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A modeling and experimental study of flue gas desulfurization in a dense phase tower

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ABSTRACT

We used a dense phase tower as the reactor in a novel semi-dry flue gas desulfurization process to achieve a high desulfurization efficiency of over 95% when the Ca/S molar ratio reaches 1.3. Pilot-scale experiments were conducted for choosing the parameters of the full-scale reactor. Results show that with an increase in the flue gas flow rate the rate of the pressure drop in the dense phase tower also increases, however, the rate of the temperature drop decreases in the non-load hot gas. We chose a water flow rate of 0.6 kg/min to minimize the approach to adiabatic saturation temperature difference and maximize the desulfurization efficiency. To study the flue gas characteristics under different processing parameters, we simulated the desulfurization process in the reactor. The simulated data matched very well with the experimental data. We also found that with an increase in the Ca/S molar ratio, the differences between the simulation and experimental data tend to decrease; conversely, an increase in the flue gas flow rate increases the difference; this may be associated with the surface reactions caused by collision, coalescence and fragmentation between the dispersed phases.

1. Introduction

Acid rain has acquired considerable concern in past decades because of the extent of its harm to the global environment. Sulfur dioxide (SO_2) waste released from fossil fuel combustion has been commonly accepted as the main cause of acid rain. Removal of SO_2 from the flue gas emitted during combustion of fossil fuels has been the focus of research worldwide since the 1970s. SO_2 poses a considerable threat to ecosystems, building materials, agriculture, as well as human health. In particular, SO_2 pollution is a very serious problem in large and mid-sized Chinese cities, where a cost efficient and highly effective desulfurization means is urgently needed [1]. Depending on the involvement of water during the desulfurization process, and how desulfurization products are dealt with, flue gas desulfurization (FGD) technology can be divided into wet, semi-dry, and dry processes [2]. Among these, the wet FGD process is the main technology used for flue gas desulfurization, which has the advantages of high desulfurization efficiency, high utilization rate of desulfurization reagents, and a stable operating environment [3–5]. Rajmohan et al. reported the removal of SO_2, as well as particulate pollutants, with an almost 99.99% efficiency [6–8]. Meikap et al. achieved 100% SO_2 removal efficiency when employing a modified multi-stage bubble column scrubber [9,10]. However, the main disadvantage of the wet scrubber is the fact that it is only suitable for flue gas desulfurization of large-scale coal-fired power plants. Moreover, the wet process has many other disadvantages, such as, the complexity of the system, which occupies a large area, high-energy consumption, severe corrosion, and extensive wastewater treatment, in addition to the large initial investment that is required [5]. In contrast, the dry process requires no discharge, has minor equipment corrosion, and is a simple structure easily maintained, as well as having a low operating cost. However, the desulfurization efficiency and utilization rate of the desulfurization reagent for the dry process are very low, which dramatically limits the application of the dry process [2].

Compared to the wet and dry process, semi-dry FGD combines advantages of both dry and wet processes, for example, rapid reaction speed, high desulfurization efficiency, and no discharge [11,12]. However, there are problems associated with semi-dry FGD technology, such as low utilization rate of desulfurization, choking phenomenon and large consumption of desulfurizer and space. To meet the standards of SO_2 removal, great efforts have been made to develop new FGD technologies with less/no waste, low cost and high efficiency [13,14].

Spray-dryer and CFB-FGD processes are two traditional semi-dry processes. Spray-dryer process has been extensively tested. However, a great drawback of this method is its large space consumption in order to maintain long flue gas residence time (10–15 s) for desulfurization reaction and slurry droplet evaporation, as well as to meet the requirement for the complicated slurrying system [15]. Circulating fluidized bed is also widely used for flue gas desulfurization, however, the choking phenomenon

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widely occurs due to unsteady flow in the bed resulting from the fact that flue gas and desulfurization reagent enter into the reactor from the bottom of the reactor, which seriously affect the efficiency of desulfurization [14,16].

Many new semi-dry process technologies have been invented in an attempt to achieve high SO_2 desulfurization efficiency at a low cost and small space consumption [17]. This paper presents data on the incorporation of a new type of semi-dry desulfurization equipment, the dense phase tower (DPT). DPT is defined as a desulfurization tower where flue gas and desulfurization reagent enter into DPT from the top of the reactor, which can prevent the choking phenomenon, thus ensuring high concentration of sorbent suspension. Moreover, flue gas superficial detention time was 5–12 s in the DPT, which dramatically reduce the size comparing to spray-dryer process. Therefore, the DPT takes the advantage of application on space-limited plants.

Flue gas first entered the DPT from a side entrance located at the top of the tower, then is mixed with the fresh desulfurization reagent and desulfurization circulating ash from a bucket elevator. The desulfurization ash is humidified as it passed through the humidifier. Finally, desulfurization ash and flue gas are distributed through a diversion plate, which is located right below the mechanical rakings. Flue gas flows downward along the tower and reacts with active ingredients of desulfurization in an effective reaction zone. After desulfurization, the flue gas enters a bag-type dust collector for dust removal and then purified flue gas is discharged from the flue channel. Meanwhile, circulating ash is transferred back to the reactor through the bucket elevator.

