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Improvements on a laser scattering technique for droplet size measurements applied to a gas–liquid separation equipment

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ABSTRACT

The knowledge of droplet size distributions in a gas–liquid separation equipment is of high relevance due to the importance of removal efficiency in these systems. Different techniques could be used to measure droplet size, being one of them the diffraction of a laser beam. The laser is located behind glasses, being the formation of droplets on the glasses one of the main problems encountered when using this technique.

Due to this major problem, different innovative solutions have been proposed and implemented to the gas–liquid separation column in order to obtain satisfactory results. A shutter mechanism, a purge gas and combination of these two solutions were tested. It was shown that the modified technique is suitable for liquid droplet measurements under ambient conditions.

It has been also shown that the combination of these two solutions reduced considerably the amount of droplets that interacts with the glasses, allowing getting better data.

1. Introduction

Droplet removal from high pressure gases is one of the most common and important operations in gas processing. Dispersed droplets may produce erosion and/or degradation of equipment involved such as breakdown of rotating equipment and contamination of dehydration or acid–gas removal units. This purification process is normally carried out in vertical vessels called scrubbers which operate in a wide range of pressures and temperatures, from atmospheric to approximately three hundred bar and from ambient temperature to over 100 °C during separation of natural gas condensates from natural gas [1].

A typical scrubber is comprised of three main parts: an inlet vane, a mesh pad and a cyclone section in order to obtain a separation efficiency according to specifications. A sketch of a scrubber can be seen in Fig. 1. The first part, the inlet vane, has as main purpose to reduce the momentum of the inlet two-phase flow and to separate the free liquid and large-sized droplets from the gas. As a second step, normally a mesh pad which consists of layers of knitted wire is used to separate small droplets from the gas flow. The mesh pad may also be used in a flooding mode, where the main purpose is to increase the average droplet size. Finally, in the upper part of the scrubber, there is commonly a bank of cyclones which remove the remaining droplets and lead the liquid back to the bottom of the scrubber. The resulting gas stream should be free of mist and according to specifications. This technique works well under atmospheric pressure, but for high pressure gases this could involve decompression of the main flow to be purified followed by a subsequent recompression in order for the gas to be fed into the gas pipe lines. Scrubbers are also used at high pressure conditions (over 50 bar). However, in contrast with atmospheric conditions, severe problems, such as droplet entrainment, re-entrainment, and droplet-wall interactions, appear at high pressure. See [1–3] for a description of the main physical phenomena taking place from lower to higher pressures.

In this work, the technique used for droplet size measurement was a laser diffraction system adapted to the

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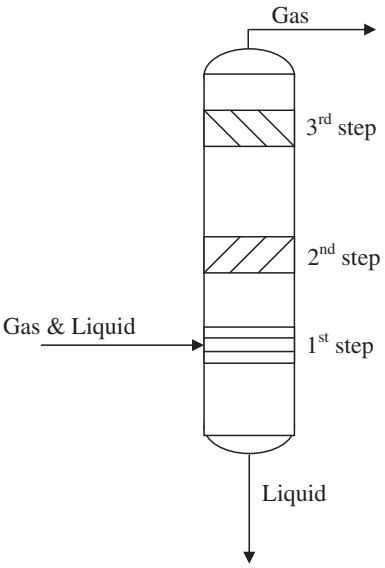

Fig. 1. A typical scrubber and the three main separation sections.

equipment. A principle sketch of the system can be seen in Fig. 2.

Laser diffraction techniques are based on quantifying the scattered light that reaches a receptor after interacting with the solid particles or droplets in the optical path. This technique has been used for many years and for several purposes. Szymanski et al. [4] have used multiple light scattering to measure droplet sizes in aerosols, while Goddeeris et al. [5] used light scattering to measure droplet sizes in dilute micro emulsions. Lamanna et al. [6] used low angle light scattering techniques to measure droplet sizes in several liquid systems in order to test the evaporation rate of droplet arrays. The method was also used for determining droplet spacing.

