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DROP SIZE MEASUREMENTS IN A LABORATORY SCALE VENTURI SCRUBBER

Diego Fernández Alonso
School of Chemical, Environmental and Mining Engineering
University of Nottingham
Nottingham, NG7 2RD, United Kingdom
José A.S. Gonçalves
Departamento de Engenharia Química
Universidade Federal de São Carlos
São Carlos – SP
Barry J. Azzopardi
School of Chemical, Environmental and Mining Engineering
University of Nottingham
Nottingham, NG7 2RD, United Kingdom
José R. Coury
Departamento de Engenharia Química
Universidade Federal de São Carlos
São Carlos – SP

Abstract. *Venturi scrubbers are high efficiency gas cleaners in which suspended particles are removed from gas streams by droplets formed by liquid atomisation, usually in the venturi throat. The size of the droplets formed is of fundamental importance to the performance of the equipment, both in terms of pressure drop and collection efficiency. In this study, drop sizes in a cylindrical laboratory scale venturi scrubber were measured using a laser diffraction technique. Gas velocity and liquid to gas ratios varied from 50 to 90 m/s and 0.5 to 2.0 l/m*^{3}*, respectively. Water was inserted as perpendicular jets at the beginning of the throat. Measurements were performed at three positions: two located along the throat, and the last one at the end of the diffuser. The data presented here are a typical example of pneumatic atomisation and can be relevant to other industrial applications such as combustion and engine technology. Finally, results are compared to available correlations and the validity of these equations is discussed.*

Keywords: Venturi scrubber, Drop size, pneumatic atomisation

1. INTRODUCTION

In the increasingly restricting legislation for the emission of pollutants there is a necessity for better cleaning devices and the improvement of those existing. Among the equipment utilised for cleaning of gases prior to release into the atmosphere, venturi scrubbers are one of the most effective. They can remove particles suspended in gaseous streams, achieving very high efficiencies even for particles of the order of microns (Dullien, 1989).

A venturi scrubber (Fig. 1) consists of a narrower part of a duct, with the form of a venturi. This arrangement causes the acceleration of a gas containing suspended particles. Scrubbing liquid is injected at some point close to the throat, and the high velocity of the gas causes its atomisation. As a result a very fine spray is created. The high relative velocity droplets/particles enhances collection by an inertial mechanism (Ekman & Johnstone, 1951).

One of the most important parameters in performance, calculations and modelling of venturi scrubbers is drop size. If the spray is atomised into very small particles the surface for particle collection would be very high. On the other hand, the single efficiency of particle collection would decrease and droplets will accelerate faster (Goel & Hollands, 1977). The classical correlation proposed by Nukiyama & Tanasawa (1938) for pneumatic atomisers has been widely used for the prediction of drop sizes in venturi scrubbers, although some studies (Boll *et al.*, 1974) suggest different equations. Some models allow for the possibility of drop size distributions. Those proposed by Bayvel (1982), or Placek & Peters (1981), are examples, but suitable and general data is not available for this purpose.

Additionally, the atomisation of a liquid jet in a high velocity gas has many more applications. In some engines fuel is injected in a similar manner to that of the present experiments. The size of the droplets and the dispersion of the jet can have a great influence in mass transfer and heat transfer, and as a consequence on the performance of the engine.

Table 1: Geometric details

Dimensions of Venturi (mm)	
Inlet Diameter	32
Throat Diameter	19
Length of Convergence	20
Length of Throat	64
Length of Divergence	74
Distance from liquid injection to beginning of test section (mm)	
Position 1 (Throat)	8
Position 2 (Throat)	55
Position 3 (Outlet)	141
Distance from beginning of test section to centre of laser beam (mm)	
Position 1 (Throat)	15
Position 2 (Throat)	15
Position 3 (Outlet)	20

