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Effect of path length on valve tray columns: Experimental study

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HIGHLIGHTS

- Hydrodynamic and interfacial area measurements on two different size columns.
- Phenomenological correlations proposed for key design parameters.
- A non-negligible effect of the flow path length on mean emulsion profiles.

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ABSTRACT

Experimental measurements of hydrodynamic and interfacial area parameters are carried out over two rectangular pilot scale valve tray columns. The effect of tray path length on extrapolation between the two columns is studied and phenomenological correlations for hydrodynamic and interfacial area are proposed. Correlations are compared both to literature and to industrial results showing good agreement and a significant improvement for the prediction of industrial conditions. Discrepancies preventing an accurate description of industrial trends are highlighted through comparison between typical emulsion height profiles on both columns.

1. Introduction

Natural gas commercialisation is subject to constraining environmental and operational specifications. Such specifications require treatment of gas streams in order to remove components such as water, heavy hydrocarbons, acid gases (CO_2, H_2S, organic sulphur compounds, COS, CS_2, HCN), nitrogen oxides (NOx), sulphur dioxide (SO_2), nitrogen compounds, volatile organic compounds (VOCs), volatile chlorine compounds (HCl, Cl_2, …) or volatile fluorine compounds (HF, SiF_4, …) (Kohl and Nielsen, 1997). Depending on their initial composition and required product specifications, gas streams are processed through several units (dehydration, desulphurisation, acid gas removal, …). For the acid gas removal unit, different kinds of technologies are employed: physical or chemical absorption, permeation, redox or cryogenics. The technology choice is mainly based on the concentration of acid compounds, selectivity to a specific compound and specifications of final products. The most common technology is gas–liquid absorption using amines solutions.

Valve trays are widely used as contactors for absorption columns because of their relatively low cost and their better performance for specific situations. Within the gas sweetening process context, absorption columns design depends greatly on the accurate determination of hydrodynamics and mass transfer parameters related to gas–liquid contactors as these have important effects on column effectiveness and operability. Actually this design relies on empirical correlations established on pilot scale units. However considerable discrepancies exit between sets of correlations encountered in the literature which makes optimisation of column design difficult to achieve. Experimental works have been carried out on hydrodynamics and mass transfer mainly on sieve trays, and little on valve trays (**sieve trays**: Zuiderweg and Harmens, 1958; Mc Allister et al., 1958; Barker and Self, 1962; Kister and Haas, 1988; Colwell, 1981; Zuiderweg, 1982; Bennett et al., 1983; Fasesan, 1987; **valve trays**: Scheffe, 1984; Pohorecki and Moniuk, 1988; Peytavy et al., 1990; Liang et al., 2008). Yet malfunctions on industrial columns still occur (Kister, 2003; Kister and Olsson, 2011), even for sieve trays which have been most studied. Divergences between literature correlations

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could be attributed to the great number of influent parameters (geometric, operational and physicochemical), the impacts of which have not all been studied thoroughly.

For a given system and an established operating condition, the overall hydrodynamic parameters on trays that are related to absorption effectiveness are mainly clear liquid height h_{Lc}, emulsion height h_{Fe} and mean liquid fraction α_L. These parameters are related to each other through the following expression:

$$h_L = \alpha_L h_{Fe} \tag{1}$$

Correlations reported in the literature for these three parameters can be sorted into two groups based on the phenomenological description adopted for the gas–liquid emulsion flow.

The most commonly used description is the one established on the hypothesis of a homogeneous mixture. This postulate justifies the use of Francis's equation describing the height over an exit weir of a stationary fluid flow. When considering the gas–liquid emulsion rate in the Francis equation, correlations for the clear liquid height over the tray are proposed in experimental studies with the following form (Stichlmair, 1978; Hofhuis, 1980; Colwell, 1981; Bennett et al., 1983; El Azrak, 1988; Liang et al., 2008):

$$h_{Lc} = \alpha_L h_{Fe} = \alpha_L h_w + C\left(\frac{\alpha_L L^2}{g}\right)^{1/3} \tag{2}$$

L is the liquid loading defined as

$$L = \frac{Q_L}{L_w} \tag{3}$$

where Q_L is the liquid rate, L_w and h_W are the width and the height of exit weir respectively, g *is the* gravitational acceleration and C is a constant taking into account the friction on the tray.

