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The influence of gas physical properties on entrainment inside a sieve tray column

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ABSTRACT

Existing entrainment prediction correlations, often used in the design of sieve tray distillation columns, have been developed mostly with air/water data. Therefore, the aim of this work was to investigate the influence of gas physical properties on entrainment, by also utilising gases with physical properties notably different from air. Air, CO_2 and SF_6 were passed through a rectangular sieve tray column (tray hole diameter of 6.3 mm and fractional hole area of 0.156). These three gases were chosen in order to cover a large gas density range of 1.2–5.8 kg/m^3. Water, ethylene glycol and *n*-butanol were used as liquids in order to achieve the desired wide range of liquid physical properties. Tray spacing and weir height were set at 615 mm and 51 mm, while the liquid rate was varied from 2.9 to 80 m^3/(h m) to cover both the spray and froth regimes. Gas flow factors ranged between 1.9 and 4.8 m/s (kg/m^3)$^{0.5}$. A database of over 500 experimental data points was generated in this study. The main objective was to use the experimental data to describe the effect of gas physical properties and gas-and-liquid flow rates on entrainment. The data were also used to evaluate the scope and limitations of current entrainment prediction models. Existing correlations fitted the air/water data well, but showed rather large deviation from the non-air/water data. A new approach to describe the influence of gas physical properties on entrainment is proposed. This approach utilises a variation of the Reynolds and Froude numbers along with the ratio of the gas to liquid density to correlate entrainment.

1. Introduction

Distillation, stripping and absorption are commonly used as separation methods in the chemical industry. In these separation processes a gas or vapor is brought in contact with liquid in a column by means of contacting devices such as packing or trays. Separation column design is based on the required number of theoretical stages to achieve a targeted degree of separation. The number of theoretical stages is calculated from knowledge of the phase equilibrium of the system. Mass transfer is further limited by the hydrodynamics of the column. The size and number of trays or packing height, the geometry of the tray or packing, the column operating conditions, the gas and liquid properties and flow rates all have an influence on the column hydrodynamics and, therefore, the mass transfer efficiency achieved. Knowledge of the influence of these parameters on column hydrodynamics will aid in improving the accuracy of current mass transfer and hydrodynamic models used in separation column design.

Separation efficiency is reduced when a fraction of the liquid on the tray is transported with the rising gas to the tray above. The reduction in efficiency caused by the entrainment of this liquid fraction (L'/L) is described by the Colburn equation (Colburn, 1936) and by the work of Mohan et al. (1983). Column operation becomes unstable when the mass fraction of liquid droplets suspended in the rising gas (L'/G) becomes

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Nomenclature

A_c	column area = 635 × 175 mm [m^2]
A_d	downcomer inlet area [m^2]
A_f	fractional hole area = A_h/A_p
A_h	hole area [m^2]
A_n	net column area = $A_c - A_d$ [m^2]
A_p	perforated area or bubbling area [m^2]
d_H, D_H	hole diameter [mm, m]
FPL	tray flow path length [mm]
Fr^*	modified Froude number
Fr^+	expanded modified Froude number
F_s	superficial vapor factor = $U_s\,\rho_g^{0.5}$ [m/s (kg/m^3)$^{0.5}$]
g	gravitational constant = 9.81 [m/s^2]
G	gas mass flow rate [kg/s]
h_L, H_L	clear liquid height [mm, m]
h_w, H_w	outlet weir height [mm, m]
h_F, H_F	froth height [mm, m]
$h_{L,ct}$	clear liquid height at the regime transition [mm]
L	mass flow of liquid entering the tray [kg/s]
L	length term in Eq. (17) [m]
L′	entrained liquid mass flow [kg/s]
L_w	weir length [mm]
P	hole pitch [mm]
Q_L	liquid flow rate per weir length [m^3/(h m)]
Re^*	modified Reynolds number
Re^+	expanded modified Reynolds number
s, S	tray spacing [mm, m]
U_s	Superficial velocity of the gas, calculated as the volumetric gas flow divided by the perforated area of the tray [m/s]

Greek letters

ρ_g	gas density [kg/m^3]
ρ_L	liquid density [kg/m^3]
σ	surface tension [mN/m]
μ_g	gas viscosity [mPa s]
μ_L	liquid viscosity [mPa s]
ζ	correction term for Eq. (2)

too large, causing flooding to occur (Kister, 1992). There are, therefore, two definitions of entrainment that has to be considered during column design and operation: The fraction of liquid entering the tray that is entrained (L′/L), as well as the ratio of entrained liquid per rising gas flow (L′/G). L′ represents the mass flow rate of entrained liquid that has been completely removed from the system.

