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半干法脱硫中应用蒸汽相变促进细颗粒脱除

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摘 要: 在喷雾干燥烟气脱硫系统中进行了应用蒸汽相变促进细颗粒脱除的试验研究: 通过向脱硫反应后的湿烟气中添加适量蒸汽, 形成细颗粒凝结长大所需的过饱和水汽环境, 进而由高效除雾器脱除凝结长大的含尘液滴。细颗粒数量浓度及粒径分布采用电称低压冲击器(ELPI)实时测量。考察了喷雾干燥烟气脱硫操作条件(如 Ca/S, 浆液量)及蒸汽添加量对细颗粒脱除效率的影响, 结果表明: 部分浆液滴和脱硫反应产物可随烟气排出脱硫反应塔, 导致细颗粒数量浓度增加; 在半干法脱硫工艺中应用蒸汽相变可促进细颗粒脱除, 脱除效率随蒸汽添加量增加而提高, 如蒸汽添加量为 0.08 kg/m³ 时, 细颗粒数量浓度脱除效率可提高到 55% 以上; 脱硫操作条件对蒸汽相变效果有较大影响。

关 键 词: 半干法脱硫; 细颗粒数量浓度; 细颗粒脱除; 过饱和; 蒸汽相变

中图分类号: X701.3 文献标识码: A

引 言

目前, 可吸入颗粒物是我国城市大气环境的首要污染物[1~2], 尤其是空气动力学直径小于 2.5 μm 的 $PM_{2.5}$ 可以长时间停留于大气中, 容易通过呼吸系统进入人体内部, 严重危害人体健康[3~4]。随着环境质量要求的提高, 控制细颗粒排放成为迫切要解决的问题之一, 但常规除尘技术的细颗粒脱除效率不能满足要求。

半干法脱硫工艺具有反应速度快、脱硫效率高、无废液排出、产物易处理等优点。脱硫过程中浆液滴与高温烟气之间发生剧烈的传热传质作用, 烟气温度降低, 相对湿度提高, 在脱硫后的湿烟气中添加适量蒸汽就可以使其达到过饱和状态。当过饱和度(蒸汽分压与相同状态下饱和蒸汽压的比值, 用 S 表示)超过颗粒物异质核化凝结所需的临界过饱和度(水蒸气以颗粒为依托发生异质核化凝结所需的最小过饱和度, 用 S_c 表示)时, 水蒸气将以颗粒为依托发生异质核化凝结长大, 从而增大了颗粒被除雾器脱除的可能性。

利用蒸汽相变作为脱除细颗粒的调节措施已有较长研究历史[5~9], 但这些研究主要是针对香烟微粒、硬脂酸、炭黑等特定细颗粒。凡凤仙等人利用数值计算方法研究了蒸汽在燃煤 $PM_{2.5}$ 和焚烧垃圾颗粒表面异质核化特性[10~11], 发现该特性主要由颗粒的物化性质和凝结液对颗粒的润湿性能决定。颜金培等人将蒸汽相变原理与湿法脱硫工艺相结合[12~13], 在湿法脱硫后的烟气中添加适量蒸汽促进细颗粒凝结长大并脱除。本研究以燃煤锅炉产生的烟气为颗粒源, 建立了一套利用蒸汽相变机理促进细颗粒凝结长大并用高效除雾器脱除的实验系统, 研究了应用蒸汽相变脱除细颗粒的原理和不同操作条件对细颗粒凝结长大及脱除的影响。

