

Experimental investigation of the performance
of a large-scale scrubber operating at elevated
pressure on live natural gas

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Abstract

Experimental results for the performance of a near-full-scale natural gas scrubber operating on a live natural gas system at high pressure are given in this article. The scrubber configuration has three types of internals in series: an inlet vane, a mist-mat and an axial cyclone bank. The variations with pressure of the fluid properties of the natural gas

system are calculated and given, and the performances of the over-all scrubber and of the individual internals at a range of gas and liquid flows and at three different pressures up to 113 barg are shown. The results show that beyond a Souders-Brown K -value of 0.15 m/s, the primary separation efficiency breaks down and that beyond this value of K , the scrubber relies on the cyclones for satisfactory separation. However, at a K -value of 0.26 m/s, the cyclone separation efficiency was poor at high pressure and decreased with increasing pressure. The liquid distribution to the cyclones was highly non-uniform, the outer cyclones receiving much more liquid than the inner ones.

Key words: Gas scrubber; large-scale; high pressure; Souders-Brown equation; inlet; mist mat; axial flow cyclone; hydrocarbon fluids;

1 Introduction

Liquid is removed from the gas in all kinds of gas processing facilities for a number of reasons, such as preventing breakdown of rotating equipment, preventing foaming, hydrate formation and fouling downstream equipment and to keep water- and hydrocarbon dew point within specifications.

In the process of separating liquid and gas, two main types of vessels are used: horizontally oriented and vertically oriented. Horizontal vessels are most often used where large amounts of liquids must be handled, e.g. inlet separators on platforms. Vertical vessels are used when the multiphase mixture has a large gas to liquid ratio. While horizontal vessels often are called separators, vertical vessels are often referred to as gas scrubbers. The

majority of natural gas scrubbers in operation today handle less than 4 vol% liquid. The operating pressures ranges from atmospheric conditions up to several hundred bars, while the temperature might range from -170° in Liquefied Natural Gas (LNG) plants up to more than $+100^{\circ}$ downstream of stripping columns.

The movement to more remote and marginal oil and gas fields and to sub-sea and even down-hole processing and separation, reduces the need for expensive platform-based processing installations and facilities for re-compression, but also demands development of increasingly robust, compact and reliable processing facilities able to operate at elevated pressures. Expenses connected with failure of such sub-sea or down-hole equipment are much larger than for platform-based or land-based equipment, placing further demands on the quality of equipment design.

Such high-quality design demands experimental data generated at realistic processing conditions. Today, design of separator or scrubber internals is normally based on experimental results obtained in air-water systems under ambient conditions. Experimental investigations on such systems have generated a wealth of relevant information about separation principles and also quantitative design data. Nevertheless, such experimental investigations also have their limitations. The physical properties of the fluid system: densities, viscosities and interfacial tension, which differ significantly for different fluid systems and vary with pressure and temperature, will influence the separation characteristics profoundly and not entirely predictably, as will the size of the separator or scrubber.

A gap exists between the knowledge coming from fundamental research on

equipment for gas-liquid separation and its application to the design of real scrubbers. For instance, the droplet size distribution is a key parameter for describing the performance of scrubber internals when these are operating at conditions such that re-entrainment does not dominate in determining the carry-over from them. However, there are no suitable methods for either estimating or measuring the droplet size distribution created in large-scale equipment operating at high pressure with varying fluid properties and flow rates and comprising a range of geometries such as bends, nozzles, vessels and a whole range of different demisting internals. Thus the droplet size distribution is not an available design parameter for large scrubbers that separate hydrocarbon liquids under high pressure. Often scrubber internals operate under conditions where re-entrainment probably dominates in determining carry-over, as is the case in this present work.

Performance data from large scale scrubbers operating at realistic conditions are scarce but valuable in order to improve understanding of the mechanisms governing performance and methods for design. Very few data from scrubbers in natural gas facilities are available, and if they are, they are usually limited to just a few operating conditions. Hence, there is a need for data obtained at a large scale where the operating conditions are varied systematically over a realistic range.

1.1 Availability of data in the public domain

Very little public-domain research is available on large scale scrubbers operating at elevated pressures and with live natural gas. Previously the authors

of this study have published results [1] from a common scrubber configuration tested with a high-pressure natural gas fluid, but in a small scale rig. Oranje [2] showed a comparison of different demisting equipment tested with processed natural gas and condensate or water as liquid. However, no information was given about the physical fluid properties nor the flow rates of the gas and liquid. The equipment was tested in a 0.5 m diameter scrubber at pressures up to 60 bara.

