Chemical Engineering Science 162 (2017) 227–244

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Synergistic effect of droplet self-adjustment and rod bank internal on fluid distribution in a WFGD spray column

Penghui Wang, Liwei Zhuang, Gance Dai *

East China University of Science and Technology, China

HIGHLIGHTS

- The "droplet self-adjustment" effect is revealed.
- Characteristics of flow distribution in a WFGD spray column are proposed.
- An expression of the critical droplet diameter against gas velocity is defined.
- A synergistic effect of the "droplet self-adjustment" and rod bank internal is indicated.

ARTICLE INFO

Article history:
Received 28 August 2016
Received in revised form 7 November 2016
Accepted 20 December 2016
Available online 31 December 2016

Keywords:
Spray column
Uniformity
Rod bank internal
Droplet self-adjustment
Synergistic effect

ABSTRACT

With increases in the throughput requirement in a spray column, a column with a larger diameter and higher gas velocity will result in flow maldistribution, reducing the desulfurization rate and increasing the energy consumption of the column. In this paper, theoretical analysis and numerical simulation are utilized to characterize the flow maldistribution in a spray column with and without rod bank internal. Distribution mechanisms of "droplet self-adjustment" generated by droplets and resistance distributed effects generated by rod bank internal are presented in addition to their synergistic effects. Numerical research shows that trends of gas velocity uniformities and liquid loads perform synchronously in spray columns without rod bank internal; these will be improved with decreases in gas velocity and increases in droplet diameter. To acquire better column efficiency, an expression for critical droplet diameter is obtained in Eq. (28). In a spray column with rod bank internal, the optimized geometry for rod bank internal is acquired for better flow distribution and a lower resistance coefficient (ζ_p): $s/d_r = 2$, $H/D = 1/8$ and $h/d_r = 2\sqrt{3}$. Under different operating conditions, variation trends of uniformities in columns with and without a rod bank internal are similar. The synergistic effect of distribution mechanisms generated by droplets and rod bank internal is shown; the distribution effect generated by droplets mitigates the peak of gas velocity to make the "droplet self-adjustment" effect work well across the whole column.

1. Introduction

The reduction of SO_2, a main component of environmental contaminants, is a worldwide goal that has garnered increased attention in recent years. Among numerous SO_2 removal techniques, wet flue gas desulfurization (WFGD) is characterized as the most effective method especially in spray columns. Because of its reliability and high efficiency, WFGD in spray columns achieves 90% flue gas desulfurization (Neveux and Le Moullec, 2011). In spray columns, reactive absorption of SO_2 is the key step that is controlled by mass transfer between absorbent droplets and flue gas. Therefore, it is important to improve the flow behaviour, especially the effective contact of gas-droplets.

Because of the stirred slurry tank in the bottom of the tower, flue gas enters the column from the side typically in a radial direction, crossing the column and impinging it onto the wall at the opposite side of the inlet. As a result, the gas velocity is distributed unevenly over the cross section because of the turning and expanding gas flow. This may not be a major concern for small columns and low gas velocity. Because of the throughput requirement, the diameter of the column will increase to more than 20 m (Weiss and Wieltsch, 2005); achieving a uniform distribution becomes increasingly difficult, and the potential for gas maldistribution also increases as the gas velocity goes up to 5–6 m/s. Gas maldistribution easily leads to gas bypass and droplet leakage; this variation

* Corresponding author.
E-mail addresses: jaunt_wph@126.com (P. Wang), zlwdml3344@163.com (L. Zhuang), gcdai@ecust.edu.cn (G. Dai).

http://dx.doi.org/10.1016/j.ces.2016.12.062
0009-2509/

in the ratio of liquid to gas over a cross section can result in reduced driving forces for mass transfer and reduced absorption. Owing to the rigid criterion for removal rate, gas bypass in only a small quantity will seriously affect the SO_2 concentration from the top of the column. Although no comparison has been demonstrated in pertinent papers for removal efficiency between industry and pilot columns under approximate conditions, SO_2 measurement by Nygaard et al. (2004) in a column on an industrial scale (D = 17.5 m) shows conspicuous variation for SO_2 concentration along the radial direction (200–1000 ppmv), suggesting a varying mass transfer rate because of gas maldistribution. In addition, some empirical and semi-empirical models (Brogren and Karlsson, 1997; Gerbec et al., 1995; Stergaršek et al., 1996) for desulfurization efficiency in pertinent publications are based on the gas plug flow. This assumption will make such models lose their accuracy with flow maldistribution.

