Numerical simulation on wastewater with flue gas in concentration tower

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Abstract. Most power plants equipped with limestone-gypsum wet flue gas desulphurization (FGD) system treat FGD wastewater by chemical precipitation which is not able to remove chloride ion completely. The wastewater treatment of concentrating and crystallizing piecewise by flue gas can solve this issue. Pretreating wastewater by undersaturated fuel gas and then concentrating by high temperature fuel gas is not only utilizing waste heat but also realizing “zero discharge”. By 3D-modeling of concentration tower and numerical simulation of evaporation, the evaporation process of wastewater droplet in concentration tower has been studied. Through simulation, the impact of four main factors (gas mass flow, initial droplet diameter, gas temperature and droplet temperature) to evaporation efficiency (EE) has been analyzed. Result indicates that the decrease of initial droplet diameter has greatest impact on improvement of evaporation. Furthermore, raise gas mass flow, gas temperature and droplet temperature in reasonable range can improve EE effectively. The conclusion provides reliable theoretical basis for technological design of concentration tower in power plants.

1. Introduction
Coal resources account for about 95% of proven fossil energy reserves as the primary energy in China. In 2018, The installed capacity of power plants increased 7.6% compared with 2017[1]. As big water user with large amount of pollution discharge, coal-fired power plants are important targets of energy-saving and emission-reduction. In July 2011, the Ministry of Ecology and Environment of PRC released Emission Standard of Air Pollutants for Thermal Power Plants[2], which greatly reduced emission limits of sulfur dioxide. By the end of 2017, installed capacity of operated thermal power plants equipped with flue gas desulfurization system accounted for 93.9% of the total capacity of coal generating units in China[3].

At present, major coal-fired power plants use Wet Flue Gas Desulfurization (WFGD) system which uses limestone or lime as absorber to remove sulfur dioxide and other pollutants[4]. During recycle using of absorber, chloride ion and fluoride ion enriched in absorption liquid. Wastewater need to be discharged and process water should be added to guarantee concentration of impurity under limits. Therefore, a set of desulfurization wastewater treatment equipment is required.

Mainly existed studies and applications of desulphurization wastewater treatment technology focus on chemical precipitation, fluidized bed, membrane separation, evaporative crystallization and spray evaporation in fuel duct[5-8]. Among these methods, the widest used by coal-fired power plant is chemical precipitation which cannot reduce chloride ion to lower concentration[9]. Besides, it is hard
to control reagent dosage corresponding to different kind of coal or load of power plant. Spray evaporation in fuel duct is atomizing wastewater and spraying into fuel duct between air preheater and dust catcher. Hot fuel gas evaporates water and dust catcher catches residual solid impurity particles, which realizes “zero discharge” of waste liquid. The advantages of this method are less equipment, simple process and relatively small space. However, fuel gas pumped from dust catcher has lower temperature, which causes that wastewater is hard to be evaporated completely. The problem may lead to corrosion of fuel duct and dust catcher[10].

Although there are several successful cases of spray evaporation in fuel duct, most coal-fired power plants still use traditional technology to treat wastewater. In addition, most relative studies of wastewater droplet evaporation are using numerical simulation method. Zhou et al. did simulation studies on how arrangement of atomizing nozzle, atomizing diameter and flow rate of fuel gas influence evaporate efficiency[11]. Zhang et al. studied on main influence factors to evaporation effect of wastewater droplet in bent duct by numerical simulation[12]. Weng et al. analysed the influence of droplet velocity from atomizing nozzle and gas-liquid ratio[13].

In order to solve the disadvantage that atomizing evaporation is hard to treat wastewater completely at large flow rate, we applied concentration and reduction as pre-processing. After pre-processing, concentrated water will be sprayed into fuel duct or bypass duct to be reheated and evaporated. The study built a model of concentration tower of a 300MW units power plant and completed numerical simulation on process of wastewater evaporation by low temperature fuel gas. The final conclusion obtained from simulation results provides reliable database for process design of crystallization tower in power plants has obtained.

2. Numerical simulation model and condition setting

2.1. Simulation theory

Computational fluid dynamics (CFD) [14] uses numerical analysis to solve and analyse problems that involve fluid flows, heat and mass transfer accurately. The study utilized ICEM CFD of ANSYS for modelling and meshing crystallization tower, and then simulated evaporation process by FLUENT.