The distribution of gas and liquid may be quite different in large scale scrubbers than in small scale laboratory scrubbers. The size of the vessel may therefore have an impact on the efficiency, thus making testing at large scale necessary to understand the performance of real scrubbers. Real scrubbers vary in size and high pressure scrubbers more than 4 meters in diameter may be used for certain applications. However, the majority of gas scrubbers in operation are much smaller. An inventory of some Statoil operated oil and gas fields show that all except 2 of 94 scrubbers are larger than 0.5 m with the vast majority in the range 1–3 meters.

The aim of this work is to generate experimental data for the operation of a large-scale scrubber acting on a live gas system at high pressure. It builds on two other investigations on pilot-scale scrubbers, one at low pressure with air/water and nitrogen/Exxsol D60 systems [3], and another at a range of pressures up to 91 barg also with two fluid systems: nitrogen/Exxsol D60 and a synthetic live natural gas [1].

1.2 Some notes on current scrubber design practise

The most used expression for sizing of gas scrubbers is that originally developed by Souders and Brown [4] for fractionating columns, involving an empirically quantified factor known as the Souders-Brown value, the K -value, or the Gas Load Factor (GLF).

We briefly recap here, giving the definition of the K -value and discussing its applicability.

The basis of the analysis leading to the K -value is a vertical force balance on a spherical droplet in an upward flowing gas.

If the droplet is held stationary, while moving at its terminal velocity $u_{g,set}$ relative to the gas flowing upward with $u_g = u_{g,set}$, the flow force, F_r balances the gravity force G_d :

$$F_r = C_d A_d \frac{1}{2} \rho_g u_g^2 = G_d = \frac{\pi}{6} d^3 g (\rho_l - \rho_g), \quad (1)$$

where C_d is the drag coefficient, A_d is the projected area of the droplet, $\frac{\pi d_d^2}{4}$ with d_d the droplet diameter, and ρ_g and ρ_l are the densities of the gas and liquid, respectively.

Rearranging, we obtain the definition of the K -value:

$$u_g \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} = \sqrt{\frac{4gd_d}{3C_d}} \equiv K. \quad (2)$$

Thus, if C_d is constant, designing and operating a column at a constant K -value means that, irrespective of *e.g.* the pressure, a droplet of a given diameter will just not be transported upward and out of the column.

The Souders-Brown equation thus takes into account the issue of the lift on a droplet of a given size in a gravitational field, and this is an issue fundamental to the separation in a scrubber. However, there are other relevant issues, which are not taken into account in design based on the K -value:

- As we show in an earlier publication [1], the K -value is not relevant to the action of separation internals based on impaction at all.
- Design on basis of the K -value does not take into account variations in droplet size, for instance due to variations in interfacial tension or other fluid properties with pressure, temperature or fluid composition.
- The K -value does not describe reentrainment of liquid, e.g. from the walls of the internals, although it does describe the upward transport of the formed droplets in a gravitational field.
- The K -value does not include the liquid load, which the separation efficiency depends strongly on.

This project is aimed at investigating the adequacy of current design practise by generating performance data on realistic systems, and point the way to improved design for more critical duties.

2 Experimental

We first describe the experimental facilities and then the properties of the fluids used.

2.1 Experimental facilities

K-lab, the experimental facility used in this project comprises an experimental loop that can test process equipment at large scale, under high pressure and with actual natural gas fluids. The lab is an integrated part of Kårstø gas plant and can make use of fluids from the main process plant.

The diameter of the test scrubber is 840 mm, and is a pressure vessel capable of withstanding pressures up to 156 barg. An interior shell containing the demisting internals can easily be inserted in the test scrubber through a quick-opening cover at the top. This configuration provides a simple and quick way of changing test scrubber internals.

The rig is a closed wet-gas loop were a large vessel—the guard separator—is charged with stabilized condensate from tankers. The loop is then pressurized with lean sales gas from the processing facility and gas and liquid is recombined into a live natural gas fluid.

The test rig is sketched in Fig. 1. The large guard separator acts as a gas and liquid reservoir. The gas is taken from the top of the guard separator and through a gas compressor that drives the gas flow in the gas loop. Liquid from a condensate tank (see below for a description of the fluid used) is continuously measured and injected into the gas loop several meters upstream of the test scrubber. The gas is in equilibrium with the injected liquid when it enters the test scrubber. This statement is supported by earlier research showing that the mass transfer in the fine mist takes place milliseconds after the injection [5], as well as proven by sampling the gas and liquid phase.