Lamanna et al. [6] found that sizes were estimated with good accuracy and developed a model to correlate all their experimental information with good results. Similar work, but using di-2-ethyl-hexyl-sebacate covered with water droplets, was performed by Wind et al. [7]. Similar techniques have been used to measure or estimate drop size distributions in several processes or equipment in different industrial applications such as pharmacology, chemical engineering, petroleum processes, and food processing [8–10]. Fore et al. [11] used video camera image analysis to study drop sizes in the nitrogen–water system at low and medium pressure in an annular gas/liquid flow situation. Other examples of studies on two-phase annular flows are papers by Azzopardi et al. [12], Azzopardi [13], Langston et al. [14], Alonso et al. [15], Simmons and Azzopordi [16] and Azzopardi [17].

Simmons and Hanratty [18] used a commercial diffraction system, very similar to the one used in this work, to measure drop size distributions in an annular gas–liquid flow. The authors compared their results with Azzopardi's model, which showed less effect of liquid flow rate than the measurements, and a new correlation was developed for small drops. The same commercial equipment was used by Dayal et al. [10] to study droplet sizes produced from a nasal spray and the influence of the physical properties on the final results.

In this work, we have used the commercial laser diffraction equipment Malvern's Insitec, for droplet size measurements in the various parts of a gas/liquid scrubber column. Initially, several measurement problems were detected when using this technique. To improve the measurement setup, new technological solutions were implemented and their advantages and disadvantages are discussed in order to optimize the technique and to develop a procedure that has satisfactory reliability and reproducibility. Due to not having the possibility of knowing the situation inside the equipment while doing experiments, a CFD (computational fluid dynamics) code, based on the commercial software fluent, was done in order to see the velocity vector profile and to reassure the behavior seen with the droplet. Even more, this software will allow us to have a better understanding of the situation inside the equipment and will be a helpful tool to predict future scenarios.

2. Experimental equipment

To perform this study, a laser scattering technique was employed to measure the droplet size and to obtain the droplet size distribution inside the experimental setup.

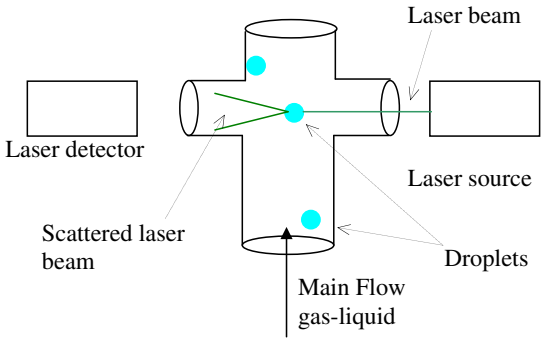

Fig. 2. Sketch of the laser system used for size measurements.

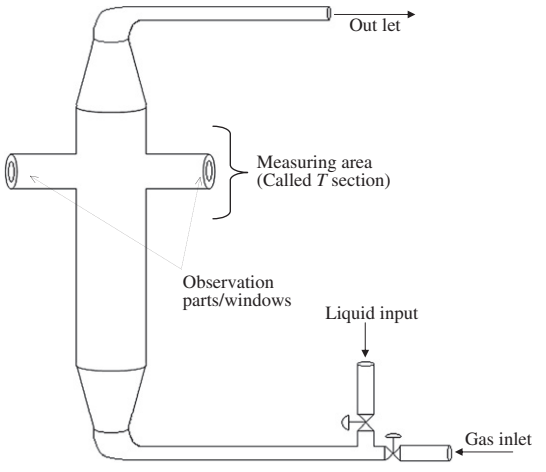

Fig. 3. Schematic design of the experimental equipment and setup.

The experiments were carried in a pilot plant column; Fig. 3 shows a schematic design of the equipment used in this work.

The inlet for both liquid and gas was from the bottom of the system, as presented in Fig. 3, while the outlet of both phases was at the top of the equipment. In the upper part of the column, there was a *T* section where the laser equipment was attached in order to perform the measurements. Data were obtained and processed with the Malvern Insitec software that allowed determination of both droplet size distribution and droplet volume fraction.

