率有很大提高。其反应过程涉及到气固液三相流动、固液粒子碰撞、水滴与浆滴蒸发、水蒸气吸附和硫盐化反应等多因素的复杂物理化学过程[1~3]。清华大学[4]、浙江大学[5]曾有喷入活化水使脱硫效率升高的报道, 认为脱硫剂脱硫活性提高的原因是水分的存在使钙基脱硫剂表面形成液膜, 硫化反应由气固反应变为液相离子反应。在活化反应器中, 与水碰撞的脱硫剂颗粒形成浆滴, 没有与水碰撞的脱硫剂颗粒则吸附烟气中的水蒸气, 两种形式的含湿脱硫剂的脱硫活性都有一定的提高。为了研究这两种形式的含湿脱硫剂在脱硫系统中的作用, 笔者在喷水活化脱硫试验装置上进行了喷水增湿活化和蒸汽活化脱硫试验研究, 包括钙硫比、喷水量、烟气速度和 SO_2 浓度等对脱硫效率的影响。为下一步深入研究提供试验基础, 也可为增湿活化脱硫装置的设计提供依据。

2　试验系统与装置

喷钙增湿活化脱硫试验装置如图 1 所示。

反应器本体为直径 400 mm 的圆筒结构, 高度为

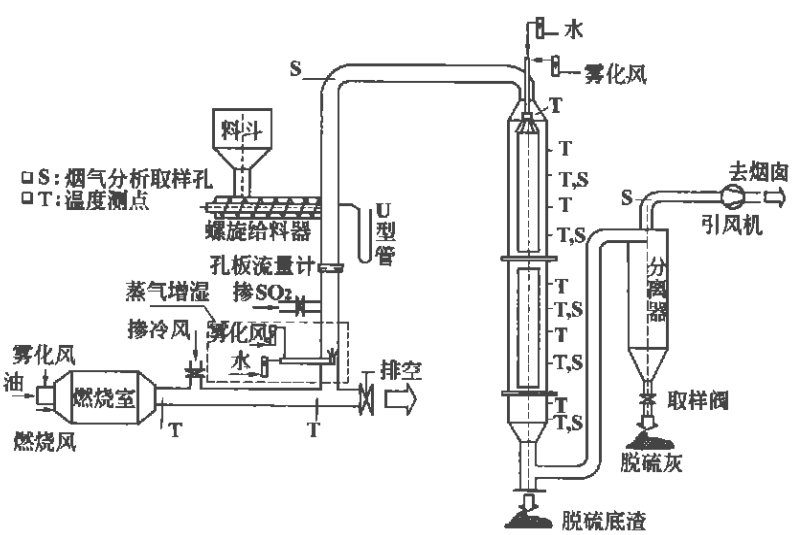

图 1　试验台示意图

6 000 mm。在活化反应器中, 热烟气流速控制范围为 1~3 m/s; 增湿水由反应器顶部喷入, 水滴粒径控制在 0.05~0.2 mm 之间。使水滴在活化器内既能

收稿日期: 2000－07－13; 修订日期: 2000－11－03

基金项目: 国家重点基础研究专项经费基金资助项目(G1999022201－04)

作者简介: 吴树志(1973－), 男, 山东荣城人, 南京市国家动力公司电力自动化研究院工控所博士。

?1994-2010 China Academic Journal Electronic Publishing House. All rights reserved.　http://www.cnki.net

与热烟气充分混合，又保证水滴能够完全蒸发，达到增湿活化的目的，脱硫产物还保持干态。为实现蒸汽增湿，在脱硫剂加入点前约 20 m 处喷入雾化水，使水雾在与脱硫剂接触前完全蒸发。试验烟气由油燃烧器产生，烟气温度和速度通过掺冷风量和排空量来调节，烟气中的 SO_2 浓度由纯 SO_2 液体钢瓶上标定过的浮子流量计读数调节，由于 SO_2 沸点较低，为保证 SO_2 气体流量均匀稳定，对 SO_2 钢瓶进行水浴加热，SO_2 添加管路外缠绕加热带，由加热带电压调节温度。试验脱硫剂为南京汤山生石灰，其粒径分布和成份见表 1 和表 2，脱硫剂由螺旋加料器添加，通过调速电机与绞龙的转速控制加料量。

