-Presented at Coal-Gen 2010-

Operating Experience of CFB Semi-dry FGD with Novel Humidification Technology in China

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Abstract: Applications of circulating fluidized bed (CFB) semi-dry flue gas desulfurization (FGD) technology are increasing globally on coal-fired boilers, MSW incinerators, and other sources because of water saving characteristics, the ability to control SO_2 emissions comparable to traditional wet FGD and, in addition, providing simultaneous removal of SO_3, acid gases and particulate. This type of CFB technology has been used in certain forms for decades, and the critical process of gas humidification has been improved dramatically through the work of the Institute of Thermal Power Engineering of Zhejiang University (ITPE), to the benefit of commercial plants in China. Based on the ITPE research data and results in full-scale implementation, this novel humidification technology maintains greater uniformity of reagent humidity in the absorber and enhances the time for reaction with pollutants. The desulfurization efficiency has shown to be markedly improved and the potential of scaling on the inner wall of the absorber was dramatically minimized. This paper will contain data derived from research as well as full-scale plant applications from commercial coal-fired boiler applications.

Introduction

Applications of circulating fluidized bed (CFB) semi-dry flue gas desulfurization (FGD) technology are increasing globally on coal-fired boilers, MSW incinerators, and other sources because of the water saving characteristics and the ability to control SO_2 emissions comparable to traditional wet FGD. Controlling SO_2 to the upper 90's % efficiency has long been a challenge of conventional dry FGD (spray dryers) due to excessive reagent consumption. As of the end of 2008, CFB FGD desulfurization installations in China have accounted for 4.62% of the FGD installations in operation [1], per Figure 1. With current single absorber unit capacity up to 300 MW, [2-3], the attractiveness also lies in simplicity of design, construction and operation, as well as the potential for simultaneous removal of multi-pollutants such as SO_3 and mercury.

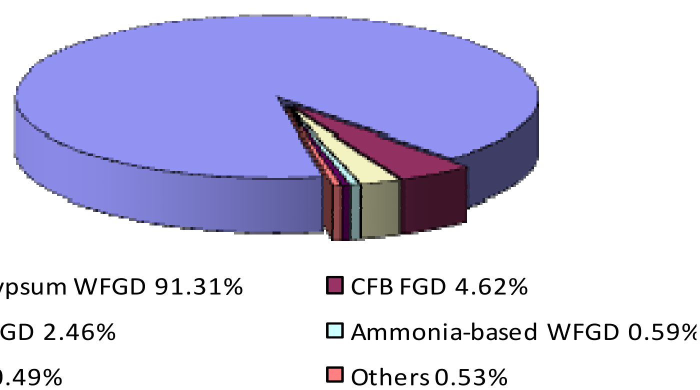


Figure 1 - Proportion of FGD Technology in China [1]

The CFB system as shown in Figure 2 is usually located downstream of the boiler air heater, and consists of the absorber vessel and a particulate-control device. In the CFB process, flue gas passes through multiple venturis and mixes with hydrated lime, water and recycled solids to create a fluidized bed where hydrated lime reacts with SO_2 and SO_3 to form calcium sulfite and calcium sulfate. Water is injected separately from the hydrated lime into the bed to obtain an operation close to the adiabatic saturation temperature of the flue gas. The CFB provides a long contact time between the sorbent and flue gas because sorbent passes through the bed several times and therefore provides for high reagent utilization and high levels of SO_2, SO_3 and acid gas (HCl & HF) removal. The flue gas laden with dry reaction products then flows to a particulate control device. Some of the reaction products collected in the particulate control device is recirculated into the bed to increase the utilization of sorbent, while the remaining fraction is sent to disposal.

