

## The Effect of Fluid Properties and Packing Size on the Hydrodynamics of Packed Columns

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The effect of fluid physical properties on the hydrodynamic behaviour in a packed column with 1.5" and 2.5" fourth generation random packing was investigated by measuring the pressure drop and liquid hold-up. Experimental data for combinations of four liquids and two gases were measured for both packings in a pilot plant setup with a column inside diameter of 393 mm and a packed bed height of 3 m. Liquid superficial flow rates in the range of 6 – 122 (m<sup>3</sup>/h)/m<sup>2</sup> and gas rates up to the flooding point were considered. The results provide significant extended information on how fluid properties affect the hydrodynamic behaviour in randomly packed columns. As expected, larger packing pieces enable higher hydrodynamic throughputs. However, the choice of packing size remains a balance between improved capacity (larger packing) and improved separation efficiency (smaller packing).

### 1. Introduction

Despite the high capital cost and energy-intensive nature of distillation, it is still one of the most widely used separation technologies in the process industry (Górak and Olujić, 2014). With the current demand for more sustainable processes, development in the field of distillation has been focussed on improving equipment and integrating processes in an attempt to increase separation efficiency and capacity, while minimizing capital expenditures and operating costs (Olujić et al. 2009). To pursue this goal, one focus area has been the improvement of performance characteristics associated with the liquid-vapour contacting devices. The contacting devices create an area for mass transfer between the co-existing phases, thus facilitating separation. One such group of contacting devices are random packings. Random packings are open area elements that are randomly packed in a column and are characterised by their capacity (maximum throughput) and their separation efficiency (how much separation is achieved). The fourth generation of random packings are state of the art and deliver better performance characteristics than older packings.

To take full advantage of the improved performance of these modern random packings in either newly designed columns or for retrofitting existing columns, accurate prediction of the hydrodynamic capacity (quantified by pressure drop, liquid hold-up and entrainment – leading to the column diameter) and separation efficiency (separation ability – leading to packed height) are required. A number of models are available in the literature that can predict the capacity and separation efficiency of randomly packed columns. Most of these models are semi-empirical and require experimentally determined constants that are dependent on the type, size and material of the packing that is used. In addition to the packing characteristics, the capacity and separation efficiency in packed columns are also influenced by, amongst others, the physical properties of the operating liquids and gases.

Typically, capacity measurements are conducted using a non-mass transfer system to ensure these effects do not distort capacity results. However, many capacity models are based primarily on experimental data that were generated with water as the liquid and air as the gas. Previous studies on the capacity of structured packing as well as on distillation trays (Uys, 2012) have shown that the physical properties play a significant role. Current models do not always correlate well with systems where the physical properties deviate significantly from that of water and air.

Against this background, an investigation into the effects of liquid and gas physical properties on the capacity of randomly packed columns was warranted. The aim of this contribution is to show these effects (characterised by pressure drop and liquid hold-up) for a fourth generation packing. Experimental results are presented for two packings of different nominal sizes and under non-mass transfer conditions.

## 2. Experimental

Pressure drop and liquid hold-up were measured for two sets of fourth generation random packing, with nominal sizes of 1.5" and 2.5". By eliminating mass transfer, the observed effects were limited to related column hydrodynamics. Four liquids (Table 1) with different viscosities, densities and surface tension and two gasses (either air or nitrogen, and carbon dioxide) with different densities (1.18, 1.15 and 1.81 kg/m<sup>3</sup> for air, N<sub>2</sub> and CO<sub>2</sub>, respectively) were used. The liquids were chosen to ensure the physical properties covered the majority of the liquid density, viscosity and surface tension ranges typically encountered in distillation systems. These two gases were chosen as non-flammable, readily available gases with a significant difference in density.

*Table 1: Experimentally measured liquid physical properties at 25°C and 101 kPa \**

Liquid	Density (kg/m <sup>3</sup> )	Dynamic Viscosity (mPa.s)	Surface Tension (mN/m)
Silicone oil	958	57	20
Ethylene glycol	1095	11	34
Isopar G	736	0.84	23
Water	995	0.89	62

\* Properties were measured after extracting samples from the column and therefore represent the real experimental values rather than pure component properties.

Experimental data were measured in a previously constructed pilot plant set-up (Figure 1) (Minne, 2017). The column has an internal diameter of 393 mm, a packed bed height of 3 m and uses a channel-type liquid distributor with an open area of 60%. The liquid rates ranged between 6 and 122 (m<sup>3</sup>/h)/m<sup>2</sup> and the gas flow rates covered the entire hydrodynamic range (pre-loading, loading and flooding range).