Uys et al. (2012) argued convincingly that there is scope for improving entrainment correlations for sieve tray columns. A considerable amount of research has previously been done with the air/water system to determine the influence of tray and column geometry and gas and liquid flow rates on entrainment. However, far less research has been done with non-air/water systems. The current database in the open literature does not contain a sufficiently comprehensive and standardised set of data to accurately model the influence of gas and liquid physical properties on entrainment. This is largely due to the fact that the database consists of limited data from various institutions with different tray and column geometries. Thus, models and correlations derived from this data could be inaccurate for other systems (Schultes, 2010). By testing over a larger range of physical properties, the influence of each property on entrainment can be identified.

Some entrainment research has indeed been done on non-air/water systems (Hunt et al., 1955; Yanagi and Sakata, 1979). These systems and their physical properties are tabulated in Table 1. The tests were performed using fixed tray- and column geometries. The entrainment correlation of Hunt et al. (1955) along with two others (Kister and Haas, 1988; Bennett et al., 1995), are shown in Table 2. Hunt et al. (1955) used a static liquid height in their experiments and, thus, the effect of liquid cross flow was not considered. Fixed hold-up conditions are seldom found in industrial applications as liquid hold-up will change with changing liquid flow rates, gas density, liquid density and gas velocity (Colwell, 1981).

The paper by Hunt et al. (1955) indicates that entrainment is independent of gas density. Their correlation includes a term for clear liquid height (h_L), which was essentially the liquid hold-up for their experiments. Liquid hold-up has since been found to be dependent on gas density (Kister et al., 1981; Colwell, 1981; Bennett et al., 1995). By including h_L in their correlation, Hunt et al. (1955) unintentionally allowed for the effect of gas density to some degree. Experimental or estimated liquid hold-up data have to be used to determine entrainment with their correlation.

Kister and Haas (1988) used the data from Hunt et al. (1955) to develop their entrainment correlations (Eqs. (2)–(5) in Table 2). Bennett et al. (1995) used the data from Yanagi and Sakata (1979) to develop their own entrainment correlations (Eqs. (6)–(13) in Table 2). The recommended range of application for the correlations in Table 2 is shown in Table 3.

The systems evaluated by Yanagi and Sakata (1979) covered a large gas density range, but at the same time the liquid properties changed (as shown in Table 1). It is advantageous to use one liquid with three or more gases, covering a range of different densities without changing column and tray geometry. In doing this, the effect of gas physical properties on entrainment is isolated from the effect of changing liquid physical properties and/or column geometry.

Considering the above, the objectives of this study were:

- Generate new entrainment data over a range of gas physical properties at gas rates higher than the range covered by the correlation of Bennett et al. (1995).
- Compare the experimental data with the entrainment prediction correlations of Kister and Haas (1988) and Bennett et al. (1995) to determine their reliability and limitations.
- Investigate the influence of gas physical properties on both definitions of entrainment (L′/L and L′/G) in order to find a correlation between entrainment, gas physical properties and gas-and-liquid flow rates.

2. Materials and methods

A detailed description of the experimental set-up used in this study is given elsewhere (Uys et al., 2012). The tray and column geometry used, is summarised in Table 4. Two sieve test trays were installed in the column. Tray spacing and weir height were set at 615 mm and 51 mm respectively, while the liquid rate was varied from 2.9 to 80 m^3/(h m) to cover both the spray and froth regimes.

Two liquids (water and ethylene glycol) were individually contacted with three gases (air, CO_2, SF_6). A third liquid,