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

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ABSTRACT

Entrainment data were measured with Isopar G, *n*-butanol, silicone oil, water and ethylene glycol in a rectangular sieve tray column to cover relatively large ranges of liquid density (739–1095 kg/m^3), surface tension (19.9–60 mN/m) and dynamic viscosity (0.9–48.8 mPa s). CO_2 was used as the gas phase. Liquid flow rates ranged between 2.8 and 80 $m^3/(h\,m)$, with gas flow factors (F_s) between 1.9 and 3.9 m/s $(kg/m^3)^{0.5}$. The results showed a complex interaction of liquid physical properties influencing entrainment. An increased surface tension and higher liquid density resulted in fewer, but larger diameter, heavier droplets that decreased entrainment. Liquid viscosity and its combination with surface tension were shown to have a non-monotonic effect on entrainment. Liquids with relatively low viscosity and low surface tension formed higher dispersion layers with many small projected droplets, thus increasing entrainment. However, an increase in liquid viscosity beyond a critical point caused a decrease in entrainment. In general, notable deviations were observed between existing, published entrainment prediction correlations and the data generated in this study. This is most probably due to the fact that such correlations had been developed with limited liquid property variations, not covering the full spectrum of this study.

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1. Introduction

The design of a separation column relies on accurate mass transfer, hydrodynamic and thermodynamic data and models. These models use the contacting device geometry, operating conditions, fluid properties and fluid flow rates to predict the operating conditions and separation efficiency in a column.

Entrainment in a tray distillation column is a hydrodynamic effect that occurs when a fraction of the liquid phase is transported by the gas phase to the tray above, i.e. it is characterised by droplets ejecting from the froth to the tray above (Bennett et al., 1995). It affects both separation efficiency and column capacity. Two definitions of entrainment can be considered during column design. The first defines entrainment as the mass flow rate of entrained liquid droplets as a fraction of the mass flow rate of the gas phase (L'/G). L' is defined as the mass flow rate of liquid droplets removed from the system due to entrainment. When L'/G becomes too large, enough liquid is transported to the trays above to cause column flooding, which drastically reduces separation efficiency (Kister, 1992). The other definition considers the same mass flow rate of entrained liquid as a fraction of the mass flow rate of liquid into the column (L'/L). Similarly, when L'/L is large, separation efficiency is reduced (Colburn, 1936; Zuiderweg, 1982; Lockett, 1986; Bennett et al., 1997).

In industrial applications, vapour–liquid systems covering a wide range of liquid properties are often encountered (Schultes, 2010). A systematic approach to collecting and processing entrainment data for systems of varying liquid physical properties is required in order to derive accurate correlations from the data for use in distillation column design. Such improved correlations are required, since popular entrainment correlations (Kister and Haas, 1988; Bennett et al., 1995) investigated by Uys et al. (2012) are, although very useful for air/water systems, less accurate for liquids other than water.

The entrainment correlations by Hunt et al. (1955) and Kister and Haas (1988) include the effect of liquid surface tension on entrainment. The correlations predict a decrease in entrainment for an increase in liquid surface tension. High surface tension liquids form larger droplets than low surface tension liquids. The greater mass of the larger droplets cause the droplets to fall back down to the liquid phase, instead of being

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Nomenclature

A_c	Column area $= 635 \times 175$ 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]
C_F	Capacity flow factor $= U_s \cdot (\rho_g/(\rho_L - \rho_g))^{0.5}$ [m/s]
d_H, D_H	Hole diameter [mm, m]
FPL	Tray flow path length [mm]
F_s	Superficial vapour factor $= U_s \cdot \rho_g^{0.5}$ [m/s (kg/m^3)$^{0.5}$]
g	Gravitational constant $= 9.81$ [m/s^2]
G	Gas mass flow rate [kg/s]
h_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]
h_w	Weir height [mm]
L	Mass flow of liquid entering the tray [kg/s]
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)]
S	Tray spacing [mm, m]
U_s	Superficial gas velocity, based on tray perforated/bubbling area [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. (1)

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carried up to the tray above. The mass of a droplet is proportional to the volume of the droplet, which means that the mass is proportional to the droplet diameter cubed (third order proportionality). The mass of a droplet has a first order proportionality to the liquid density. Therefore, the decrease in entrainment noticed for an increase in liquid surface tension is mainly caused by the increase in the diameter of the liquid droplets.

