Numerical simulation and field test study of desulfurization wastewater evaporation treatment through flue gas

Jia-jia Deng, Liang-ming Pan, De-qi Chen, Yu-quan Dong, Cheng-mu Wang, Hang Liu and Mei-qiang Kang

ABSTRACT

Aimed at cost saving and pollution reduction, a novel desulfurization wastewater evaporation treatment system (DWETS) for handling wet flue gas desulfurization (WFGD) wastewater of a coal-fired power plant was studied. The system's advantages include simple process, and less investment and space. The feasibility of this system has been proven and the appropriate position and number of nozzles, the spray droplet size and flue gas temperature limitation have been obtained by computational fluid dynamics (CFD) simulation. The simulation results show that a longer duct, smaller diameter and higher flue gas temperature could help to increase the evaporation rate. The optimal DWETS design of Shangdu plant is 100 μm droplet sprayed by two nozzles located at the long duct when the flue gas temperature is 130 °C. Field tests were carried out based on the simulation results. The effects of running DWETS on the downstream devices have been studied. The results show that DWETS has a positive impact on ash removal efficiency and does not have any negative impact on the electrostatic precipitator (ESP), flue gas heat exchanger and WFGD. The pH values of the slurry of WFGD slightly increase when the DWETS is running. The simulation and field test of the DWETS show that it is a feasible future technology for desulfurization wastewater treatment.

Key words | CFD, field test, flue gas treatment, wastewater treatment, wet flue gas desulfurization

Jia-jia Deng
Liang-ming Pan (corresponding author)
De-qi Chen
Hang Liu
Mei-qiang Kang
Key Laboratory of Ministry of Education of Low-grade Energy Utilization Technologies and Systems,
School of Power Engineering,
Chongqing University,
Chongqing 400044,
China
E-mail: *cneng@cqu.edu.cn*

Yu-quan Dong
Cheng-mu Wang
Shuke Technology Co. Ltd,
Chengdu 610041,
China

INTRODUCTION

Coal-fired power plants represent the largest source of power grid supply around the world, especially in China. The statistical data from (China Electricity Council 2012) show that coal-fired power generation capacity is 3.7104 trillion kWh, which accounts for 74.41% of total electrical generating capacity in 2012. Since the vast majority of SO_2 emissions are from coal-fired boilers, the coal-fired power plant must be equipped with a sulfur dioxide removal device at the requirement of national environmental regulations. The limestone-gypsum wet flue gas desulfurization (WFGD) process system is the most frequently installed scrubber due to many advantages such as high desulfurization efficiency, high reliability, adaptability of different coals, high absorbent utilization, high equipment operation rate, cheap absorbent, and easy to obtain.

During the slurry recirculation, the accumulation of chlorine and heavy metals which come from coal-fired fume results in unexpected effects, such as lowering the pH of the absorption solution and making equipment prone to corrosion and erosion (Tatani *et al.* 2003). For the corrosion and erosion protection of the equipment and gypsum quality requirements, the content of chloride in the spraying slurry must be less than the design chloride level (Zhang *et al.* 2009); thus a certain amount of wastewater should be discharged periodically to reduce the chloride level in limestone-gypsum WFGD system.

According to the requirement of environmental protection regulations, the wastewater must be treated (Bandyopadhyay 2009) before discharging. The conventional method systems (He & Qi 2010; Liu 2011) have been applied for many WFGD wastewater treatment systems. For example, the chemical precipitation, filtration, electrodialysis, ion exchange and ultrafiltration assisted by complexation (Charerntanyarak 1999; Gotoh *et al.* 2004; Trivunac & Stevanovic 2006) treatments have been conducted to remove heavy metals compounds in water streams.

doi: 10.2166/wst.2014.359

However, the operation status of the conventional treatment is not good because of the high operation costs and secondary pollution problem (Gao& Chen 2008).

In recent years, the research on wastewater treatments focused mainly on novel treatments (Yang *et al.* 2013) and alternative technologies (Tidwell *et al.* 2014) rather than conventional physical and chemical treatments(Charerntanyarak 1999; Huang *et al.* 2013). A novel evaporation treatment (Yang *et al.* 2013) has been developed to treat the wastewater because of the zero-discharge performance. Some papers (Strandberg 1994; Brown 1997; Yu &Xu 2004; Shaw 2008) describe a desulfurization wastewater evaporation treatment system (DWETS).

