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Hydrodynamic characteristics of a three-stage dual-flow sieve plate scrubber

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ABSTRACT

Experimental study has been carried out in a dual-flow sieve plate scrubber to study the flow characteristics such as dry plate and total tray pressure drop, average clear liquid height and fraction of holes passing gas. The flow characteristics were observed for air–water system at different gas liquid rates with 8.297×10^{-4} to 27.6×10^{-4} Nm^3/s gas flow rates (Q_G) and liquid flow rates (Q_L) of 20.649×10^{-6} to 48.183×10^{-6} m^3/s. The dry plate pressure drop values are measured experimentally and compared with the predicted values from the existing correlation in the literature. The experimental results of tray total pressure drop and average clear liquid height on tray are plotted against gas load factor (F_s) based on which the flow regimes on present dual-flow sieve plate are discussed. The fraction of holes passing gas values are calculated using correlations available in the literature using average plate pressure drop. The average clear liquid height values from experimental study are matched well with the predicted values of average clear liquid heights from the modified form of clear liquid height correlation.

1. Introduction

Wet scrubbers are important air pollution control devices for cleaning large volumes of industrial effluent gas streams and they remove particulates and dangerous gases simultaneously by capturing into the droplets or pool of liquid and dissolving or absorbing into the liquid respectively (Semrau, 1977; Frank and Nancy, 2005). Different types of dusts like explosive, flammable, cement and foundry dusts can be collected and various gaseous pollutants like acid mists, furnace fumes can be absorbed with the wet scrubbers. Plate column scrubbers, spray column scrubbers and bubble column scrubbers are most important devices and many other types of scrubbers developed to appropriate particular pollutant removal with greater collection efficiencies (Raj Mohan et al., 2008; Meikap et al., 1999, 2002; Bandyopadhyay and Biswas, 2006; Bangwoo et al., 2007). Plate scrubbers are being used in many chemical industries for individual and simultaneous removal of acid gases and dust particles from industrial flue gases. Plate without down comer is called as dual-flow plate.

Dual-flow sieve trays which consist of punched holes are most commonly used for their simple design, economical viability, less susceptible to fouling, easy installation and maintenance (Kister, 1992; Wankat, 1988; Trambouze, 1999). Liquid and gas flow alternatively through the sieves of dual-flow plate in opposite direction which also provides self-cleaning of plate (Garcia and Fair, 2002). The dual-flow tray develops a two phase dynamic mixture from the alternative flow of two phases through the sieves (Zhang et al., 2015). The

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absence of down-comers and more area for bubbling enhances the capacity of the plate by 20% higher than normal sieve plates with down-comers due to this the dual-flow trays have high capacities and low pressure drops (Furzer, 2000; Domingues et al., 2010). The positive weeping of liquid from tray above is key difference between dual-flow tray and normal tray which creates high gas–liquid contact space. The satisfactory efficiencies can be achieved using dual-flow trays within the design values of flow rates but the efficiencies are small due to little contact time between gas and liquid (Trambouze, 1999). The absence of down comer in dual-flow trays increases the effective area and they can achieve more than 90% efficiencies (Walas, 1990).

The operating ranges of dual-flow sieve plates are classified by Miyahara et al. (1990) as froth and transition based on gas velocities. The froth is at relatively low gas flow rates and transition is at high gas flow rates. They have also mentioned that the complete spray regime cannot be occurred in dual-flow due to simultaneous passage of gas and liquid develops bubbling and suppressed jetting at the hole. The transient jetting between bubbling and jetting at a single hole and between froth and spray at multiple holes from quantifying the phenomena of the transition from froth to spray on a sieve plate have been earlier noticed and reported in the literature (Miyahara et al., 1983; Miyahara and Takahashi, 1984). Recently, Zhang et al. (2015) have observed four main flow regimes of wetting, bubbling, froth and fluctuating on dual-flow valve trays based on F_s where F_s is gas load factor based on superficial area ($V_G \rho_G^{0.5}$, (m/s) $(kg/m^3)^{0.5}$) and V_G is superficial gas velocity and ρ_G is gas density. They have also suggested that the bubbling and froth regimes are feasible operating regimes for industrial application. This paper reports the experimental investigations of clear liquid height, tray pressure drop, and fraction of holes passing gas. It also reports the comparison of the present results of clear liquid heights of dual-flow sieve plate with the values predicted from the equation that has arrived after modifying the correlation reported in the literature.