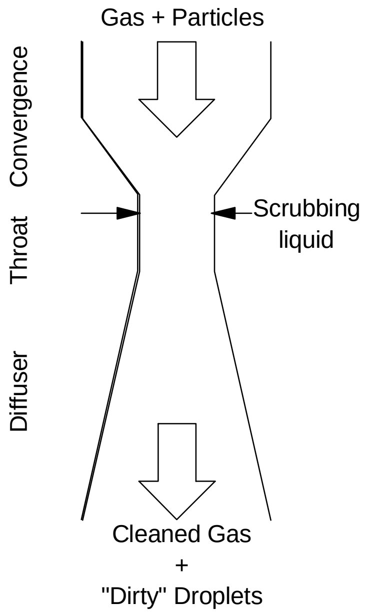


Figure 1: Schematic representation of a venturi scrubber

2. EXPERIMENTAL ARRANGEMENT

The present experiments were carried out on the facilities at the University of Nottingham. The cylindrical laboratory-scale venturi scrubber was machined from acrylic resin. Details of the venturi geometry and measurement positions are given in Table 1. Air from the laboratory mains was metered by an orifice plate, and flowed downwards through the venturi. Pressure was kept at a constant value of 1.5 bar at the entrance of the venturi. A valve allowed setting the flow of gas to our target values, corresponding to gas velocities at the throat of 50 m/s, 70 m/s and 90 m/s. The accuracy was estimated to be ±4%.

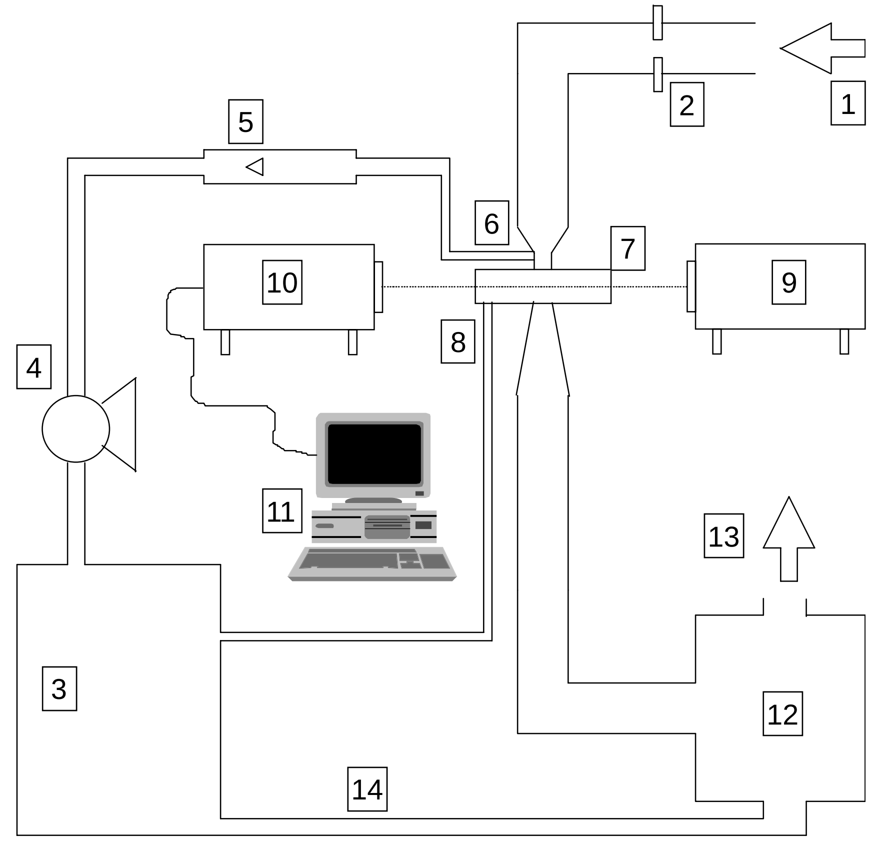
Liquid was introduced through five 1 mm diameter orifices evenly distributed around the circumference. Five was chosen as an appropriate number to provide reasonable throat coverage, and to avoid the possible frontal collision that would be produced by an even number of jets. Water flow was measured using calibrated rotameters.

Drop sizes were measured at three different locations. The first point (position 1), located at the throat, 23 mm from the point of liquid injection was chosen because it provided an insight into the newly created spray. The second point (position 2), 70 mm from the point of injection of liquid, was located very close to the end of the throat. The last point (position 3) was located right after the end of the divergence. These three points would allow the study of the evolution of drop sizes along the venturi.

The technique chosen for drop size measurements is based on laser light diffraction scattering. A laser beam is used to illuminate the flow. A part of the light is diffracted, producing a pattern of diffraction characteristic of the drop size distribution. After crossing the sample the light scattered is received on concentric rings, sensitive to light intensity. This intensity is converted to an analogical signal and sent to a PC. In the computer the information is processed by means of the mathematical model proposed by Swithenbank *et al.* (1976), based on the theory of Fraunhoffer diffraction. This technique has been extensively used for the study of drop sizes in dispersed flows (Teixeira, 1988, Zaidi *et al.*, 1998), mainly annular flow. Further details about this technique can be found in these references.

