MIXED-PHASE FEEDS IN MASS TRANSFER COLUMNS AND LIQUID SEPARATION

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The flashing feed sections of crude oil vacuum towers are especially prone to liquid entrainment. This can be detrimental to the performance of the packings/trays above the feed. It is also of disadvantage in case liquid is collected and recirculated back to the furnace. Therefore it is common practice to use special inlet devices that help preventing or minimizing liquid entrainment while maximizing the flash conditions. Such devices are also frequently used in gas/liquid separators.

The similarity rules for the mixed-phase feed inlet are discussed and applied to a 1 m diameter air/water simulator that is used as a model for a crude oil vacuum tower of 5.25 m inner diameter. For a given inlet device the turbulent flow field of the dry vapour is fully determined by four essentially geometrical dimensionless parameters. The Froude number and the flow parameter account for the two-phase nature of the flow.

Two devices with vanes (a short assembly and the modified Schoepentoeter™ inlet device) and a standard feed without any device are tested experimentally in the air/water simulator. Their liquid disengaging capability is assessed by means of the entrainment rate. In the present installation the more complex device reaches virtually zero entrainment below a gas load factor of 0.08 m/s. The entrainment rate of both devices is fairly independent of the flow parameter while the standard feed shows more entrainment when the flow parameter is increased. Compared to the standard feed the short assembly improves only at the higher flow parameter.

KEYWORDS: mixed-phase feed, inlet device, crude oil vacuum tower, liquid entrainment, packing, flashing feed

INTRODUCTION

Vapour feeds have been the subject of various experimental [1–5] and numerical [5–7] investigations. An example with a feed section in a crude oil vacuum tower was presented in [8]. However, to our knowledge no experimental or numerical study is available to the public that tries to quantify the liquid entrainment for different inlet devices.

Three systems have been investigated in the present study (see Figure 1): a) a standard radial feed without any special device, b) a radial inlet with a *short vane assembly* consisting of two vertical and three horizontal vanes that intersect, and c) a *vane ladder inlet device* (with 2 times 7 vanes), known as Schoepentoeter™ inlet device. The three

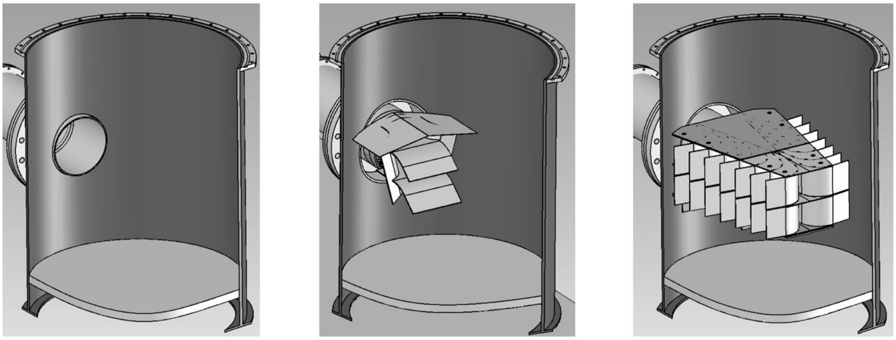
(a) (b) (c)

Figure 1. Inlet systems as installed in the 1 m diameter air/water simulator

inlets have been evaluated by means of computational fluid dynamics (CFD) and compared with the orifice baffle. In terms of uniformity of flow below the packing, the *short vane assembly* is much better than the standard feed. The *Schoepentoeter device* generates a slightly better flow field below the packing, but at the expense of a much heavier construction. If the goal were uniquely to achieve a uniform vapour flow the *short vane assembly* would serve the purpose. However, we do not know its effectiveness in separating liquid from the mixed-phase stream. On the other side, the *Schoepentoeter device* is primarily designed for liquid disengagement, which the CFD simulation did not account for. The numerical flow simulation of a dispersed phase is theoretically possible by integrating trajectories of particles with a given weight, but in practice there are still unsolved numerical issues that prevent the method from quantitatively predicting liquid entrainment and disengagement. More conclusive results are expected from an experimental investigation. However with one complication: While CFD would allow simulating a column with its real dimensions, the experiments rely on the size of the experimental facility available. Model theory is then required for the scale-up.

