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Dust Collection in Venturi-Scrubbers

F. Mayinger and M. Neumann*

Detailed knowledge of the fluid dynamic behaviour in a Venturi-scrubber is required for a reliable prediction of the particle collection efficiency. Dispersion processes, interfacial area, acceleration of the fluid particles and pressure drop in the throat of the Venturi-scrubber were investigated in a pilot plant in order to gain a better understanding of these phenomena.

The results show that the dust collection in a Venturi-scrubber occurs predominantly in the atomization zone and that the process of dust collection may already be completed after a flow path of only a few centimetres. At first the liquid does not disintegrate into droplets but into a large number of sheet-like particles. Based on these results empirical equations are suggested for representation of the mass transfer process.

1. Droplet-Model and Particle Collection Efficiency

The droplet model of *Barth*, shown in Fig. 1, was adopted as a basis for the calculation of separation efficiency of wet scrubbers and the required quantity of liquid. The dust particles colliding with the droplet were considered to be collected. In the determination of trajectories of the dust particles, the laws of classical hydrodynamics were applied for calculating the flow field around the droplets, which were assumed to be spherical; for estimation of the frictional drag at small velocity differences, Stokes's law was used.
An interesting recent development was the extension of this classical theory by *Leschonski* and *de Silva* [1] to include cross current scrubbers. In addition, these workers considered the probability of the dust particle colliding with the droplet under the assumption of potential flow around it. A relation, originally given by *Rumpf*, was applied to calculate the drag coefficient as a function of the Reynolds number.

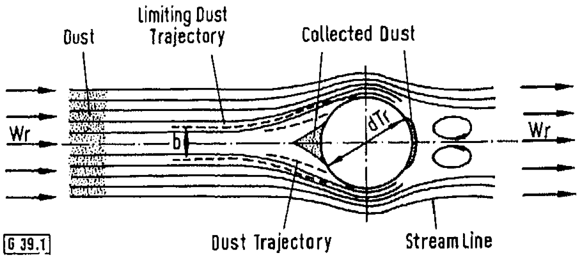

Fig. 1. Flow lines and dust particle trajectories during flow around a spherical droplet (according to Barth).

As previously determined by *Barth*, these calculations indicate that the specific purified gas volume shows a distinct maximum as a function of the droplet size. In addition, the calculations show, that the particle collection efficiency increases exponentially with increasing liquid-gas ratio, on the other hand less water is used, when the average droplet size becomes smaller. *Leschonski* and *de Silva* predicted a practically complete dust separation with droplets of diameter between 10–30 μm, and at a volumetric water-gas ratio of about 1 l/m^3. If the droplet size is trebled, twice the quantity of water is required.

Theoretical considerations based on the droplet model, result, at least in the identification of the important characteristic parameters and model laws for the collection of fine dust particles; in addition, at small differences in gas and liquid velocities they lead to useful equations. They show above all that there must be an optimal droplet size with regard to collection efficiency and energy dissipation.

Venturi-scrubbers are a special type of wet-approach scrubbers, in which the liquid is dispersed by means of a gas stream. Starting with general considerations of liquid dispersion, initial observations on the droplet size distribution in Venturi-scrubbers were made by *Nukiyama* [2] and extended by *Ueoka* [3] through analysis of the effect of flow path on the concentration of liquid particles. Finally, on the basis of new measurements *Calvert* [4] established more reliable drag coefficients of accelerated droplet swarms and, in addition, he considered the variation of relative velocity downstream from the Venturi throat.

Eventually the equations were improved through adjustment of the empirical coefficients according to new data on the dust collection efficiency, which were reported in the mean-

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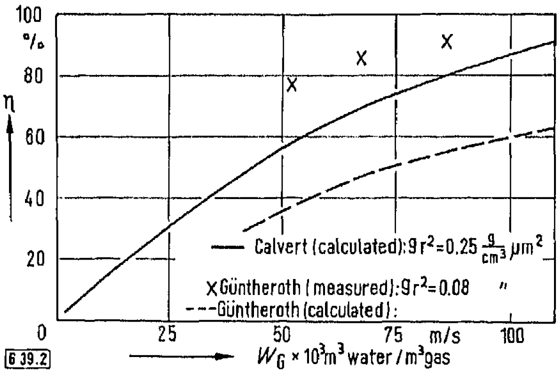

Fig. 2. Comparison between measured and calculated separation efficiencies.

time [5–7]. These coefficients should reflect other physical phenomena and limiting values such condensation effects which, apart from inertial forces, affect the dust collection. Variation in the dust particle size distribution resulted in different optimum values for the droplet size, gas velocity in the throat and volume ratio of liquid to gas. A comparison between calculated separation efficiencies and the corresponding experimental values [8, 9] was made by *Büttner* [10]. Calculated and measured separation efficiencies are shown in Fig. 2 as a function of the product of liquid-gas ratio and the gas velocity in the throat.