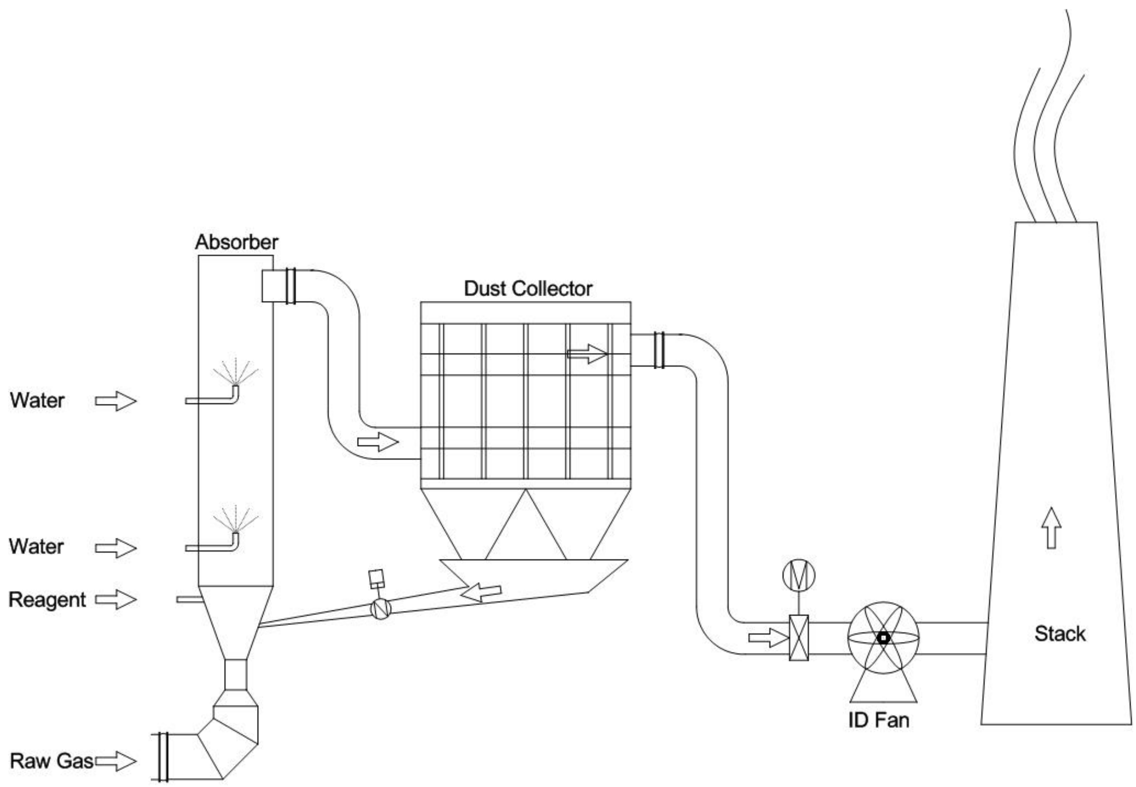


Figure 2 – Circulating Fluid Bed Process

The Institute for Thermal Power Engineering (ITPE) of Zhejiang University initiated research on the CFB FGD technology in 1980s with laboratory experimentation and pilot-scale testing (Figure 3). Building on the sucess of the pilot testing, the CFB process was demonstrated at the field scale in 1999 at the Hangzhou Jinjiang Green Engergy MSW incinerator (Figure 4). ITPE continues to conduct research on the CFB technology and pilot scale tesing would be readily available to support new applications.

Figure 3– Pilot Test Appataus

Figure 4 - JinJiang Demonstration Project

This CFB technology has been supplied at over 135 coal fired boiler and MSW incinerator installations throughout China with the following features:

- The installations have been evenly split bewteen coal-fired boilers and MSW incinerators, with four units on salt furnaces.
- The technology has been applied to a wide range of unit capacities ranging from 58,000 Nm^3/h to 983,300 Nm^3/h (6 to 200 MW equivalent).
- The process has treated flue gas with maximum inlet SO_2 up to 6600 mg/Nm^3
- Multiple and single units have been supplied on a per boiler basis.
- CFB system can adapt to load variations in the range of 40% to 110% design load of unit.
- The desulfurization efficiency greater than 95% has been demonstrated.

Marsulex Environmental Technologies (MET) actively searched for an advanced Dry FGD technology to license and introduce to the North American market, and the right match was established with Zhejiang ITPE's inventive and advanced multi-stage humidification CFB technology. MET recognized that examples of the advanced dry FGD technology in the North American market have established expectations, thus future units must have highly refined designs and reach new limits of performance. The advantage of working with ITPE is the systematic research program they conducted toward the product development. A methodical approach to applying the core design principles to the over 135 varied applications has provided the experiencial data for accurate process modeling. MET has been able to readily embrace the advanced technology because of its history with the first generation of dry technology, having installed 29 spray dryer absorbers of its own design prior to 2001.

During early operation of CFB system, ITPE found one of the key design parameters of CFB desulfurization process is the particle humidification inside the absorber. The humidification water is used to cool the flue gas and provide water to promote the reaction between acid pollutants and the hydrated lime reagent. The reaction between acid pollutants and hydrated lime is a gas-solid reaction whose reaction rate is low in the absence of water. Humidification of the particles converts the gas-solid reaction between the lime and flue gas pollutants to an ionic reaction in the liquid phase whose reaction rate is tens times that of the gas-solid reaction. Optimal humidification is required to achieve high desulfurization efficiency. Over-wetting of the reagent particles may result in scaling inside the absorber because the over-wet particles cannot be sufficiently dried and may adhere to the absorber wall. Scale formed on the absorber wall can decrease the flue gas flow cross section and deteriorate the uniform distribution of flue gas leading to a reduction in the desulfurization efficiency. Moreover, if the scale is removed from the wall, it may lead to damage or plugging of the upstream venturi and collapse of the absorber bed.

