

Reprint

„The Role of Minute Droplets in the Separation of Aerosols from Gases “
(Chem. Eng. Process., 26 (1989) 201-205, Prof. Dr. J.M. Chawla, CALDYN Ettlingen)

Abstract

Air pollution is caused to a large extent by submicrometre liquid and solid particles called ‘aerosols’. Separation of aerosols from residual gases is a major problem today. Well-known equipment like the venturi scrubber cannot handle submicrometre aerosols successfully. However, enlargement of the aerosols by condensed water vapour and subsequent separation by inertia forces in an air jet containing minute water droplets can lead to an acceptable process with moderate energy consumption. The generation of minute water droplets and their role in the separation of aerosols from gases is described in this paper.

Kurzfassung

Die Verunreinigung der Umgebungsluft wird zum größten Teil durch Aerosole verursacht. Aerosole sind Feststoffe oder Flüssigkeitsteilchen mit Durchmessern < 1µm. Entfernen dieser Aerosole aus Abgasen ist das eigentliche Problem der heutigen Gasreinigung. Die herkömmlichen Techniken - wie z.B. der Venturi-Wäscher - sind hierbei regelmäßig überfordert. Vergrößerung der Aerosolteilchen durch Wasserdampfkondensation und anschließende Abscheidung durch Trägheit ist eine elegante Methode zur Abgasreinigung. Die Rolle der feinen Wassertropfen bei der Aerosol-Vergrößerung durch Kondensation und bei der Trägheitsabscheidung wird hier untersucht.

Introduction

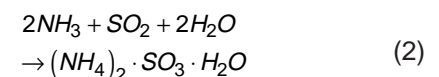
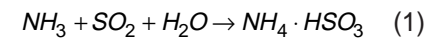
Most industrial plant procedures include cleaning of residual gases. Highly efficient systems like the venturi scrubber can successfully handle particles which are greater than 1µm. The cost and energy consumption of such systems if employed for the separation of submicrometre aerosols, in particular between 0.1 and 0.6µm, are very high and are unacceptable in most industrial applications. Enlargement of the aerosols by condensation and separation by impaction is an elegant method to separate aerosols from residual gases of power plants, chemical plants and incinerators. The effect of the diameter of the water droplet and its relative velocity on the growth and separation of the aerosol is investigated here. A process of atomization which fulfils the conditions required for the separation of submicrometre aerosols and finally an apparatus for industrial application are described briefly.

Generation of aerosols

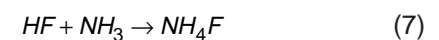
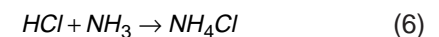
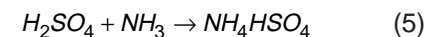
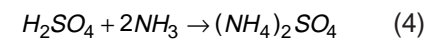
If reactions take place in the gaseous phase, they may lead to the generation of aerosols. The Walther process, developed by Krupp Koppers for flue gas desulphurization using ammonia, is considered here as an example /1/. This process was developed with the aim of establishing a desulphurization method with the following features:
- avoidance of waste-water and other waste products;
- production of the marketable nitrogenous fertilizer ammonium sulphate from the sulphur dioxide contained in the flue gases;
- reheating of the clean gases without external heating energy.
Depending upon the partial pressures of the ammonia gas, sulphur dioxide gas and water vapour, the

following reactions take place and generate aerosols from SO₂, SO₃, HCl and HF /2/.

(A) Aerosol generation by SO₃:



(B) Aerosols generated by SO₃, HCl and HF:



These reactions take place in the gas phase and lead to ammonium salts which are hygroscopic and absorb water vapour from the environment to form a salt solution. The aerosols grow to a stable diameter depending upon the relative humidity in their vicinity. The generation of aerosols is a statistical process. Aerosols of various sizes with different salt masses may be generated. A separation process for salt aerosols with a diameter $d_{s0} \geq 0.05\mu m$ (corresponding to $\cong 10^{-16}g$ salt mass) is described here.