Referring to Figure 1, the liquid enters the column at the top, where the liquid distributor evenly distributes the liquid onto the packing. The liquid then flows down the column, over the packing and into a collection sump at the bottom. From this sump it is again recirculated to the top of the column via a heat exchanger. The heat exchanger ensures that the temperature in the column remains constant. A blower recycles the gas through the system. The gas enters the bottom of the column through a gas distributor and then flows upward through the packed bed. Following de-entrainment (de-misting) the gas exits the column into a surge tank, from where it is recirculated by the blower.

The pressure drop was measured, while the column was operational, using a finely calibrated differential pressure cell. The liquid flow rate, gas flow rate and pressure drop were allowed to stabilise and after a minimum of five minutes, once pressure stability was achieved, pressure drop readings were sampled (once per second) for a period of two minutes. The average of 120 readings were taken as the actual pressure drop corresponding to the set operating conditions. To measure the liquid hold-up, the liquid feed to the column was closed off and simultaneously the liquid exiting the packed bed was redirected to the liquid hold up tanks. Sufficient time (approximately 15 minutes) was allowed for the column to drain and the amount of liquid in the hold-up tanks was quantified. Subsequently, the hold-up in the column was carefully calculated by also accounting for the liquid captured in the liquid distributor and other parts of the system.

The loading and flooding points were determined from the experimentally measured pressure drops using an unbiased method based on statistics, as first proposed by Lamprecht (2010) and later refined by Minne (2017).