It can be seen that a fairly good agreement is obtained for large particle diameters, whereas for small diameters, the theory underestimates by far the separation efficiency of the Venturi-scrubber, as shown in particular, by measurements of *Güntheroth* [9]. The discrepancy between measurement and calculated values becomes very pronounced for dust particle diameters of under 1 μm, when theory predicts negligible collection efficiencies, whereas a well designed Venturi-scrubber collects over 90% dust particles of diameters between 0.3 and 0.5 μm, as shown by measurements of *Güntheroth*. In order to improve the theory, it appears essential to investigate further the formation of the interface, the relative gas-liquid velocity and pressure drop in the scrubber.

2. Liquid Atomization in the Venturi-Scrubber

Systematic investigations of the jet break-up, development of the interface, acceleration of the washing liquid and of the pressure drop in the scrubber were conducted in a pilot plant, at the Institut für Verfahrenstechnik of the Technical University of Hannover, in conjunction with Baumco Essen and financed by the Federal Ministry for Research and Technology. The pilot plant could be operated up to a volumetric gas flow of 4,500 Nm^3/h, and the throat was of rectangular cross-section with an area of 85 cm^2. To control the plant and for adaptation to different volumetric gas flows, the throat section was equipped with pivot valves, which could reduce the cross-sectional area of the throat. The washing liquid was added through simple holes, arranged in two rows on both sides in the Venturi throat.

Paraffin wax particles of diameters between 0.3 and 0.5 μm, simulating dust, were uniformly distributed over the air stream entering the scrubber. For production of the paraffin dispersion an aerosol generator was used, in which molten paraffin wax was atomized in special nozzles. The generator was initially designed by *Klumb* and later developed by *Gütheroth* [9]. Paraffin wax was selected as the material to be separated, in order to test a material most difficult to wet and consequently, the most difficult collection conditions.

The measurement of liquid atomization was carried out by means of high speed photography with exposure times of 10^{-8} to 10^{-7} s. It was possible, with this technique, to represent clearly water particles of diameters under 10 μm and flowing with superficial velocities up to 100 m/s. The photographs of liquid atomization in the Venturi-scrubber confirmed the originally qualitative observation of *Hesketh* [11], that initially the liquid did not break up into droplets. However, he was unable to demonstrate the formation of sheet-like particles with a very large interfacial area, described in the present paper. The high shear stress and momentum forces of the gas stream, which exceed the droplet forming surface tension in the throat, are obviously responsible for the formation of such particles.

Fig. 3 shows a photograph of the jet break-up over the whole throat length; for a satisfactory optical survey, water was fed only from one side. In the figure, two zones – "1" and "2" are marked by circles, and they will be considered in detail later in the paper. For that purpose it is essential to apply a considerably higher optical resolution, which however permits the analysis of only a small sector of the water jet.

Figs 4 and 5 show such sections of zone "1", that is of a region situated directly in or behind the narrowest part of the Venturi-throat.

In Fig. 4 a special photographic procedure was applied, namely the double exposure technique. It consisted of taking two photographs, one after the other, on the same plate. In this case, the time interval between the two exposures was 10^{-5} s. The above technique made it possible to determine exactly the velocity of the water particles with respect to magnitude and direction. Fig. 4 shows a particular form of a lamellar liquid particle, resulting from the shear stresses in the gas flow. This parachute-shaped lamella, swelled and expanded as can be seen by comparing the two exposures. On the basis

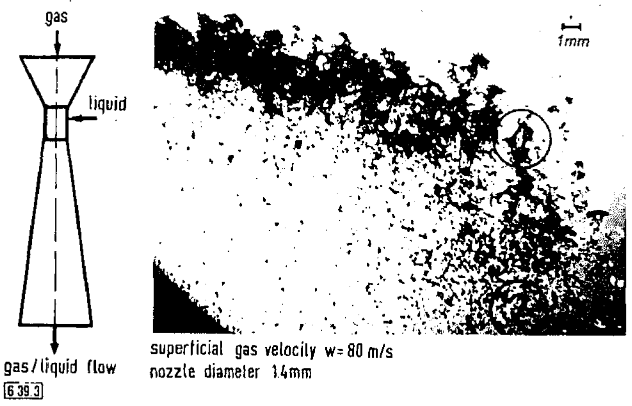

Fig. 3. Jet break-up (Photographic survey).