The liquid used was mainly water, but some experiments with 96 wt.% ethanol were also performed. The gas was pressurized (6 bar) air though the experiments were done at atmospheric pressure. The column was 2.5 m high and had a diameter of 30 cm. The *T* section was 15 cm long and the diameter 12 cm. On the side sections, borosilicate glasses were attached.

The measurements were hampered by splashing of droplets onto the glasses, as described in Section 3. Because of this, different technological solutions were implemented. The first approach was the use of a secondary purge gas. This has the main aim of creating a gas flow inward toward the main flow and thereby prevents droplets from reaching and attaching to the windows. The system used is presented in Fig. 4a–c. In Fig. 4c can be seen two holes, one blows gas radially to the side extension, while the second one blows gas tangentially into the side extension, this is to avoid deposition of droplets in this part of the equipment.

It is important to notice that the flow of secondary gas used for the purge system needs to be small to avoid a considerable perturbation on the main flow. However, it has to be large enough as to produce a flow from the glass to prevent droplets from impacting on it.

The second technique implemented was a shutter system that reduces the exposure time of the glasses to the main flow with droplets. This mechanism allows the user to make measurements when required by opening the shutter. The shutter system used can be seen in Fig. 5I–IV.

Previous work done by Marchetti et al. [19] has shown that the laser scattering technique used was suitable for measuring liquid droplets with satisfactory accuracy. Due to its good reproducibility and repetitively, the equipment used by Marchetti et al. [19] was mounted on a holder in order to locate the laser at the *T* section of the column of Fig. 3. In this lab equipment, droplets were produced by entrainment of liquid by gas at the bottom of the column and determine by a diffraction technique at the measuring area (*T* area in Fig. 3).

At the measuring section, five different configurations of glass, shutter and/or purge gas were implemented. The five tested configurations can be seen in Fig. 6I–V. It is important to point out that the aim with this technique is to have a very reproducible measure over time, and that means that the system should always have the same droplet size distribution. However, it is possible that the amount of droplet being analyzed is different from time to time; this could be seen on the volume fraction quantity, but the droplet size quantity should always be in the same value.

3. Results and discussion

3.1. Case I. Simple glass

When using configuration I given in Fig. 6I, droplets from the main flow were guided against the glasses due to secondary flows setup by the main flow. In order to verify the influence of the main flow, a CFD simulation was

Fig. 4. Purge system. (a) Main view of the apparatus. (b) Back view of the system. (c) View of the two inlet of gas.

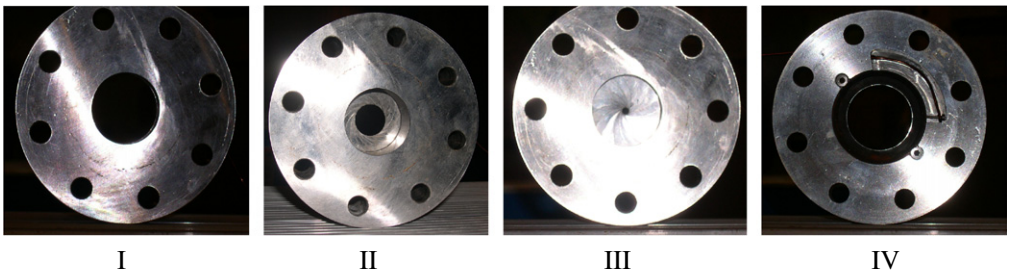

Fig. 5. Shutter system. (I) complete open shutter. (II) Partially close shutter. (III) Complete closed shutter. (IV) reverse side of the system.