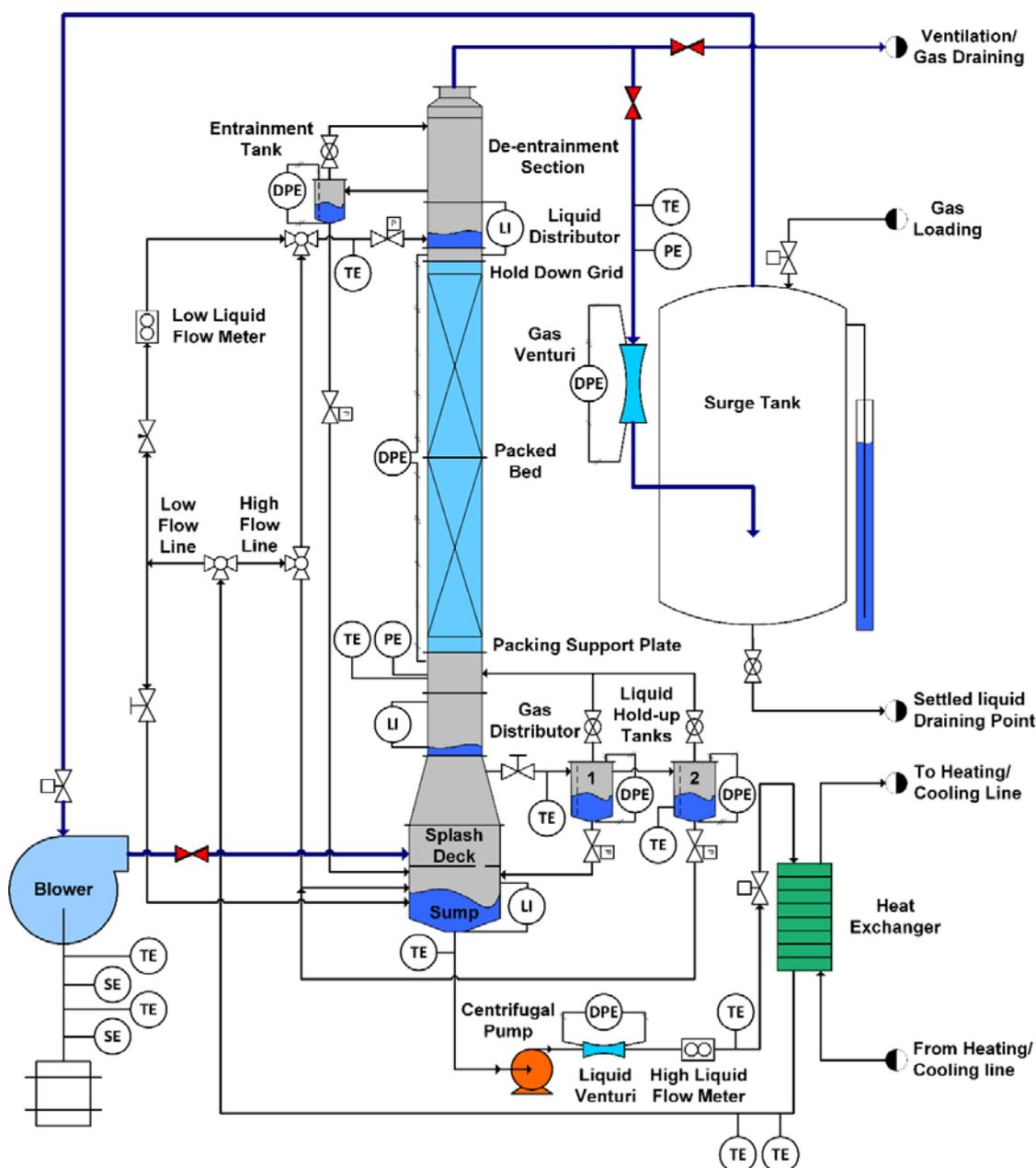


Figure 1: Process Flow Diagram of Pilot Plant used for measuring all Experimental Data

### 3. Results & Discussion

#### 3.1 Effect of Physical Liquid Properties

Four liquids with a range of physical properties were investigated. Comparing these liquids, no more than one physical property is the same between the different liquids, while the remaining properties differ. Therefore, it remains a challenge to isolate the effect of a single physical property, but the prominent effects of the type of liquid – and hence the physical properties – on the pressure drop and liquid hold-up can be seen in Figure 2 (a typical example comparing the various liquids in CO<sub>2</sub> as gas phase).

Silicon oil and Isopar G have a much lower flooding velocity than that of ethylene glycol and water. It is postulated that the lower flooding velocity of silicone oil can mostly be attributed to its high viscosity. A higher viscosity will resist the downward flow of the liquid in the column, thus resulting in a lower flooding velocity. Isopar G, on the other hand, has a significantly lower density than the other liquids. This lower density requires a lower upward drag force to counteract the gravitational force, thus also resulting in a lower flooding velocity.

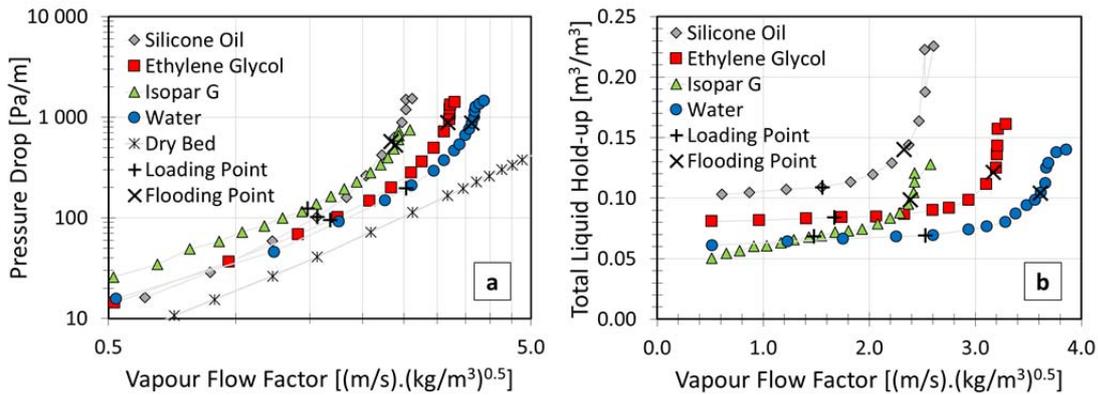


Figure 2: Comparison of the measured (a) pressure drop and (b) liquid hold-up as a function of vapour flow factor for various liquids with CO<sub>2</sub> for 2.5" packing at 73 (m<sup>3</sup>/h)/m<sup>2</sup>

Due to the interactive nature of the various properties, assigning specific trends to specific liquid physical properties should be done with due caution. It is, however, clear that the physical properties play a major role in the hydrodynamic behaviour and the generated data offer significant value. In particular, the data can aid in evaluating the ability of various capacity models to predict the hydrodynamic data and thus assist in future model development. Figure 3 shows the ability of the Billet and Schultes (1991, 1993, 1995 and 1999), Mackowiak (1990, 1991 and 2009) and Stichlmair et al. (1989) models to predict silicone oil + air data and it clearly illustrates the need for improvement or extension of these models.