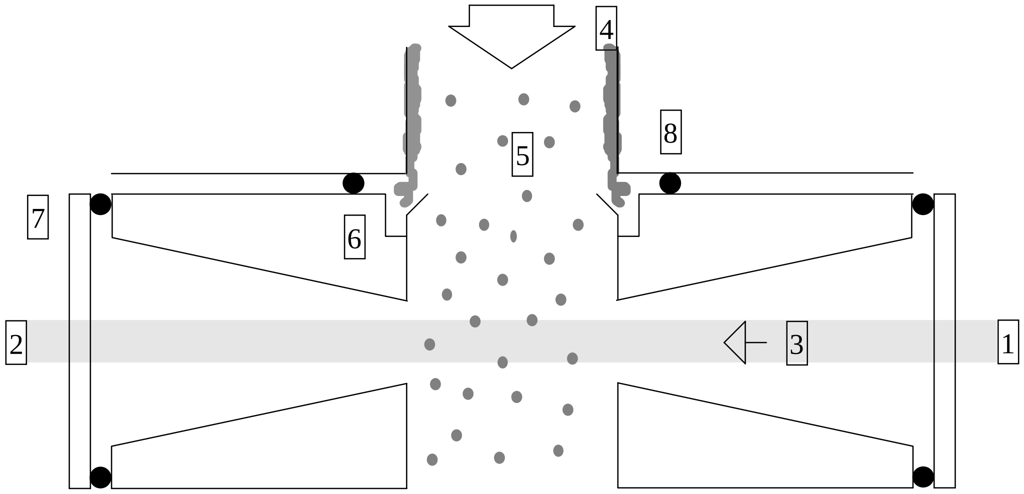
A Malvern 2600 particle analyser was used. This model is commercially available, and widely used for particle size analysis. The beam of a low power He-Ne laser (3 mW) was expanded to 9 mm diameter. It was collected by Fourier-transformer 300 mm focal distance lenses after crossing the sample. This set-up provides the measurement of drop sizes in the range of 5.8μm to 564μm. This range covered the drop present.

One of the main problems associated with optical measurements concerns the optical access into the flow. This problem may be overcome by the design of special test sections. Our test sections have special windows made of borosilicate glass allowing the passage of the beam in and out of the pipe. Additionally, the test sections should provide a minimum disturbance to the flow. As has been noted by Boll (1973) and Azzopardi (1993), a part of the water injected in venturi scrubbers deposits on the walls flowing as a shear driven film. The film disturbs the beam, so it must be removed just before the point of sampling. A circumferencial slot 1 mm wide with a protrusion of 1 mm into the pipe successfully removed all the film (Fernández Alonso *et al.*, 1999). Some air flowed through the slot as well, but it was not significant compared to the total flow of air. An additional small flow of air was injected close to the windows to keep them clean, avoiding the deposition of droplets from the spray. All these arrangements produce a minimum disturbance of the flow, as it is described in Teixeira (1988).



1-Air from laboratory mains	6-Venturi	11-Computer
2-Orifice plate	7-Test section	12-Cyclone
3-Water tank	8-Film removal	13-Air purged
4-Water pump	9-Laser transmitter	14-Water recycle
5-Rotameters	10-Laser receiver	

Figure 2: Schematic representation of experimental set-up



1-Laser transmitter	4-Film	7-Borosilicate window
2-Laser receiver	5-Spray	8-Rubber ring
3-Laser beam	6-Film removal slot	