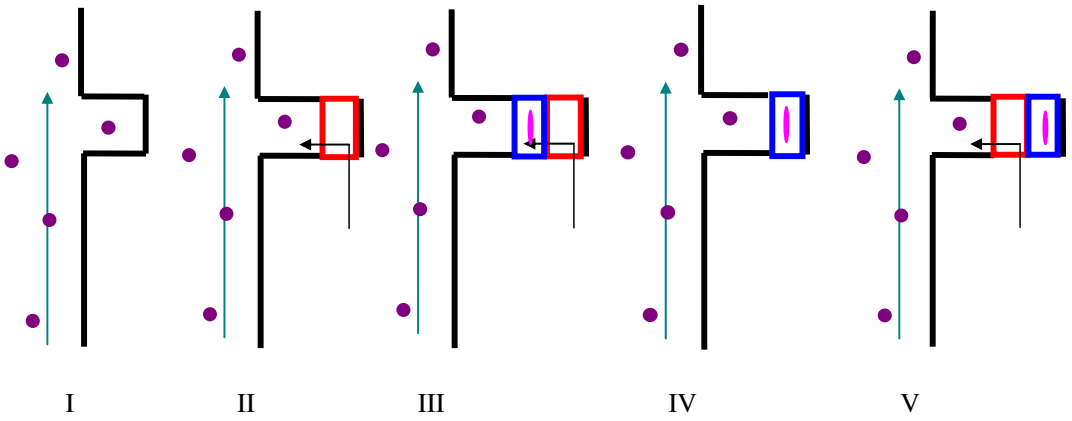

Fig. 6. Different system tested. (I) glass alone. (II) Purge gas system. (III) Shutter system and Purge gas, shutter close to the main flow. (IV) Shutter system. (V) Shutter system with Purge gas, the latest close to the main flow.

done of the experimental setup. The velocity profile can be seen in Fig. 7 where it is easy to see that droplets in the main flow have a significant chance of hitting the glasses. This was also experienced experimentally, and when opening the system for cleaning, droplets were found over the glasses. Fig. 8 shows a photo of the glasses after measurement and how droplets have splashed on it.

When the measurement is performed and droplets have splashed on the glasses, the laser light will also be scattered due to the deposited droplet. Since, this is a dynamic process, and also because droplets start draining on the glass, this makes the measurements very inaccurate. So in a time dependant system, like the one on this work, it is impossible to obtain a constant background that could be statistically erased. Therefore, the measurements with glass alone will give different droplet sizes as long as the measurements are performed. This can be seen in Fig. 9, where for different times, the mean diameter is changing. It is important to notice that there is no breakup/coalescence of the droplet and the changes in the diameter are due to the errors in the measurement.

It is important to notice, for the entire droplet size plot, that the y axis, labeled volume fraction, is relative to the amount of droplets being measured and not to the droplet size. Therefore, the height of each peak is not relevant for this work and only the mean droplet size should be constant over time.

3.2. Case II. Used of a purge gas

In order to improve the measurements shown in Fig. 9, the purge system alternative was tested. In this case, the