If only small amounts of liquid are captured in the inlet section of the test

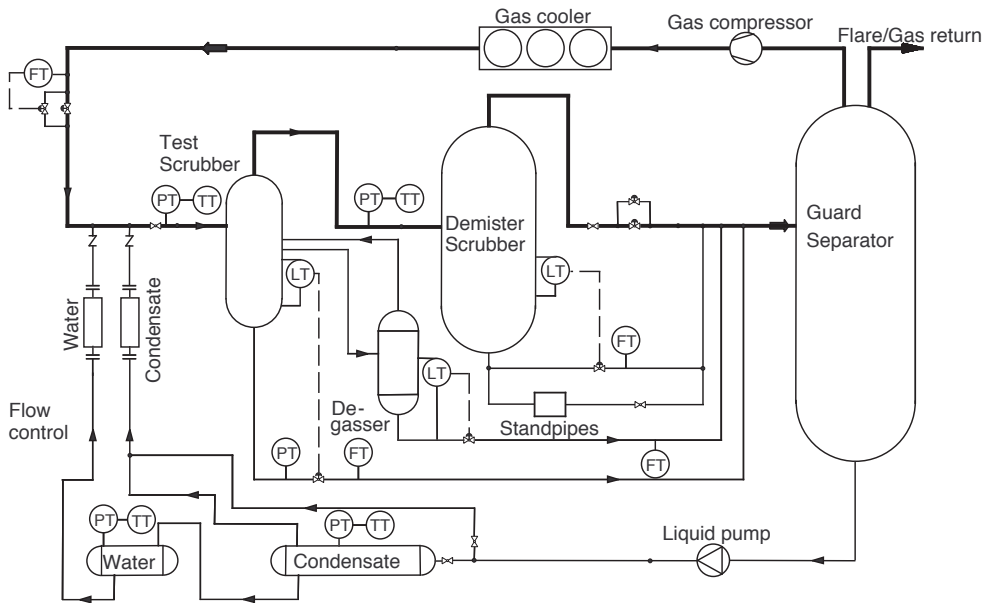


Figure 1: A simplified diagram of the wet gas loop at K-lab. The main gas flow is marked by the thick line, while the thin lines represent the liquid flow.

scrubber, this liquid is measured by monitoring the liquid level in the bottom using both level radars and pressure differential cells. It is also possible to monitor the level visually through level gauges connected to the vessel. If the liquid flow rate from the inlet vane is large, it is continuously measured by one of two coriolis meters mounted at the liquid pipe in the bottom of the scrubber.

The liquid that is captured by demisting internals with a separate drain chamber is drained to the degasser, where it is measured either by liquid accumulation tests or by a coriolis meter as described for the bottom of the test scrubber.

The liquid carry-over from the test scrubber is collected in the demister

downstream of the test scrubber also shown in Fig. 1. The internal diameter of the demister is 1800 mm, more than twice that of the test scrubber. The internals of the demister are an inlet vane, 2 mesh pads and a deck of filter coalescers that can remove droplets down to sub-micron size.

If only very small amounts of liquid is separated in the demister scrubber, it can be drained to one of three stand pipes of 1", 2" or 6" in diameter. If the liquid load is so large that the 6" standpipe is overloaded during a test, a liquid accumulation test in the bottom of the demister is possible. Larger liquid rates in the demister can be measured by continuously draining the liquid through one of two coriolis meters that have different measuring ranges.

The K-lab test rig can operate at a large range of operating conditions shown in Table 1. Liquid concentrations ranging from 0.01 to 3 vol% and K -values up to 0.35 m/s should cover the vast majority of vertical scrubbers currently in operation. Due to limitations in the compressor, the rig cannot be operated below 20 barg. The upper limit of 148 barg is not the upper limit of scrubbers in operation today, several examples of scrubbers operating at pressures above 200 barg can be found.

The design of the rig is such that the uncertainty in the liquid measurements should contribute to an uncertainty in scrubber efficiency calculations of no more than $\pm 0.05\%$ for the range operating conditions specified in Tab. 1. The efficiency is calculated as the average over a test period, which is normally of 15–30 minutes duration and follows an initial process stabilization period. The process conditions are held stable as possible during the test period.

Testing at the large-scale rig is time and cost consuming, but the produced data are also very unique as scrubber efficiency data from this geometry

Table 1: The operating range of the K-lab test rig

Design pressure [barg]	156
Operating pressure [barg]	20–148
Design temperature [°C]	-46–100
Operating temperature [°C]	20–60
Gas rate [Am ³ /hr]	40–1900
Liquid rate [Am ³ /hr]	0.01–60
Liquid concentrations [vol%]	0.01–3
K -value [m/s]	0.03–0.35

and/or pressure scale has never been published in the public domain. Due to the expenses and time limitations, the experimental scheme had to be designed with care. The liquid load was varied using two constant K -values of 0.15 and 0.26 m/s. The tests were carried out at three operating pressures: 28, 55 and 113 barg.

A 3-D drawing of the setup is shown in Fig. 2. The internals used for droplet separation, *i.e.* the cyclones, mist mat and inlet vane are identical to those used in two other, smaller scale, rigs, and have been described in detail in [3].