Figure 3: Schematic representation of test section

3. RESULTS AND DISCUSSION

3.1 Mean Drop size, $D_{3,2}$

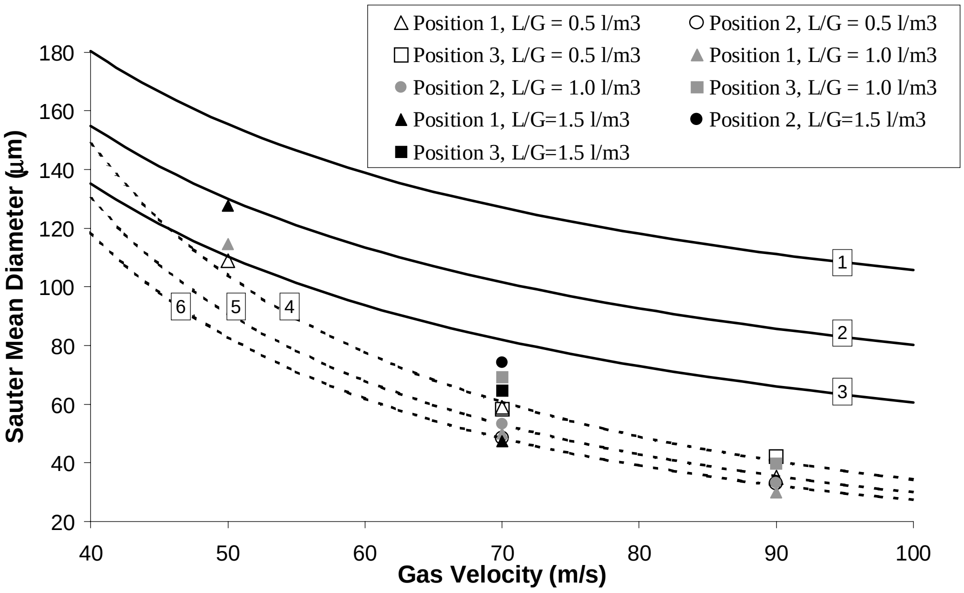
The equipment utilised in these experiments provided data of size distribution directly in mass. The range of sizes (5.8μm to 564μm) was divided in 32 interval equally divided in logarithmic scale. This data could easily be transformed in number or surface distributions if necessary using the proper geometric relationships.

Average or mean particle diameters, $D_{i,j}$, are in general defined as (Lefebvre, 1989):

$$D_{i,j} = \frac{\int_0^\infty d^i f(d)}{\int_0^\infty d^j f(d)} \tag{1}$$

In Eq. (1) f (d) is the particle size distribution in number. In the case of venturi scrubbers the most suitable is the $D_{3,2}$, also known as Sauter mean diameter. This diameter is appropriate because it gives the mean value in terms of mass / surface ratio. This relationship is the most suitable because particle collection takes place on the surface of droplets, and the acceleration caused by the drag forces is proportional to the droplet surface. This is the reason why droplet sizes and correlations for venturi scrubbers are presented in terms of this particular diameter.

Two main parameters were varied in the present experiments for each axial position, gas velocity and liquid to gas ratio. The effect of gas velocity can be observed in Fig. 4, which shows the expected effect, as drop size decreases with gas velocity. On the other hand, the effect of liquid to gas ratio does not appear very clear (Fig. 5). It could be possible that the results of the experiments are not accurate enough to detect the influence of the liquid to gas ratio. In any case, the importance of gas velocity is much more important than that of the liquid to gas ratio.



