

Annular Liquid Films on a Vertical Wire with Counter Current Gas Flow - Experimental Investigations

Jochen Grünig*, Matthias Kraume

Technische Universität Berlin, Chair of Chemical Engineering
Straße des 17. Juni 136, D-10623 Berlin

*jochen.gruenig@tu-berlin.de

A new type of packing for distillation and absorption processes, consisting of bundles of vertical wires, is expected to have advantages compared to conventional packings in terms of maldistribution and pressure loss. To have an insight into the fluid dynamics, hold-up experiments with liquid films on a single vertical wire in a counter current gas flow were conducted. The varied parameters were the gas and liquid load; water and ethanol were used as liquids which both show a characteristic flow pattern including a basis film and teardrop shaped beads. It turned out that the liquid hold-up is not influenced by the gas load below the loading point. To explain an increasing bead thickness with rising gas load, which had revealed in previous experiments, it is supposed that the beads assume a more compact shape but maintain their volume in general. Further results indicate that the transport of liquid is shifted to the beads at higher gas velocities.

1. Introduction

Modern structured packings in distillation and absorption columns offer high separation efficiency at moderate pressure drop but suffer maldistribution of the liquid phase. To achieve a high efficiency over the whole height of the column the liquid has to be redistributed after a certain distance. A new idea is to employ bundles of vertical wires as packing elements to overcome this drawback. A liquid distributor feeds every single wire with liquid separately. Since there are no interconnections between the wires the liquid flows on defined paths and maldistribution should not occur. Furthermore, the pressure drop should be relatively low because the gas phase flows in straight gas channels between the wires which is advantageous especially for vacuum distillation.

For a detailed view on the fluid dynamics and mass transfer as well as to predict the performance of such packing, the liquid film on a single vertical wire is observed experimentally. In the experiments, the annular liquid film on the wire is exposed to a counter current gas flow to obtain the physical conditions that would arise in the packing. The film develops undulations after a certain run length which appear as liquid beads flowing over a thin basis film. The formation of waves on liquid films has been studied by many researchers for planar films (Kapitza, 1948; Brauer, 1956) and films on threads and wires (Goren, 1962; Hattori et al., 1994), but the influence of a counter current gas flow on liquid films on wires (or threads) has not been investigated sufficiently.

Own film thickness measurements revealed an increase of the bead thickness at higher gas loads (Grünig et al., 2007). This suggests that the liquid is retained by the gas flow leading to a higher liquid hold-up. Due to this consideration, the test plant was adapted to perform hold-up experiments. Hold-up measurements of liquid films at the inside of tubes were performed by Feind while closing ball valves at the ends of the tube and collecting the liquid (Feind, 1960). This principle can not be applied when using a wire. For this reason, a different solution was used which is explained in section 2.1.

2. Methods and materials

2.1 Experimental setup

The experimental setup is shown in Fig. 1. A wire (\varnothing 1 mm) (1) is clamped in a vertical glass channel (1000 mm x 20 mm x 20 mm) (2) centrally. Liquid is supplied from a feed tank (5) to the upper end of the wire by a concentric nozzle (Inner diameter 2 mm) and flows down as annular film. During its way down the film develops bead-shaped structures (9) and a thin basis film (10). At the bottom of the channel the liquid film is collected by a sample tube (12) and guided into a storage tank (3) which stands on a balance. The liquid is recirculated into the feed tank by a gear pump (4). If liquid is thrown at the walls of the channel (11), it is separated and discharged from the liquid cycle. Air enters at the bottom of the channel and flows in counter current to the liquid. It leaves the channel and passes a phase separator (7) before it is released into the environment.

A digital high-speed camera (6) and image processing software were used to measure the local film thickness and frequency of the beads.