喷水量由烟气的热平衡计算：

$$C_g^{T_g}\times T_g\times V_g + C_w^{T_w}\times T_w\times M_w = (C_g^{T_g}\times T_g + C_{st}^{T}\times M_w)\times T$$

其中 C_g、C_w、C_{st} 分别指烟气、水和水蒸气的定压比热，T_w 指水温，T_g、T 分别指喷水增湿前后的烟气温度。V_g、W_w 分别指烟气量和喷水量。由于酸露点温度难以准确计算，按烟气的蒸汽露点计算饱和温距。在热平衡计算后，根据喷水量和烟气温度计算烟气湿含量，最终得出不同喷水量下的饱和温距。

试验时，反应器的沿程温度分布由 K 型热电偶测量，由于反应器内的流场为气、液、固三相共存的流场，插入流场中的热电偶测量的温度不是单纯的气相温度，但是测量结果可用于监测雾化水的蒸发情况。进出口的 SO_2 浓度由德国 Rosemount 公司制造的 NGA2000 多组分气体分析仪测量。根据进出口的 SO_2 浓度计算脱硫效率。

表 1 脱硫剂粒径分布

粒径区间/μm	>75	75~45	45~30	30~20	20~10	10~5	<5	质量平均粒径
含量/%	13.6	7.2	6.1	6.7	25.6	17.9	22.9	17.47μm

表 2 脱硫剂成份

名 称	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	SO_3	烧失量
含量/%	1.88	0.30	1.04	0.036	65.90	0.69	0.076	0.034	0.35	28.7

3 试验结果与分析

3.1 活化器内温度变化

不同饱和温距下沿程温度测量结果如图 2 所示。由图可见，喷水前，入口温度为 140 ℃，由于向周围环境散热，沿轴向温度缓慢地降低。喷水后，喷水点后温度迅速降低，这是由于雾化水喷射黏附在热电偶上，在 1 500 mm 处，温度迅速上升，达到最高点后又开始缓慢下降。这表明，喷入的雾化水迅速蒸发，到 3 000 mm 处已基本蒸发完全。控制合理的饱和温距，可以使脱硫灰以干态形式排出活化反应器，使脱硫灰易于处理，避免烟道腐蚀。

3.2 钙硫比对脱硫效率的影响

钙硫比对脱硫效率影响曲线见图 3。在试验钙硫比变化范围内，随着钙硫比的增加，脱硫效率增加。钙硫比增加，相应烟气中的脱硫剂颗粒浓度增加，雾化水滴捕捉的脱硫剂总量增加，脱硫效率提高。但是，由于温距和喷水量保持不变，则钙硫比增大，水钙比减小，脱硫剂的活化效率降低，使得脱硫效率随钙硫比增加而升高速度变慢。

3.3 饱和温距对脱硫效率的影响

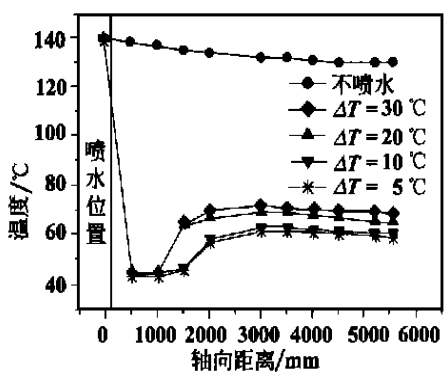

图 2 反应器沿程温度

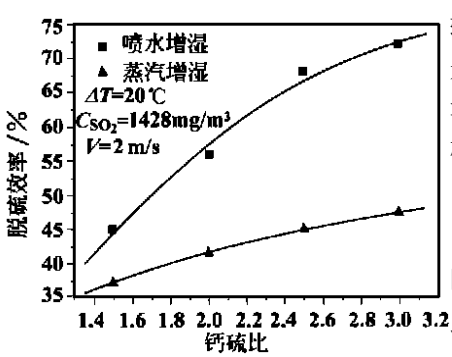

图 3 钙硫比对脱硫效率的影响

饱和温距决定的喷水量直接影响水钙比、雾化水滴捕捉脱硫剂总量、水滴浆滴蒸发时间和烟气相对湿度，因此对脱硫效率影响比较明显。图 4 是不同饱和温距下的脱硫效率变化。由图可见，ΔT 为 5 ℃时的脱硫效率比 30 ℃时高出 30 个百分点。但是 ΔT 过低，容易引起活化反应器和后部烟道及烟囱内结露腐蚀，因此确定适当的 ΔT 是反应器设计和运行的重要环节。