1 实验系统

实验系统如图 1所示, 主要由全自动燃煤锅炉、脱硫反应塔、旋风除尘器、蒸汽发生器、湿度调节室、烟温调节室、除雾室、引风机和测试控制系统组成。

烟气体积流量为 70 Nm³/h, 由额定耗煤量为 10 kg/h 全自动燃煤锅炉产生。脱硫塔高 2 000 mm, 直径 273 mm, 自塔顶喷入粒径为 25~40 μm 的 $Ca(OH)_2$ 浆液滴。旋风除尘器用于预脱除粒径大于 10 μm 的粗颗粒。向直径 300 mm、长 1 500 mm 湿度调节室中注入水蒸气调节烟气湿度。烟温调节室为列管式换热器, 直径为 450 mm, 高 2 000 mm。细颗粒数浓度和粒径分布采用 Dekati 公司生产的电称低压冲击器(ELPI)实时测量, 粒径测量范围为 0.023~9.314 μm。采用德国 MRU 公司 Delta 2000 CD-Ⅳ型烟气分析仪实时测试 SO_2 浓度。

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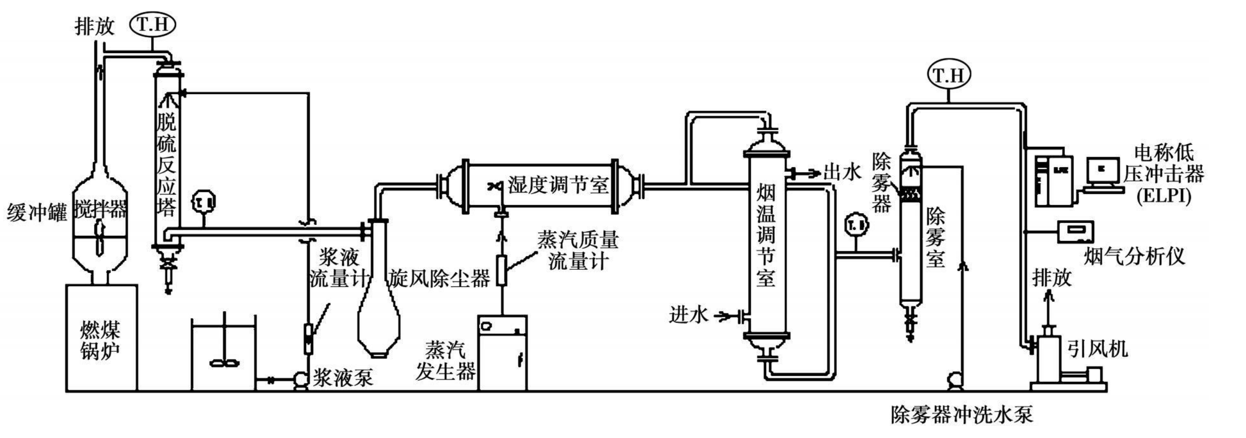


图 1　实验系统示意图

2　结果与讨论

2.1　半干法脱硫对细颗粒数浓度分布的影响

半干法脱硫对细颗粒数浓度分布影响的测试结果如图 2所示。脱硫塔入口、出口和除雾室入口烟气温度分别为 129、62和 51 ℃，脱硫浆液质量浓度为 15%，喷入量为 6 L/h，Ca/S=1.5，脱硫塔出口处烟气露点温度 t_d约 47 ℃。由图可见，半干法脱硫前后细颗粒在 ELPI可测范围内均呈单峰分布，峰值粒径约为 0.04 μm，峰值浓度达到 10^7 个/cm³。喷入脱硫液后，颗粒总浓度提高约 10%。蒋振华在半干法脱硫塔入口和引风机出口采样进行能谱分析[14]，发现脱硫前后 S元素质量百分数从 4.42%增加到 12.93%，Ca元素从 0.99%增加到 8.81%。据此分析，增加的颗粒主要来自干燥的脱硫浆液滴和脱硫反应产物。