The flue gas parameters of the boilers in China vary due to unstable coal sources and significant load swings. Therefore, the volume of humidification water must be changed often to adapt to the fluctuation of flue gas parameters. With the initial single stage humidification design, scaling by over-wetting of particles was observed. For these transient conditions, reduction of humidification water can avoid the over-wetting of the particles, but the desulfurization efficiency will decrease. Aiming to solve this problem, ITPE developed a novel humidification technology to minimize the potential for scaling and improve the desulfurization efficiency compared to single stage humidification.

Multi-Stage Humidification Technology

The novel feature of the ITPE CFB technology is the focus on optimal humidification in the reaction zone. The course of drying a wetted particle is divided into two stages illustrated in Figure 5 [4-6]:

1. The constant-rate drying stage
2. The falling-rate drying stage

The constant-rate drying stage is the stage that the drying rate is a constant value when sufficient water is present for reaction and the rate does not change with increased water content. The falling-rate drying stage is the stage that the drying rate decreases as the water content decreases and falls below the critical water content. The critical water content is defined as the point that constant-rate drying stage switches to falling-rate drying stage.

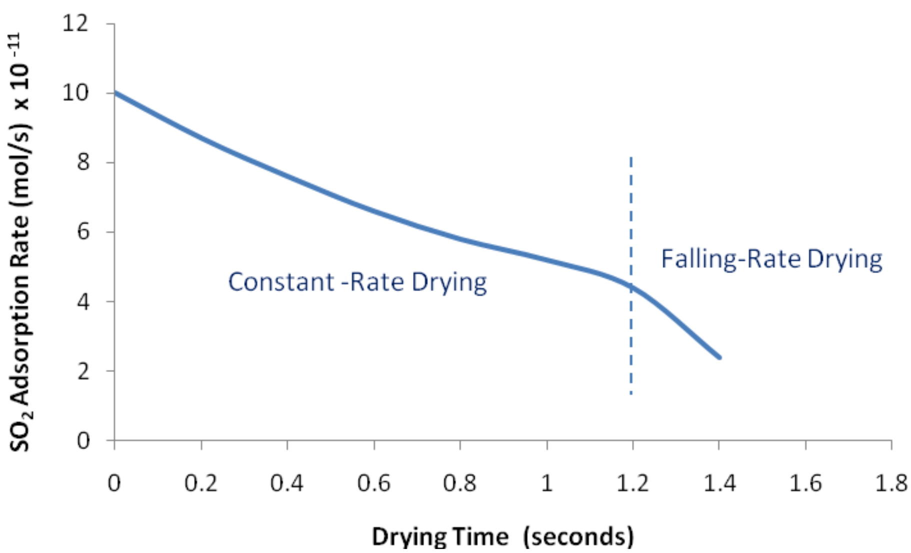
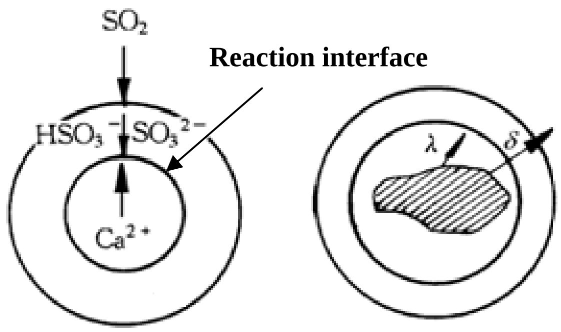


Figure 5 - Two Stages of the Particle Drying Process

In the constant-rate drying reaction stage, the reactions between the reagent and the acid gases are fast liquid phase ionic reactions. The SO_2 is absorbed and dissolved in the water on the surface of the particles and forms new components, HSO_3^- and SO_3^{2-}, which instantaneously react with dissolved lime. The constant drying stage accounts for the majority of the SO_2 removal and is illustrated in Figure 6.