In the DWETS (Figure 1), the desulfurization wastewater discharged from a WFGD tank is atomized into droplets by dual fluid atomizer nozzles which are located at the duct between the air pre-heater and electrostatic precipitator (ESP). The atomized wastewater droplet will be evaporated rapidly due to high flue gas temperature. The humidity of the flue gas increases because of evaporation of spraying water, which will reduce the specific resistance of flue gas, and then the ash removal efficiency will be increased (Yu &Xu 2004). The chemical content of wastewater crystallizes and will be removed by the downstream ESP (Ran & Zhang 2010).

This DWETS technology requires less equipment and fewer commodities, which facilitates a more rapid construction schedule and less operation cost. However, few researches have been performed on a feasibility study of the DWETS technology.

METHODS

In DWETS technology, the potential risks to downstream equipment because of the changes of flue gas temperature, humidity and non-fully evaporated droplets are still unknown.

For the success of DWETS and the safety of downstream equipment, computational fluid dynamics (CFD) simulation models and a field test facility were set up. This investigation was divided into two parts. The first part is the CFD simulation feasibility analysis by the commercial software FLUENT that focuses on the evaporation process of droplets. The targets of CFD simulation are to find out the installation position, the number of nozzles, the size of spray droplets and the flue gas temperature limitation to make sure that the droplets have fully evaporated before entering the ESP to avoid potential risk for electrical field short-circuiting.

The second section is the field test on Shangdu power plant, which is located in the Neimenggu Mongolian autonomous region of China. The field test was carried out to verify the impact on downstream equipment due to the flue gas temperature, humidity and property change. The real-time running parameters of the boiler, ESP, gas-gas heater (GGH) and flue gas desulfurization (FGD) were recorded to analyze the impact on the equipment.

The simulation of the flue gas flow and evaporation process should obey the mass conservation, momentum equation and the energy conservation, and conservation of different species. The droplets' movement is governed by Newton's second law, and the evaporated process follows the convective mass transfer.

There is no mass loss and gain during the evaporation process; thus the equation for mass conservation of flue gas can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \bar{u}_i) = S_m \quad (1)$$

in which S_m is the mass source term generated by the evaporation process from the droplet to gas phase.

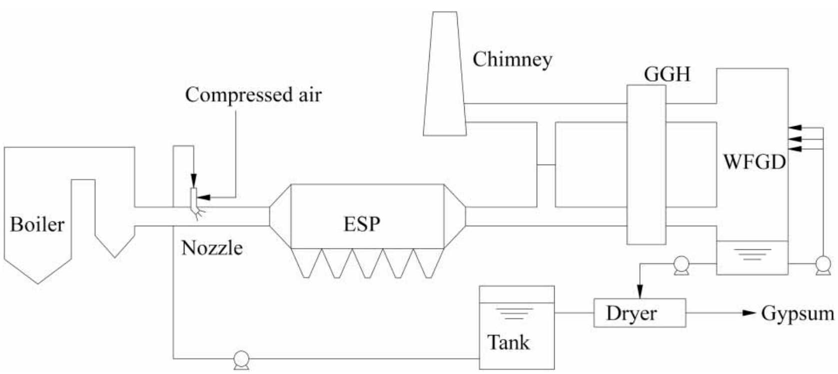

Figure 1 | Schematic of DWETS.

The momentum equation of the flue gas is denoted by:

$$\frac{\partial \rho \bar{u}_i}{\partial t} + \frac{\partial \rho \bar{u}_i \bar{u}_j}{\partial x_j} = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right] - \frac{\partial}{\partial x_i}\left(-\rho \overline{u_i' u_j'}\right) - \frac{2}{3}\frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial \bar{u}_j}{\partial x_j}\right)\right] + \rho g_i + F_i \quad (2)$$

The energy conservation of flue gas is:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_j}(\rho \bar{u}_j h) = \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j} + \frac{\mu_T}{\sigma_T}\frac{\partial T}{\partial x_j}\right) + q_j \quad (3)$$

The species (including O_2, H_2O, N_2, CO_2) transportation equation of flue gas is:

$$\frac{\partial}{\partial t}(\rho c_s) + \frac{\partial}{\partial x_i}(\rho \bar{u}_i c_s) = \frac{\partial}{\partial x_i}\left(D_p \frac{\partial c_s}{\partial x_i} + \frac{\mu_T}{\sigma_c}\frac{\partial c_s}{\partial x_i}\right) + S_i \quad (4)$$

in which $\bar{u}_i$, $\bar{p}$ and μ_T denote the average velocity of the fluid, the average pressure and turbulence viscosity respectively. c_s is the concentration of the components and $-\rho \overline{u_i' u_j'}$ is the Reynolds stress tensor caused by turbulent fluctuation.