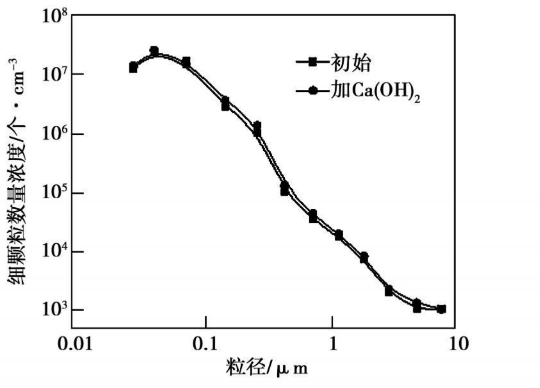


图 2　半干法脱硫对细颗粒数量浓度分布的影响

2.2　半干法脱硫中应用蒸汽相变脱除细颗粒的原理

低温脱硫浆液在塔内与高温烟气间发生传热传质过程，烟气温度降低的同时提高了相对湿度。脱硫塔出口温度一般控制在烟气绝热饱和温度以上 10～25 ℃[15]，因而可以在添加蒸汽的同时降低烟温，使烟气过饱和度达到细颗粒凝结长大的要求。由图 3可见，使 50 ℃相对含湿量 φ为 0.8的烟气达到过饱和状态的途径有 3种：一是在烟气中添加蒸汽（途径 a→b）；二是将烟气冷却降温（途径 a→d）；三是将降温和添加蒸汽相结合（途径 a→c）。由于半干法脱硫后烟气温度较高，采用第三条途径较合理。

过饱和水蒸气以颗粒为凝结核发生异质核化凝结所需的临界过饱和度与颗粒的物化性质和烟气条件密切相关。根据 Fletcher异质成核理论[16~18]，不可溶球形颗粒的临界过饱和度 S_{cr}为：

$$S_{cr}=\exp\left[\frac{V_L}{kT}\left(\frac{8\pi\sigma^3}{3kT\ln(4\pi R_p^2K_c)}f(m_\theta, r)\right)\right] \tag{1}$$

式中：k—波尔兹曼常数，J/K；T—水汽温度，K；V_L—一个水分子的体积，m³；K_c—动力常数，m²/s；σ—表面张力，N/m；R_p—颗粒半径，m；r—完全润湿的球形粒子的临界半径，m；m_θ（≤1）—水与颗粒接触角的余弦值；$f(m_\theta, r)$—m_θ、r的函数，其值随 m_θ的减小而增大。相同外部条件下同一种细颗粒具有相同的 m_θ值。

当过饱和度 S大于 Kelvin效应下颗粒表面过饱和度 S_a时，可以用 Kulmala方程描述颗粒凝结长大速率 dR_p/dt与烟气过饱和度之间的关系[19]：

$$\frac{dR_p}{dt}=\frac{(S-S_a)}{\rho R_p\left[\frac{R_gT}{\beta_mM_vDP_\infty[1+(S+S_a)P_\infty/(2P)]}+\frac{S_aL^2M_v}{\beta_tR_gKT^2}\right]} \tag{2}$$

式中：S—烟气过饱和度；S_a—Kelvin效应下的颗粒

表面过饱和度；ρ—颗粒密度，kg/m³；D—凝结蒸汽的扩散系数，m²/s；R_g—气体常数，J/(kg·K)；L—水的气化潜热，J/kg；K—热导率，W/(m·K)；M_v—蒸汽摩尔质量，kg/mol；P_∞—饱和蒸汽压，Pa；P—总压，Pa；β_m、β_T—质量流量和热流量的修正系数。

由式(2)可知，颗粒凝结长大速度以及凝结长大后含尘液滴粒径都随过饱和度提高而增加，当水汽在颗粒上凝结使得烟气过饱和度降至 S_s时，颗粒停止长大。由 $dR_p/dt=0$可得到理论上颗粒长大所能达到的最终粒径。此外，Heidenreich S等人研究发现该凝结长大过程可以迅速完成[9]。