1,2,3 – Nukiyama-Tanasawa (1938) for L/G=1.5, 1.0 and 0.5 l/m^3 respectively

4,5,6 – Boll (1974) for L/G=1.5, 1.0 and 0.5 l/m^3 respectively

Figure 4: $D_{3,2}$ *versus* velocity of the gas at the throat

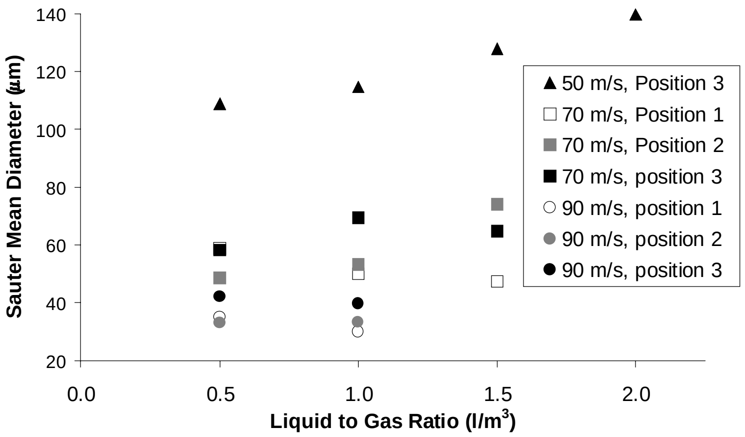


Figure 5: $D_{3,2}$ *versus* liquid to gas ratio

Two main correlations have been proposed for drop sizes in venturi scrubbers. The equation proposed by Nukiyama & Tanasawa (1938) has been widely used (Boll, 1973, Calvert, 1970). Nukiyama & Tanasawa (1938) counted manually the number of impactions of droplets of different liquids on microscope slides. Their results have been criticised (Wessman, 1981), as it would have a tendency to overestimate drop sizes. Small drops do not impact on the slide as efficiently as the big ones. Additionally, the very small droplets evaporate almost immediately. This correlation has been used extensively in venturi scrubbers, even if the method and arrangement of liquid injection from these experiments is different to those found in venturi scrubbers. Their correlation is given by:

$$D_{3,2} = \frac{5.85 \times 10^{-4}}{v_r} \sqrt{\frac{\sigma}{\rho_l}} + 10^{-3} \left(\frac{\mu}{\sqrt{\sigma \rho_l}} \right)^{0.45} \left(\frac{1000\, Q_l}{Q_g} \right)^{1.5} \tag{2}$$

Where, v_r is the relative velocity liquid/gas, σ is the surface tension liquid/gas, ρ_l is the density of the liquid, and Q_l and Q_g are the volumetric flowrates of liquid and gas, respectively. All variables are in S.I. units.

Following the arguments noted, it is not surprising that Nukiyama & Tanasawa (1938) correlation predicts droplets larger than those found in these tests. It is also important to note that the effect of liquid to gas ratio in the present experiments is negligible, or at least much smaller than predicted from this correlation.

Boll *et al.* (1974) presented one of the few studies of drop sizes in venturi scrubbers. They injected water as jets, in a manner similar to that of the present experiments. The method of droplet size analysis they applied was based on the attenuation of a beam of monochromatic light. The measurements of particles are not direct using this method, as it is necessary to know their velocity. They calculated this velocity theoretically using the standard drag coefficient for a sphere and assuming that the droplets were created instantly at the point of injection. As a results of their experiments they proposed the following correlation for a system of water and air:

$$D_{3,2} = \frac{4.2 \times 10^{-2} + 5.65 \times 10^{-3} \left(\frac{1000\, Q_l}{Q_g} \right)}{v_r^{1.602}} \tag{3}$$

