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A concise algorithm for calculating absorption height in spray tower for wet limestone–gypsum flue gas desulfurization

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A B S T R A C T

In this paper, a concise model for wet limestone–gypsum flue gas desulfurization system with spray tower has been presented, aiming at the prediction of the absorption height in a spray tower. The equations of droplet motion and mass balance were incorporated and developed to simulate the droplet movement, distribution and mass transfer of SO_2 in the absorption section. The calculation results were in good agreement with the plant values of the absorption height. The influences of operating parameters on the absorption height were analyzed. The results show that absorption height declines with increasing liquid–gas ratio and pH value of the slurry, and increases with increasing droplet diameter, gas flow rate, gas temperature, inlet SO_2 concentration and absorption efficiency, respectively. As the most sensitive parameter, the droplet diameter is crucial for the good prediction of absorption height. This model can provide engineering guidance to design a spray tower absorber.

1. Introduction

It is well known that sulfur dioxide exists in the flue gas of power plants and industrial boilers leading to acid rain which damages buildings, vegetation and surface water [1–3]. SO_2 is also considered to be toxic to humans by inhalation [4,5]. Throughout the world, the pollutant emission standards have become increasingly strict over the past ten years [2,6]. Efficient removal of SO_2 can be achieved mainly by means of desulfurization techniques.

Generally speaking, the flue gas desulfurization (FGD) technology can be classified into three sub-categories: wet FGD, dry FGD and semi-dry FGD. By contrast, as the most mature technology, limestone–gypsum wet flue gas desulfurization (WFGD), primarily due to high efficiency of SO_2 absorption, low investment cost, reliable operation, and low price of absorbent, has been widely used in the most power plants worldwide, especially in China [7–9]. Obvious advantages can also be achieved in some other plants with large quantities of flue gas, variable coal properties, and unstable loads of boilers [10]. In addition, over the past ten years, new WFGD technologies aimed at corrosion protection, anti-fouling and wastewater treatment have been developed [7,11,12]. Accordingly, the wet lime-slurry absorption technology still has an application value for SO_2 abatement.

The absorption of SO_2 in wet desulfurization units is realized in absorption towers. There are several types of towers, such as spray towers, packed towers, jet bubbling reactors, venture scrubbers and double loop towers [13]. The most commonly used and best studied wet scrubber is the countercurrent spray tower employing liquid distribution at different levels in the absorber [14–16]. Advantages of spray tower are: simple construction, lack of complicated spray elements, resistant to corrosion, large handling capacity and low investment costs [17].

Over the past few decades, considerable numbers of studies have been conducted on fluid mechanics in spray tower. Schmidt and Stichlmair [18] investigated liquid distribution in spray scrubbers of different sizes with concurrent flow of gas and liquid. However, in this case, only narrow, concurrent scrubbers were considered. Michalski [19] developed a complete model of hydrodynamic characteristics of a FGD scrubber on the basis of analysis of spray polydispersity, and the relations for pressure drop, dispersed phase concentration, and residence time along the scrubber height were obtained. Li et al. [20] presented a model on aerodynamic characteristics of FGD spray scrubber, and a discussion on drop resistant time, gas pressure drop and mass transfer area was carried out based on this model. With these issues in mind, mass transfer characteristics in spray tower should be taken into consideration subsequently.

The spray droplets are involved in variable motion, resulting in both the specific surface area and the mass transfer coefficient change along the absorption zone, while chemical factors coupled with physical processes [21]. Therefore, the simulation of desulfurization process has become complicated. Researchers have done a lot of theoretical analysis, and several existing models for spay tower are summarized in Table 1. It can be seen that majority of these models are focused on system optimization, and rarely used in design. Furthermore, complexity is inevitable.

The height of absorption zone is highly concerned by engineers, ascribed to a higher absorption zone is always accompanied with higher

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Table 1
List of mass-transfer models reported in literature for SO_2 abatement in spray tower.

Reference	Scale	Method	Comment
Olausson et al. [22]	Experimental	Two-film theory	Sensitivity to changes in sulfite oxidation or in SO_3^{2-} and Mg^{2+} concentrations is low.
Gerbec et al. [23]	Pilot	Penetration theory	Non-stationary model primarily based on slurry pH. Possible disturbances of plant operation can be predicted.
Brogren and Karlsson [24]	Unknown	Penetration theory	Limestone dissolution is mass transfer controlled at low pH while surface kinetics controls dissolution rates at high pH.
Warych Szymanowski [25]	Industrial	Two-film theory	Cost optimization is presented based on thermodynamic equilibrium and droplet diameter equals to 2.9 mm.
Gómez et al. [6]	Industrial	Euler–Euler approach Two-film theory	Eulerian–Eulerian treatment of multiphase flow is illustrated. Enormous computing is required.
Zhong et al. [10]	Industrial	Unsteady theory Two-film theory	Influences of combination mode of different spray levels to desulfurization efficiency are analyzed.
Zhang et al. [26]	Industrial	Two-film theory	Droplet velocity is assumed to be a constant. Variation of pH in slurry and mass transfer rate of CO_2 can be ignored.
Dou et al. [27]	Experimental	Two-film theory	A one-dimensional model of external mass-transfer with effects of a chemical enhancement factor and sulfite concentration is developed. The Sauter mean diameter is obtained from experiment.
Marocco et al. [21,28]	Industrial	Euler–Lagrange approach Two-film theory	CFD model coupled with desulfurization process. Both evaporation of slurry droplets and droplet–wall interaction are considered.
Kallinikos et al. [29]	Industrial	Two-film theory	Absorption rate of SO_2 is strongly affected by liquid dispersion. Optimization of WFGD system operation is obtained.
Neveux and Le Moullec [30]	Industrial	Euler–Euler approach Two-film theory	Chemically enhanced, absorption interaction between gas, liquid, and solid phases is taken into consideration. Drop size and enhancement factor have significant effects on results.