The standard k-ε turbulence model (Zhou 1991; Chen 1997) is used for simulating the flue gas turbulent flow in the duct due to robustness, economy, and reasonable accuracy for a wide range of turbulent flows.

$$\rho \bar{u}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon \quad (5)$$

$$\rho \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad (6)$$

in which $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$ represents the turbulence viscosity, G_k- denotes the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to influence of buoyancy force on turbulence respectively, $\sigma_k, \sigma_\varepsilon$ represent the turbulent Prandtl number for k and ε, respectively; $C_{3\varepsilon}$ is a constant; $C_{2\varepsilon} = 1.92$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$.

The motion equation of a single droplet complies with Newton's second law:

$$m_p \frac{d\vec{u}_p}{dt} = \sum \vec{F}_p + m_p \vec{g} \quad (7)$$

in which m_p denotes the droplet mass (kg), $\vec{u}_p$ is the droplet velocity (m/s), $\vec{g}$ is the gravity acceleration (m/s^2), and $\sum \vec{F}_p$ represents other forces: buoyancy, drag force, pressure gradient force, virtual mass force, Basset force, Magnus force, Saffman force, thermophoretic force, etc.

When the temperature of the droplet reaches the vaporization temperature and lower than boiling temperature, the droplet is evaporated according to:

$$m_p(t + \Delta t) = m_p(t) - S_m \quad (8)$$

$$S_m = N_i A_p M_{w,i} \Delta t \quad (9)$$

where $M_{w,i}$ is the molecular weight of ith species (kg/kmol), m_p is the mass of droplet (kg), A_p is the surface area of the droplet (m^2), N_i is the molar flux of vapor (kmol/m^2.s), Δt is the time step (s), and S_m is the mass source in Equation (1).

The rate of droplet evaporation is governed by convective mass transfer, with the flux of droplet vapor into the gas phase related to the gradient of the vapor concentration between the droplet surface and the bulk gas flow:

$$N_i = k_m(C_{i,s} - C_{i,\infty}) \quad (10)$$

in which k_m is the convective mass transfer coefficient (m/s), $C_{i,s}$ is the vapor concentration at the droplet surface (kmol/m^3), and $C_{i,\infty}$ is the vapor concentration in the bulk gas (kmol/m^3).

RESULTS AND DISCUSSION

The desulfurization wastewater discharge of Shangdu power plant is 6.2 t/h. The flue gas flow of each boiler is 2,360,000 Nm^3/h at boiler maximum continuous rating (BMCR) condition and the temperature of flue gas is 145 °C.

The simulated droplet trajectories at BMCR condition inside different ducts are shown in Figure 2, and the initial average sauter diameter of droplets is 100 μm. Figures 2(a) and 2(b) show the droplets' trajectory in the short and long duct respectively. It can be seen that some liquid wastewater droplets flow into the ESP if the nozzles are mounted in the short duct, but if the nozzles are mounted in the long duct, the droplets would be fully evaporated because of long droplet residence time.