The Lagrangian discrete phase model in ANSYS FLUENT follows the Euler-Lagrange approach. The fluid phase is treated as a continuum, while the dispersed phase is solved by tracking a large number of particles, bubbles, or droplets through the calculated flow field[15]. The model includes particle motion theory, dynamic drag theory, heat and mass exchange theory[16], etc.

ANSYS FLUENT predicts the trajectory of a discrete phase particle by integrating the force balance on the particle, and can be written (for the x direction in Cartesian coordinates) as

$$\frac{du_p}{dt} = F_p(\bar{u} - \bar{u}_p) + \frac{\partial}{\partial x} \left[ \rho \frac{\partial \bar{u}_p}{\partial x} \right] + \bar{F}$$

(1)

Here, $\bar{u}$ is the fluid phase velocity, $\bar{u}_p$ is the particle velocity, $\rho$ is the fluid density, $\rho_p$ is the density of the particle, $\bar{F}$ is an additional force term, $F_p(\bar{u} - \bar{u}_p)$ is the drag force per unit particle mass.

The evaporation-condensation model is available with the mixture and Eulerian multiphase models[17]. The liquid-vapor mass transfer is governed by the vapor transport equation.

$$\frac{\partial}{\partial t} (a \rho_v) + \nabla \cdot (a \rho_v \bar{V}_v) = \dot{m}_{l \rightarrow v} - \dot{m}_{v \rightarrow l}$$

(2)

$v$ is vapor phase, $a$ is vapor volume fraction, $\rho_v$ is vapor density, $\bar{V}_v$ is vapor phase velocity, $\dot{m}_{l \rightarrow v}$, $\dot{m}_{v \rightarrow l}$ the rates of mass transfer due to evaporation and condensation, respectively. These rates use units of kg·s⁻¹·m⁻³.

ANSYS FLUENT defines positive mass transfer as being from the liquid to the vapor for evaporation-condensation problems. Based on the following temperature regimes, the mass transfer can be described as follows:
if $T_i > T_{sat}$,

$$m_{i-v} = \text{coeff} \times a_i \rho_i \frac{(T_i - T_{sat})}{T_{sat}}$$  \hspace{1cm} (3)

if $T_i < T_{sat}$:

$$m_{v-i} = \text{coeff} \times a_v \rho_v \frac{(T_v - T_{sat})}{T_{sat}}$$  \hspace{1cm} (4)

coeff is a coefficient that can be interpreted as a relaxation time. $a$ and $\rho$ are the phase volume fraction and density, respectively.

2.2. 3D physical model

Concentration tower is designed as cylinder with 1.2m in diameter and 10m in height. Simplified model and meshing are shown in figure 1. Fuel gas inlet is set at the bottom of tower wall and outlet is set at the top.

![Simplified model and meshing of concentration tower.](image)

Simulation adopts Euler/Lagrange discrete particle model to calculate evaporation. Fuel gas is set to be continuous phase while wastewater droplet is set to be discrete second phase. On the premise that simulate results are corresponding with reality, hypothesizes are made to simplify simulation process. (1) Fuel gas and vapor are regarded as ideal gas. Impact of impurity in fuel gas and wastewater to evaporation is ignored[18]. Thus, fuel gas and desulphurization wastewater are replaced by air and water, respectively. (2) Walls of concentration tower are set to be insulated and reflect, which means walls do not conduct or radiate heat to droplets. Besides, after contacting walls, water droplets go back into fuel gas and continue heat and mass transfer. (3) Droplets are regarded as globular and the shape do not change during evaporation. Swirl flow inside drops and collision and breakup among drops are ignored[19]. (4) Influence of components like atomizing nozzles and brackets to flow field is ignored. By summarizing relative references[13-15, 20], major impact factors to evaporation are fuel gas flow velocity, atomizing diameter, fuel gas temperature, etc. In this simulation, fuel gas mass flow rate, initial atomizing diameter, fuel gas temperature and humidity are chosen to be four varieties after analysing.

The fuel gas inlet of concentration tower is set to be velocity inlet, where the turbulence intensity $I$ is calculated by equation (5):
Normally, the temperature of undersaturated fuel gas is 80-130°C. The height of tower bottom is set as 0m. Thus, desulphurization wastewater is sprayed by sprinkler from 9.5m high inside the concentration tower. Average EE is calculated by 500 droplets in every 0.1s.

3. Results and analysis

3.1. The change of relative humidity contour depends on time

Under the condition of droplets diameter at 2mm and fuel gas mass flow at 3.5kg/s, the change of relative humidity contour depends on falling time has been analysed. As shown in figure 2, relative humidity contour falls quicker at the central axis line of concentration tower. The reason is that with the choice of cone-solid injector, density of droplets at central axis is higher and relative humidity is larger. Droplets near central axis evaporate slower, which causes that the contour lines fall quicker.