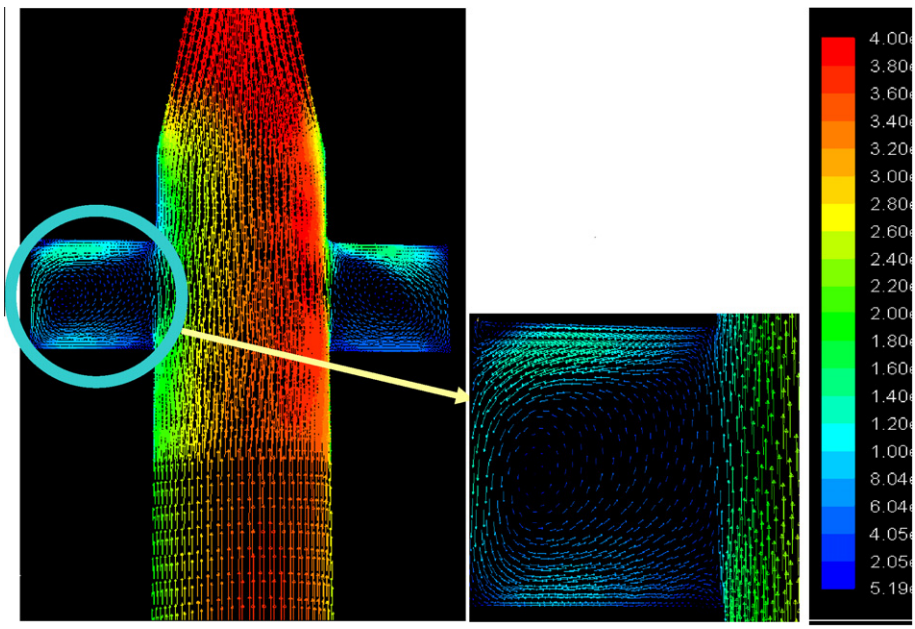

Fig. 7. CFD result of the T section of the experimental setup.

Fig. 8. Glasses with liquid droplet splashed.

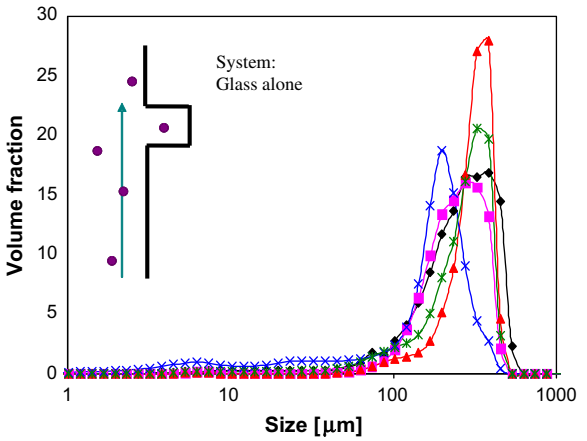

Fig. 9. Measurements without purge or shutter as function of time. (●) $t = 0$, (■) $t = 10$, (▲) $t = 20$ (✻) $t = 50$, (X) $t = 60$.

same gas as in the main flow was used. This gas is at its saturation point and the purge gas was slightly dried in order to avoid any condensation on the glass. In this way, no droplet was introduced from this secondary inlet. The flow rate was adjusted to avoid having a large flow rate that could produce a considerable modification to the main flow. This solution had the aim of blowing the droplets back to the main stream. Fig. 10 shows the results obtained when a purge gas was implemented. Even though an improvement can be seen in comparison with the results from Fig. 9, there are still some fluctuations in the average droplet size from measurement to measurement. This could be due to the fact that not all droplets are being rejected away from the glasses and some of them still reach the glass and thereby produce a noisy background signal.

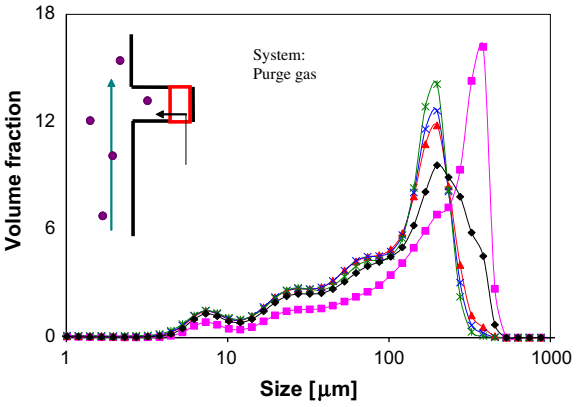

Fig. 10. Measurements when using purge gas as function of time (s). (●) $t = 0$, (■) $t = 10$, (▲) $t = 20$ (✻) $t = 30$, (▼) $t = 60$.

3.3. Case III. Implementation of a shutter system

In a second step, the shutter system was tested. The shutter was a conventional photographic shutter with an *ad hoc* design made in our facilities to be able to adjust it to the experimental system. The laser beam from the emission source has a smaller diameter than the laser that has been scattered and reaches to the receiver. Therefore, in order to reduce the exposure area of the glasses, the shutter used for the emission side was smaller than the one required for the receiver. The results obtained with the shutter technology implemented can be seen in Fig. 11. It can be seen that even though the measurements are quite good, the droplet size still have showed fluctuation from one time to another and therefore improvements were required.