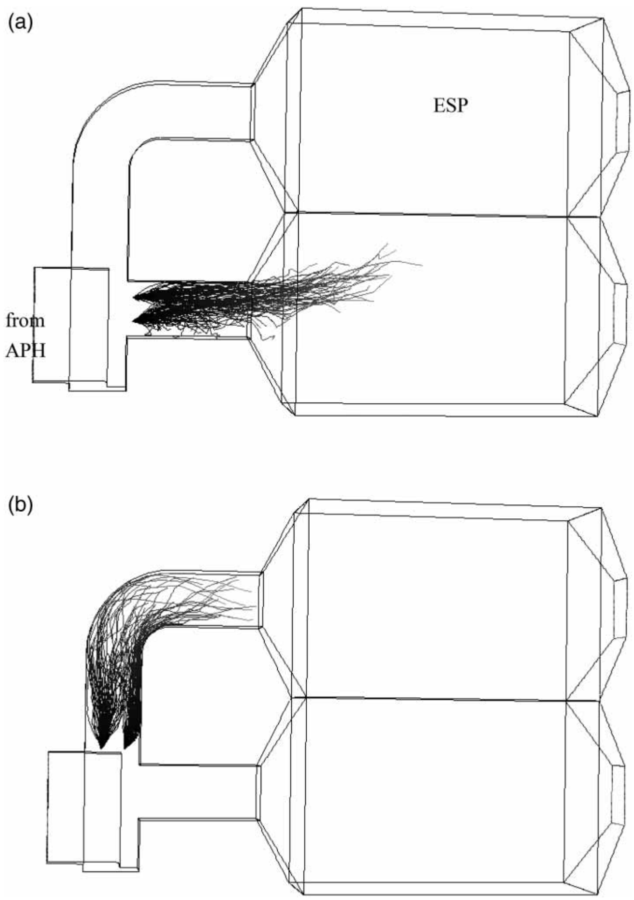

Figure 2 | Wastewater droplets' trajectory inside duct. (a) Short duct, (b) long duct.

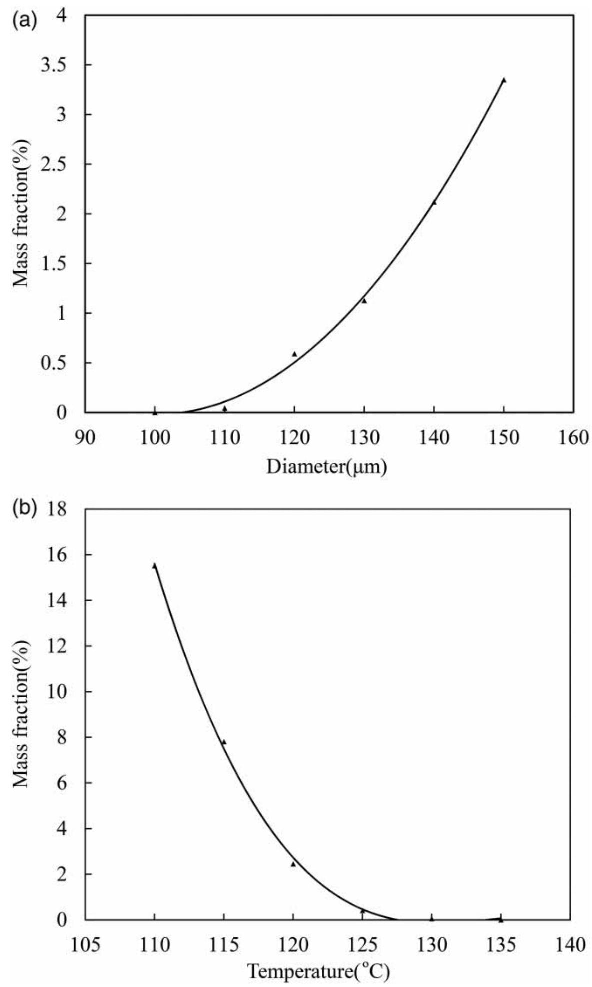

Figure 3 | Non-fully evaporated droplet mass fraction inside the long duct. (a) Different initial diameter, (b) different gas temperature.

The appropriate nozzle mounted position of the Shangdu project is the top of the long duct, and two nozzles are enough to treat all wastewater.

The non-fully evaporated droplet mass fraction will increase as the initial diameter increases and the flue gas temperature falls. When mounting the nozzle in the long duct, the non-fully evaporated droplet mass fraction at the inlet of the ESP at different initial droplet diameter when the flue gas temperature is set at 130 °C is shown in Figure 3(a). Figure 3(b) shows the non-fully evaporated droplet mass fraction at different flue gas temperatures when the initial droplet diameter is 100 μm. From Figure 3(a), it can be seen that the non-fully evaporated mass fraction of droplets increases characteristically as the initial diameter increases; the droplet will be fully evaporated when the diameter is less than 105 μm. Figure 3(b) shows that the non-fully evaporated mass fraction of droplets decreases characteristically with the increasing flue gas temperature; when the flue gas temperature is higher than 127 °C, all droplets would be fully evaporated, which implies that the lowest flue gas temperature limitation of the DWETS system is 127 °C. For system safety, the spraying droplet diameter should be less than 100 μm and the flue gas temperature should be higher than 130 °C.