Aerosol growth by condensation

The vapour pressure reduction at the surface of a water droplet of diameter d is, according to Kelvin /3/,

$$\frac{p}{p_s} = \exp\left(\frac{4 \cdot \sigma \cdot \tilde{M}_L}{d \cdot R \cdot T \cdot \rho_L}\right) \quad (8)$$

The vapour pressure reduction, p/p_s , for pure water droplets is given in Fig.1 as a function of the droplet

diameter d for a water temperature of 50°C. Considering salt aerosols of ammonium sulphate with an initial pure salt diameter ds_0 (in μm) and a salt mass m , the vapour pressure reduction on the surface of the aerosol /4/ (salt solution) is given by

$$\frac{p}{p_s} = \left(1 + \frac{6 \cdot i \cdot m \cdot \tilde{M}_L}{\rho_L \cdot \pi \cdot d^3 \cdot \tilde{M}_{s0}} \right)^{-1} \quad (9)$$

Combining eqns. (8) and (9), the vapour pressure on the aerosol surface is given by

$$\frac{p}{p_s} = \left(1 + \frac{6 \cdot i \cdot m \cdot \tilde{M}_L}{\rho_L \cdot \pi \cdot d^3 \cdot \tilde{M}_{s0}} \right)^{-1} \cdot \exp\left(\frac{4 \cdot \sigma \cdot \tilde{M}_L}{d \cdot R \cdot T \cdot \rho_L} \right) \quad (10)$$

This is indicated by the broken curves in Fig.1. The curves show the stable equilibrium diameter of the salt solution as a function of the environmental vapour pressure.

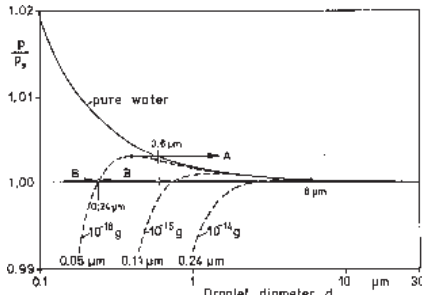


Fig. 1: Vapour pressure reduction at the surface of a salt aerosol

The salt aerosol with an initial salt mass of 10^{-16}g will grow constantly as shown by the arrow A as long as the vapour pressure p/p_s is higher than 1.00224 (this corresponds to a pure water droplet of diameter $0.6\mu\text{m}$). If the pure water droplets in the vicinity of the salt aerosol have a diameter of $2\mu\text{m}$ ($p/p_s=1.001$), the equilibrium stable diameter of the salt aerosol is $0.26\mu\text{m}$. For water droplets of diameter $6\mu\text{m}$ ($p/p_s=1.00022$) the stable diameter of the salt aerosol is $0.24\mu\text{m}$, as shown by the arrow B. The stable equilibrium diameter of the aerosol is $0.23\mu\text{m}$ for pure water droplets of diameter $26\mu\text{m}$ in the vicinity of the aerosol. The stable diameter for $p/p_s=0.950$ (95% relative humidity)

is $0.14\mu\text{m}$. Aerosols with an initial salt mass of 10^{-15}g ($ds_0=0.11\mu\text{m}$) grow to a stable diameter of $0.3\mu\text{m}$ in an atmosphere with a 95% relative humidity, and to $0.6\mu\text{m}$ in a saturated atmosphere. It is evident from the curves in Fig.1 that the stable diameter is a very strong function of p/p_s (or the relative humidity). Considering $p/p_s=1.00022$ (corresponding to pure water droplets of diameter $6\mu\text{m}$), an aerosol with 10^{-16}g salt cannot be enlarged by condensation to diameters greater than $0.24\mu\text{m}$.