MODEL THEORY AND PARAMETERS

The shape of the dry flow field, i.e. the non-dimensional velocity distribution of gas in geometrically similar feed sections of packed towers depends on four non-dimensional parameters (see Table 1) which all relate to purely geometrical features [7], including the gas load ratio **F**, that represents the diameter ratio between the column and the feed nozzle put to the square. The normalized packing resistance is the only important characteristic imposed by the packing above the feed section, provided the packing bed is high enough, typically half a column diameter. The packing resistance factor f_p is defined by the pressure gradient in the packing and the dynamic head or the F factor

Table 1. Non-dimensional parameters for the geometry, the dry flow and the two-phase system

Definition	Description
$\mathbf{H} = H/D$	Normalized clearance feed nozzle – packing
$\mathbf{S} = H_s/D$	Normalized clearance feed nozzle – sump
$\mathbf{F} = F_n/F = c_{G,n}/c_G$	Factor or gas load ratio between feed nozzle and column
$\mathbf{P} = Df_p$	Normalized packing resistance
$\mathbf{Re} = D\bar{w}\rho_G/\mu_G$	Reynolds number based on superficial gas velocity in the column
$\mathbf{Ma}_n = w_n/c$	Feed nozzle Mach number
$\mathbf{Fr} = \frac{\bar{w}^2}{gD} \cdot \frac{\rho_L}{\rho_L - \rho_G}$	Froude number
$\boldsymbol{\varphi} = \frac{\dot{m}_L\sqrt{\rho_G}}{\dot{m}_G\sqrt{\rho_L}}$	Flow parameter
$\mathbf{We} = \frac{\Delta u^2 \rho_L d}{\sigma}$	Weber number (Δu is the local velocity difference between a droplet and the surrounding vapour)

to the square.

$$\frac{\Delta p}{\Delta z} = f_p \frac{\rho_G \bar{w}^2}{2} = f_p F^2/2 \tag{1}$$

It can be determined experimentally by measuring the dry pressure drop through the packing bed. As the pressure drop of the packing depends of the specific surface area or its hydraulic diameter, the parameter **P** is also a purely geometrical parameter comparable to a ratio between the column diameter and the hydraulic diameter of the packing. A finer packing results in a larger **P**. Two gas entries are geometrically similar if all four parameters have the same values. For two towers of different diameters to be similar the larger tower needs a coarser packing. Under this condition the gas flow is also similar provided it is turbulent in both cases.

The fifth dimensionless parameter is the Reynolds number which should be identical for dynamic similarity of the gas flow. However, far above transition from laminar to turbulence the flow remains independent of the Reynolds number. In this case an *extended similarity* with different but high enough Reynolds numbers is accepted.

Today the vapour velocity at the feed nozzle of crude oil vacuum towers is designed for 80% of speed of sound, and the Mach number is quite close to unity. Except from the feed nozzle the assumption of an incompressible flow (**Ma** < 0.3) is applicable in the rest of the column.

Uniformity of the flow distribution is an important prerequisite for best performance of the packing bed. It can also help minimizing liquid entrainment if the gas carries condensed phase. The uniformity can be quantified in terms of the coefficient of variation *K*. It is evaluated on a horizontal plane through the column and equals the standard deviation of the vertical flow field $w(x, y, z = const)$ in relation to the average superficial velocity $\bar{w}$ on the same plane. *K*-values obtained with CFD for different inlet devices have been presented in [7].

When introducing liquid as a second phase the following additional phenomena come into play: 1) Gas-liquid interaction, driven by the deceleration and acceleration of droplets, 2) the mass flow ratio liquid to gas, 3) the liquid phase scale, typically an average drop size *d* and a size distribution function, 4) the two-phase flow regime in the feed nozzle (annular, dispersed etc.).

Dependent on their size, droplets will follow the liquid flow more or less exactly. The flow of very small droplets will be driven by viscous forces, while the dynamics of larger droplets is driven by inertia. In order to maintain similarity of the droplet trajectories the Froude number must be identical for both the equipment and its model. The parameter **Fr** shown in Table 1 corrects for the density difference, and uses the liquid density ρ_L for normalization. In practice, the gas load factor

$$c_G = \bar{w}\sqrt{\frac{\rho_G}{\rho_L - \rho_G}} = \sqrt{\mathbf{Fr}\frac{\rho_G}{\rho_L} \cdot gD} \tag{2}$$

or the F-factor have been used instead of **Fr**. For reading convenience we prefer to present the results with c_G instead of **Fr**. Notice that c_G is not appropriate if results of columns with different diameters should be compared.