3.4 SO_2 浓度对脱硫效率的影响

SO_2 浓度对脱硫效率的影响见图 5。从图中可以看出，随着 SO_2 浓度的升高，脱硫效率略有降低。从传质动力方面看，SO_2 浓度提高，有利于 SO_2 气体通过浆滴表面向浆滴内部扩散，也有利于气固硫化

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

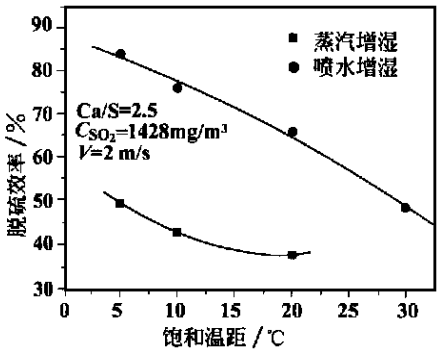

图 4　饱和温距对脱硫效率的影响

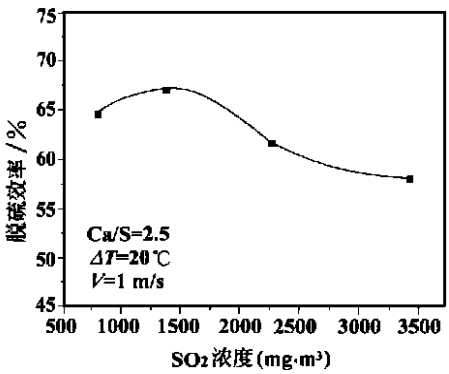

图 5　SO_2 浓度对脱硫效率的影响

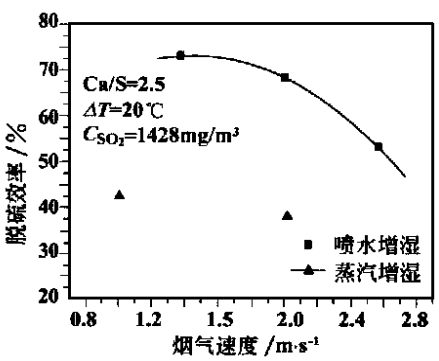

图 6　烟气速度对脱硫效率的影响

反应, 使脱硫效率有升高的趋势; 但是在相同的钙硫比下, 较高的 SO_2 浓度需要较多的脱硫剂, 而受饱和温距的限制, 雾化水量保持不变, 脱硫剂活化效率降低, 使参与液相反应的脱硫剂份额减小。由于喷水活化能提高脱硫效率的主要原因就是液相脱硫反应的存在, 所以两方面的作用使脱硫效率的降低幅度较小。

3.5　烟气速度对脱硫效率的影响

烟气速度提高, 雾化水滴和浆滴的蒸发速度加快, 由于受反应器高度限制, 浆滴停留时间缩短, 脱硫反应时间相应缩短, 使脱硫效率降低。图 6 是不同烟气速度下的脱硫效率变化。由图可见, 在 1.4 m/s 的速度下的脱硫效率比 2.6 m/s 下的脱硫效率要高出约 20 个百分点, 这说明处理烟气量及烟气速度是设计活化反应器的重要参数, 直接影响到反应器的截面积和高度, 在实际反应器设计中, 要充分考虑烟气速度对脱硫效率的影响。

3.6　喷水增湿与蒸汽增湿脱硫性能对比

从图 3、图 4 和图 5 中可以看出, 在相同的饱和温距, 相同试验参数下, 喷水增湿比蒸汽增湿的脱硫效率高得多。这证明, 在喷水增湿活化反应器中, 水滴捕捉脱硫剂颗粒形成的浆滴在脱硫反应中的作用永远大于未碰撞脱硫剂颗粒通过吸湿的作用。因此, 提高脱硫剂颗粒被捕集的活化效率, 是进一步提高脱硫效率的重要措施。

4　结论

试验条件下, 通过控制合适的饱和温距, 喷水活化脱硫技术可以在保持脱硫灰为干态, 烟气不冷凝的情况下, 显著提高脱硫效率。在钙硫比为 2.5, ΔT 为 10 ℃, 烟气速度为 2 m/s, SO_2 入口浓度为 1 428 mg/m^3 时, 脱硫效率可以达到 76%。在影响脱硫效率的诸参数之中, 钙硫比增大脱硫效率升高, 而饱和温距、SO_2 浓度及烟气速度的增大都使脱硫效率降低。