The second phenomenological description used for the gas–liquid flow is the trajectory model. In this model the liquid motion towards the tray exit is the effect of droplet ejection over the exit weir. This description points out the importance of momentum transfer from the ascending gas to the cross liquid flow. As a consequence, the flow parameter *FP*, representing the ratio of the liquid to the gas inertia, is used for correlations describing hydrodynamic parameters:

$$FP = \sqrt{\frac{\rho_L}{\rho_G}}\frac{U_L}{U_G} \tag{4}$$

where U_L is the horizontal liquid velocity defined as

$$U_L = \frac{Q_L}{h_{Lc} \times L_w} \tag{5}$$

U_G is the vertical gas velocity toward the active area A_a defined as

$$U_G = \frac{Q_G}{A_a} \tag{6}$$

and ρ_L and ρ_G are the liquid and gas densities, respectively. To access the horizontal liquid velocity U_L, the knowledge of clear liquid height h_{Lc} is required. Thus for empirical correlations, different authors have used the flow ratio Ψ instead of the flow parameter *FP* (Dhulesia, 1983, 1984; Békássy-Molnár and Mustafa, 1991; Mustafa and Békássy-Molnár, 1997):

$$\psi = FP \times h_{Lc} = \sqrt{\frac{\rho_L}{\rho_G}}\frac{L}{U_G} \tag{7}$$

The clear liquid height is then written as a power law of ψ:

$$h_{Lc} = A\psi^{\alpha} \tag{8}$$

Several studies agree well with the fact mean liquid fraction α_L is mainly dependent on gas inertia (Bennett et al., 1983; Liang et al., 2008). Some efforts have been made to propose dimensionally coherent correlations by using the Froude number *Fr*, comparing gas inertia to liquid weight on the tray (Hofhuis, 1980; Colwell, 1981; Zuiderweg, 1982; Chen and Fan, 1995):

$$Fr = \sqrt{\frac{\rho_G U_G^2}{g\rho_L h_{Lc}}} \tag{9}$$

The interfacial area and the mass transfer coefficients on both liquid and gas sides are also important parameters for column design. For these parameters less phenomenological descriptions can be found and the reported expressions are mainly put under a power law form (Badssi et al., 1988; Peytavy et al., 1990; Pohorecki and Moniuk, 1988). Furthermore little experimental work on the mass transfer parameters has been made on reasonably large pilot units to account for the hydrodynamic effects (Scheffe, 1984; El Azrak, 1988; Liang et al., 2008). For these parameters the choice of a characteristic liquid velocity seems more problematic as well. Indeed, depending on the studies, two characteristic liquid velocities are encountered: the liquid loading L or the liquid velocity U_{La} based on active area Aa:

$$U_{La} = \frac{Q_L}{A_a} \tag{10}$$

The effect of column dimensions which impact scalability to larger sizes has been less studied. Studying hydrodynamics on sieve trays, Hofhuis (1980) used two different size columns and proposed dimensional coherent correlations for hydrodynamic parameters and regime transitions. Other works have used different sets of experimental data and have indirectly considered the effect of the column size (Colwell, 1981; Zuiderweg, 1982; Bennett et al., 1983; Chen and Fan, 1995).

Krishna and Van Baten (2003) have carried out a CFD study where the effect of column diameter has been investigated through the modelling of two different columns. In this work the authors showed an important impact of scale effects especially on the mixing characteristics.

In the present work the effect of path length L_P, the distance travelled by the liquid on a tray between the entrance and the exit weir, is investigated by carrying out hydrodynamic and interfacial area measurements. Two different path lengths are considered: L_P=0.36 m and L_P=0.96 m. This geometric parameter has not been studied thoroughly in literature. Table 1 gives some examples of characteristic path lengths L_P from the literature and shows that some works have been conducted on relatively small path lengths L_P in comparison to industrial units.

The two columns considered in this work are presented in Section 2. Section 3 is dedicated to the comparison of hydrodynamic parameters and interfacial area measurements. In Section 4, some attempts are made in order to propose phenomenological

Table 1
Examples of L_P (m) values in literature versus industrial units.

Piqueur and Verhoeye (1976)	Bennett et al. (1983)	Mustafa and Békássy-Molnár (1997)	Fasesan (1987)	Uys et al. (2012)	Liang et al. (2008)	Dhulesia (1984)	Industrial units
0.15	0.15	0.28	0.43	0.475	0.53	0.89	0.5/0.8