We used computational fluid dynamics (CFD) to simulate the temperature and pressure drop, desulfurization efficiency, temperature and pressure distribution, circulating ash concentration distribution and circulating ash trajectory. CFD provides a method to build and run models that can simulate gas dispersion in such geometrically complex situations. Based on a CFD analysis, the FLUENT software solves the three-dimensional Reynolds averaged equations for flow, pressure, turbulence parameters and concentration distribution.

Pilot-scale experiments on actual flue gas from Shijiazhuang Iron and Steel Co., Ltd., were performed using the DPT process. We studied the Ca/S molar ratio influence on desulfurization efficiency, water addition and the influence of flue gas flow rate on decreases in flue gas temperature and pressure. Pilot-data showed a good match with the theoretical simulation data. The experimental data provide the basis for the industrial scale operation of the factory. The simulated and experimental results have provided guidelines for the industrial applications of the DPT process in several power and sintering plants in China.

2. Materials and methods

2.1. Apparatus and procedure

The apparatus for the pilot DPT series of experiments is described as follows (Fig. 1). The reactor (1.2 × 1.2 × 5.0 m) included a vertical rectangular tower containing humidification, dust removal, and cycle-ash transport system. Six parallel mechanical rakings, totally contained within three internal layers, were installed at a position 3/4 of the way from the top of the DPT. The mechanical rakings, as well as the diversion plate located right below them, were made from manganese alloy steel. The humidification system consisted of a SJ5 bi-axial humidifier, water tanks, metering pumps, and other devices. Five to ten hollow water sprayers with a droplet size less than 40 μm were installed vertically on the four sides of the humidifier. The dust removal system included 88 low pressure Φ130 × 2000 mm pulse-jet bags, a W-0.3/8-Pa air compressor, a 0.2 m^3 gas tank, submerged-type pulse valve and an integrated pulse meter control box. The cycle-ash transport system included a scraper conveyor in the lower part of the tower, a bag-type dust collector, a DL160-30 m bucket elevator and other devices for the removal of the desulfurization by-product. There were openings for testing and sampling flow, pressure, temperature, humidity, SO_2 concentration, dust concentration and other national standard parameters located on the tower body and outlet and inlet of the flue gas channel. Insulation materials (thickness: 50 mm) covered the outside of the tower. In addition, electric heating devices were installed on the top of the tower and part of the ash bucket. A schematic diagram of the test equipment is shown in Fig. 1.

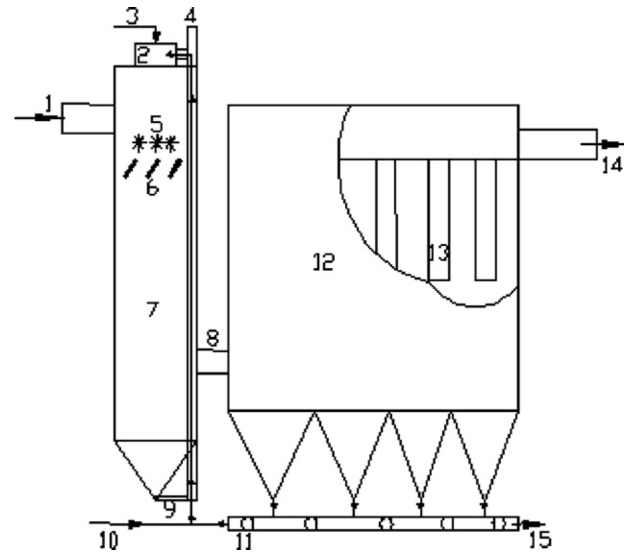

Fig. 1. Schematic diagram of the experimental setup: (1) Flue gas Inlet; (2) Humidification Unit; (3) Humidification Water; (4) Bucket Elevator; (5) Internal Mechanical Raking; (6) Internal Diversion Plate; (7) DPT Desulfurization Reactor; (8) Middle Flue gas Channel; (9) Tower Bottom Conveyor Scraper; (10) New Desulfurization reagent; (11) Circulating Ash Transport System; (12) Bag-type Dust Collector; (13) Bag; (14) Flue gas Outlet; (15) Discharge Ash.

2.2. Experimental flue gas and desulfurization reagent

The experimental device was built beside the flue gas channel of the #3 Sintering Machine Fan, which was located behind the electrostatic precipitator that is the pre-treatment unit for the sintering flue gas (in the Shijiazhuang Iron and Steel Co.). Test flue gas was produced by a high temperature sintering process. The SO_2 concentrate at the reactor entrance was the flue gas that came out of the electrostatic precipitator located right after the sintering plant; the SO_2 concentrate at the outlet of the reactor was the clean gas that came out of the bag-type dust collector. The desulfurization reagent was a white lime powder with mesh size ∼100 and contained active ingredients totaling 89%. Flue gas flow rate was 2000–5000 Nm^3/h, temperature at the system inlet was 100–140 °C, flue gas superficial detention time was 5–12 s, SO_2 concentration in the flue gas inlet was 800–2000 mg/Nm^3, Ca/S molar ratio was 1.0–1.8, water flow rate was 0–0.75 kg/min. The mass flow rate of the reagent (lime) was 1.0–9.0 ton/h, and the recycle mass flow rate of ash was 5.0–50 kg/h.

3. Mathematical model

We used FLUENT to simulate the gas–solid flow in the DPT. FLUENT is a software program used for the simulation and analysis of fluid flow, chemical reaction and heat transfer in a complex geometry zone, after setting the boundary conditions.