The simulation results show that a longer duct with a smaller diameter and a higher flue gas temperature could help to increase the evaporation process. The optimal DWETS design is 100 μm of initial droplet diameter sprayed by the two nozzles located at the long duct when the flue gas temperature is higher than 130 °C. Therefore, the DWETS should be automatically shut off when the flue gas temperature is lower than 130 °C.

Based on the results of the CFD analysis, the field test facility was installed and the test was carried out in the Shangdu power plant. The DWETS field test was run to study the impact on the ESP, GGH and WFGD. The DWETS was started at 11:45 and continued to 16:45, the boiler load was also recorded. Figure 4 shows the boiler load data from 06:45 to 16:45. It can be seen that the boiler load fluctuated between 70 and 95%. There was a significant decrease of the boiler load before the DWETS was started and the trend of the boiler load did not change. The boiler load decreased from 92 to 75% before DWETS was started because of grid dispatching; thus the downstream GGH inlet temperature decreased because of the boiler load decrease.

The running parameters of the ESP are current, voltage and power. The parameters are shown in Figures 5 and 6. There is no significant change after starting the DWETS.

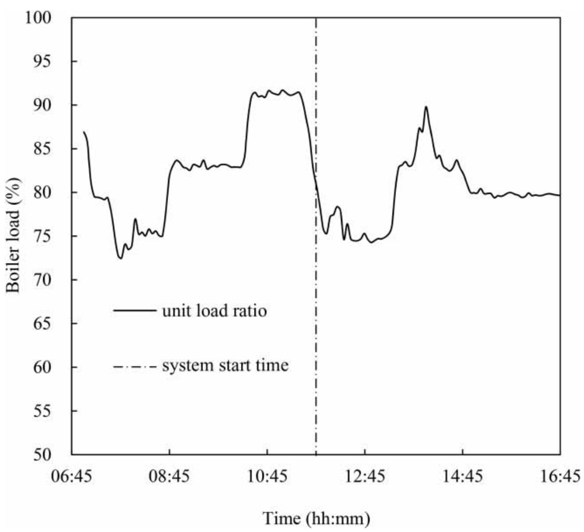

Figure 4 | Boiler load history.

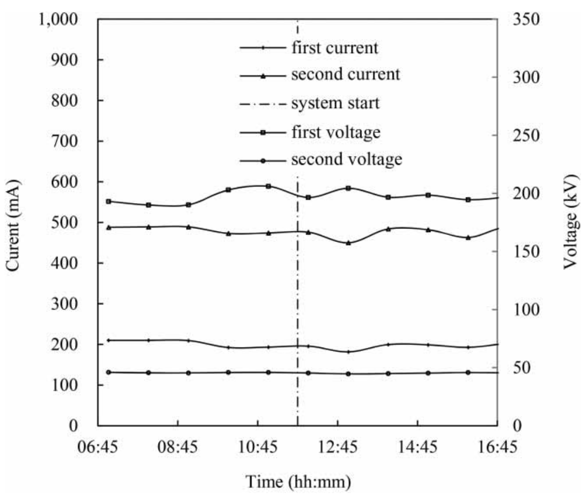

Figure 5 | Voltage and current history of ESP field.

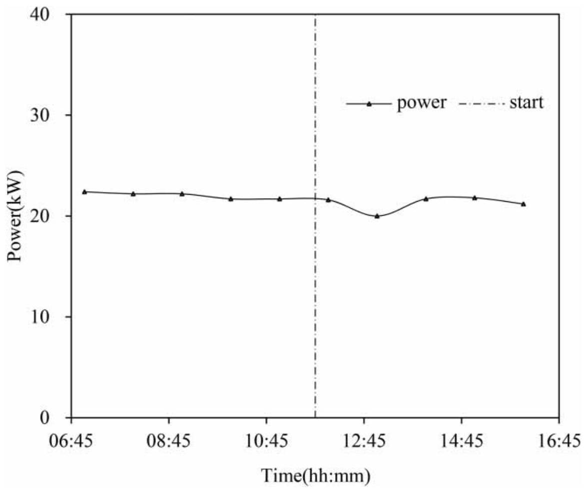

Figure 6 | Powerhistory of left ESP field.