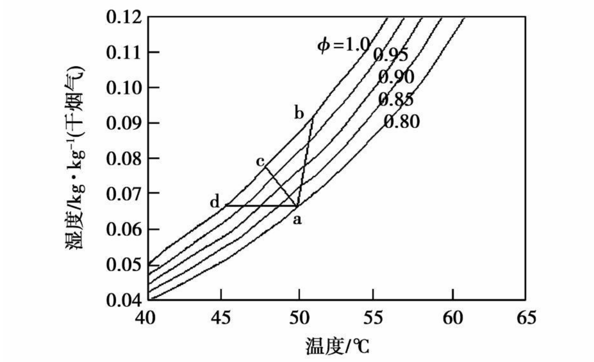


图 3　烟气实现饱和过程示意图

2.3　操作参数对细颗粒蒸汽相变脱除效果的影响

2.3.1　Ca/S的影响

实验选取 Ca/S=1.0、1.5和 2.0，调节浆液浓度保持喷入的浆液所含水的流量为 5.1 L/h，半干法脱硫塔入口、出口烟温约为 128、61 ℃，脱硫塔出口处烟气露点温度 t_d约 47 ℃，利用烟温调节室将除雾室入口温度调至 50 ℃。

蒸汽添加量为 0.06 kg/m³时，除雾室入口烟气过饱和度为 1.41(假定过饱和水蒸气未冷凝，下同)，颗粒分级脱除效率如图 4(a)所示(颗粒初始浓度为加入脱硫剂但未添加蒸汽时的数浓度，下同)。可见，随钙硫比提高，颗粒分级脱除效率降低。这主要是由于：(1)保持 SO_2浓度不变，提高钙硫比使得脱硫反应产物($CaSO_3$、$CaSO_4$、$Ca(HSO_3)_2$等)增多，部分产物在浆液滴干燥过程中结晶析出形成细颗粒并分散到烟气中；(2)浓度提高的浆液滴蒸发干燥后形成更多细颗粒；(3)颗粒数浓度增加使每个颗粒上可凝结水汽量减少，从而使凝结长大后的含尘液滴粒径减小，难以被除雾器脱除。

Ca/S=1.0、1.5、2.0，蒸汽添加量为 0.02、0.04、0.06、0.08 kg/m³(除雾室入口对应的过饱和度分别为 1.04、1.22、1.41、1.59)时，细颗粒总脱除效率如图 4(b)所示。可见，随 Ca/S提高，各蒸汽添加量下细颗粒总脱除效率均下降，如蒸汽添加量为 0.08 kg/m³时，细颗粒总脱除效率依次为：62.7%、60.1%、55.0%。此外，细颗粒脱除效率随蒸汽添加量增大而提高，这主要是由于过饱和度提高和可凝结水汽量增加使得发生凝结长大的细颗粒数量增多且长大形成的含尘液滴粒径增大。