λ is the distance from particle surface to the reaction front, (m)
δ is the distance from particle surface to the liquid film, (m)

Figure 6 - Constant-rate Drying Stage (ionic reaction)

The chemical reaction equations in constant-rate drying stage are shown as equation (1) to equation (7).

$$H_2O \leftrightarrow H^+ + OH^- \quad (1)$$

$$SO_2(aq) + H_2O \leftrightarrow H^+ + HSO_3^- \quad (2)$$

$$HSO_3^- \leftrightarrow H^+ + SO_3^{2-} \quad (3)$$

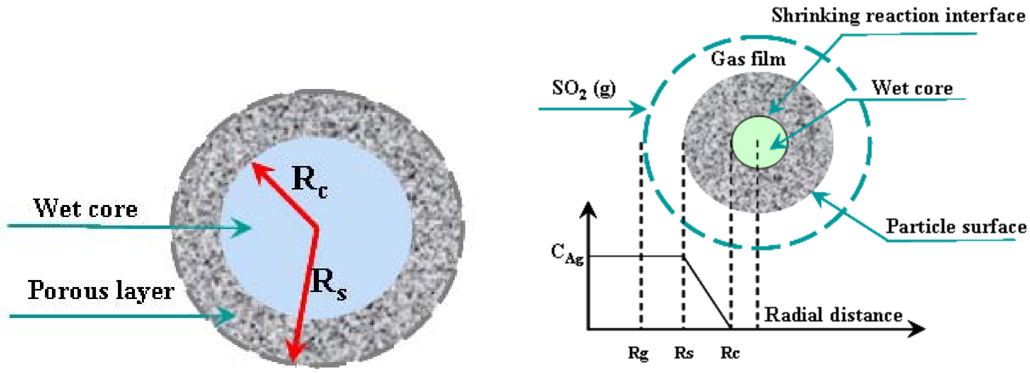
$$Ca(OH)_2(s) \leftrightarrow CaOH^+ + OH^- \quad (4)$$

$$CaOH^+ \leftrightarrow Ca^{2+} + OH^- \quad (5)$$

$$Ca^{2+} + SO_3^{2-} + 1/2H_2O \leftrightarrow CaSO_3 \cdot 1/2H_2O(s) \quad (6)$$

$$CaSO_3 + 1/2O_2 + 3/2H_2O \rightarrow CaSO_4 \cdot 2H_2O(s) \quad (7)$$

During the falling-rate drying stage, the reaction rate decreases because the reactions between acid gases and reagent are controlled by gas-solid mass transfer. The diffusion through the porous product layer formed on the surface of the wet particles becomes the limiting step for further moisture removal or SO_2 absorption. The falling-rate drying stage is shown in Figure 7 with the corresponding chemical reaction equations provided in equation (8) and equation (9).



(C_{Ag} : SO_2 concentration in gas film)

Figure 7 - Falling-rate Drying Stage (gas solid reaction)

$$Ca(OH)_2(s) + SO_2 \rightarrow CaSO_3 + H_2O \qquad (8)$$

$$CaSO_3 + 1/2O_2 \rightarrow CaSO_4 \qquad (9)$$

The SO_2 absorption rate is high in constant-rate drying stage and slows in falling-rate stage. ITPE defines the critical moisture content as sufficient to maintain the high SO_2 absorption in the constant-rate drying stage and before the falling-rate stage. At the critical moisture point, the reaction rate is almost 20 times to that of zero moisture, as shown in Figure 8.

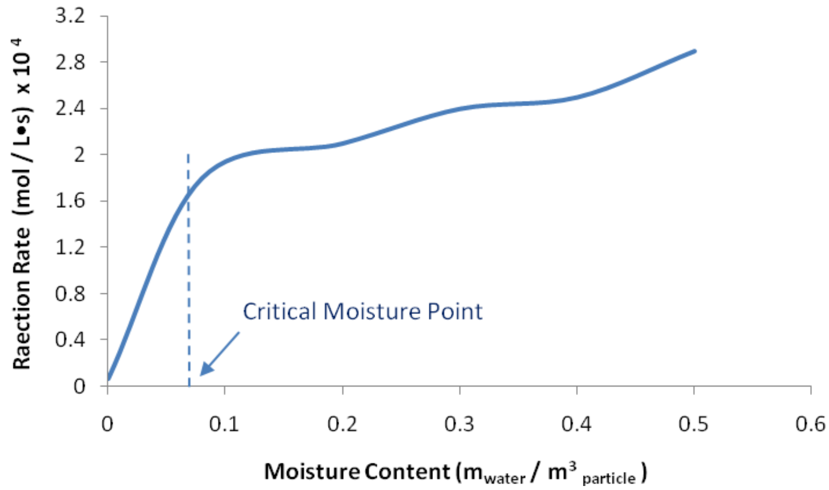


Figure 8 - Moisture Content versus Reaction Rate

CFB Technology with Multi-Stage Humidification

To increase the SO_2 absorption rate in the absorber without changing the other parameters, the time must be prolonged for which the water content in the wet particles is above critical moisture value. Based on the research and field data, a novel multi-stage humidification technology was developed to distribute the water in stages to insure the uniform humidity during the reaction process in the absorber. This extends the time period when the humidity content is above the critical moisture point [7-10], as shown in Figure 9.