The next parameter is the liquid load, which can be expressed in terms of liquid mass flow ratio to gas mass flow ratio. At low liquid loads the gas flow field remains unchanged while high liquid loads increase the interaction. Hence, for moderate liquid load we expect that the liquid entrainment is fairly independent of the ratio. Traditionally, the liquid load is represented by means of the flow parameter $\boldsymbol{\varphi}$, which is the ratio between the average kinetic energies of the liquid and the gas put under the square root.

The remaining influence factors relate to the liquid droplet size distribution and the flow regime in the feed nozzle. At the absence of an exact method to determine the flow regime theoretically we have to rely on empiricism. Based on Baker's chart [9] the annular or dispersed regimes are the most likely encountered in the present application. We focus on dispersed flow and simulate it by injecting liquid by means of spray nozzles.

Finally, the drop size distribution tested in the model should be representative. The Weber number is the nondimensional parameter that should be taken into account. However, the critical Weber number, a measure of the maximum droplet size, is unknown, varies from set-up to set-up and must be determined experimentally. By applying empirical correlations for typical applications [10–11], critical droplet sizes may vary considerably. In practice average sizes around 100 μm are expected. Droplet diameters of the model and the real installation should be identical; but it is difficult to generate a defined droplet size distribution that agrees exactly with the one present in the large scale industrial column.

The amount of liquid entrained in the feed section should be as small as possible. A dimensionless measure for the entrainment $E = \dot{m}_{L,e}/\dot{m}_L$ is defined by the ratio of entrainment vs. the amount of liquid that enters through the feed nozzle.

Exact similarity between the real industrial installation and its model is achieved if the dimensionless parameters of the geometry and the two-phase flow assume exactly the same values. Furthermore the flow regime in the feed nozzles must agree. For extended similarity we require incompressible, well developed turbulent flow, which translates in $\mathbf{Ma} < 0.3$ and $\mathbf{Re} \gg \mathbf{Re}_{crit}$. Typical values and a comparison with the values achieved in the experimental set-up will be discussed further down.

EXPERIMENTAL FACILITY AND METHOD

An atmospheric air/water test column for packing or tray testing has been revamped to accommodate the vapour feed experiments (Figure 2). It is made from transparent PVC. Its internal diameter is 1 m, the height 7.5 m. The new air feed section allows mounting radial and tangential feeds with an inner pipe diameter of 0.28 m. Air is circulated by means of a 110 kW radial ventilator, flows through the transparent spray section and the inlet device (if present) before entering the feed section of the column. The feed section is limited by the horizontal bottom wall and a circular double pocket vane pack (KCH Type 628 vertical flow vane type G/L with 2 bends, height 235 mm, placed 620 mm above the centre of the feed nozzle) that imposes a dry pressure drop gradient in accordance with the resistance factor $f_p = 107\ \mathrm{m}^{-1}$. The vane pack simulates the packing bed of the wash section. A chimney tray is normally present between the feed and the wash section of the vacuum tower. Such a tray would affect the entrainment measured experimentally by the vane pack and introduces another set of design parameters that would greatly complicate the assessment of inlet devices. For this reason no chimney tray is used in the experiment. Two column diameters above the vane pack, the vapour passes through an entrainment catching tray with MVG™ valves. Two segments of the Sulzer structured packing MellapakPlus™ 252.Y are placed directly on top of it in order to remove any remaining liquid. Finally the air leaves the column through a mesh pad and returns to the ventilator.