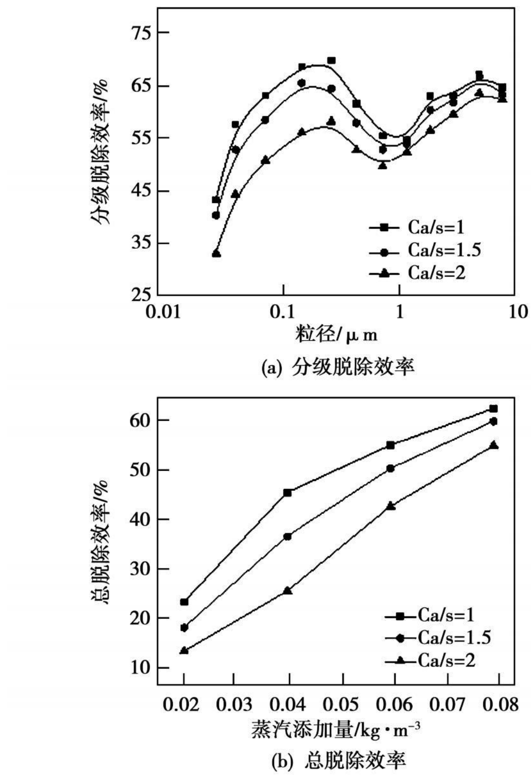


图 4　不同钙硫比下细颗粒脱除效率

2.3.2　浆液量的影响

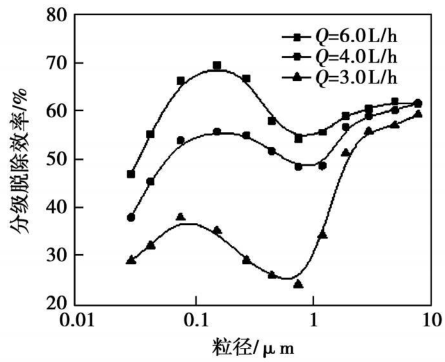
在相同 Ca/S条件下，浆液量影响烟气湿度、浆液滴蒸发干燥时间及干燥后形成的细颗粒粒径、近绝热饱和温差等。实验选取 Ca/S=1.5，浆液量为 3.0、4.0和 6.0 L/h，脱硫塔入口和出口烟气温度分别为 128、129、128 ℃和 77、70、61 ℃，脱硫塔出口处相应的露点温度分别为 35、41和 47 ℃，除雾室入口烟温为 50 ℃。

蒸汽添加量为 0.08 kg/m³时，除雾室入口烟气过饱和度分别为 1.15、1.32和 1.59，细颗粒分级脱除效率如图 5(a)所示。可见，随浆液量增加，细颗粒脱除效率明显提高，这主要是由于浆液量增加使烟温降低且含湿量提高，从而发生凝结长大的细颗粒数量增多，且最终形成的含尘液滴粒径增大，提高了细颗粒脱除效率。

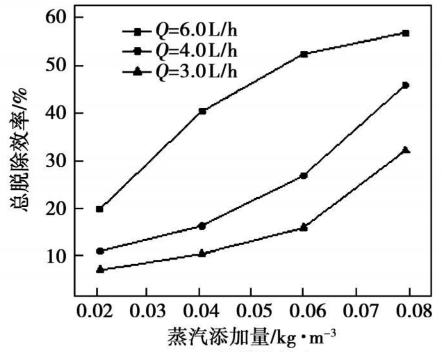
蒸汽添加量为 0.02、0.04、0.06和 0.08 kg/m³

时细颗粒总脱除效率试验结果如图 5(b)所示。可见, 浆液量增加可以显著提高细颗粒脱除效率, 如蒸汽添加量为 0.06 kg/m³ 时, 细颗粒总脱除效率分别为 16.5%、27.2%和 52.3%。

因此, 在满足半干法脱硫正常运行的条件下, 增加浆液量不仅有利于降低近绝热饱和温差, 提高脱硫效率, 还可以提高烟气相对湿度, 对建立过饱和水汽环境促进细颗粒凝结长大有积极作用。



(a) 分级脱除效率



(b) 总脱除效率

图 5　不同浆液量下细颗粒脱除效率

2.3.3　蒸汽添加量的影响

考察蒸汽添加量对 SO_2 和细颗粒脱除效率影响, 其试验条件为: Ca/S=1.5, 浆液量为 6 L/h, 脱硫塔入口、出口、除雾室入口烟温为 129、62和 51 ℃。蒸汽添加量为 0.02、0.04、0.06、0.08 kg/m³ 时, 除雾室入口烟气相对湿度 ϕ 分别为 0.95、1.12、1.30和 1.47。蒸汽添加量对 SO_2 脱除效率影响的试验结果如图 6所示。可见, 脱除效率随蒸汽添加量增加有小幅提高。其原因主要是: 随烟气过饱和度提高, 更多蒸汽在被烟气带走的干燥脱硫剂颗粒表面凝结, 润湿的脱硫剂颗粒继续吸收 SO_2。