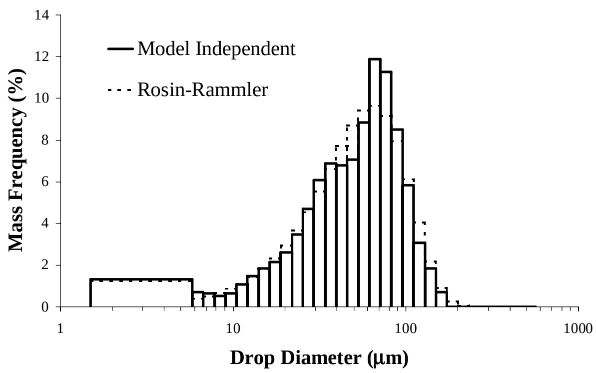


Figure 6.a: Histogram of mass frequency. Position 2, Vgas=90 m/s, L/G=0.5 l/m^3

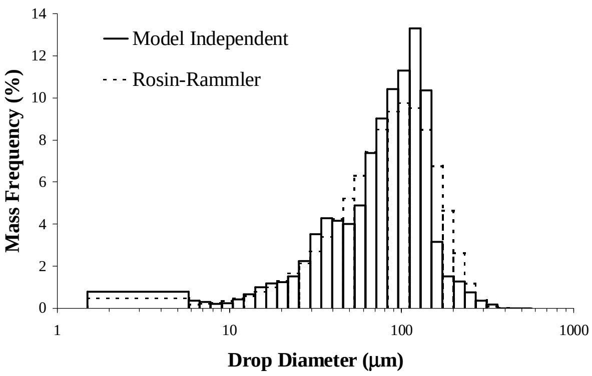


Figure 6.b: Histogram of mass frequency Position 2, Vgas=70 m/s, L/G=1.0 l/m^3

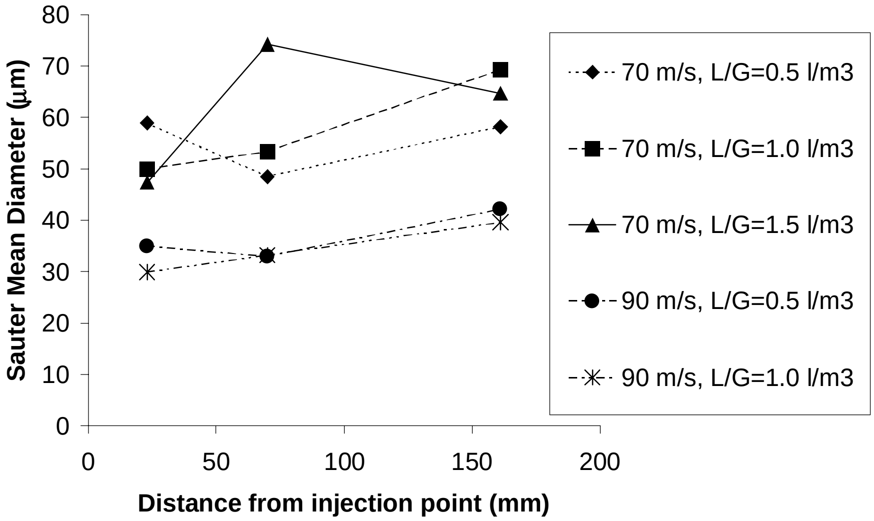


Figure 7: $D_{3,2}$ along Venturi

Units and symbols in Eq. (3) are the same of those of Eq. (2). However, in Eq. (3) v_r refers to the gas velocity at the point of transverse injection, slightly upstream of the throat in the case of Boll *et al.* experiments.

The effect of liquid to gas ratio in Eq. (3) is not as strong as in Eq. (2), which is in accordance to our experiments (Fig. 4). The predictions obtained using this correlation compare very well to the present experiments, and fall within the range of error of the experimental values. Only for a gas velocity of 50 m/s the agreement is not as good, being the experimental values around 10% higher than those predicted by Boll *et al.* (1974).

3.2 Drop size distribution and evolution along the venturi

The laser diffraction technique employed in the present tests allows the determination of the drop size distribution. In all the experiments we found that the particle size distributions had a single peak or maximum. One of the most popular single-peaked statistical distribution functions utilised for sprays is the Rosin-Rammler function. Figure 6 shows some typical histograms, and how this function fitted reasonably well the experimental distribution. The Rosin-Rammler in its cumulative form can be expressed as (Lefebvre, 1989):

$$1-\phi = exp(-(D/X)^n) \qquad (4)$$

Where ϕ is the fraction of total mass contained in drops of diameter less than D, X and n are constants characteristic of the distribution. The parameter n provides a measure of the spread of drop sizes. The higher the value of n the more uniform is the spray. The parameter X is the drop diameter such that 63.2% of the total liquid mass is in drops of smaller diameter. It can be related to the $D_{3,2}$ by means of the gamma function:

$$\frac{X}{D_{3,2}} = \Gamma\left(1 - \frac{1}{n}\right) \tag{5}$$

The parameters in the Rosin-Rammler function, together with the Sauter mean diameter were used in order to compare the particle size distribution for different positions. The evolution of the Sauter mean diameter along the venturi is not very clear. It tends to be higher at the outlet, except for one experimental value (Fig. 7). Again the influence of liquid to gas ratio appears negligible, or too small to be detected in these tests. The parameter n in the Rosin-Rammler distribution varies around 2 (1.70-2.25) in all cases. It is interesting to note that there is a clear evolution of this parameter along the venturi (Fig. 8). The parameter n decreases from point 1 (close to the injection point) to point 2 (downstream, at the throat) and is more or less constant from point 2 to point 3 (end of diffuser). It can be concluded that the drop size distribution is not constant along the venturi, becoming wider as droplets travel downwards.

When the Sauter mean diameter is used to track the evolution of drop sizes in the venturi the results are not very clear (Fig. 7). In contrast, the centre of the interval with higher mass raises along the scrubber, as can be observed on Fig. 9.