energy consumption and desulfurization efficiency [10]. Today, designs of spray towers are essentially based on empirical and/or semi-empirical correlations that are only valid within limited ranges of the design parameters. Hence, an appropriate model for WFGD system should be developed to estimate the height of absorption zone. Unfortunately, it is lack of specialized design model on a spray absorber, and the applications of methods mentioned above seem to be very complicated. This paper is focused on those problems to develop a concise model for prediction of absorption height and provide convenience for engineers. Furthermore, the influences of operating parameters on absorption height will also be discussed.

2. Model development

A simplified representation of the limestone–gypsum WFGD system is shown in Fig. 1. The main system consists of an absorption tower and a reaction tank. The flue gas enters the tower at its bottom and comes out from its top. The clean flue gas leaves the absorber through the outlet duct after removing the entrained water droplets by a mist eliminator. The slurry containing suspended limestone from the reaction tank is sprayed at the top of the tower over several spray levels with a dedicated recirculation pump. Each spray bank is provided with numerous spray nozzles for better distribution of the slurry. The slurry drops fall down and flow out from the tower bottom after reacting with the flue gas. In this way, the flue gas and the slurry come in contact in counter current mode for the effective absorption of SO_2 by the slurry. The reaction tank with forced oxidation is to remove SO_2 from flue gas and to produce gypsum as a saleable product. The pH value of the slurry is adjusted by adding limestone particles at a certain flow rate.

2.1. Assumptions

The hydrodynamic and heat-transfer characteristics in spray tower are considerably complicated. Specifically, the slurry droplet size depends largely on the type of spray nozzle and spraying mechanism. The pressure nozzle, as a conventional disperser, is widely employed in current industrial practice. The liquid dispersion largely depends on the pressure drop through the nozzle. Moreover, the drop size decreases with increasing the pressure of liquid [29]. Generally speaking, the representative drop size ranges from 1.2 to 1.5 mm [31]. However, this range may be extended due to the combination of several factors: the poor atomization quality after a long-term operation [29], the drop coalescence, and the wall effect [21]. Thus, the droplet distribution cannot be described as a specific function. In addition, the gas temperature in the tower is certainly not a constant. However, it rapidly reaches a relative stable value on account of the considerable difference between the liquid and gas phases on the specific heat capacity.

The chemical processes in spray tower include lots of mass transfer phenomena and chemical reactions [28]. In order to find a simple approach for the prediction of absorption height, a mathematical model is developed based on the following assumptions:

1. Flue gas is an ideal gas in plug flow because the liquid volume fraction inside the tower is lower than 5–8% [21]. The gas temperature in most absorption zone is nearly a constant based on the above analysis. In

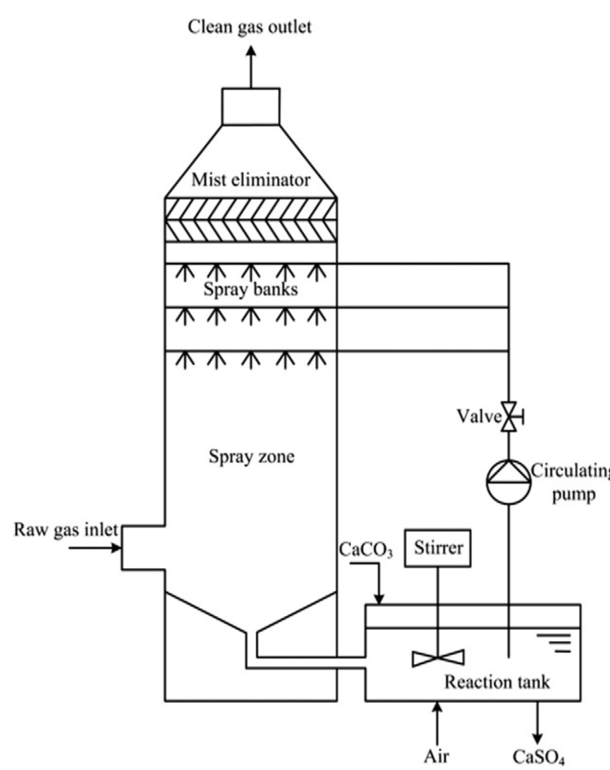

Fig. 1. Schematic diagram of the limestone–gypsum spraying desulfurization system.