在不同蒸汽添加量下, 细颗粒分级脱除效率和总脱除效率测试结果如图 7所示。可见, 蒸汽添加量变化对粒径较小的颗粒脱除效率影响显著而对粒径较大颗粒的影响较小, 根据 Fletcher异质成核理论[16~17], 临界过饱和度 S_r 与颗粒初始粒径成反比, 所以粒径较大的颗粒能优先凝结长大。对于粒径较小的颗粒, 如第四级 (粒径 $d\approx0.144$ μm), 蒸汽添加量由 0.02 kg/m³ 增至 0.08 kg/m³, 其脱除效率从 22.7%增加到 63.8%。此外, 等量提高蒸汽添加量, 细颗粒脱除效率增幅减小。如第二级 (粒径 $d\approx$ 0.039 μm), 3次等量 (每次提高 0.02 kg/m³)提高蒸汽添加量, 细颗粒脱除效率增幅分别为 18.8%、12.8%和 8.7%, 这主要是因为烟气过饱和度和可凝结水汽量增至一定值后, 继续提高烟气过饱和度对细颗粒脱除效率影响逐渐减弱, 从图 7(b)所示的总效率变化趋势也可以看出这一规律。

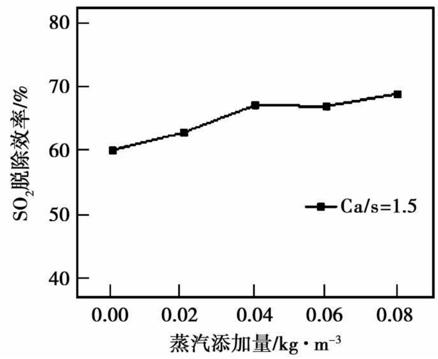
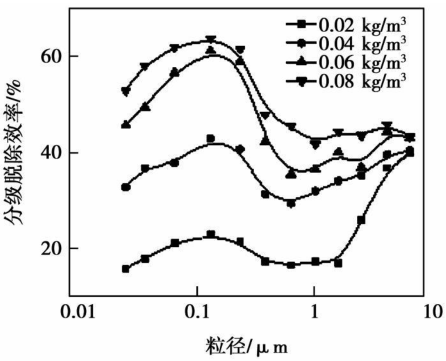
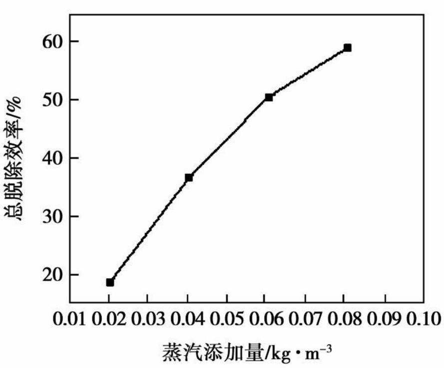


图 6　蒸汽添加量对 SO_2 脱除效率的影响



(a) 分级脱除效率



(b) 总脱除效率

图 7　蒸汽添加量对细颗粒脱除效率的影响

3 结 论

(1)半干法脱硫使烟气中细颗粒数浓度增大,总增幅约 10%,粒径小于 0.15 μm的亚微米颗粒增加尤其明显。

(2)保持喷入的浆液含水量不变,随 Ca/S提高,脱硫反应产物和脱硫液蒸发干燥形成的细颗粒增多,导致细颗粒脱除效率下降。如蒸汽添加量为 0.08 kg/m^3、Ca/S=1.0、1.5、2.0时,细颗粒总脱除效率分别为 62.7%、60.1%和 55.0%。

(3)保持 Ca/S不变,浆液量增多使得烟气过饱和度提高和可凝结水汽量增多,促进了细颗粒的凝结长大与脱除。如 Ca/S=1.5,浆液量为 3.0、4.0、6.0 L/h,蒸汽添加量为 0.06 kg/m^3 时,细颗粒总脱除效率分别为 16.5%、27.2%和 52.3%。

(4)蒸汽添加量增大可提高烟气过饱和度和可凝结水汽量,促使更多细颗粒核化凝结长大并且长大后的含尘液滴粒径也有所增大,从而提高了细颗粒脱除效率。如 Ca/S=1.5,浆液量为 6 L/h,蒸汽添加量分别为 0.02、0.04、0.06和 0.08 kg/m^3 时,细颗粒脱除效率为 18.6%、36.7%、50.7%和 59.2%。