Water is supplied from the tank below the column. The liquid is evenly distributed into the air stream by means of three spray nozzles placed in the transparent spray section of the feed nozzle. They are arranged in a triangular pattern and fed by three 3/8″ tubes, which branch from the water supply tube. Their distance from the inlet device wall is set 100 mm; under this condition virtually all liquid enters the device as a spray. The declination relative to the vertical is set such that the upper and the lower half of the feed nozzle receive approximately the same amount of liquid. The nozzles Bete TF12FC7 are of spiral type with an operating range of 13.7 to 23.7 litres per minute (at 1 to 3 bar pressure), the spray angle is 120° and the average droplet diameter of 250 to 280 μm was specified. However, photographs and image processing indicate that smaller droplets were generated

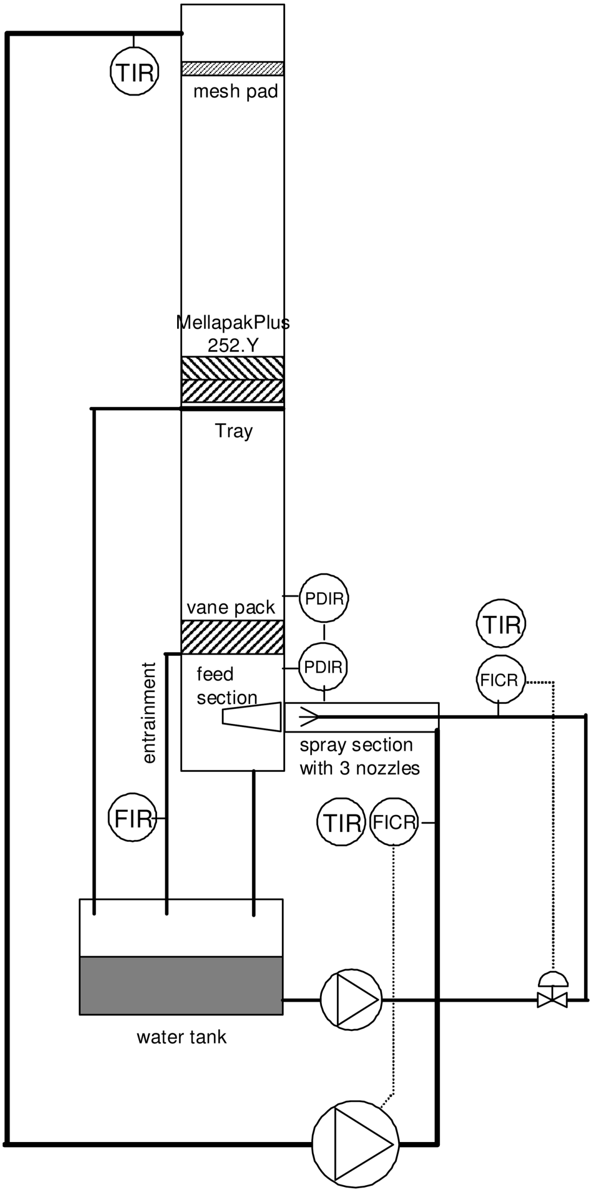

Figure 2. The 1 m air/water simulator

in the present installation. The droplets were about a factor two smaller because the water is introduced into an air stream of higher velocity (30–60 m/s).

A part of the water is disengaged in the feed section, reaches the bottom of the column and leaves it through a pipe. The entrained part of the liquid is collected in the vane pack or in the entrainment catching tray. The water of the bottom, the vane pack and the tray returns to the water tank.

The air flow is measured with an optimized pitot tube of type Deltaflow DF25GF-DN500 (by Systec Controls) mounted in the vertical part of the air supply. The power of the ventilator is driven by a frequency converter. The volumetric rate of the liquid feed is measured using a Krohne MID flow meter and controlled by valves. The flow rate of the liquid collected by the vane pack is also measured by an MID flow meter (Endress + Hauser); the liquid rates from the bottom and the entrainment catching tray are metered manually by means of a bucket and a stop watch. Furthermore it is possible to measure the pressure drop over the inlet device and the vane pack. The temperature of air is measured with the pitot tube in the air supply and a second time after leaving the column. The temperature of the water is measured before it enters the spray nozzles. A personal computer and the *LabviewTM* software are used to control the feed rates and to collect the data.