3.4. Case IV. Purge and shutter (purge close to the glass)

As none of the above solutions worked perfectly alone, a third approach was considered using both alternatives simultaneously. The shutter system was placed close to the main flow with the purge gas on the glass beside of it. This system worked reasonably well and allowed the measurements to continue for an hour with just little

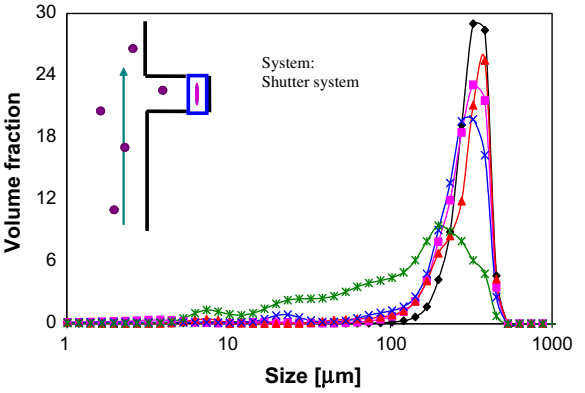

Fig. 11. Measurements when using a shutter as function of time (s). (●) $t = 0$, (■) $t = 10$, (▲) $t = 20$, (✻) $t = 30$, (■) $t = 60$.

changing in the mean diameter, as seen in Fig. 12. However, the droplets that managed to get past the shutter and did not either reach the glass or blown back to the main flow but precipitated between the shutter and the glass producing a small spool of liquid. This reservoir of liquid played a negative role in the measurements: when the shutter was closed, the purge gas could very easily produce entrainment over the confined liquid. The entrained droplets could easily deposit on the glass and produce a distortion of the scattered light. This is seen in Fig. 13.

3.5. Case V. Shutter and purge (purge close to the main flow)

Based on this last problem, it was decided to try locating the shutter closest to the glass and the purge gas on the column side. Even though liquid might continue to pass through the shutter, when the droplets fall down making a liquid reservoir, there will be no gas that can produce new droplets. This configuration was tested and measurements could be maintained with excellent accuracy for over 2 h of operation time. The results are presented in Fig. 14, where the accuracy in the droplet size distribution can be seen. The mean droplet diameter is the same for all measurements.

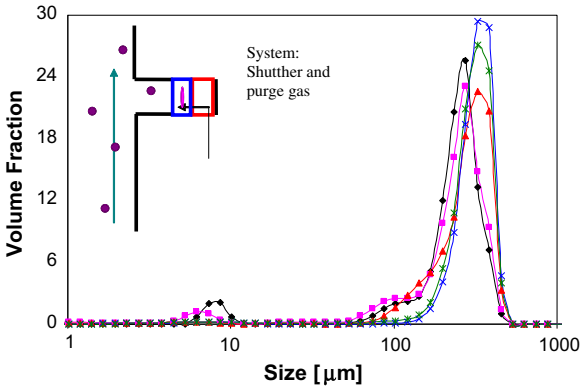

Fig. 12. Measures when the shutter is close to the main flow. (●) $t = 0$, (■) $t = 10$, (▲) $t = 20$, (X) $t = 30$, (✻) $t = 60$.

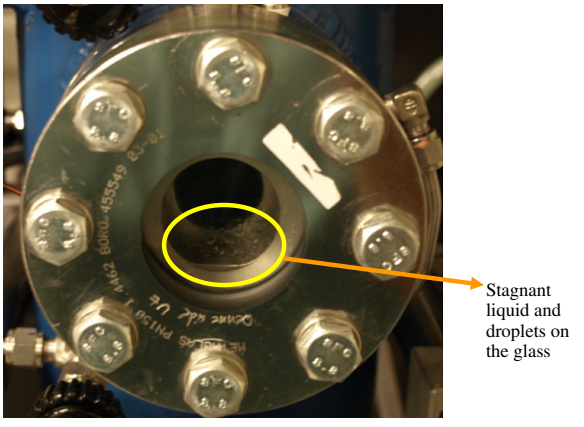

Fig. 13. Liquid hold up between the shutter and the glass. Droplets form on the glass due to possible liquid entrainment by the purge gas.