2. Experimental setup and technique

The experimental apparatus of three stage dual-flow sieve plate column is schematically represented in Fig. 1. Perspex glass is used to make the column of 2.6 m height with 0.152 m (6 inches) inner diameter and the column has a frusto-conical (slant angle 64.8°) gas outlet at the top section. The three plates (T_{1-3}), gas distributor (G_d) and liquid distributor (L_d) were made of stainless steel with 3×10^{-3} m thickness and holes with 3×10^{-3} m size. The photograph of the dual-flow sieve plate is shown in Fig. 1 (S_P). The plates were placed at 0.61 m (24 inches) spacing. The space between plates is a stage. The air supply to the column is facilitated by an air compressor (AB). The compressed air was stored in tank and the outlet of the tank is connected to an air rotameter (R_1). The air rotameter outlet is fitted to the column gas inlet at the bottom section of the scrubber and it passes through a gas distributor for uniform gas flow and the gas flows in upward direction through the sieves of the plates and comes out from gas outlet at the top of the scrubber. The liquid pumped to the column from liquid inlet at the top using 0.5 horsepower centrifugal pump (P) from a water tank (T). A rotameter (R_2) was used for controlling the liquid flow rate and liquid distributor facilitates the uniform liquid flow. The liquid flows downward through the plates and finally drains out at the bottom of the column and can be collected in the water collector (S). Five pressure ports (P_1–P_5) were made to the column to measure the pressure drop across each tray and entire column. The pressure ports were connected to U-tube manometers (M_{1-4}) in which carbon tetrachloride (CCl_4) was used as manometric liquid. Four quick acting solenoid valves (V_{S1-S4}) are fitted to the column at inlets and outlets of gas and liquid to measure the liquid hold up.

In the actual experiments, the gas flow rates were operated in the range of 8.297×10^{-4} m^3/s to 27.65×10^{-4} m^3/s and the liquid flow rates were in the range 20.649×10^{-6} m^3/s to 48.183×10^{-6} m^3/s. As the experiment proceeds, the liquid started forming a layer which is clear liquid (S_{cL}) and its height is clear liquid height and gas passed through this layer in bubbling manner at lower gas flow rates. The gas flow through the clear liquid on the plate developed the froth (S_F) and it can be seen in Fig. 1. Wetting, bubbling and froth regimes are observed in this study.

3. Results and discussion

3.1. *Pressure drop*

The pressure drop of tray is a key parameter which affects the distribution of gas particularly at lower pressure (Wijin, 1998). Distribution of gas on plate influences the performance and gas–liquid mass transfer efficiency at operating conditions. The energy dissipated due to the fluid flow through the tray can be represented by pressure drop which includes pressure drops of wet and dry plate (Angelov and Gourdon, 2012; Luyben, 2012). The pressure drop of dry plate is loss in the pressure because of the flow of gas through the tray holes when the liquid flow or liquid on the tray is absent and it contributes notable portion of total plate pressure drop (Fasesan, 1987). Besides reflecting the tray operating conditions, the dry-plate pressure drop reflects the performance and can be used for calculation of hydraulic parameters (Bennett et al., 1983; Qian et al., 2006). The tray pressure drops are calculated using the measured difference of heights of CCl_4 in the two limbs of manometer with Eq. (1).

$$\Delta P = (\rho_{CCl_4} - \rho_G) g \Delta h \quad (1)$$

where ΔP is the pressure drop (Pa), ρ_{CCl_4} is CCl_4 density (kg/m^3), ρ_G is air density (kg/m^3), g is gravitational acceleration (m/s^2) and Δh is manometer head (m).

The dry plate pressure drop of three dual-flow sieve trays can be seen in Fig. 2 and from the figure it can be understood that the increase in superficial velocity of gas increases the pressure drop of the dry-plate. Furthermore, the dry plate pressure can be calculated using the derived expression Eq. (2) for flow through orifices (Sinnott, 2005).

$$P_d = 51 \left(\frac{V_h}{C_o}\right)^2 \left(\frac{\rho_G}{\rho_L}\right) \quad m \quad (2)$$

where the orifice coefficient C_o is a function of the plate thickness, hole diameter, and the hole to perforated area ratio, V_h is the gas velocity through the holes (m/s) and ρ_L is liquid density (kg/m^3). The experimental results of dry plate pressure drop are compared with the predicted values and the top plate dry plate pressure drop is nearly matching with the predicted dry plate pressure drop. The dry plate pressure drop is different for the plates due to the unequal gas distribution on the plates though they are geometrically similar.