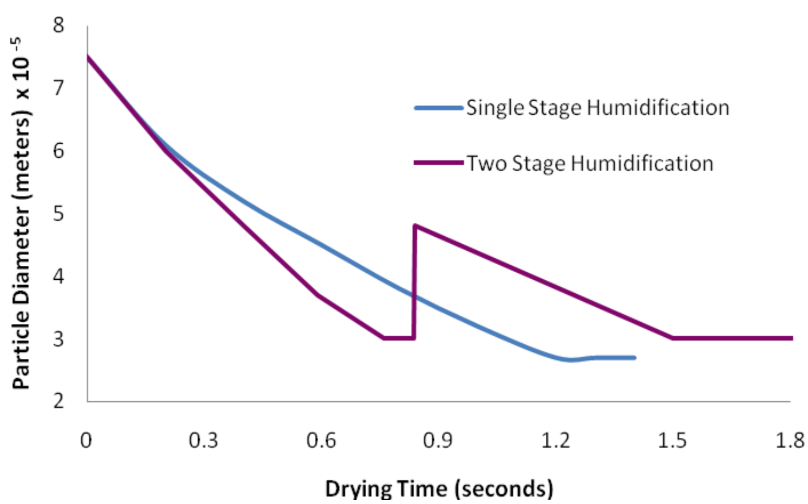


Figure 9 - Schematic Diagram of Two-Stage Humidification

Multi-stage humidification is an important feature of ITPE's CFB process which improves desulfurization efficiency by keeping the water content of the reagent above critical moisture point and prolonging the constant-rate drying stage for the wetted particles. Moreover, the potential scaling on the inner wall of absorber in single stage humidification is reduced with multi-stage humidification because the water is more uniformly distributed throughout the reaction zone.

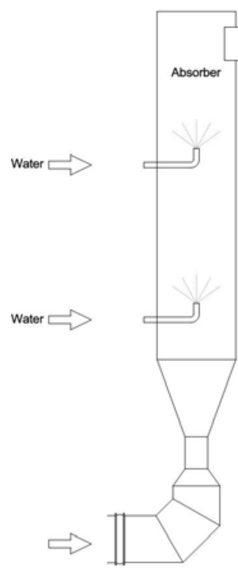


Figure 10 – Multiple Humidification Injection

The desulfurization efficiency increases with increased stages of humidification while the total water consumed is unchanged. Considering the complexity of multiple injection and project economics, two-stage humidification is optimal for the CFB process. The dual humidification points of the ITPE process are detailed in Figure 10. The lower nozzles are arranged above the lower rim of the straight section of the absorber and the upper nozzles are positioned in the middle of the straight section. The spacing from the upper nozzle to lower nozzle is determined by the drying period.

According to field tests, SO_2 removal efficiency can be improved more than one percent point when the two-stage humidification technology is used, as shown in Figure 11. The

SO_2 removal efficiency increased 1.5 percent when the proportion of the second stage humidification water volume to total humidification water volume increased from zero to 20 percent. Based on ITPE operating experience, the proportion of second stage humidification water to total humidification water is generally below 20 percent in order to avoid over-wetting of particles.

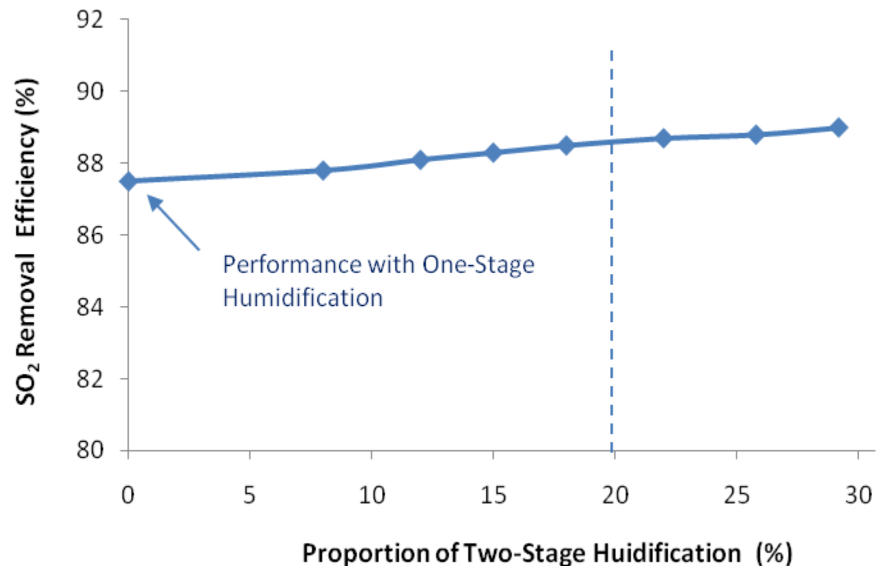


Figure 11 - SO_2 Removal Efficiency versus Proportion of Second Stage Humidification