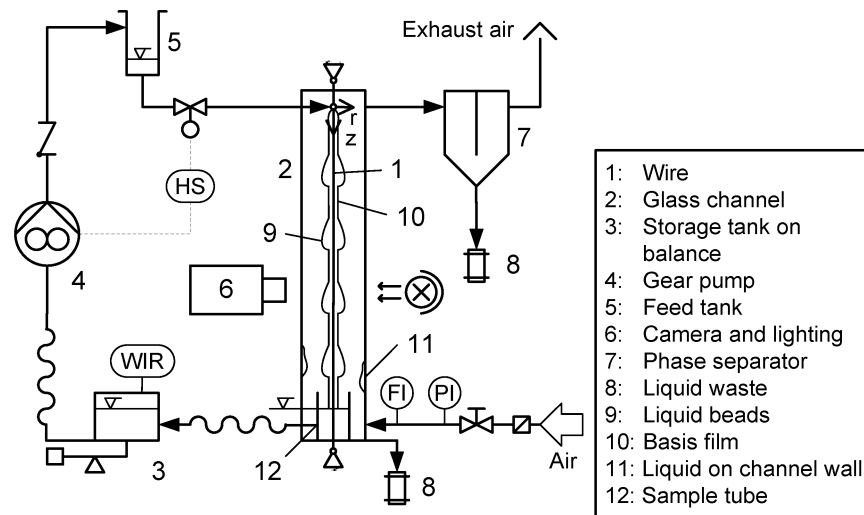


Fig. 1. Experimental setup

A detailed description of the film thickness experiments is given in a previous publication (Grünig et al., 2007). The pump and the liquid supply to the wire can be shut of

simultaneously. Thus, the remaining amount of liquid that drains into the storage tank after shut-off corresponds to the liquid hold-up and can be detected as jump in the weight of the storage tank. For this purpose the sample tube is connected with the sample tank in the way that they have the same liquid level.

2.2 Used substances, parameters and test conditions

Since the surface tension is an essential parameter in the fluid dynamics of film flow, water and ethanol were used as liquids with respect to their strongly differing surface tension (see Tab. 1). Purified water was taken from a reverse-osmosis system. Ethanol of synthesis quality with a purity of 99.9 % was used. The filtered air was taken from the pressured air supply and was expanded to system pressure which was at most 5 mbar above ambient pressure. All measurements were made at ambient temperature of $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$. The varied parameters were the liquid load B and the gas load F ; their definition is given in the nomenclature at the end of this paper.

Tab. 1. Physical properties of the liquids at 20°C (Wohlfarth and Wohlfarth, 1997)

	Density ρ_l [kg/m^3]	Viscosity η_l [mPa s]	Surface tension σ_l [mN/m]
Water	998	1.0	72.7
Ethanol	790	1.2	22.3

2.3 Liquid hold-up measurements

The specific liquid hold-up HU_l was determined by analyzing the difference of the weight ΔM_{tot} of the storage tank before and after the abrupt shut-off of the liquid supply (see Fig. 2). In the same moment, the air supply was also shut off to allow the draining and to minimize the evaporation of the remaining liquid on the wire. Since the liquid level rises both in the storage tank and the sample tube, a correction is made for the amount of liquid that stays as surplus in the sample tube. When a constant weight was reached, all of the liquid except a negligible small amount had been drained from the wire and the liquid supply as well as the air supply was switched on again. Before the next shut-off procedure could be executed, a steady state of the weight had to be reached. Ten steps were evaluated for one parameter set to aver-

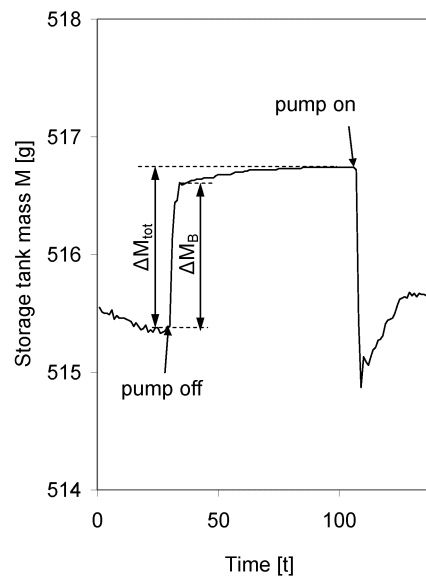


Fig. 2. Example of hold-up examination

age the results. The specific liquid hold-up is calculated as follows:

$$HU_1 = \frac{\Delta M_{\text{tot}}}{\rho_l L_w} \quad (1)$$

When looking at the shape of the steps, there are two regions: I). A steep rise in the beginning and II). a moderate declining slope afterwards until a constant value is reached. The first region is caused by the fast draining beads; the second comes from the remaining slow draining basis film. This allows an estimation of the bead hold-up HU_B of all beads on the wire with the mass difference ΔM_B of region I:

$$HU_B = \frac{\Delta M_B}{\rho_l L_w} \quad (2)$$

3. Results and discussion

The results of the hold-up measurements are presented in Fig 4. The different measurement ranges of the gas load result from the particular load limits of the liquids at certain liquid loads. Naturally, both liquids show rising hold-up with increasing liquid load. However, ethanol has significantly higher liquid hold-up at all liquid loads compared to water. On the one hand this is caused by the lower density and higher viscosity of ethanol leading to larger film thickness. On the other hand the higher surface tension of water causes stronger fluctuations in film thickness leading to larger beads. These are expected to have a higher falling velocity and thus less residence time resulting in a lower hold-up. Remarkably, there is no identifiable influence of the gas load on the hold-up of both liquids at all liquid loads over the whole range of the gas load. This is similar to the behavior of the liquid hold-up in packed columns below the loading point (Billet and Schultes, 1993). The reason why no increase of the hold-up can be observed is that the beads disintegrate at the loading point and are not collected by the sample tube.

When opposing these results with the findings of the film thickness measurements (Fig. 3), an interesting aspect is the occurrence of a constant hold-up at all gas loads in combination with growing bead thickness at higher gas loads while the basis film thickness remains constant. These apparently conflicting results can be reconciled when considering the shape of the beads. Fig. 6 shows an image of the bead shape at different gas loads. It can be clearly seen that the bead assumes a more compact shape at high gas loads.