At the beginning of each testing sequence air and water are first allowed to circulate at an average operating point in order to achieve a representative temperature of at least 30°C and equilibrium humidity. Then, entrainment curves are measured as a function of varying gas load factors c_G at a constant flow parameter $\boldsymbol{\varphi}$. Hence, for each operating point both the vapour and the liquid flow rates must be adjusted. At steady state the temperature difference between the feed liquid stream and the air stream leaving the column is normally less than 0.3°C. The data is then collected on the computer for more than five minutes, checked for uniformity and averaged. The entrainment rate is directly measured with the flow meter in the tube leaving the vane pack. At normal operation below flooding the vane pack is able to collect all liquid entrained. Above this point at approximately $c_G = 0.14$ m/s additional liquid is removed by the entrainment catching tray. By additionally metering the amount of liquid leaving the bottom of the column and the tray it is possible to check the mass balance of the system. Below flooding of the vane pack a relative error of the mass flow rates below 1% is achieved.

MODEL AND INDUSTRIAL DESIGN

Designing vapour inlets of large towers is especially challenging due to the low clearance between the feed nozzle and the wash section. While uniform vapour flow and a low liquid entrainment rate would require a large open space, the relative clearance **H** tends to be smaller the bigger the tower is. Furthermore the relative nozzle diameter is also small, which results in an unfavourably great gas load ratio **F**.

The dimensions of the air/water simulator, the physical properties and the values achievable under atmospheric operation are shown in the first column (A) of Table 2. Taking into account properties and typical flow rates the simulator translates into

Table 2. Typical values achieved in the air/water simulator (A) and how this translates into the conditions of a similar vacuum tower (B)

		A) Air/water simulator (model)	B) Similar vacuum tower (industrial design)
Dimensions of the feed section			
Tower diameter	D/m	1.0	5.25
Feed nozzle diameter	d_n/m	0.28	1.47
Distance feed nozzle centre to packing	H/m	0.62	3.26
Distance sump to feed nozzle centre	H_s/m	0.51	2.68
Packing type		Vane pack	Mellapak™ 170.X
Pressure drop factor	f_p/ m^{-1}	107	20
Typical operating condition			
Pressure at feed section	p/mbar	970	40
Temperature	T/K	303	673
Gas load factor	c_G/m/s	0.085	0.1
Mass flow ratio liquid to vapour	$\dot{m}_L/\dot{m}_G$	0.3	0.57
Physical properties			
Mole weight	M/g/mol	29	363
Vapour density	ρ_G/kg/m^3	1.15	0.26
Liquid density	ρ_L/kg/m^3	996	816
Vapour viscosity	μ_G/mPa s	0.019	0.0085
Liquid viscosity	μ_L/mPa s	0.8	0.6
Non-dimensional parameters			
Clearance feed nozzle–packing	$\mathbf{H}$	0.62	0.62
Clearance feed nozzle–sump	$\mathbf{S}$	0.51	0.51
Vapour load ratio	$\mathbf{F}$	12.76	12.76
Packing resistance	$\mathbf{P}$	107	107
Reynolds number in tower	$\mathbf{Re}$	$1.5\ 10^5$	$9\ 10^5$
Feed nozzle Mach number	$\mathbf{Ma}_n$	0.09	0.53
Froude number	$\mathbf{Fr}$	0.609	0.609
Flow parameter	φ	0.010	0.010

a similar crude oil vacuum tower of 5.25 m inner diameter as shown in the second column (B) of the table. In accordance with the extended similarity most dimensionless parameters match except the Reynolds numbers and the feed nozzle Mach numbers. However, for the Mach number the value should be below 0.3 in order to meet the incompressibility condition, which is not the case. Fortunately the average Mach number inside the feed section is much smaller. Another weakness of the experimental set-up is the maximum liquid flow rate of the spray nozzles that limits the flow parameter at 0.01 (ratio liquid to gas 57% of mass flow), while typical towers are operated up to flow parameters of 0.018 (mass flow ratio of 100%). Larger flow parameters can be measured in the experiment, but only at a limited range of c_G. The greatest unknown is the droplet size distribution.

RESULTS

In Figure 3 air/water entrainment curves of the three inlet systems are shown for two typical flow parameters (0.007 and 0.01). Notice that the experiments cover the upper range of the gas load factor c_G normally encountered in crude oil vacuum towers. The *short vane assembly* leads to intermediate results and the *modified Schoepentoeter* shows best performance. The entrainment curves of the two vane devices are almost independent of the liquid load or flow parameter φ.