Absorber is the key component of the CFB system with more than 90% of total SO_2 removal efficiency occurring in the vessel. A good flow field inside the absorber must be maintained to prevent the local abrasions and scaling and maximize the mass transfer and reaction inside the absorber. To ensure the good flow field inside the absorber and flue, Computational Fluid Dynamics (CFD) modeling shall be conducted to simulate flow inside the absorber before detailed design. Guide vanes are usually placed in the direction changing positions to improve the flow uniformity inside the absorber and flow promoting rings are set inside the absorber to improve the air flow. The CFD modeling provides vital insight on the gas velocity distribution, solid velocity distribution, system pressure drop and minimum load operation. A case on pressure drop calculation of absorber and a case on rectification of the venturi design are shown in Figure 12 and Figure 13, respectively.

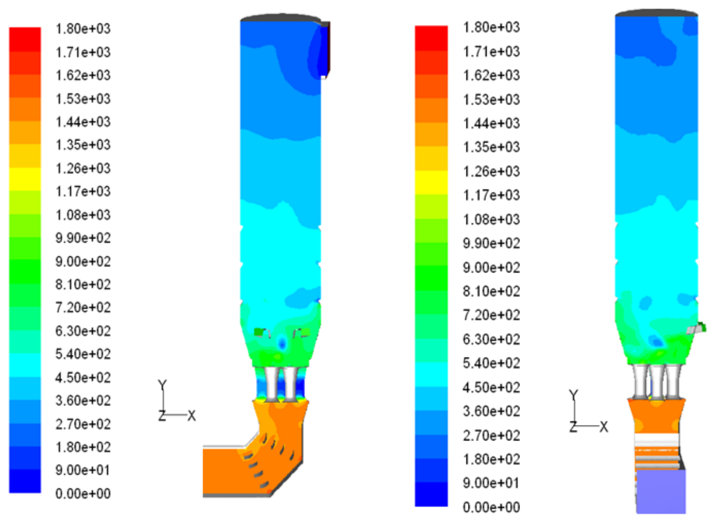


Figure 12 - Pressure Drop Profile of Absorber

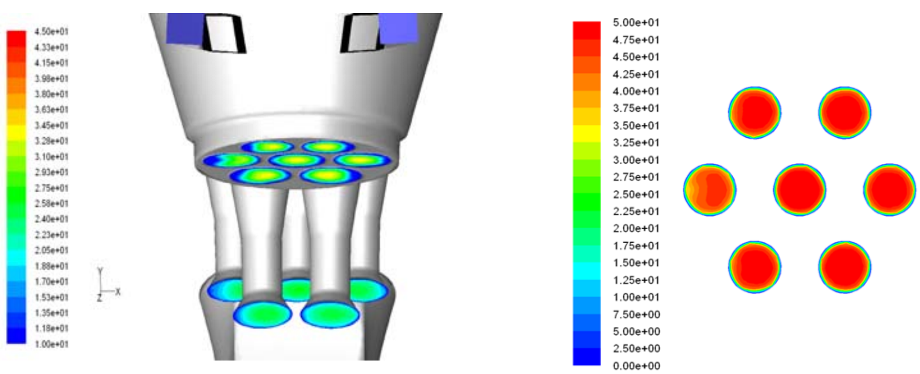


Figure 13 - CFD Result on Rectification of Venturi

Presently, the CFB system has been applied to coal fired boilers, MSW incinerators and sintering machines at more than 135 installations in China. The scaling on absorber wall is minimized with application of the two-stage humidification technology.

Case Analysis

The operation and performance of the CFB installations at the Wangneng Power Plant MSW incinerator and coal-fired Power Plant of SINOPEC Guangzhou Branch Company and Matou Power Plant are discussed below. The general parameters of these three example installations are summarized in Table 1. Both coal-fired equipment trains include an upstream existing ESP since both customers sell the ESP ash.