The 31 cyclones in the deck were a slightly modified version of the cyclones used in the work of Verlaan [6]. They have an internal diameter of 5 cm, and a height of 25 cm. They are of the axial-flow type with swirl vanes (exit angle 45°), and are equipped with vertical slits in the wall for liquid drainage. The cyclones were modified relative to those of Verlaan by installing a vortex finder as described in [3]. The drain compartment is divided in two parts

with separate drain pipes as will be discussed in more detail later.

The mesh pad, constructed in stainless steel, is identical to the Style A investigated by Brunazzi and Paglianti [7]. The wire diameter is 0.27 mm and the void fraction 0.98.

The inlet vane captures some of the incoming liquid, and distributes the incoming gas through a series of vanes at the sides over the column cross-section.

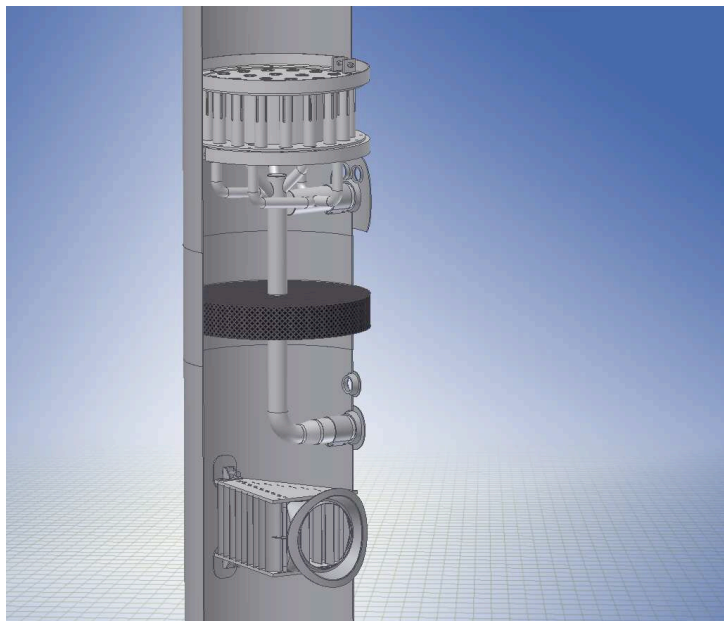


Figure 2: The test scrubber configuration. Lowest is the inlet vane, in the middle the mist-mat and on top is the cyclone deck

The liquid was injected in the straight inlet pipe through nozzles placed more than 10 meters upstream of the inlet vane.

The different liquid flow rates in the rig were measured by Rheonik Coriolis meters, 1/4", 1", 2" or 3" in size depending on the range required. In those

cases where the liquid flow rates were below the range of the coriolis meters, the rates were measured by liquid accumulation tests in either the vessels shown in Fig. 1 or in standpipes of 2" or 6" size. The liquid level in these cases was measured by using guided wave level radars from Magnetrol, that are capable of measuring liquid level with millimeter precision. More information about the rig and its instrumentation can be found in [8].

2.2 Fluid Properties

The rig was pressurized with real, dry natural gas, that was recombined with dead natural gas condensate. The liquid was injected in spray form so far upstream of the test scrubber that an equilibrium was established between the gas and liquid phases before the mixture reached the scrubber. For each of the three pressures used, 28, 55 and 113 barg, a new fluid composition was calculated. In fact, the pressure and temperatures in the rig would vary somewhat from one experiment to another, and therefore an integrated fluid calculation system constantly updated the physical fluid properties.

Changes in the liquid rates caused by condensation or evaporation were accounted for in the separation efficiency calculations.

The thermodynamic equations used to calculate the gas and liquid compositions in equilibrium were the SRK EOS modified with the Peneloux volume correction [9, 10].

In order to evaluate the accuracy of the fluid composition calculations, samples of the equilibrium liquid and gas phases were taken at two different pressures. The samples were then analyzed in a commercial laboratory that

uses a GC in accordance with the ASTM D-1945 standard for gas composition analyses, and a frequency densitometer in accordance with the ASTM D-4052 standard for liquid density measurements. The liquid composition was analysed by use of an HP 5890 Plus/Perkin Elmer Autosystem XL chromatograph in accordance with an internal laboratory standard.

For the gas composition calculations the C9+ fraction and for the liquid composition calculations the C10+ fractions were lumped into one fraction with a corresponding characteristic density and molecular weight.