Studies about flow maldistribution have been conducted in many industrial processes that can be classified into two types. One concerns flow equalization through a bundle of parallel channels or tubes, such as a micro-reactor (Al-Rawashdeh et al., 2012) that should meet the requirement of high purity and yield and a tube-and-shell heat exchanger (Mueller and Chiou, 1988) that aims at uniform flow and temperature distribution to achieve high efficiency and a long lifespan. In general, since continuous flow in separated channels cannot adjust the distribution by itself, the preliminary flow distribution before entering separate channels should be critical. Therefore, these studies focus on the design of manifolds or distributors (Wang, 2011). The other concerns flow equalization over a large cross section, such as a packed column (Olujić et al., 1991) that optimizes the gas inlet and a distributor to lower the "penetration depth" to take full advantage of the whole structured packing. This type of flow maldistribution is induced by flow expansion from a small inlet to a large column. Flow maldistribution over a large cross section should be mitigated by means of introducing internals which provide additional resistance to fluid since all fluid seeks the path of least resistance. The mechanism of distribution optimization is called resistance distributed mechanism (Idelchik et al., 1991).

The problem of flow distribution in a spray column belongs to the latter type of flow maldistribution. Compared with flow distribution in a packed column, packings are inherent internal placed across the whole column to mitigate flow maldistribution. While in a spray column, even though the column is empty inside, when the slurry sprays from nozzles, falling droplets are acting on the gas to provide resistance for the flow distribution which are the special "internals". This phenomenon is only mentioned in a few papers (Wang et al., 2015; Weiss and Wieltsch, 2005), and no detailed explanation is proposed for the flow distribution mechanism of droplets to gas. Despite the distribution effect by droplets, flow maldistribution should still exist in columns with a large diameter and high gas velocity. Many patents have been filed to introduce various internals to assist the distribution adjustment. B&W Company (Dudek et al., 1999) placed a sieve tray in a spray column and modified the gas inlet from a square to divergent square tube and column from a cylinder to a cone shape; Lin (Bin and Jiangning, 2014) used a draft tube near the gas inlet; several air deflectors are specified at the column to lead the gas flow direction by Wang (Wang et al., 2014a). A Venturi Rod Layer was developed by Ducon Company that is made up of several horizontal rod banks equipped with different column heights. Generally, gas maldistribution is adjusted by resistance provided by internals in the plane (sieve tray and Venturi Rod Layer) and in space (draft tube and air deflectors). In a spray column with flue gas and limestone slurry because of the unwanted formation of gypsum on the internals, internals in space with a large surface amount should be prohibited. Although the internals above are used in practical applications, neither their distribution mechanisms nor relevant factors for optimization are discussed.

In the present study, a column internal named rod bank internal is introduced; it is composed of two layers of rod banks with a close staggering arrangement (Fig. 1) and is placed over the cross section above the gas inlet. In fact, rod banks are frequently used as heat exchangers (Liu et al., 2013; Shi and Wan, 1996; Wang et al., 2014b) but have not yet been used as an internal for flow distribution improvement in a reactor.

Computational fluid dynamics (CFD) is an ideal approach for column hardware design and flow distribution prediction. In a spray column without rod bank internal, the liquid phase has a low volume fraction (<10%) and is composed of droplets that can be simulated using the DPM (discrete parcel method). Some studies are conducted to explore a spray column by means of the CFD method. Marocco (Marocco and Inzoli, 2009), Montanes (Montanes et al., 2009) and Brown (Brown et al., 2014) developed their own CFD models for flow and concentration field prediction in a spray column. In these studies, a high spraying density of the slurry and a low gas velocity decrease the potential of gas maldistribution; herein, the focus is on the establishment of models and the analysis of the SO_2 removal rate without considering the problem of flow distribution. Until now, flow field optimization is only mentioned for the geometry design of the column (Xu et al., 2010), but studies about the mechanism of flow distribution in a spray column are not explored in detail by the CFD method; this is the focus of the present study.

When the rod bank internal is introduced, several liquid forms such as droplets and films may coexist, making DPM inappropriate (Ruan et al., 2009). In the research of a spray column with a sieve tray, Dudek et al. (1999) used the Euler-Euler model, a macroscopic method that treats two phases penetrating each other. Rather than considering the balance equations in such a local and instantaneous manner, this method partially eliminates detailed interfacial information and simplifies the complex interactions. Each phase in the model has a continuum and momentum equation; the volume fraction is used to present the content of each phase, and the interactions between phases are defined. Thus, this model is proper for the column region with or without rod bank internal.

In the present paper, first, the mechanisms of flow distribution are analysed theoretically in a spray column with and without rod bank internal; then, numerical simulation is conducted in a spray column without an internal to further explore the mechanism effect generated by droplets and obtain proper operating conditions for better column efficiency. Finally, numerical simulation in a column with rod bank internal discusses the distribution mechanism generated by rod bank internal as well as the synergistic effect of distribution effects generated by droplets and rod bank internal; additionally, the geometry of the rod bank internal is optimized, and a spray column with an optimized rod bank internal is simulated under different operating conditions to test its characterization.

2. Theoretical analysis of flow distribution mechanism

2.1. Flow distribution in spray column

As stated above, corresponding with packings in a packed column, spraying droplets in a spray column are the "internals" for flow distribution. When droplets fall down from the top of the column, the drag force from gas should act on droplets while the counterforce of drag forces should act on gas and become the only factor for flow distribution. Therefore, the key for flow distribution in a spray column is the interaction between the gas and falling droplets.