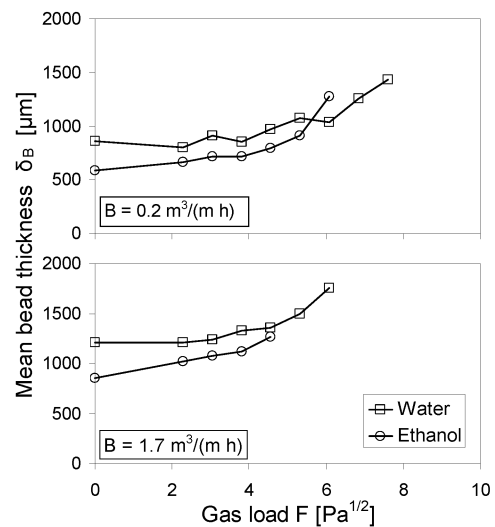


Fig. 3. Bead thickness

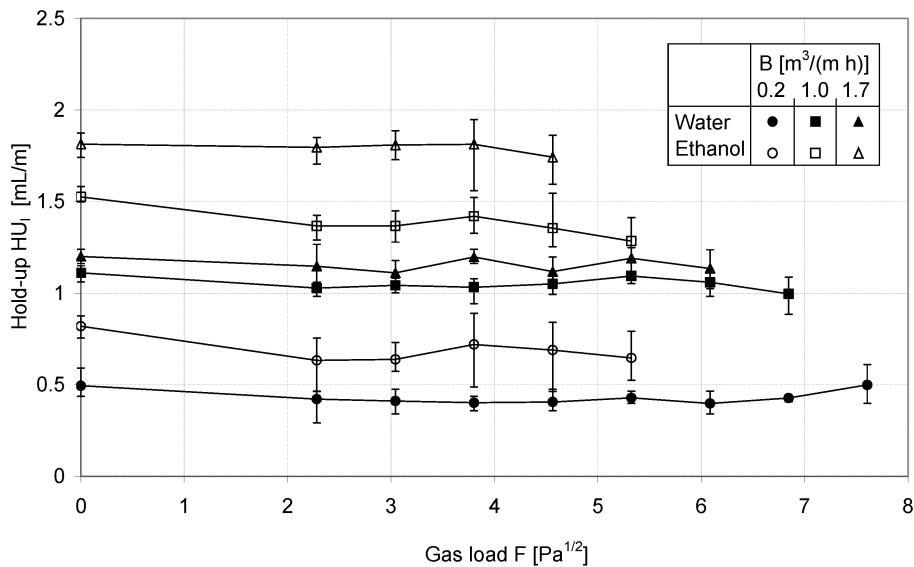


Fig. 4. Liquid hold-up depending on gas load F and liquid load B

This would mean that the bead thickness is rather increased by the change of the shape than by the growth of volume.

Fig. 5 shows the portion of the hold-up that is ascribed to the beads. There is a trend that at higher gas loads the amount of liquid which is transported by the beads increases. In the case of water at high gas and liquid loads almost all of the liquid seems to be transported by the beads. However, since the drain-off characteristics of the flow have

to be considered a direct comparison to the ratio of bead and basis film thickness at steady state flow conditions can not be made.

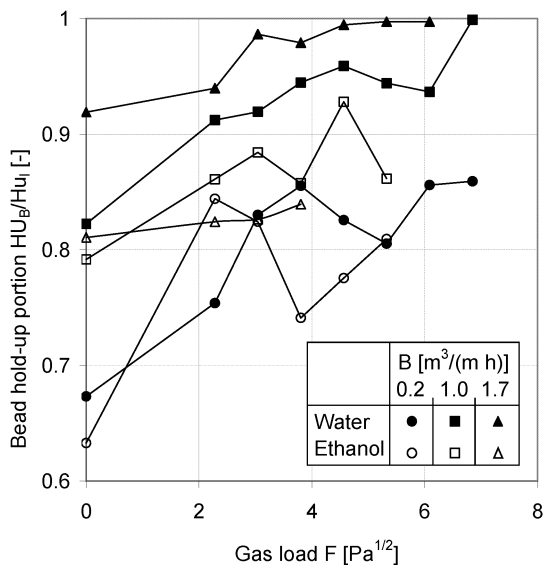


Fig. 6. Bead hold-up portion

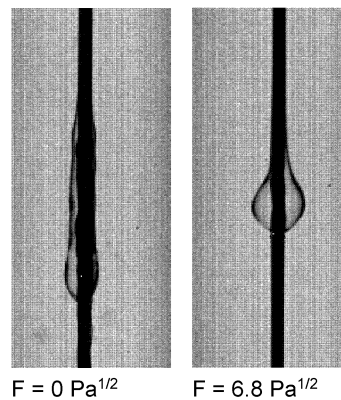


Fig. 5. Shape of beads at different gas loads F

4. Conclusions

The results show that there is no influence of the gas load on the liquid hold-up below the loading point. This behavior is known from the fluid dynamics of packed columns. An increase in bead thickness at rising gas load merely indicates the change of the bead shape and not necessarily the growth of the bead. Due to the bead deformation, an increasing amount of liquid is transported by the beads at rising gas load. It is still not clearly known how this affects the mass transfer in the liquid and gas phase. To achieve a better understanding of the complex relation between fluid dynamics and mass transfer, further experiments should aim on measuring the liquid and gas side mass transfer.

Nomenclature

$B = \dot{V}/C_W$	[m ³ /m s]	liquid load
C_W	[m]	circumference of wire
$F = v_g(\rho_g)^{1/2}$	[Pa ^{1/2}]	gas load
HU	[m ³ /m]	specific liquid hold-up
L_W	[m]	wetted length of wire
M	[kg]	mass
\dot{V}	[m ³ /s]	volume flow rate
v_g	[m/s]	superficial gas velocity
δ_B	[m]	bead thickness
η	[Pa s]	dynamic viscosity
ρ	[kg/m ³]	density
σ	[N/m]	surface tension

Subscripts

B	bead
g	gas
l	liquid
tot	total
W	wire

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