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WFGD水力旋流器中石灰石颗粒分级试验与数值模拟＝Gradation Experiment and Numerical Simulation of Limestone Particles in a WFGD (Wet-method Flue Gas Desulfuration) Hydrocyclone［刊，汉］/ YAN Zhen-rong, GENG Li-ping, YANG Mo (College of Energy Source and Power Engineering, Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093), LUO Xiao-ming (Shanghai City Special-purpose Equipment Surveillance and Inspection Technology Research Institute, Shanghai, China, Post Code: 200062) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(3). —321～325

In a WFGD (Wet-method Flue Gas Desulfuration) device, the gradation experiment of a hydrocyclone shows that when the particle mass concentration of limestone slurry is 15%, at the overflow port it will be 30%. The overflow particle diameter is concentrated at less than 30 μm. With an increase of the particle diameter, the particle recovery rate at the bottom outlet will also increase. When the particle diameter reaches 30 μm, the particle recovery rate will already approach 100%. The numerical simulation results show that the Reynolds stress turbulent flow model, free surface multi-phase flow model and Stokes-Lagrange model can depict very well the limestone particle gradation movement and regularity featuring a complex three-dimensional motion in the hydrocyclone. A numerical simulation method with no need to give a flow division ratio for the initial boundary condition and to preset an air column was adopted and the simulation results showed the formation of air column and eddy flow of the fluid. The gradation efficiency of particles in different diameters thus obtained is in relatively good agreement with that tested under the condition of a high inlet mass concentration. Key words: wet-method flue gas desulfurization, hydrocyclone, limestone particle, flow division and gradation, numerical simulation

气液双流程烟气脱硫塔内脱硫效率与传质性能的研究＝Study of the Desulfuration Efficiency and Mass Transfer Performance of a Gas-liquid Double-flow-path Flue Gas Desulfuration Tower［刊，汉］/ SUN Zhong-wei (Department of Building Services Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong, Post Code:), ZHOU Qu-lan, HUI Shi-en, XU Tong-mo (National Key Laboratory on Multiple-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). —326～329

With calcium carbide dregs serving as desulfuration agents in the test, a relevant experimental study was performed of the desulfuration performance and mass transfer characteristics of a gas-liquid double-flow-path liquid-curtain type desulfuration tower. Through tests and measurements, the influence of such main parameters as flue gas flow rate, circulating slurry quantity and liquid-gas ratio etc. on the desulfuration performance of the above desulfuration tower was given. In the meantime, a relevant mass transfer model for the gas-liquid double-flow-path liquid of a desulfuration tower was presented, for instance: $Sh = 16.226 Re_g^{0.863} Re_l^{-1.64}$ and $Sh = 27.126 Re_g^{-0.77} (L/G)^{-1.64}$. Based on the above-mentioned model, the complicated gas-liquid mass transfer process between the slurry and flue gases in the double-flow-path tower can be quantitatively calculated by using the empirical correlation formula expressed by the flue gas Reynolds number, slurry Reynolds number and liquid-gas ratio, the influencing law of which can offer important guiding data for studying the reaction characteristics of sulfur dioxide in the liquid curtain type wet-method flue gas desulfuration system and its application in the practical engineering projects. It has been found during the test that when the circulating slurry quantity increases, the total desulfuration efficiency will enhance accordingly. With an increase of the liquid-gas ratio, the total desulfuration efficiency will also rise accordingly. When the flue gas flow rate increases, however, the related desulfuration efficiency will decrease correspondingly. The experimental study shows that when the liquid-gas ratio is higher than 20 L/m³, the desulfuration efficiency will be over 90%. The PH value, however, exercises a very little influence on the mass transfer. Key words: liquid-curtain type gas-liquid two-phase flow, wet-method flue gas desulfuration, mass transfer, desulfuration efficiency