Table 1 – Design Summary for Example Installations

	Matou	Guangzhou	Wangneng
Location	North China	South China	East China
Boiler / Incinerator	PC boiler	PC boiler	MSW Incinerator
Capacity	200 MW	50 MW	400 t/d
Flue Gas Flow	983,253 Nm^3/h	295,000 Nm^3/h	70,000 Nm^3/h
SO_2 Concentration	2,963 mg/Nm^3	2,000 mg/Nm^3	550 mg/Nm^3
SO_2 Removal Efficiency	≥90%	≥90%	≥70%
Layout	Pre-ESP+Absorber+ESP	Pre-ESP+Absorber +Baghouse filter	Absorber+Baghouse filter
Start-Up	July, 2008	March, 2009	March, 2008

Wangneng Waste to Energy Power Plant

The Wangneng power plant shown in Figure 14 is a waste to energy thermal power plant located in Huzhou, Zhejiang Province. The steam for electric power generation comes from the two incinerators which are used to burning the MSW from Huzhou city. The capacity of each MSW incinerator is 400 ton per day. The equipment train consisting of the absorber vessel and pulse-jet fabric filter was designed for SO_2, dust, HCl and mercury removal efficiencies of 70%, 99.9%, 95% and 90% respectively for each equipment train.

Figure 14 - Wangneng Waste to Energy Power Plant

The Wangneng system has been operational since March 2008. After nine months' operation, performance test results demonstrated the performance indexes were met and exceeded the required emission limits. The average outlet emission of SO_2, particulate, HCl and mercury and the corresponding removal efficiencies are summarized in Table 2:

Table 2 – Wangneng Performance Test Results

Pollutant	Emissions mg/Nm^3	Removal Efficiency %
SO_2 Emissions	9 - 13	95
Particulate Emissions	4.0 – 5.7	> 99.9
Hydrochloric Acid	9.8 – 14.0	> 95
Mercury	0.05 – 0.06	> 90

SINOPEC Guangzhou Power Plant

The Power Plant of Guangzhou Branch Company of the SINOPEC Group is located near Guangzhou city. The SO_2 and dust emission requirements for this plant are relatively strict due to the plant's close proximity to the downtown of Guangzhou city. In order to keep selling ash and allocate space for the CFB/BH equipment train, the existing three field ESP was truncated to a two field ESP.

Figure 15 - SINOPEC Guangzhou Power Plant CFB System

The system was designed to reduce the inlet SO_2 concentration of 2000 mg/Nm^3 to 200 mg/Nm^3, corresponding to a design SO_2 removal efficiency of 90%. One hour averages plotted in Figure 16 show the overall SO_2 removal efficiency exceeded the guarantee value.

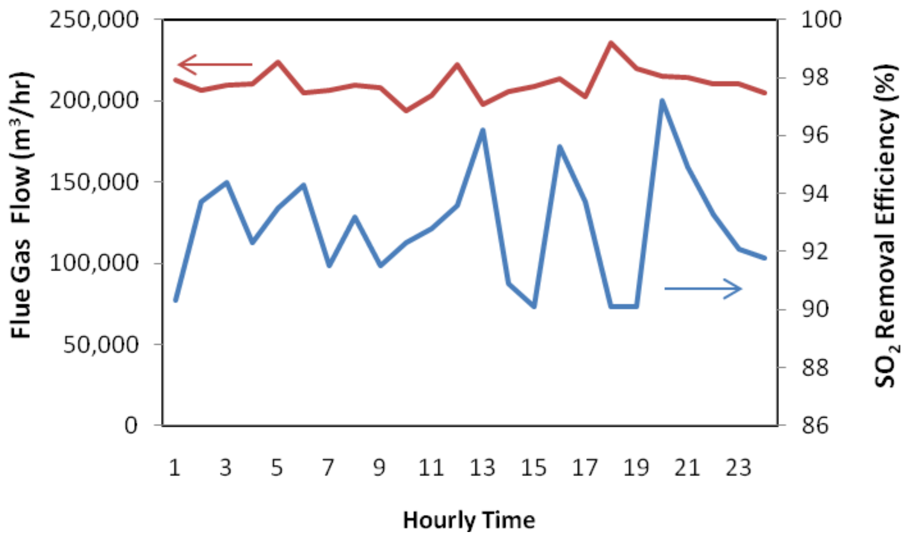


Figure 16 - Guangzhou Power Plant Hourly Operation

Matou Power Plant

The Matou Power Plant is a mine-mouth power plant near two coal mines in North China. The design CFB SO_2 removal efficiency is no less than 90% based on an inlet SO_2 concentration of 2,963 mg/Nm^3 when burning the design coal. The CFB FGD technology was chosen because North China has limited water resources. The Matou CFB vessel is the largest vessel size undertaken by ITPE for this 200 MW power plant (Figure 17). In order to keep selling ash and allocate space for the CFB/BH equipment train, the existing five field ESP was truncated to a three field ESP.