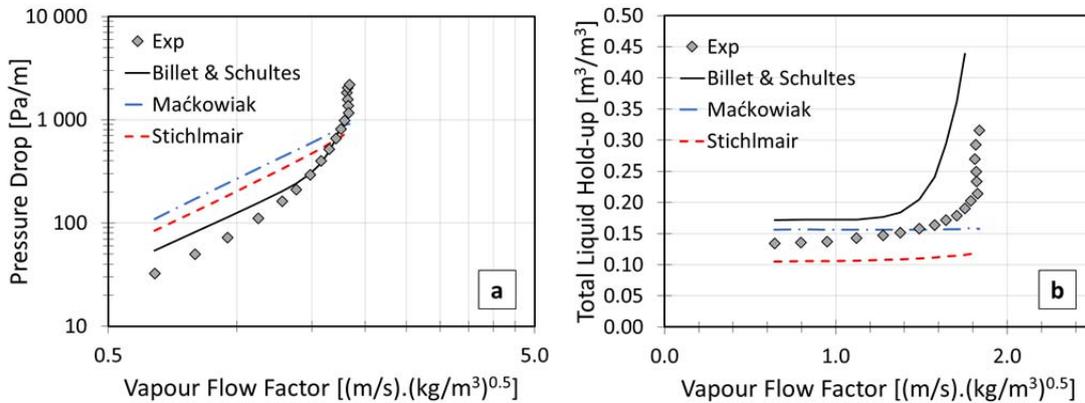


Figure 3: Comparison of the experimental (a) pressure drop and (b) liquid hold-up as a function of vapour flow factor with various model predictions for silicon oil + air systems for 1.5" packing at 73 (m<sup>3</sup>/h)/m<sup>2</sup>

### 3.2 Effect of Gas Density

Experimental results indicate that the pressure drop and liquid hold-up trends (versus the vapour flow factor) for the same liquid, packing and liquid flow rate with air or nitrogen as gas phase coincide with corresponding trends with carbon dioxide as gas phase. This is illustrated in Figure 4 (a) and (b), as an example. Since the vapour flow factor is a function of the square root of the gas kinetic energy, it is clear that a certain gas kinetic energy is required to induce a certain liquid hold-up and pressure drop. However, Figure 4 (c) and (d) show that at constant superficial gas velocities, different trends are observed. At the same superficial gas velocity, carbon dioxide, with a higher gas kinetic energy as a result of its higher density, produces a higher pressure drop and higher liquid hold-up above the loading point.