The compositions from these analyses were compared to the fluid composition calculations in the first test run after the sample was taken. The analyses of the two liquid and gas samples were compared with the calculated compositions. Detailed tables of this comparison are available in [8]. Pooled estimates of the deviations calculated from:

$$s_{pooled} = \sqrt{\frac{\sum_i^{N_c} (x_e - x_c)^2}{N_c/2}} \quad (3)$$

where N_c is the number of components, which is also the number of degrees of freedom in the estimate of s_{pooled} . x_e and x_c are the measured and calculated mole percentages, respectively. The resulting estimated deviations were 0.43, 1.48, 0.29 and 0.25 mol% for the two liquid and two gas samples, respectively.

These deviations between analysis and calculation are generally larger than the uncertainties in the composition analyses, indicating a slight inaccuracy in the calculation routines, due to both experimental effects and the quality of the thermodynamic relations used.

As mentioned, the fluid composition in the test scrubber changes slightly due to small changes in process conditions. However, the small variations do

not change the calculated values of the physical fluid properties more than $\pm 0.5\%$. Typical values of the physical properties are listed in Table 2.

Table 2: Typical physical fluid properties in the test scrubber at the three test pressures

	28 barg	55 barg	113 barg
Gas density [kg/m ³]	22.0	46.0	104.0
Liquid density [kg/m ³]	704.0	682.0	640.0
Gas viscosity [cP]	0.012	0.013	0.016
Liquid viscosity [cP]	0.450	0.385	0.260
Interfacial tension [mN/m]	14.5	10.9	5.0

The quality of the calculated physical properties is difficult to evaluate, but the liquid density was continuously measured by coriolis meters. The measured densities were always within 1.4% of the calculated values. The densities of the liquid samples in Table 2 were measured at the actual temperature and pressure of the guard separator at the time of the sampling. The measured density was 0.7% less than the calculated density for the lowest pressure and 2.2% larger for the highest sample pressure.

No viscosity or interfacial tension measurements are available that can verify the calculated values. The presence of small concentrations of heavier components in the fluid may increase the uncertainty of the calculations.

3 Results and Discussion

First, the performance of the cyclone deck is described first and then that of the inlet vane and mistmat together.

3.1 Performance of the cyclone deck

In all experiments, the liquid was injected in the tubing upstream of the scrubber, so that some of the liquid was separated by the internals before it arrived at the cyclone deck. It was therefore not possible to tune the liquid flow to the cyclones precisely, so as to keep it constant while varying the gas flow. It was, however, possible to measure the liquid flow to the cyclones precisely, and so to keep the gas flow constant, while varying the liquid load in a somewhat haphazard manner. The liquid flow to the deck was measured as the sum of the overhead and captured fractions from the deck, such that the measured efficiency does not include the effect of the primary internals.

The cyclone separation efficiency with a K -value—calculated from the left-hand-side of Equation (2) using the superficial gas velocity in the scrubber vessel—of 0.26 m/s is shown in Fig. 3.

The efficiency seems to increase with increasing liquid load up to 100–150 l/hr per cyclone while at higher liquid loads, the trend is the opposite. For this K -value, the efficiency with the 55 barg operating pressure is better than at 113 barg, although this conclusion is weakened by the fact that only one condition was tested at 55 barg.

The separation efficiency is higher at the lower K -value, and therefore the

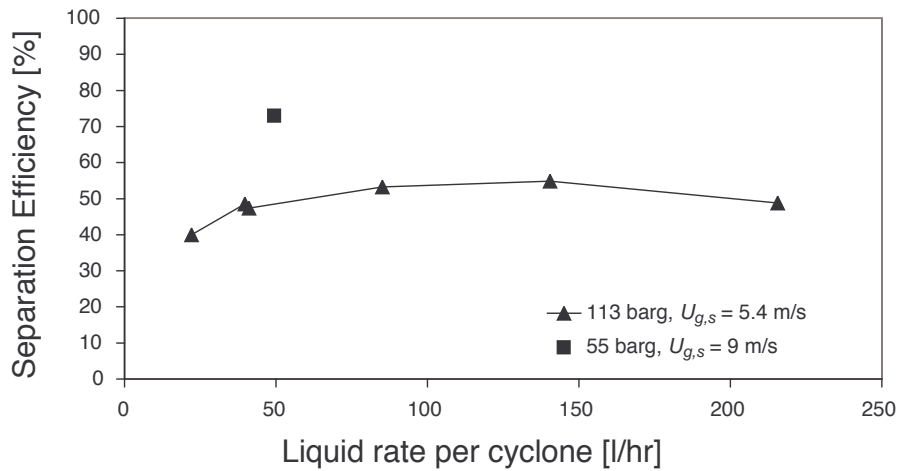


Figure 3: The cyclone efficiency as function of the average liquid flow to the deck per cyclone for vessel $K = 0.26$ m/s at two different pressures. The velocity in the legend refers to the superficial velocity in the cyclone

lower gas velocity. Cyclones would normally be expected to separate small droplets better as the gas velocity is increased, so this indicates that, under these conditions, re-entrainment rather than a small incoming droplet size limited the separation efficiency of the cyclones.