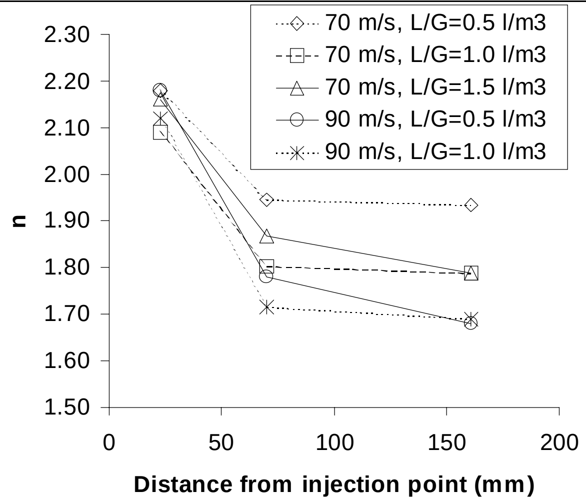


Figure 8: Parameter n of Rosin-Rammler along venturi

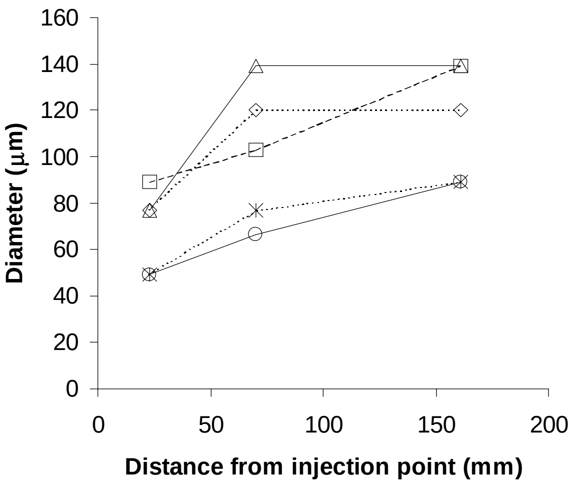


Figure 9: Centre of interval with higher mass frequency along venturi

3.3 Phenomena affecting drop size changes along the venturi

There are many possible factors that may provoke changes of drop size. In this section we will discuss qualitatively the effect of some of them. A detailed numerical study is beyond the scope of this work.

Data from Goncalves *et al.* (1999) has shown that an important fraction of the spray can be deposited on the walls of the equipment. If there is a preferential deposition of droplets of a given diameter this phenomenon would cause a change in the particle size distribution. The entrained fraction (Goncalves *et al.*, 1999, Viswanathan *et al.*, 1997) varies more significantly immediately after the point of liquid injection. This phenomenon has certainly an important role in the changes of drop sizes, particularly between points 1 and 2.

Once the liquid is injected it will be accelerated due to the high relative velocity gas/liquid. The magnitude of that acceleration will depend on drop size, smaller droplets being accelerated faster. The different acceleration of drops can cause the variation of concentration of a given size. This different relative velocity between droplets of different sizes can provoke collision. As a result, the drops could coalesce. On the other hand, if the collision is very energetic it can cause a further disintegration of the drops into smaller ones. It is also possible that droplets can break-up along the venturi, so called secondary atomisation.

Additional phenomena are possible as well. In the present experiments evaporation did not have a major role, as pressure was kept at 1.5 bar. The liquid deposited on the walls of the equipment can be re-entrained, complicating even more the analysis.

At the moment there is not satisfactory mathematical modelling of drop sizes changes along the venturi scrubber. The inclusion of all the factors mentioned above can prove to be very difficult to implement in a model, although simplified analysis could eventually lead to good results.

4. CONCLUSIONS

From all the previous discussions it can be concluded:

- Gas velocity is the determinant factor influencing drop sizes in venturi scrubbers. Liquid to gas ratio plays a minor, if not negligible role.
- The Nukiyama & Tanasawa (1938) equation overpredicts considerably the $D_{3,2}$, particularly for high gas velocities. This correlation exaggerates the effect of liquid to gas ratio.
- The Sauter mean diameters are well correlated by the equation proposed by Boll *et al.* (1974).
- The Rosin-Rammler statistical function gives reasonable fitting to the empirical drop distributions found in these experiments.
- The parameter n in the Rosin Rammler distribution varies between 2.1-2.2 for position 1, and between 1.7 to 1.95 for positions 2 and 3.
- Drop sizes change along the venturi, particularly along the throat.
- The size distribution of droplets becomes wider as droplets progress along the venturi.

When water is inserted as jets we propose the estimation of drop sizes this way:

If droplets are assumed to be uniform use Eq. (3) for $D_{3,2}$. If a size distribution is to be used, a Rosin-Rammler function with parameter n equal to 2 gives reasonable results. The parameter X can be estimated using Eq. (3) and Eq. (5).