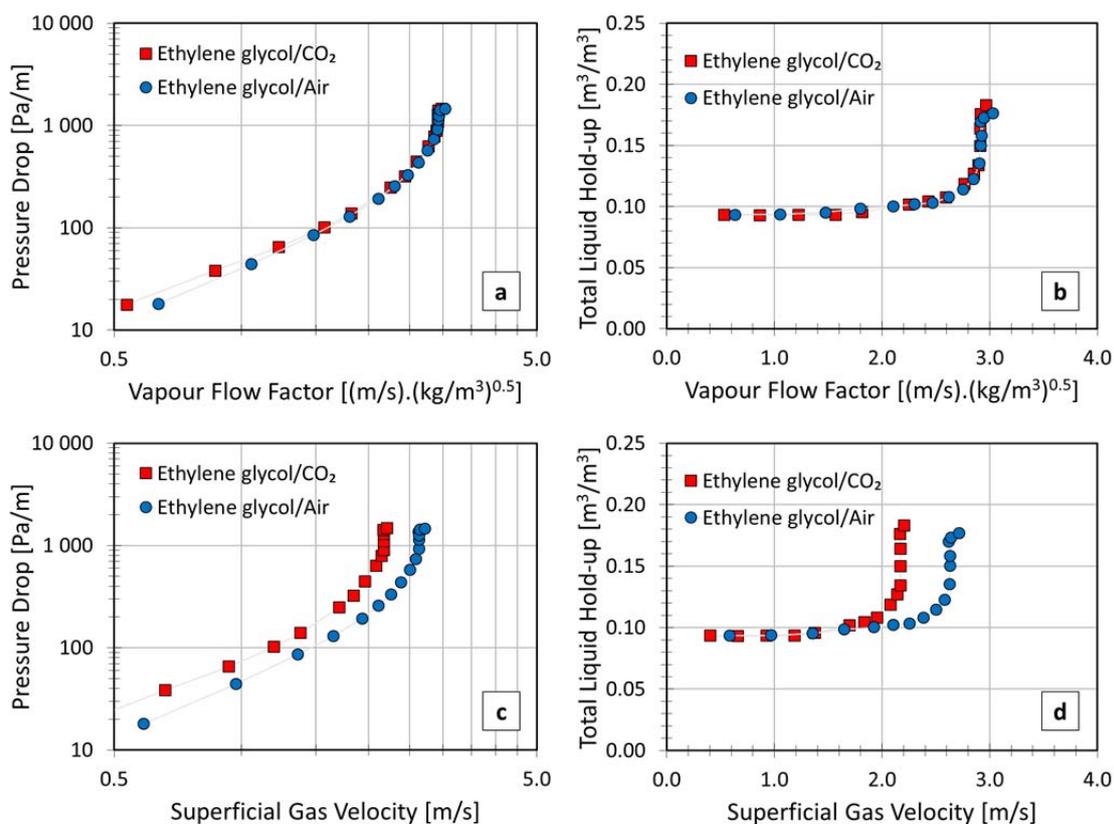


Figure 4: Comparison of measured (a) and (c) pressure drop and (b) and (d) liquid hold-up as a function of (a) and (b) vapour flow factor and (c) and (d) superficial gas velocity for ethylene glycol with air and CO<sub>2</sub> for 2.5" packing at 98 (m<sup>3</sup>/h)/m<sup>2</sup>

### 3.3 Effect of Packing Size

The general effect of the increase in packing size from 1.5" packing to 2.5" packing is a reduction in both pressure drop and liquid hold-up, and an increase in capacity (as illustrated for ethylene glycol in Figure 5).

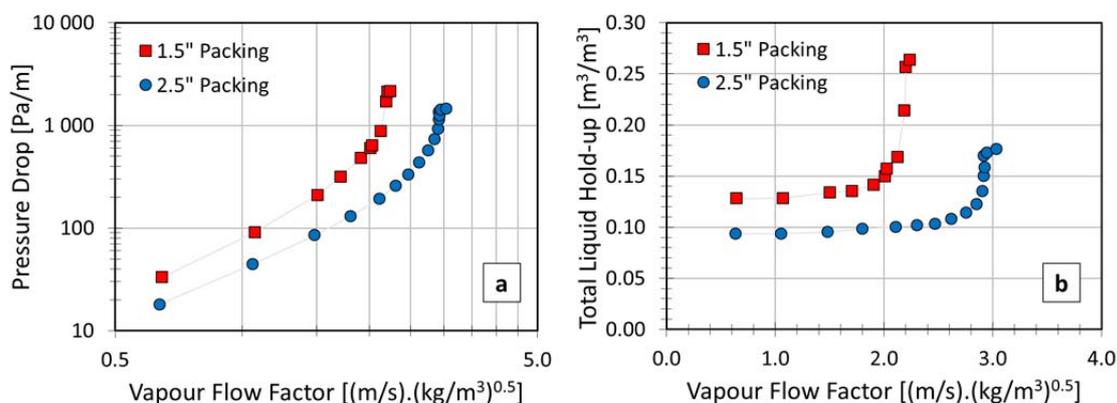


Figure 5: Comparison of measured (a) pressure drop and (b) liquid hold-up for ethylene glycol with air for 1.5" and 2.5" packing at 98 (m<sup>3</sup>/h)/m<sup>2</sup>

The pre-loading pressure drop of all liquids at all liquid flow rates is approximately 50% lower with the 2.5" packing relative to the pressure drop of the 1.5" packing. With all four liquids, the larger packing produced an increase in capacity of approximately 11 % at a superficial liquid flow rate of  $6 \text{ (m}^3/\text{h)/m}^2$ , with this percentage increasing to approximately 37 % at a superficial liquid flow rate of  $122 \text{ (m}^3/\text{h)/m}^2$ . From a simple capacity point of view, the larger packing thus performs better. Following intuition, this can be attributed to the larger open area and lower resistance to flow. However, the smaller the nominal size of the packing, the higher the effective surface area per unit volume packing, thus most probably resulting in a higher separation efficiency. The choice of packing size is thus a balance between improved capacity with larger packings and higher separation efficiency with smaller packings.

#### 4. Conclusions

This investigation has shown that both the liquid and the vapour physical properties play a crucial role in the hydrodynamic behaviour (pressure drop and liquid hold-up) of a distillation column. While the results from this study were not sufficient to fully isolate the individual effects of liquid density, surface tension and dynamic viscosity, it provided useful evidence of their influence on the hydrodynamic behaviour of a column. Related modelling work has also highlighted the limited ability of popular capacity models to account for the effect of the physical properties. Therefore, the measured data can also be used to assist in future model development and improvement.

The study has also shown that, from a hydrodynamic perspective, larger packings perform better. However, one should bear in mind that optimum packing size selection is a balance between higher separation efficiency (with smaller nominal size packings) and higher capacity (with larger packings).

The current study has collected a large amount of data that can be used in the future for model development. Future work would thus entail the improvement of current capacity models, so that they can account better for the effects of fluid physical properties.

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