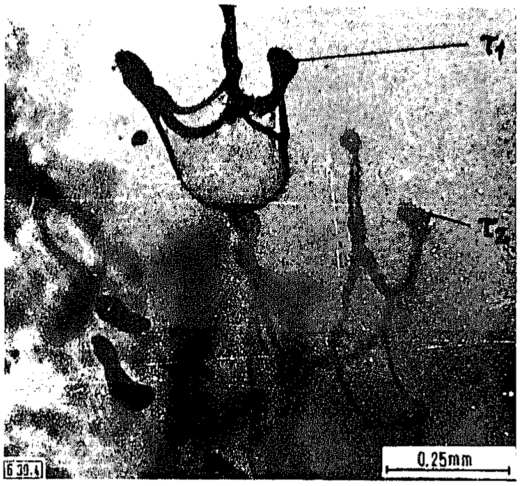

Fig. 4. Parachute like sheet (zone "1"). $\tau_2 - \tau_1 = 10^{-5}$s

of volume magnification, it can also be concluded, that gas flows into the parachute whereby the dust becomes enclosed by the liquid sheet. A simple equilibrium of forces and a balance of momentum show that there must be a considerable difference between the velocities of the liquid particles and the gas, as otherwise the shear or momentum forces could not result in such a considerable deformation of the droplet, thus overcoming the influence of surface tension.

However, in practice, it is not the parachute shaped particles which are predominantly formed but flat sheets and ligaments. Their dimensions vary between a few tenths of a millimetre and several millimetres. In no experiment was the surface tension of water reduced by the presence of detergents or impurities.

During passage through the throat, the water particles become considerably accelerated, and thus the external flow forces acting on the particles are reduced. This results in re-establishment of the effect of the surface tension and consequently in the regeneration of droplets. In some cases, an excessive expansion of the sheet-shaped particles was observed, when they disintegrated into several little droplets, as can be seen in Fig. 5.

Series of photographs, taken at short time intervals, led to the assumption of a high turbulence because of considerable random motion of the liquid particles. In fact, high turbulence is to be expected in a two-phase flow with such a big difference in the densities of the two components. Therefore, the question arises whether, in view of the observed phenomena, the assumption of a laminar flow around the droplet is still relevant for the calculation of collection efficiency in a Venturi throat. However, it should be noted that the sheet-shaped particles have a life-time of only a few thousandths of a second, after which they revert to droplets of different sizes, as seen in Fig. 6, which shows a photograph of zone "2" (Fig. 3).

Fig. 6 is also a double exposure photograph, where each droplet is represented twice, within an interval of 10^{-6} s. At this point, the turbulence is considerably smaller and the droplets show essentially a directed flow, as can to observed from their paths in Fig. 6.

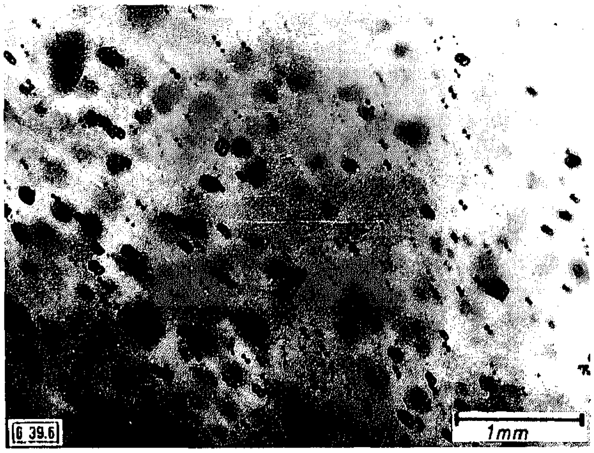

Fig. 6. Droplets at the end of the atomization zone.

3. Separation Mechanism

Before considering the effective collection mechanism the question of the time required to separate the dust should be discussed. In general, collection efficiency is determined by the resistances to mass transfer in the gas and liquid phases. There occur limiting cases when the resistance to mass transfer can be neglected on one side of the interface as, e.g. during dust collection in the liquid phase, as the particle is considered to be collected, after having been wetted by the liquid. In that case the resistance to mass transfer is in the gas phase and to achieve wetting, it is only necessary to overcome the surface tension. Therefore an increase in the mass transfer coefficient and an enlargement of the interfacial area suggests an improvement in collection efficiency. Sheet-like particles have a much larger surface area than droplets of the same liquid volume.