The ESP outlet dimensionless dust concentration and inlet temperature of GGH are shown in Figure 7, in which the dimensionless dust concentration is the ratio between test dust concentration and design dust concentration. It can be seen from Figure 7 that the dust concentration reduced slightly; this means that the ash removal efficiency will be increased when the DWETS is running, and the inlet temperature of GGH is reduced corresponding to the synchronous reduction of the boiler load.

The effect of the DWETS on the FGD system was studied when the system was running. The desulfurization efficiency and pH value of slurry were recorded, as shown in Figure 8. It can be seen that, after starting the DWETS, the desulfurization efficiency had no significant change. However, the pH value of slurry increased slightly. This is because the humidity of the flue gas increases when the

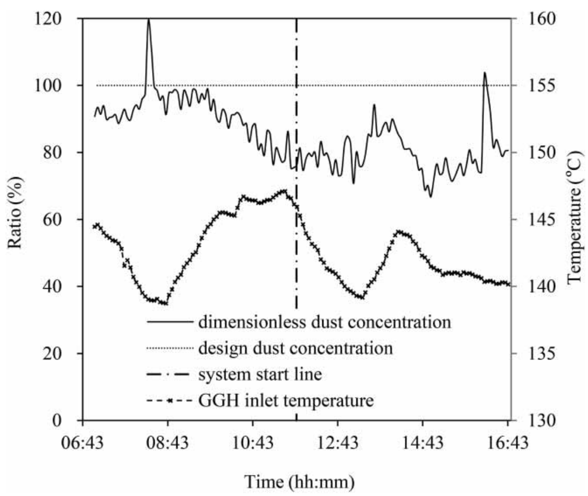

Figure 7 | ESP outlet dust concentration and GGH inlet temperature.

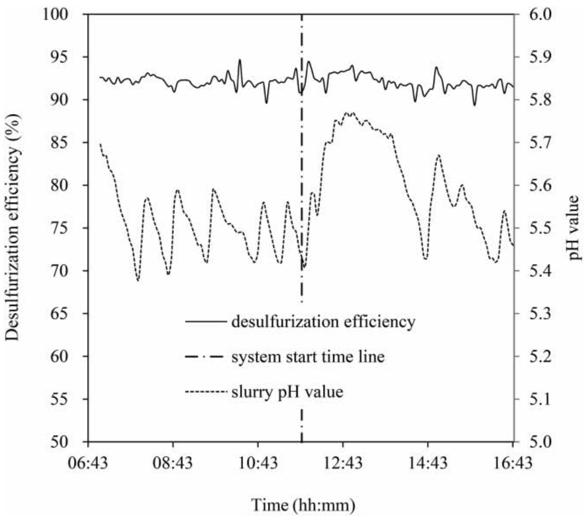

Figure 8 | Desulfurization efficiency and slurry pH value.

DWETS is running, which results in more water condensing inside the WFGD tower; as a consequence, the pH value would show a small increase.

The DWETS does not significantly change the electric parameters of the ESP and has a good effect on dust removal efficiency. The inlet temperature changes of GGH have the same trend as the boiler load. After the start of DWETS, there is no significant effect on desulfurization efficiency, but the pH value of slurry increases slightly.

CONCLUSION

This paper presented a desulfurization wastewater treatment system without pollutant discharge. Field test studies were carried out based on a CFD simulation feasibility analysis and the conclusions are as follows:

1. Based on the results of CFD simulation, the DWETS is feasible for coal-fired power station wastewater treatment. The appropriate position, the number of the nozzles, the size of the spray droplets and the flue gas temperature limitation were defined.
2. The DWETS field test at the power plant shows that there is no negative effect on the ESP, GGH and WFGD, and it has some positive effects on dust removal efficiency. The pH value of the slurry of WFGD increases slightly when the DWETS is running.

The simulation and field test of the DWETS show that it is a feasible technology for desulfurization wastewater treatment without pollutant discharge.

ACKNOWLEDGEMENT

The authors are grateful for the support of the Shuke Technology Co. Ltd under contract.