Droplet development, break-up and size influences entrainment (Bennett et al., 1995). Decent et al. (2009) investigated droplet formation from a viscous liquid jet emerging from a rapidly rotating orifice. The size of the droplets (which formed as the liquid jet disintegrates) was monitored, as well as the length that a liquid slug reached before breaking up to form droplets. They showed that liquid viscosity has a non-monotonic influence on droplet size and the break-up length of a liquid slug into a droplet.

Fakhari and Rahimian (2011) investigated the deformation and fragmentation of droplets in free fall. They found that gas viscosity played no significant role in droplet break-up, but that liquid viscosity was the principal factor in the mechanism of droplet disintegration. Pan and Hung (2010) studied the behaviour of a droplet upon impact with a wet surface. Their study showed that an increase in liquid viscosity inhibited disintegration into secondary droplets. A droplet's size and its tendency to deform and break up into smaller units under the influence of shear forces have a definite effect on entrainment. Considering the findings of these investigators, the influence of liquid viscosity on entrainment and tray hydrodynamics should be investigated in more detail.

With the wide variety of column geometries reported in literature, for different gas/liquid systems, it is rather difficult to determine the influence of liquid physical properties without considering the influence of tray and column geometries. Therefore, the tray and column geometries were kept constant in this study. The main objectives of the study were as follows:

- Contribute new entrainment data that covers relatively large ranges of liquid density (739–1095 kg/m^3), surface tension (19.9–60 mN/m) and dynamic viscosity (0.9–48.8 mPa s) to the open literature.
- Evaluate the influence of liquid physical properties such as density, surface tension and dynamic viscosity on the dispersion characteristics and the resulting entrainment from a phenomenological basis.
- Compare the experimental data with the air/water entrainment prediction correlations from Kister and Haas (1988) and Bennett et al. (1995). This will allow an evaluation of the applicability and limitations of these correlation predictions when compared with non-air/water data.

2.   Materials and method

2.1.   Selecting the liquids

Liquids were selected to represent a large range of densities, surface tensions and viscosities. Flash point and vapour pressure were also considered in order to keep mass transfer effects negligible. Liquids with high flash points and low vapour pressures were preferred. Following these criteria, Isopar G, *n*-butanol, silicone oil, water and ethylene glycol were selected and individually contacted with CO_2 to generate an experimental database consisting of 256 entries. These liquids and their physical properties are tabulated in Table 1.

To minimise the risk of potential fires or explosions, CO_2 was used as the gas phase. The surface tension, density and dynamic viscosity of liquids were determined at 25 °C for each experimental run. The liquid density was measured with hydrometers (0.5 kg/m^3 resolution) while the liquid surface tension was measured using a Sigma 702 surface tensiometer (0.01 mN/m resolution). Liquid surface tension was measured with the liquid in contact with air. Liquid viscosity was measured with an Anton Paar Physica MCR501 2007 Rotaviscometer (0.01 mPa s resolution).

Kister et al. (1981) did not include liquid viscosity in their correlation, based on results from single-hole studies that showed little effect of liquid viscosity on entrainment. However, they only investigated liquid systems over a relatively small liquid viscosity range of 0.89–2.42 mPa s. The liquid viscosity range for the work reported here was specifically broadened to between 0.9 and 50 mPa s. Some work involving high liquid viscosity applications has been done by Mahiout and Vogelpohl (1985), Böcker and Ronge (2005) and Li et al. (2008). Unfortunately, none of these studies have drawn firm conclusions regarding the effect of liquid viscosity on tray column hydrodynamics. Mahiout and Vogelpohl (1985) used glycerol solutions to investigate the influence of liquid viscosity on mass transfer. They found that, for liquid viscosities smaller than 60 mPa s, an increase in liquid viscosity will lead to a large reduction in the mass transfer coefficient. However, they made no mention of its effect on column hydrodynamics, such as entrainment.