Attention was paid to the liquid distribution over the cyclone deck. A special layout for the drain chamber (see Fig. 4, left) made it possible to divide between the liquid separated by the outer 18 and the inner 13 cyclones, and hence to quantify radially uneven liquid distribution to the cyclone deck.

It was found that the outer cyclones captured 2–2.5 times as much liquid per cyclone as the inner ones. Other results [1] have shown that the fractional separation efficiency decreases with increasing liquid load, so that the liquid flow to the cyclones may differ even more.

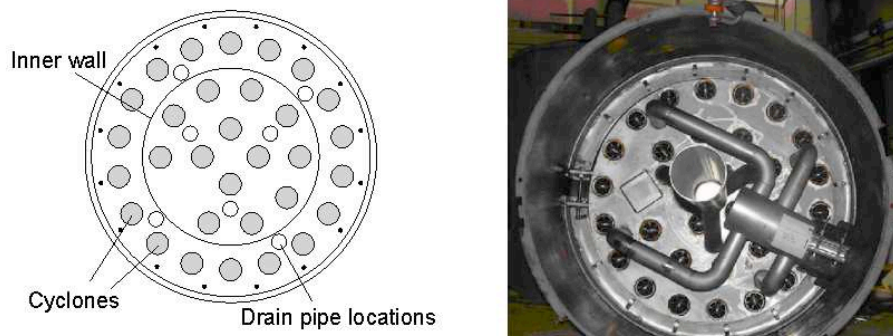


Figure 4: Left: schematic of the special drain arrangement for the cyclone deck in a top view. An inner wall was placed in the drain chamber so that the liquid from the outer and inner cyclones were drained separately. Right: photo of the drainage arrangement

There are two possible reasons for this uneven distribution:

- The inlet vane may distribute gas and liquid unevenly over the cross-section, and this uneven distribution may persist also above the mesh pad. The inlet vane may distribute gas and liquid unevenly over the cross-section, and this uneven distribution may persist also above the mesh pad. The uneven distribution of gas above a vane has been shown in other publications [11].
- The drain manifolds under the cyclone deck block part of the cross-section in the center limiting flow to the central part of the deck. The photo to the right in Fig. 4 shows this to be the case to some extent, but the 3-D drawing in Fig 2 shows that the horizontal drain tubes were some distance below the deck, allowing the flow to redistribute to some degree above the tubes.

Thus caution should be applied if designing a large cyclone deck on basis of the performance of a single cyclone.

The pressure drop in the cyclones was measured as the sum of the pressure drop from:

1. Upstream of the cyclone deck to the drain chamber
2. The drain chamber to downstream of the cyclone deck

The measured cyclone pressure drop thus does not include the pressure drop over any of the primary separation internals. The pressure drop in the cyclones increases with increasing inlet liquid concentration as shown in Fig. 5, as the Euler number:

$$Eu = \frac{\Delta P}{\frac{1}{2}\rho_g v_g^2}.$$

The pressure drop can be seen to be somewhat larger at 55 barg than at 113 barg, the difference rising from about 2% at low liquid loading to about 6% at 0.5 vol%. The opposite trend with pressure was found for the mesh pad (see below). At 113 barg the pressure drop increases by about 8% when the liquid load is changed from very low up to 1 vol%.

3.2 Performance of the inlet vane and mesh pad

The liquid concentration in the inlet pipe was held constant at 0.2 vol% for K —calculated using the superficial velocity in the scrubber vessel—ranging from 0.1 to 0.26 m/s at 55 and 113 barg. The efficiency of the inlet vane

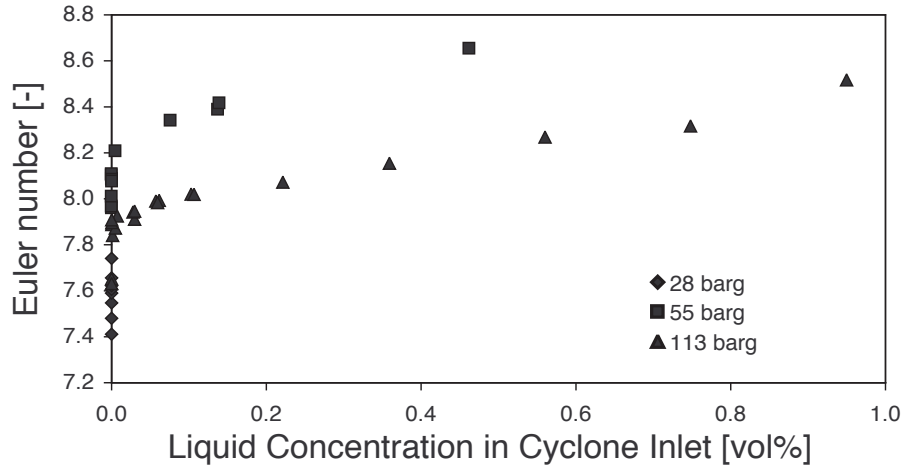


Figure 5: The figure shows the Euler number over the cyclone deck at varying liquid concentrations in the cyclone inlet. The liquid concentration is calculated based on the total gas and liquid flow rates to the cyclone deck