![Figure 2. The change of relative humidity contour depends on time at central plane.](image)

3.2. Effect of fuel gas mass flow rate on EE

Under the condition of droplets diameter at 2mm, fuel gas and droplets initial temperature at 90°C and 50°C, respectively, the change of EE depends on height and time has been analysed with gas mass flow rate at 2.8kg/s, 3.5kg/s and 4.2kg/s. Figure 3 shows the growth of EE slower slightly as falling time increases. The general linear relation between two factors indicates that gas mass flow has nearly no effects on EE. Figure 4 describes that the growth rate of EE decreases gradually as falling height raises. Since gas and droplets flows against each other, droplets with higher EE as well as less mass fall slowly by the influence of drag force. After falling 9.5m to the bottom, droplets evaporate 8%, 7.6% and 7.2% respectively under three kinds of gas flow rate. In normal vibration range, gas mass flow rate has slight effect on evaporation. In practical operation, flow rate of fuel gas from dust catcher to concentration tower is controlled by induced draft fan. Since larger gas flow rate increases operation consumption, a relatively small flow rate should be chosen under the assurance of EE.
3.3. Effect of droplets initial diameter on EE

An example has been taken as gas mass flow rate at 3.5kg/s, gas and droplet initial temperature at 90℃ and 50℃, respectively. The change of EE depends on falling height and time has been analysed under five kinds of droplets diameter as shown in figure 5. All the growth speeds of EE decrease as falling height raises. Smaller droplets have larger specific surface area contacting with fuel gas, which improves relative heat absorption as well as EE. Droplets with initial diameter at 1mm reach 15% of EE after falling 3m high, which indicates significant evaporation effect. Figure 6 describes the general linear relation between EE and falling time. The reason of this result is that smaller droplets with larger EE have to spend more time on dropping due to contrary gas flow. It is obvious that sprinkler with minor spraying diameter achieves better evaporation effect. However, minor diameter means greater energy consumption, that is why we have to consider operation energy consumption and wastewater treatment efficiency synthetically.

3.4. Effect of gas and droplets initial temperature on EE

Figure 7 shows the change of EE depends on falling time under different gas inlet temperatures with the condition as gas mass flow at 3.5kg/s, droplets diameter at 2mm and droplets initial temperature at 50℃. After falling 2s, droplets in fuel gas with initial temperature at 80℃ get average EE at 6.5%, while droplets achieve EE at 8.5% in fuel gas with initial temperature at 130℃. Since higher fuel gas temperature shorten time duration of vapor pressure at droplet surface raises to saturated state, the increase of gas temperature promotes evaporate rate remarkably. Therefore, assurance of gas initial temperature above limit is an important measure to keep EE in concentration tower steady. Figure 8 describes that the change of EE depends on falling time under different droplets initial temperatures with the condition as gas mass flow at 3.5kg/s, droplets diameter at 2mm and fuel gas initial temperature at 50℃. After falling 2s, droplets with initial temperature at 60℃ get average EE at 8.2%,
while EE improve 50% as droplets temperature raises 20℃. In practical process, taking insulation measures of wastewater tube between desulfurizing tower and concentration tower is an efficient method to improve EE.

![Figure 7. Change of EE depends on falling time under different fuel gas initial temperature.](image1)

![Figure 8. Change of EE depends on falling time under different droplets initial temperature.](image2)

4. Conclusion

Through numerical simulation of droplets evaporation, several conclusions have been obtained.

1) The change of fuel gas mass flow has nearly no influence on EE depends on time. Because of contrary flow, droplets spend more time on dropping to the tower bottom under larger gas flow rate, which leads to more EE.

2) Droplets with smaller diameter has larger specific surface area as well as greater EE. Under the condition that fuel gas initial temperature at 90℃ and mass flow rate at 3.5kg/s, the EE of droplets with initial temperature at 50℃ and diameter at 1mm reaches 15% after falling 3m, which indicates significant evaporation effect.

3) Droplets EE grows remarkably as the increase of gas and droplets temperature.

4) The decrease of droplets initial diameter as well as the increase of gas mass flow and droplets temperature have obvious effect on EE improvement, while operation consumption raises. In practical design, operation cost has to be reduced under the guarantee of wastewater treatment efficiency.

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