通过蒸汽增湿与喷水增湿脱硫效果比较, 可以发现, 水滴捕捉脱硫剂颗粒形成的浆滴在脱硫反应中的作用远远大于吸湿脱硫剂颗粒在脱硫反应中的作用, 为进一步研究增湿活化机理和提高脱硫效率提供了试验基础和依据。

参考文献:

[1] GERALD H. NEWTON. Modelling the SO_2-slurry droplet reaction [J]. AIChE Journal, 1990, **36**(12): 1243－1249.

[2] MARK R. STOUFFER. An investigation of the mechanisms of flue gas desulfurization by in-duct dry sorbent injection[J]. Ind Eng Chem Res, 1989, **28**(5): 20－27.

[3] LIFAC North America Inc. LIFAC Sorbent injection desulfurization demonstrattion project final report volume Ⅱ: Project performance and economics[R]. DE－FC22－90PC90548, U S: Depart of Energy Report, 1990.

[4] 陆永琪. 钙基吸着剂增湿活化脱硫等试验研究[J]. 电站系统工程, 1998, **5**(7): 49－53.

[5] 高翔. 水份对钙基脱硫剂性能影响的研究[J]. 燃烧科学与技术, 1999, **5**(1): 39－45.

（辉　编辑）

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved.　http://www.cnki.net

基于面向对象的透平级设计优化专家系统的研究＝**A Study of the Expert System for Turbine Stage Design Optimization Based on an Object-oriented Approach** [刊, 汉] / TONG Tong (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036), FENG Zhen-ping (Energy and Power Engineering Institute under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049), LUO Guo-xi (Taiyuan Fengxi Machinery Works, Taiyuan, China, Post Code: 030027) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —481 ~ 483

With the help of a design method based on an object-oriented approach an expert system for turbine stage design optimization has been studied and developed. The expert system enjoys such merits as a high modularization level and favorable man-machine interface, etc. Representing a new design philosophy and approach for conducting turbine stage design the recommended system can play a significant role in promoting the further application of artificial intelligence technology in the field of turbomachinery design. **Key words**: object-oriented approach, turbine stage, optimization, expert system

两段燃烧流化床锅炉的设计方法＝**The Design method for a Fluidized Bed Boiler with Two-stage Combustion** [刊, 汉] / HU Guo-xin, LI Ya-hong, FAN Hao-jie and LIU Yan-qin (Energy and Power Engineering Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —484 ~ 487

A new type of fluidized bed boiler with two-stage combustion is designed for use in a gas and steam cogeneration plant, featuring low emissions of harmful gases. Because of this it is especially suited for gasification units and central heating plants of small and medium-sized enterprises in economically developed rural districts. The authors present the operating principles and design requirements of a two-stage combustion system as well as the thermodynamic calculation method of the relevant gasification section. A gasification equilibrium model was set up to predict the gas components with related calculations being performed. The calculation results have been found to be in fairly good agreement with industrial measurement and test data. On the basis of the calculation results and a theoretical analysis effective measures are proposed to rationally organize the two-stage combustion. **Key words**: two-stage combustion method, gasification, gas and steam cogeneration plant, fluidized bed

增压流化床燃烧用的煤水混合物流变特性研究＝**A Study on the Rheological Properties of Coal-water Paste Fired in a Pressurized Fluidized Bed Combustor** [刊, 汉] / LU Ping, ZHANG Ming-yao, XU Yue-nian (Thermal Energy Engineering Research Institute under the Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —488 ~ 490

By way of experimental research a systematic analysis was conducted of the influence on the rhelogical properties of coal-water paste (CWP) of such a variety of factors as moisture content, particle distribution, addition of limestone and pipe diameter change, etc. The results of the experimental investigation indicate that the CWP will have good flowing properties at a very low moisture content (Wt = 22.16%) if a proper particle distribution has been selected. The addition of limestone can markedly decrease the flow resistance of CWP in pipeline and improve its transport characteristics. The data obtained from experiments show that the rheological properties of the CWP approximate those of a Bingham fluid. **Key words**: pressurized fluidized bed combustor, coal-water paste, rheological properties, experimental study