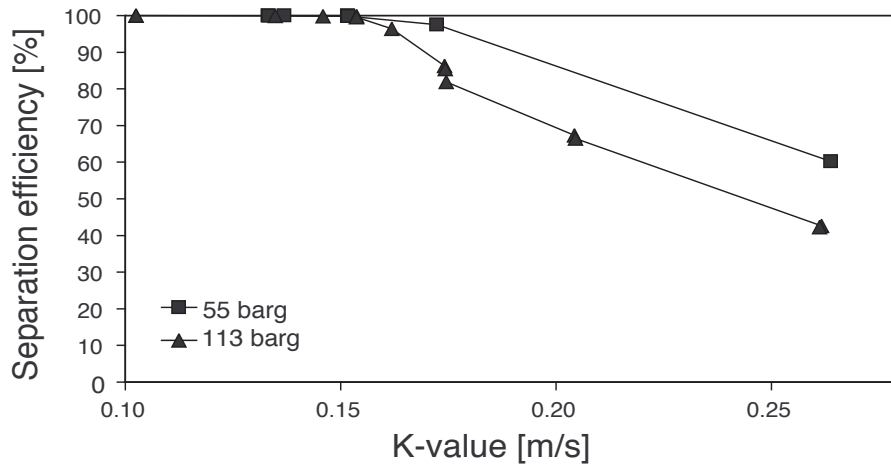


Figure 6: The primary efficiency for a liquid concentration in the inlet pipe of 0.2 vol%

and mesh pad—hereinafter referred to as the primary efficiency—is plotted in Fig. 6.

The efficiency is seen to decline rapidly when K exceeds 0.17–0.18 m/s. Once again, the efficiency is lowest at the higher of the two tested operating pressures, and at $K = 0.26$ m/s more liquid is lost than separated by the primary separation internals.

For $K = 0.17$ m/s at 113 barg pressure, three repetitions were carried out. In the repetition that gave the lowest efficiency, the liquid flow rate in the test scrubber and degasser was continuously measured by coriolis meters, while liquid accumulation tests were carried out for the two other repetitions. In spite of the liquid flow rate being only moderate in these experiments, the liquid capacity in the bottom of the test scrubber only allowed tests of 10–15 minutes duration, something which may have increased the uncertainty in the two results where the accumulation test method was used.

The primary efficiency has been tested as function of liquid concentration in the inlet pipe at two different K -values, 0.15 and 0.26 m/s; the results are shown in Fig. 7. The NORSOK-standard [12] recommends that a scrubber with inlet vane and mesh and cyclones as the present one, should be designed with maximum K of 0.15 m/s. The results show that the inlet vane and the mesh are capable of performing the separation at this value of K without the need for any cyclones. Only at 113 barg pressure case a significant amount of liquid carry-over is seen, but the efficiency is still better than 99.5%. The results indicate that the mesh pad is in a non-flooded condition at $K = 0.15$ m/s within the tested range of liquid loadings, so the liquid carry over in the 113 barg case may be small droplets that have penetrated

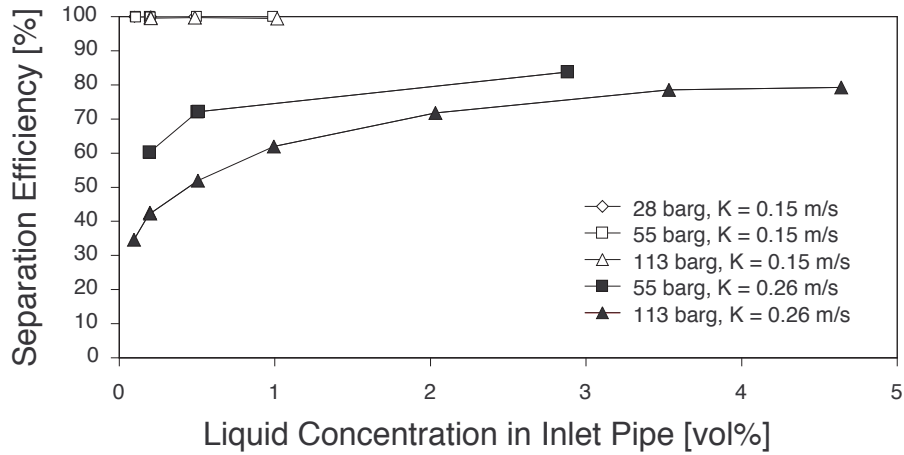


Figure 7: The primary efficiency as function of the liquid concentration in the inlet pipe for two values of K

the mesh pad.