REFERENCES

Bandyopadhyay, S. 2009 Targeting minimum waste treatment flow rate. *Chem. Eng. J.* **152** (2–3), 367–375.

Brown, J. R. 1997 Pure Air's Advanced Flue Gas Desulfurization Clean Coal Project. In: *Proceedings of the 1997 Air & Waste Management Association's 90th Annual Meeting & Exhibition, Air & Waste Management Association, Toronto, Canada*.

Charerntanyarak, L. 1999 Heavy metals removal by chemical coagulation and precipitation. *Water Sci. Technol.* **39** (10–11), 135–138.

Chen, Y. L. 1997 *The Model of Turbulence Simulation*. Press of University of Science and Technology of China, Hefei (in Chinese).

China Electricity Council 2012 List of 2012 Basic Data Electricity Statistics of China. http://www.cec.org.cn/guihuayutongji/tongjxinxi/niandushuju/2013-11-07/111737.html (in Chinese).

Gao, Y. & Chen, Z. S. 2008 New treatment scheme of zero discharge for deSOX waste water. *Huadian Technol.* **30** (4), 73–75 (in Chinese).

Gotoh, T., Matsushima, K. & Kikuchi, K.-I. 2004 Adsorption of Cu and Mn on covalently cross-linked alginate gel beads. *Chemosphere* **55** (1), 57–64.

He, Z. Q. & Qi, L. M. 2010 Wastewater treatment process of flue gas desulfurization in the power plant. *Technol. Water Treat.* **36** (3), 133–135 (in Chinese).

Huang, Y. H., Peddi, P. K., Tang, C. L., Zeng, H. & Teng, X. J. 2013 Hybrid zero-valent iron process for removing heavy metals and nitrate from flue-gas-desulfurization wastewater. *Separ. Purif. Technol.* **118**, 690–698.

Liu, Z. P. 2011 Design and operation of FGD wastewater treatment system in a power plant. *China Water Wastewater* **27** (2), 65–67 (in Chinese).

Ran, J. Y. & Zhang, Z. R. 2010 Numerical study on evaporation characteristics of different substance droplet in low temperature flue gas. *Proc. CSEE* **30** (26), 62–68 (in Chinese).

Shaw, W. A. 2008 Evaporation of wastewaters from wet gas scrubbing operations. In: *25th Annual International Pittsburgh Coal Conference, PCC, September 29, 2008–October 2, 2008*, CSREA Press, Pittsburgh, PA, USA.

Strandberg, R. 1994 The open recirculating cooling system as a primary component in the zero water discharge mechanism of a waste to energy plant. In: *The International Water Conference 55th Annual Meeting, Pittsburgh, PA, USA*.

Tatani, A., Imai, T. & Fujima, Y. 2003 Effect of Mn^{2+} on sulfite oxidation in limestone scrubbing. *Energy Fuels* **18** (1), 54–62.

Tidwell, V. C., Macknick, J., Zemlick, K., Sanchez, J. & Woldeyesus, T. 2014 Transitioning to zero freshwater withdrawal in the U.S. for thermoelectric generation. *Appl. Energy* **131**, 508–516.

Trivunac, K. & Stevanovic, S. 2006 Removal of heavy metal ions from water by complexation-assisted ultrafiltration. *Chemosphere* **64** (3), 486–491.
Yang, B., Zhang, L., Lee, Y. & Jahng, D. 2013 Novel bioevaporation process for the zero-discharge treatment of highly concentrated organic wastewater. *Water Res.* **47** (15), 5678–5689.
Yu, Q. Y. & Xu, L. B. 2004 Treatment of wastewater from limestone-gypsum flue gas desulfurization in power plant. *Electric Power Environ. Protect.* **20** (3), 47–51 (in Chinese).
Zhang, Z. W., Jing, W. J. & Shen, L. F. 2009 Effect of chlorine ion concentration on wet limestone gypsum desulfurization technology. *Indust. Safety Environ. Protect.* **35** (11), 28–29 (in Chinese).
Zhou, L. H. 1991 *The Turbulent Two-phase Flow and Combustion Numerical Simulation*. Tsinghua University Press, Beijing (in Chinese).

First received 4 April 2014; accepted in revised form 4 August 2014. Available online 26 August 2014