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An experiment investigation of particle collection efficiency in a fixed valve tray washing column

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ABSTRACT

The collection efficiency is one of the key parameters to evaluate the performance of washing columns, and the gas–liquid flow characteristic is an important factor affecting collection efficiency. In this work, the gas–liquid flow characteristic and its effect on collection efficiency in a fixed valve column have been investigated. The experimental results show that the fixed valve washing column is capable of generating higher gas holdup than a standard bubble column under similar situations. For different particle sizes, with increasing gas holdup, the changes of the trends in collection efficiency are different. For particles larger than 1 μm, the collection efficiency increases with gas holdup while for particles finer than 1 μm, the collection efficiency either decreases (0.5–1 μm) or decreases initially and then increases again (0.3–0.5 μm). The collection efficiency increases with liquid-to-gas ratio but decreases with bubble size, bubble velocity and particle loading. The contribution of each tray to the collection efficiency is different. A correlation is developed for predicting the collection efficiency of particles and the experimental values agree well with the predicted values.

1. Introduction

The opposed multi-burner (OMB) gasification technology consists of coal treatment, coal gasifier, gas preliminary cleanup and black water treatment processes [1]. The gas preliminary cleanup process, which runs at high temperature and pressure, plays an important role in the whole system. During this process, the particles are removed from syngas produced in the gasifier before syngas reaches downstream [2]. Unlike the syngas preliminary cleanup in GE gasification technology [3], in the OMB gasification preliminary cleanup process, a combination of mixer, cyclone separator and washing column is adopted [4].

In general, the conventional scrubbers usually recur to some form of inertial collection of particles as the primary mechanism of capture [5]. Unfortunately inertial forces become weak as particle size decreases, and collection efficiency decreases rapidly as particle size decreases. As a result, it is necessary to greatly increase the energy input to significantly improve the efficiency of collection of fine particles [6].

Bubble column is very suitable for removing tiny particles from the gas. However, the efficiency in a normal bubble column is very limited, due to the limitation of specific interfacial area α. In addition, a large amount of energy is to be spent on generating small bubbles. Thus the collection efficiency of single-stage bubble column cannot be very high. In order to achieve high collection efficiency, the bubble columns must be operated in series or in multiple stages [7]. However, there were very limited studies on scrubbing of particles by multiple stages bubble columns. Many of the processes reported have been covered by patent protections [8,9]. The plate washing column is widely used in air pollution control and gas–solid separation for aerosol sampling and industrial applications. The large interfacial area and low pressure drop of such a system, combined with the fact that when foam is broken, the particles are concentrated into a small volume, make the process promising [10].

A literature survey revealed that most of the studies were reported on the washing of particle, some of which are highlighted here. Ranz and Wong [11] undertook fundamental studies on the mechanisms of collection of dust particles in several elementary collectors, such as rectangular and round aerosol jets impinging on flat plates, and cylindrical and spherical collectors placed in aerosol streams. They proposed a correlation for determining the efficiency of impaction, even under the most complicated situations. Fuchs [12] attempts a theoretical explanation for the experimental observations of pool scrubbing of particles. He derived the particle removal efficiencies due to inertial impaction, Brownian diffusion and Gravitational sedimentation by assuming that particles are homogeneously distributed in each bubble. Lee and Gieseke [13] obtained the particle collection efficiencies due to Brownian diffusion and Interception on the basis of Kuwabara's cell model. Later Jung and Lee [14] extended the flow field of Kuwabara's cell model to treat the flow field around gas bubbles and liquid droplets by taking into account the effects of the internal circulation inside the bubbles or droplets on the outside flow field and on the particle

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collection efficiency. In recent years, Meikap and Biswas [7] investigated the collection efficiency of a modified multi-stage bubble column (MMSBC) scrubber. Experimental results show that almost 100% removal efficiency of fly-ash can be achieved in this system. Park and Lee [15,16] developed a novel aerosol filtering device, the swirl cyclone scrubber that mainly consists of a cyclone and a swirl scrubber. They derived the model of particle collection efficiency due to Brownian diffusion, inertial impaction and gravitational sedimentation on the basis of Fuchs theory. However, there are no theoretical models that are especially applicable to the tray columns.

In the present investigation a fixed valve tray washing column operating in three stages had been designed, and the effects of the gas–liquid flow characteristics such as gas hold-up, bubble size, bubble velocity, gas to liquid ratio and some physical parameters such as the number of trays, and inlet particle loading on collection efficiency have been investigated. An empirical correlation is developed for predicting the performance of the fixed valve tray washing column incorporating the pertinent variables of the systems studied.

2. Mechanism of particle collection

When particle-laden gas passes through a water layer, a number of small bubbles are formed. In this process, particles entrained in bubbles rising through the water are collected on the bubble surface due to various transport mechanisms including Brownian diffusion, gravitational sedimentation and inertial impaction. Fig. 1 illustrates the principle of particle collection in a rising bubble.