The situation is different for the standard feed. While the entrainment for $\varphi = 0.007$ is about 2% at the lowest vapour load factor c_G it reaches 5% for $\varphi = 0.01$ and increases

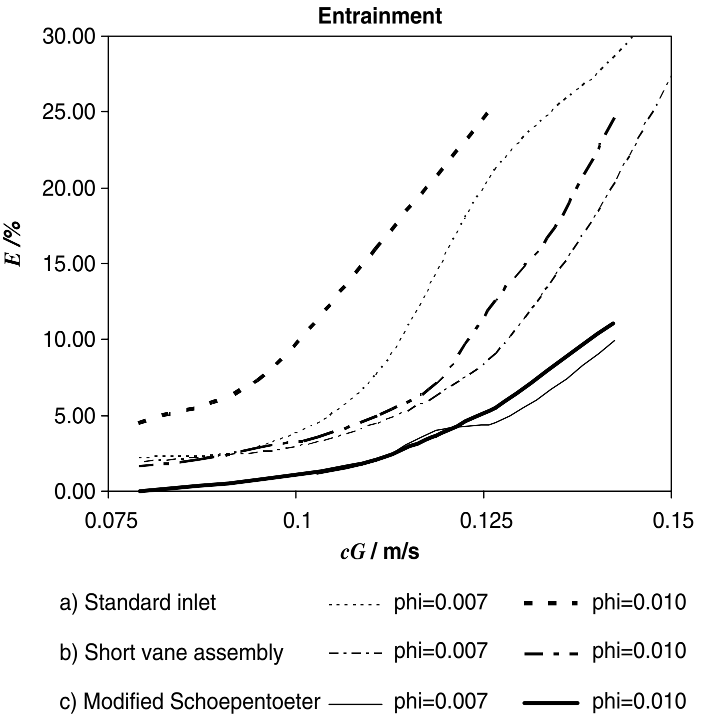

Figure 3. Air water entrainment E obtained in the simulator

quickly with c_G. It was observed that most of the liquid was carried through the feed section and impinges on the column wall opposite the inlet. A liquid film is formed on the wall and develops also in upward direction. As the load factor or the flow parameter increases, more droplets reach the wall. The film grows also in upward direction, reaches the vane and gives rise to further entrainment. The standard feed generates a very instable, oscillatory flow leading also to wave formation in the sump.

The *short vane assembly* divides the vapour/liquid flow into three main streams, a central and two lateral ones. The lateral streams follow the column wall where the liquid is immediately separated by centrifugal force and coalesces to form a film on the wall. Entrainment by the upper portion of the film reaching the vane pack is only observed at high load factors around 0.12 m/s. The liquid carried by the central stream seems to contribute most to the entrainment. It follows approximately the same trajectory as observed in the standard feed. This could explain why this device is not more efficient at the low flow parameter. However, at $\varphi = 0.01$ it improves considerably. A further advantage is the smooth and steady vapour flow without any disturbance in the sump.

The curves with lowest entrainment have been measured with the *modified Schoepentoeter*. Most of the liquid is disengaged by the vanes and virtually zero entrainment is reached below $c_G = 0.08$ m/s. The vapour flow is very smooth. Of all devices tested so far this one had the lowest pressure drop, in the order of 1 to 2 mbar only.

The *modified Schoepentoeter* can handle air/water loads up to 0.11 m/s while entraining 2% liquid (based on total liquid entering the device). The *short vane assembly* can handle loads up to 0.085 m/s for the same 2% entrainment criterion, which translates into a 0.1 m/s for the similar crude oil vacuum tower B of Table 2. While the air/water entrainment rates are helpful in comparing the performance of different devices, care must be taken when transferring this information to the real scale vacuum tower: First, the fraction of small droplets that are easily entrained is larger. Secondly, the proportions in large towers are less favourable as the diameter ratio column to feed nozzle is greater (greater **F**-value). Entrainment could therefore be larger. On the other hand a part of the entrainment would not reach the packing because it is collected by the floor of the chimney tray not taken into account in the experiments.

Another open question is related to the interaction between the liquid and the column wall, especially if the inlet device is smaller. It is expected that a larger distance to the wall would especially affect the entrainment curves of those feed systems that depend on flow to column wall interaction, typically the standard feed but also the *short vane assembly* to some extent. Such questions will be addressed in a future publication that reports results of the next phase of the project.

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