半干法脱硫中应用蒸汽相变促进细颗粒脱除＝Application of the Steam Phase Change in Semi-dry-method Desulfuration to Promote the Removal of Fine Particles［刊，汉］/ LIU Jin-hui, SONG Shi-juan, YANG Linjun (College of Energy Source and Environment, Southeast University, Nanjing, China, Post Code: 210096), XIN Cheng-yun (College of Chemical Industry and Environment, Zhongbei University, Taiyuan, China, Post Code: 030051) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(3). —330～334

In a mist spray dry flue-gas desulfuration system, experimentally studied was the application of steam phase change to help remove fine particles. With a due amount of steam being added to the wet flue gases after the desulfuration reaction, a supersaturated water steam environment necessary for the condensation and growth of fine particles was formed and the condensed and grown-up dust-burden droplets were subsequently removed by a highly efficient demister. The fine particle number concentration and particle diameter distribution were real-time measured by using an electrical low-pressure impactor. Furthermore, the influence of operating conditions for mist spray dry flue-gas desulfuration (such as Ca/S and slurry quantity) and the amount of steam added on the fine particle removal efficiency was also investigated. It has been found that a part of slurry droplets and products from the desulfuraation reaction can be evacuated from the desulfuration tower together with the flue gases, leading to an increase of the fine particle number concentration. In the semi-dry method desulfuration process, the steam phase change can be used to help remove the fine particles and the removal efficiency will enhance with an increase of the amount of steam added. When the amount of steam added is 0.08 kg/m³, the removal efficiency of the fine particle number concentration can increase by over 55%. The desulfuration operation conditions exercise a relatively big influence on the effectiveness of the steam phase change. Key words: semi-dry-method, desulfuration, fine particle number concentration, removal of fine particles, supersaturation, steam phase change

地表水水源热泵输配系统优化模型的研究＝Study of a Model for Optimizing a Surface-water Source Heat Pump Transmission and Distribution System [刊, 汉] / BAI Xue-lian, ZHANG Yan-jun, WANG Hou-hua (College of Urban Construction and Environment Engineering, Chongqing University, Chongqing, China, Post Code: 400045) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(3). —335～339

With minimum energy consumption for transmission and distribution serving as an ultimate objective, relevant requirements for indoor comfort and building energy conservation as the restriction conditions and by utilizing the optimization tools box of Matlab, studied was a model for optimizing a surface water source heat pump transmission and distribution system with the main factors influencing the energy consumption of the surface water source heat pump transmission and distribution system being identified. By using the above-mentioned method, an applied analysis of the water source heat pump test system was conducted and an optimized cooling and frozen water flow operation scheme for the system changing with load rates was obtained. For a system operating at a part load for the majority of time, the optimized operation can save energy consumption by over 10% as compared with the constant flow rate operation. The optimization model can be easily used for practical engineering projects, providing optimum parameters for the design and operation of a transmission and distribution system and realizing a flow rate regulation and control with the change of the load rates. The foregoing can effectively reduce the energy consumption in water source water transmission and distribution, and enhance the system energy utilization efficiency. Key words: water source heat pump, water transmission and distribution system, water pump, energy consumption, optimization model

生物质与城市生活垃圾混烧特性的实验研究＝Experimental Study on the Mixed Combustion Characteristics of Biomass and Municipal Solid Waste [刊, 汉] / XIE Hai-wei, ZHANG Yan (Tianjin City Key Laboratory on Refrigeration Technology, College of Mechanical Engineering, Tianjin Commerce University, Tianjin, China, Post Code: 300134), ZHANG Yu-feng (Environment College, Tianjin University, Tianjin, China, Post Code: 300072) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(3). —340～343

In the light of the shortcomings of the power generation method by burning a mixture of municipal solid waste and biomass resulting in inferior economic benefits, set up was a biomass and municipal solid waste mixed combustion