These tools should help in the modelling of venturi scrubbers, making possible the implementation of sound based models. The prediction of pressure drop, particle collection and mass absorption should be more accurate, allowing the optimisation by numerical ways.

The available data in the literature on drop sizes specifically in venturi scrubbers is limited (Boll *et al.*, 1974, Atkinson & Strauss, 1978, Wessman, 1981 and Bayvel, 1982).The present work was made with the purpose of lessening this lack of data in the case of water injected as perpendicular jets, which is now made available for the engineer modelling venturi scrubbers.

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REFERENCES

Atkinson, D.S.F., & Strauss, W., 1978, Droplet size and surface tension in venturi scrubbers, Journal of the Air Pollution Control Association, vol. 28, n. 11, pp. 1114-1118.

Azzopardi, B.J., 1993, Liquid distribution in venturi scrubbers: The importance of liquid films on the channel walls, Chemical Engineering Science, vol. 48, n. 15, pp. 2807-2813.

Bayvel, L.P., 1982, The effect of polydispersity of drops on the efficiency of a venturi scrubber, Transactions of the Institution of Chemical Engineers, vol. 60, pp. 31-34.

Boll, R.H., 1973, Particle collection and pressure drop in venturi scrubbers, Industrial and Engineering Chemistry Fundamentals, vol. 12, n. 1, pp. 40-50.

Boll, R.H., Flais, L.R., Maurer, P.W., & Thompson, W.L., 1974, Mean drop size in a full-scale venturi scrubber via transmissometer, Journal of the Air Pollution Control Association, vol. 24, n. 10, pp. 932-938.

Calvert, S., 1970, Venturi and other atomizing scrubbers efficiency and pressure drop, AIChE Journal, vol. 16, n. 3, pp. 392-396.

Dullien, F.A.L., 1989, Industrial Gas Cleaning, Academic Press, New York.

Ekman F.O., & Johnstone, H.F., 1951, Collection of aerosols in venturi scrubbers, Industrial and Engineering Chemistry, vol. 43, n. 6, pp. 1358-1363.

Fernández Alonso, D., Gonçalves, J.A.S., Azzopardi, J.J., & Hills, J.H., 1999, Improvements to the modelling of venturi scrubbers, 2nd European Congress of Chemical Engineering, October 5-7, Montpellier.

Goel, K.C., & Hollands, K.G.T., 1977, Optimum design of venturi scrubbers, Atmospheric Environment, vol. 11, pp. 837-845.

Gonçalves, J.A.S., Fernández Alonso, D., Azzopardi, B.J., 1999, Experimental study of hydrodynamics in venturi scrubbers with two different liquid injection arrangements, 2nd International Symposium on Two-Phase Flow Modelling and Experimentation, May 23-26, Pisa.

Lefebvre, A.H., 1989, Atomization and Sprays, Hemisphere Publishing Corp., New York.

Nukiyama, S., & Tanasawa, Y., 1938, An experiment on the atomisation of liquid by means of air stream, Transactions of the Society of Mechanical Engineers (Japan), vol. 4, n. 14, pp. 86-93.

Placek, T.D., & Peters, L.K., 1981, Analysis of particulate removal in venturi scrubbers – Effect of operating variables on performance, AIChE Journal, vol. 27, n. 6, pp. 984-993.

Swithenbank, J., Beer, J.M., Taylor, D.S., Abbot, D., & MacCreath, G.C., 1976, A laser diagnostic technique for the measurement of droplet and particle size distribution, Experimental diagnostics in gas phase combustion systems, Prog. In Astronaut and Aeronauts, vol. 53, pp. 421-447.

Teixeira, J.C.F., 1988, Turbulence in annular two-phase flow, University of Birmingham.

Viswanathan, S., Gnyp, A.W., St. Pierre, C.C., 1997, Estimating film flow rate in a venturi scrubber, Particulate Science & Technology, vol. 15, pp. 65-76.

Wessman, E.D., 1981, Experiments on droplet size distributions in a laboratory scale venturi scrubber, PhD Thesis, University of Waterloo.

Zaidi, S.H., Altunbas, A. & Azzopardi, B.J., 1998, A comparative study of phase doppler and laser diffraction techniques to investigate drop sizes in annular two-phase flow, Chemical Engineering Journal, vol. 71, pp. 135-143.