Figure 17 - Matou Power Plant CFB System

The Matou CFB system has been operational since July 2008. The performance test was conducted by the Thermal Power Research Institute (China) in November 2008. The average value of SO_2 removal efficiency in two days was 92.9%, which is above the design SO_2 removal efficiency. The comparison of design SO_2 removal efficiency and the test SO_2 removal efficiency in two separate days during the test is provided in Figure 18.

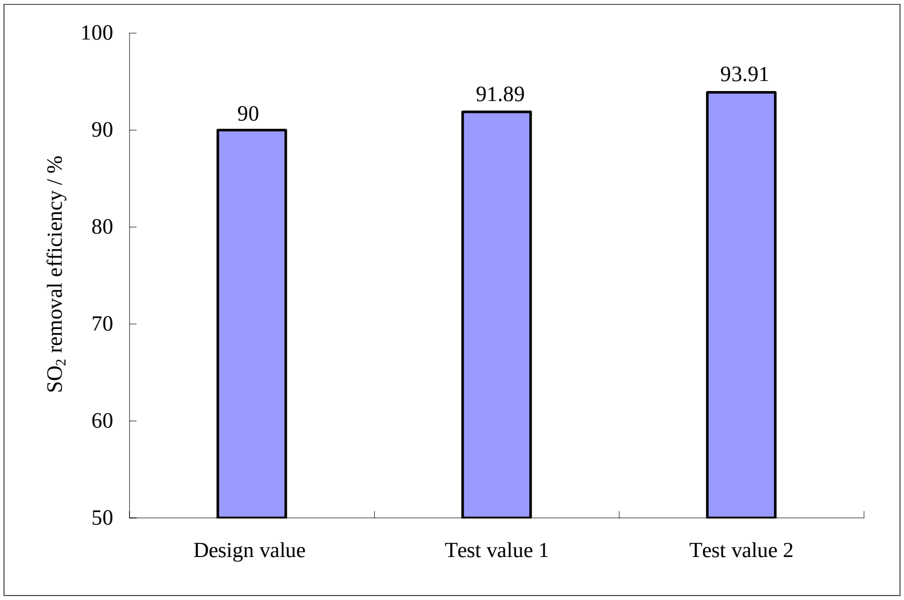


Figure 18 – Matou Design versus Performance SO_2 Removal Efficiency

Conclusion

MET has joined forces with ITPE to supply this widely demonstrated and proven CFB technology in North America. The CFB semi-dry desulfurization technology with multi-stage humidification provides for high desulfurization efficiency and minimizes the potential scaling risk on the inner wall of absorber. According to the field data from the ITPE's installations, two-stage humidification can boost the desulfurization efficiency by 1.5 percent without any observed scaling. The commercially demonstrated ability of advanced CFB semi-dry technology to provide very high removal levels of SO_2, SO_3 , mercury and other multi-pollutants provides an economic alternative to either conventional spray dryer or wet-type FGD .

References

[1]. http://www.ndrc.gov.cn/gzdt/t20090220_262130.htm

[2]. Zeng S, Luo H. Comparison of dry and wet flue gas desulfurization process for 300 MW coal fired unit. Modern Economic Information, 2009, (23): 299-300

[3]. Meng J, Li Y. Application and progress of flue gas desulphurization technology. J of Shanghai University of Electric Power, 2009, 25(6): 593-598

[4]. Gao X, Luo Z, Liu N, Ni M, Cen K. Desulfurization characteristic of calcium-based sorbent during activation process. Journal of Chemical Engineering of Japan, 2001, 34(9): 1114-1119

[5]. Neathery J K. Model for flue gas desulfurization in a circulating dry scrubber. AIChE J, 1996, 42 (1): 259-268

[6]. Newton G H, J. Gramlic. Modeling the SO_2–slurry droplet reaction. AIChE. J, 1990, 36: 1865-1872

[7]. Teng B, Gao X, Luo Z, Cen K. Study of the effect of second grade water on semi-dry flue gas desulfurization. Electric Power Environmental Protection,2006, 22(3): 22-25 (in Chinese)

[8]. Gao X, Liu H, Teng B, Luo Z, Ni M, Cen K. Experimental study on influence of multi-stage humidification on semi-dry flue gas desulfurization. Journal of Zhejiang University (Engineering Science), 2007, 41(12): 2082-2086 (in Chinese)

[9]. Teng B. Experimental and theoretical study on semi-dry flue gas desulfurization. Ph. D thesis, 2004 (in Chinese)

[10]. Wang N, L Luo Z, Gao X, Cen K. Study of new semi-dry flue gas desulfurization. Journal of Power Engineering, 2003, 23(4): 2586-2588 (in Chinese)