Conditions for mass transfer would become less favourable, if the flow around the liquid particle was laminar. This can however be excluded because of the following simple considerations: The differences in velocity between the gas and the liquid particles are 30–80 m/s in this region of the throat, i. e. a few centimetres below the nozzles. When the dimensions of the sheets are between 0.5 and 1 mm, the Reynolds numbers for the liquid particles vary from 10^3 to 6×10^3, i. e. they are far outside the Stokes's region. The question arises as to what value should be taken as the characteristic length in the Reynolds number. Should it be thickness, length or some mean value, nevertheless for each of them the Stokes' regime is exceeded. The values indicate that even at a directed gas flow, the laws of laminar flow cannot be applied to the flow past the particles. The high, mean turbulences observed in two phase flows, are an additional important factor [12].

Consequently, in this region of the throat, there is no diffusive mass transfer, characteristic of laminar flow. As a result of large interfacial area and high turbulence, the collection processes, which are entirely or largely determined in the gas phase, may be intensified to such an extent that they are completed before the flow slows down again in the diffuser and formation of droplets sets in. This is not valid for absorption processes, in which diffusion or a slow chemical reaction in the liquid phase are of considerable importance.

The interfacial area, relevant for the collection process, and its variation along the flow path in the Venturi-throat can also be determined with the aid of a fast chemical model reaction e.g. oxidation of aqueous Na_2SO_3 described by Nagel [13]. Na_2SO_3 is added to the washing liquid, and the reacted sulphite or oxygen consumed is measured. The interfacial area can be calculated from the quantity of converted oxygen. However, due to short residence times in the Venturi-throat, corrections have to be applied on account of the finite reaction rate.

Fig. 7. presents the profile of the interfacial area per unit volume at a superficial gas velocity of 80 m/s in the throat and a liquid-gas ratio of 2.46 l/m³. The interfacial area shows a distinct maximum directly under the jets, i. e. in the region of where liquid is subjected to the greatest shear stresses and momentum forces. Systematic measurements, at superficial gas velocities between 40 and 115 m/s and liquid-gas ratios between 0.5 and 2.5 l/m³ have shown that over 80% of the exchange surface develops in the first 40 mm of the flow path.

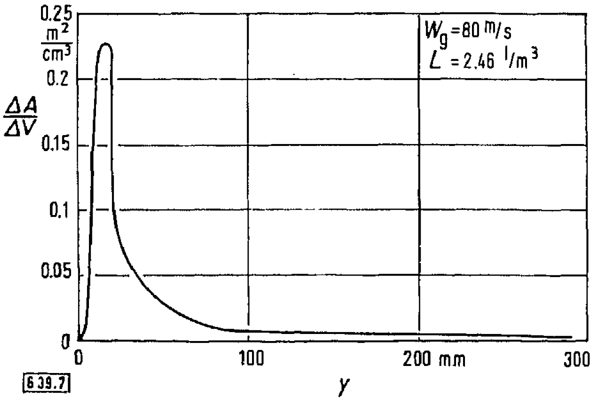

Fig. 7. Interfacial area as a function of the flow path.

Apart from the available interfacial area the gas-phase mass transfer coefficient is a parameter affecting the collection efficiency. The mass transfer coefficient depends largely on the turbulence or the relative velocity between the liquid particles and the dust-loaded gas. A local relative velocity can be determined by the already described optical method, i. e. using the double exposure technique. This gives the absolute velocity of that particle. If, in addition to the superficial gas velocity, the mass flow rate is measured and considered together with the gas velocity profile over the flow cross-section, the local difference between velocities of liquid and gas particles may be obtained.

However for the overall collection efficiency in the Venturi-scrubber, an average value reflecting different flow conditions over the whole flow cross-section is of relevance rather than the local relative velocity.

According to Eq. (1), derived from simple definitions of two-phase flows, there exists a relation between the slip s or the relative velocity w_r of the phases and the density ratio ρ_f/ρ_g, the ratio of gas mass flow rate to the overall rate of the two phases $\dot{x}$, as well as the gas hold-up ϵ. $\dot{x}$ is defined by Eq. (2), and ϵ by Eq. (3).