We chose to vary the concentration in the incoming stream rather than the absolute liquid flow to the mesh pad in these experiments to make comparison between different scales possible. Nevertheless, comparisons between different scales must be done with caution, since the size of the pad can affect the performance. This underlines the need for testing on large scale, close to the field scale, as we are doing in this work.

At $K = 0.26$ m/s the mesh pad is in a flooded condition, and the separation efficiency is well below the efficiency that at $K = 0.15$ m/s. For the lowest liquid concentrations at the highest test pressure, the primary efficiency drops below 40%. However, at this K -value the efficiency is very dependent on the liquid concentration. For both test pressures the efficiency increases with

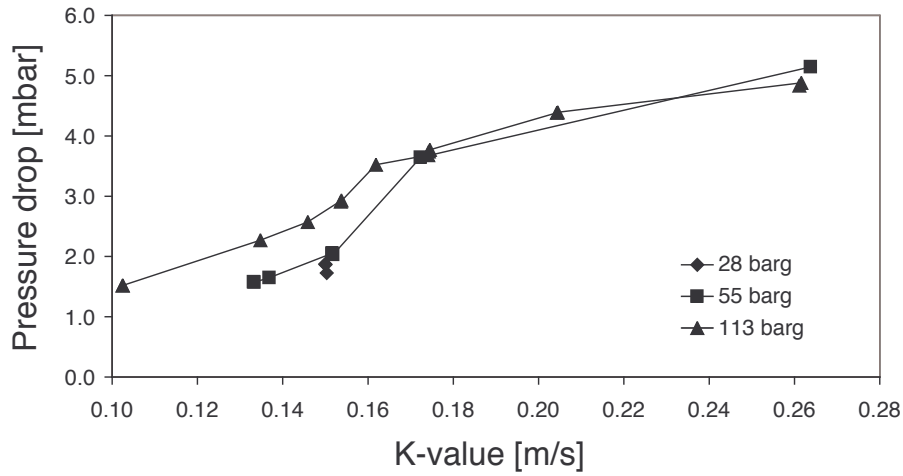


Figure 8: Mesh pad pressure drop when 0.2 vol% liquid was injected in the inlet pipe

increasing liquid concentration.

Pressure drop measurements over the mesh pad with 0.2 vol% liquid injected in the inlet pipe are shown as function of K -value in Fig. 8. The pressure drop information is limited for the 28 and 55 barg cases, but for the 113 barg case a detailed trend of the pressure drop at varying liquid concentration is produced. At a K -value of 0.15 m/s, the pressure drop increases with increasing operating pressure.

No sudden increase in pressure drop was found around mesh pad flooding, although such an increase had been expected. The pressure increases slightly steeper around 0.15–0.17 m/s. This may indicate that a transition to flooded conditions takes place.

4 Conclusions

The first experimental data on a full-sized standard scrubber configuration, equipped with inlet vane, mist mat and a cyclone bank, acting at high pressures on real, live natural gas have been presented in the open literature in this article.

The results have shown that:

- The calculation procedures used for the composition and physical properties of the live natural gas system gave reasonable results.
- The liquid distribution to the cyclones in the bank was highly non-uniform, the outer cyclones receiving at least 2-2.5 as much liquid as the inner ones. This may partly be due to obstruction of the central cyclones by the drainage system, but probably also due to inherently non-uniform cross-sectionally in the large scrubber.
- The dimensionless pressure drop, Eu , was nearly independent of pressure as expected [13], although it decreased slightly, by 4 or 5%, from 55 to 113 barg. Eu increased by about 6 or 7% as the liquid flow to the cyclone was increased up to 1 vol%. This is in accordance with earlier studies [14].
- The primary separation efficiency (the separation efficiency of the inlet vane and the mesh pad) broke at a K -value of about 0.15 m/s, both at 55 and 113 barg, and that a scrubber working at higher K -values relies on the cyclone bank for satisfactory separation. This globally confirms that the Norsok [12] recommendation of $K \leq 0.15$ m/s for this

type of scrubber is reasonable, but also shows that below this limit the primary separation internals actually suffice over a wide range of liquid flows to the scrubber without the need for cyclones. The primary separation efficiency for $K = 0.26$ m/s was much lower. It increased with increasing liquid concentration.

- The cyclone separation efficiency at higher K -values was only moderate, and decreased with increasing pressure. In light of the previous point, this is something to be aware of.

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