The most dominating mechanism for particle collection in a washing column is mainly dependent on particle diameter. Among these mechanisms, inertial impaction and gravitational sedimentation play an important role for capture particles larger than 5 μm, while diffusion is essential for capture particles finer than 1 μm [10]. Fuchs [12] derived the following collection efficiency of a bubble due to diffusion mechanism:

$$\eta_d = 1.8\sqrt{\frac{k_B TC}{3\pi\mu d_p v_b R_b^3}} \tag{1}$$

where k_B is the Boltzmann constant, T the absolute temperature, μ the viscosity of the air, d_p the particle diameter, and C the Cunningham slip correction factor.

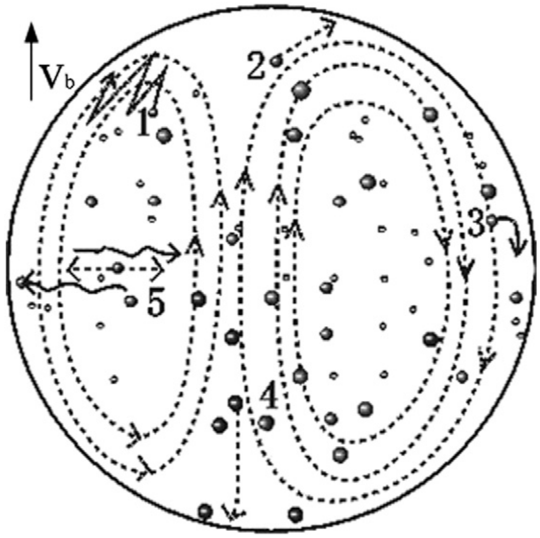

Fig. 1. Particle removal mechanisms of fixed valve tray washing column.

For single bubble, Fuchs [12] also derived the impaction and sedimentation collection efficiency of particles. The impaction collection efficiency of particles, η_{imp} in the tray column is as follows:

$$\eta_{\text{imp}} = \frac{\rho_p d_p^2 v_b C}{4\mu R_b^2} \tag{2}$$

and the sedimentation collection efficiency of particles, η_{sed} is

$$\eta_{\text{sed}} = \frac{g\rho_p d_p^2 C}{24\mu R_b v_b} \tag{3}$$

where R_b is the bubble of radius, ρ_p the particle density and v_b the rising bubble velocities.

Even if the trajectory of a particle does not depart from the streamline, a particle may still be collected when the particle passes within one particle radius from the bubble surface. This phenomenon is known as interception mechanism of particle removal [14]:

$$\eta_{\text{int}} = \left(\frac{1-\varepsilon_g}{J}\cdot\frac{1}{d_b}\right)d_p + \left(\frac{1-\varepsilon_g}{J}\cdot\frac{2}{d_b^2}\right)d_p^2 \tag{4}$$

where

$$J = 1-\frac{6}{5}\varepsilon_g^{1/3} + \frac{1}{5}\varepsilon_g^2.$$

If significant evaporation or condensation takes place, Stefan flow can impose an additional aerodynamic impact on the motion of particles. In this study, this effect is neglected.

According to Fuchs theory [12], by assuming that the various deposition mechanisms are uncoupled and additive [16,17], the particle concentration decay in a spherical bubble can be expressed as:

$$\frac{dc}{dz} = -\kappa c = -c\left(1.8\sqrt{\frac{k_B TC}{3\pi\mu d_p v_b R_b^3}} + \frac{\rho_p d_p^2 v_b C}{4\mu R_b^2} + \frac{g\rho_p d_p^2 C}{24\mu R_b v_b} + \left(\frac{1-\varepsilon_g}{J}\cdot\frac{1}{d_b}\right)d_p + \left(\frac{1-\varepsilon_g}{J}\cdot\frac{2}{d_b^2}\right)d_p^2\right) \tag{5}$$

where κ is the combined influence of Brownian diffusion, inertial impaction, gravitational sedimentation and interception.

The four terms appearing in the right-hand side of Eq. (5) represent Brownian diffusion, inertial impaction, gravitational sedimentation and interception, respectively. The Cunningham slip correction factor C is given as [18]:

$$C = 1 + 2.284\frac{\lambda}{d_p} + 1.116\frac{\lambda}{d_p}\exp\left(-0.4995\frac{\lambda}{d_p}\right) \tag{6}$$

where λ is the mean free path length of air molecules. For large enough Reynolds numbers, i.e., for $Re \geq 3.1\ (\rho L\sigma_s^3/g\mu_L^4)^{0.25}$, which holds true for the operational conditions considered in the present study, the rising velocity of a bubble is given as [19]:

$$v_b = u_g/\varepsilon_g - u_l/\varepsilon_l \tag{7}$$

where ε_l is liquid holdup.

Finally, integrating Eq. (5), the particle collection efficiency of the fixed valve tray washing column is

$$\eta_{total} = 1 - \exp(-\kappa H_F) \tag{8}$$

where H_F is the froth height.