$$S = \frac{w_g}{w_f} = \frac{1-\epsilon}{\epsilon} \, \frac{\dot{x}}{1-\dot{x}} \, \frac{\rho_f}{\rho_g} \tag{1}$$

where

$$\dot{x} = \frac{\dot{M}_g}{\dot{M}_g + \dot{M}_f} \tag{2}$$

$$\epsilon = \frac{V_g}{V_g + V_f} = \frac{A_g}{A_g + A_f} \tag{3}$$

In the above equations $\dot{M}$ denotes mass flow, V volume, and the indices "g" and "f" refer to gas and liquid. The densities of both phases are known and $\dot{x}$ can easily be determined by the usual mass flow measurement methods, as can be seen from Eq. (2). The hold-up ϵ was determined by the gamma ray attenuation method, based on the principle of different absorption of gamma-rays in media of different densities [14]. The average gas hold-up across the overall flow cross-section can be measured by this technique by a lateral displacement of the measurement equiment, perdendicular to the direction of flow. The relative velocity w_r, which can then be calculated by means of Eq. (1), is a mean for all liquid particles, flowing through the test section. Volume of the test section is the product of the flow cross-sectional area and the diameter of the gamma ray beam, which was 2 mm in this instance. The determination of the mean relative velocity by this method reflects the fact, illustrated by the flow profile, that the fluid particles do not become uniformly accelerated across the whole cross-section. In addition the variation in the acceleration process caused by differing geometry of the liquid particles is taken into account as seen in Fig. 4. Parachutes are more accelerated than droplets and small droplets more than large ones. At the same time, means were calculated of statistical distributions of the lamellae

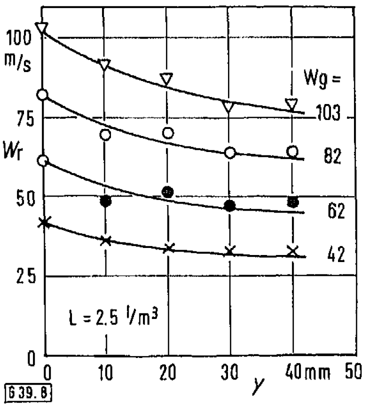

Fig. 8. Mean relative velocity vs distance travelled with superficial gas velocity as parameter.

over particular cross-sections. Fig. 8 shows the mean relative velocities w_r, determined in this way as functions of the flow path at different gas velocities in the throat. The liquid-gas ratio was 2.5 l/m^3.

The data illustrate that initially the washing liquid is strongly accelerated just under the jets; subsequently the water particles gain only a little more acceleration.

In existing publications, the pressure loss in the Venturi-scrubber is frequently quoted as a parameter, characteristic of the collection efficiency of the scrubber. Consequently, the pressure distribution was systematically investigated as a function of the flow distance y, at different superficial velocities in the throat and different liquid-gas ratios.

As an example, Fig. 9 presents the pressure distribution across the whole Venturi-scrubber for the liquid-gas ratio of L = 1 l/m^3 and gas velocity in the throat w_g = 75 m/s. A very substantial pressure drop of the two-phase flow occurs in the region of the throat, particularly in zone "2", where also the most intensive development of the interface was observed. In the diffuser, the flow shows a gradual pressure recovery due to the enlargement of the cross-section; however, owing to further two-phase friction losses, the pressure gain was much smaller than theoretically possible, which was confirmed by a calculation.

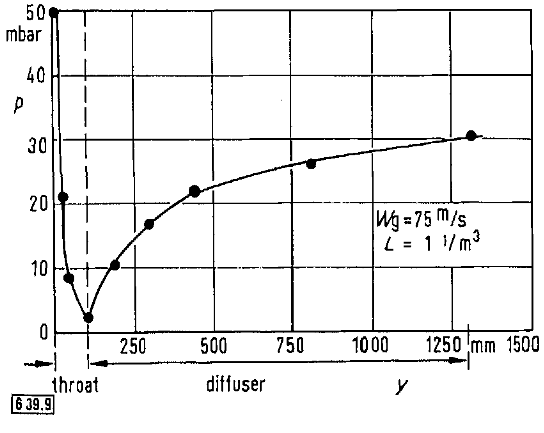

Fig. 9. Pressure distribution in a Venturi-scrubber.

4. Future Prospects

The measurements of interfacial area, relative velocity of the phases and of pressure drop showed that the dust collection occurs predominantly in the atomization zone of the washing liquid up to 40 mm below the jets. As demonstrated by optical observations it was there that the washing liquid formed sheet-like particles. Consequently, the assumption of the droplet-model for the calculation of collection efficiency in Venturi-scrubbers for submicron dust particles, is not appropriate.

Since no theoretical equations have as yet been published for the calculation of mass transfer between gas and liquid during a very turbulent two-phase flow, where the gas is the continuous phase, an attempt ought to be made to formulate an equation containing dimensionless numbers for the gas-phase mass transfer coefficient by analogy to similar equations for momentum transfer; the liquid-phase mass transfer coefficient can be neglected for the dust collection process.

The aim of the authors' further investigations will be to represent the product of the mass transfer coefficient and interfacial area as a function of suitable dimensionless numbers.

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