With the aim of testing the system for other droplet sizes, the main flow was reduced to half of its original value and measurements were done using the same purge/shutter system. As expected, when the flow is reduced, it was found that the mean droplet size is reduced, changing from a mean droplet size of 325 μm–276 μm. This allowed us to see that the system could be suitable also for smaller droplets. To obtain significantly smaller droplets, 96 vol.% ethanol was employed instead of water. When using this new compounds, a bimodal plot was obtained, having a small droplet size mean value lower than 10 μm. Fig. 15 shows the results while also allowing us to see a bimodal plot.

The most important observation is, however, that both peaks maintain a constant mean droplet size for measurements lasting of over 2 h, showing the good accuracy of this combined solution.

4. Conclusions

It was shown in this work that a new combined shutter and purge gas system for laser diffraction measurements could be used for undisturbed measurements of liquid

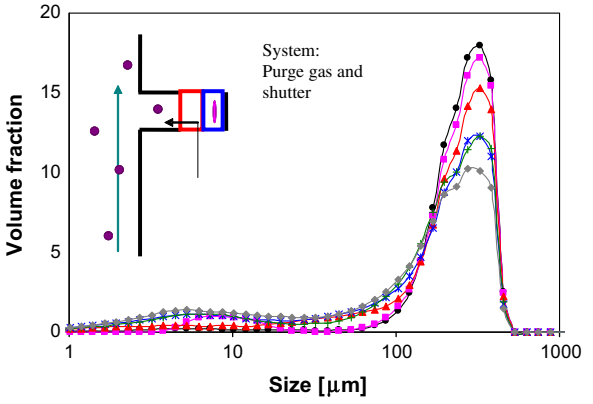

Fig. 14. Measurements when using both shutter and a purge gas as function of time (s). (●) $t = 0$, (■) $t = 10$, (▲) $t = 30$, (✻) $t = 40$, (+) $t = 50$, (♦) $t = 60$.

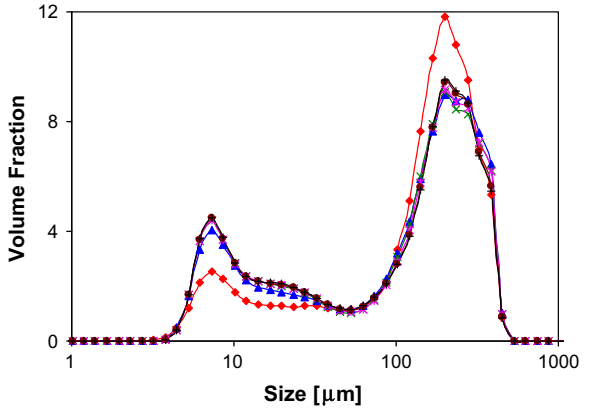

Fig. 15. Measurements when using both shutter and a purge gas as function of time (s). (◆) $t = 0$, (▲) $t = 20$, (X) $t = 30$, (✻) $t = 60$, (●) $t = 90$, (+) $t = 120$.

droplets present in a gas stream. Two liquids with different surface tensions were tested verifying the good reproducibly in the measured droplet size distributions.

In the pilot plant system, CFD simulations were shown to be a predictive tool of the purge gas problem. The simulations made the problem visible and provided a prediction when using the laser scattering technique in a larger separation column.

The first results obtained are related to the liquid–air system at ambient pressure and temperature, with the major aim of validating the measurement system. It was found that satisfactory results for the droplet size measurement could be obtained for two quite different liquids. In a second step, results obtained for a pilot plant system showed that the measurements were not satisfactory when using the system on its own, due to the interaction of droplets with the glasses which lead to a perturbation of the laser signal. This problem was studied with different configurations of purge gas system and a triggered shutter. Neither of these solutions separately reached the desirable accuracy that this type of systems required. Therefore, a combination of both has been developed and implemented. When using the combined system, all the experimental data obtained in the test column showed good accuracy and reproducibility.

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