增湿活化脱硫试验研究＝**Experimental Investigation of Humidification Activated Desulfurization** [刊, 汉] / WU Shu-zhi, ZHAO Chang-sui, LIU Xian-zhuo (Thermal Energy Engineering Research Institute under the Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —491 ~ 493

Spray water activated and steam activated desulfurization tests were conducted on a hot-state desulfurization test stand. Also investigated were the desulfurization performance under different values of Ca/S ratio, saturation approach temperature, SO_2 concentration and gas speed. The results of the investigation indicate that as compared with a pure absorbent

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

spray technique both the steam humidification activation and spray-water humidification activation can contribute to an enhancement of desulfurization efficiency. However, the spray-water activation is much more effective than steam activation. Moreover, there will be an enhancement in desulfurization efficiency in case of an increase in Ca/S ratio and a decrease in saturation approach temperature, SO_2 concentration and flue gas speed. As regards desulfurization by spray-water humidification activation the desulfurizer droplets play a by far greater role in desulfurization than the desulfurizer moisture sorbent. **Key words**: desulfurization, humidification activation, experimental investigation

油焦浆、水焦浆燃烧特性的试验研究＝**An Experimental Study of the Combustion Characteristics of Oil-coke Slurry and Water-coke Slurry** [刊, 汉] / XIONG Yuan-quan, SHEN Xiang-lin (Thermal Energy Engineering Research Institute under the Southeastern University, Nanjing, China, Post Code: 210096), ZHENG Shou-zhong (materials Bureau of National Electric Power Co., Beijing, China, Post Code: 100016) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —494 ~496

Under low-speed heating conditions the combustion characteristics of oil-coke slurry (mixture of petrol-coke powder and heavy oil) and water-coke slurry (mixture of petrol-coke powder and water) were studied through the use of a thermogravimetric analytical method. These combustion characteristics are compared with those of petrol-coke and pulverized coal. Furthermore, the above results were analyzed from the perspective of a work mechanism. **Key words**: oil-coke slurry, water-coke slurry, combustion characteristics, thermogravimetric analytical method

利用电厂粉煤灰再生劣化抗燃油的试验研究＝**An Experimental Study on the Utilization of Power Plant Pulverized Coal Ash for Regeneration of Deteriorated Fire-resistant Oils** [刊, 汉] / LI Zhi (Testing Research Institute of Guangdong Electric Power Industrial Bureau, Guangzhou, China, Post Code: 510600) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —497 ~498

A contrast analysis was conducted of pulverized coal ash and several kinds of commonly used adsorbent. Optimum technological conditions were explored through an orthogonal test of regeneration by the use of a contact method. Moreover, a quality contrast analysis has also been performed of the fire-resistant oil prior to and after the regeneration. **Key words**: pulverized coal ash, regeneration, fire-resistant oil, test

气动系统中管路的二维粘性流场计算＝**Calculation of a Two-dimensional Viscous Flow Field in the Pipe of a Pneumatic System** [刊, 汉] / BAO Gang, LI Yu-jun, LI Jun, WANG Zu-wen (Pneumatic Technology Center under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —499 ~502

With the help of an algorithm SIMPLE a two-dimensional viscous flow field was calculated with respect to a pipe, which has its two ends fitted with a throttle orifice. This is performed for facilitating an in-depth study of pipe flow characteristics in a pneumatic system and the law of variation of various parameters. A stagnation pressure and stagnation temperature were set at the pipe inlet. On the basis of the pipe geometric characteristics and flow features a calculation zone has been divided into five domains with corresponding domain algorithm being given. The results of numerical calculation indicate that the algorithms provided can clearly reflect the flow characteristics in the pipe and the variation trend of relevant parameters. With the method under discussion it is possible to calculate not only the flow field within the pipe but also the flow field of the jet flow zone at the end of the pipe. **Key words**: algorithm SIMPLE, pipe, pneumatic system, sub-domain algorithm

恒热流时污垢对管内对流换热过程热力学性能影响的分析＝**An Analysis of the Effect of Fouling on the Thermodynamic Performance of Convection Heat Exchange Process in a Tube under Constant Heat Flux Conditions** [刊, 汉] / WU Suang-yin, ZENG Dan-ling, LI You-rong (Power Engineering Institute under the Chongqing University, Chongqing, China, Post Code: 400044) // Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net