Aerosols of about $0.3\mu\text{m}$ in diameter are very effective at scattering light and cause visibility effects similar to a summertime haze. Aerosols with an initial salt mass of about 10^{-16}g ($ds_0=0.05\mu\text{m}$) to 10^{-15}g ($ds_0=0.11\mu\text{m}$) leading to a stable salt solution (aerosol) diameter of about $0.25\text{--}0.6\mu\text{m}$ cause the major scrubbing problem. These aerosols cannot be enlarged by condensation unless the pure water droplets in their vicinity are equal to $0.6\mu\text{m}$. It is practically impossible to atomize water with a maximum droplet diameter of $0.6\mu\text{m}$. A process to separate these aerosols by inertial forces is described below. The salt aerosols grow to $0.25\mu\text{m}$ within a very short time ($\approx 0.03\text{s}$) according to /5/:

$$t = \frac{\rho_L \cdot \tilde{M}_g \cdot (d^2 - d_{s0}^2)}{8 \cdot \delta \cdot \rho_g \cdot \tilde{M}_L \cdot p_s \cdot \left(\frac{p}{p_s} - 1 \right)} \quad (11)$$

Aerosol separation by inertial forces

The aerosols enlarged to a diameter of over $0.25\mu\text{m}$ by condensation can be removed by impaction with high velocity water droplets. The removal efficiency is a function of the impaction parameter

$$\psi = \frac{\rho_L \cdot u_R \cdot d_{s0}^2}{18 \cdot \eta_g \cdot d_L} \quad (12)$$

and the Reynolds number

$$\text{Re} = \frac{u_R \cdot d_L}{\nu_g} \quad (13)$$

as shown in Fig.2 /6/.

The removal efficiency η is 0.28 for a water droplet of diameter $6\mu\text{m}$ moving with velocity of 50ms^{-1} rela-

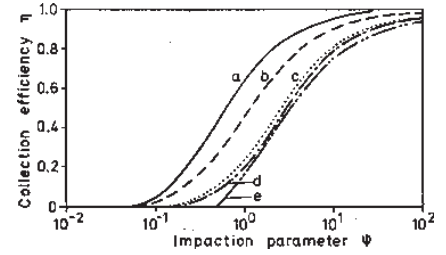


Fig.2: Removal efficiency η as a function of the impaction parameter ψ for different Reynolds numbers. Curve a, $\text{Re} \gg 1$; b, $\text{Re}=60.8$; c, $\text{Re}=40$; d, $\text{Re}=10.2$; e, $\text{Re}<1$

tive to the aerosol. This shows that, for acceptable inertial collection, water droplets of about $6\mu\text{m}$ are required. The relative velocity between the water droplet and the aerosol should be about 50ms^{-1} .

A process for the generation of minute droplets of diameter about $6\mu\text{m}$ moving with a high velocity relative to the aerosol particles is described here.

Generation of minute water droplets

Controlled atomization with a given maximum droplet size d_L can be achieved by employing the low sonic velocity in a liquid/gas mixture. This process of atomization consumes less energy than do the pneumatic systems. The layout of an atomizing nozzle employing the low sonic velocity in a liquid/gas mixture is shown in Fig.3.

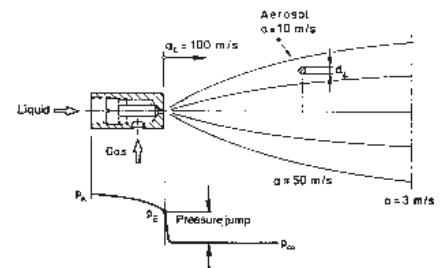


Fig.3: Layout of the nozzle, with the pressure distribution inside and outside the mixing chamber

Liquid and gas, flowing with low velocities, are mixed together in a mixing chamber and accelerated to the sonic velocity of the two-phase mixture. The flow velocity at the outlet of the nozzle cannot exceed the

sonic velocity (critical mass flow rate). If the ambient pressure p_∞ is reduced, or the system pressure p_A is increased, a pressure jump $p_E - p_\infty$ is achieved at the nozzle outlet [7]. The liquid/gas mixture is subjected to this pressure jump while flowing through the nozzle. The pressure in a liquid drop is higher than the ambient pressure by

$$\Delta p = 4\sigma/d_L \quad (14)$$

where σ is the surface tension. It is postulated now that a drop with a diameter d_L is just stable if the pressure jump

$$\Delta p_j = p_E - p_\infty = 2 \cdot \Delta p \quad (15)$$

All the drops with diameters greater than d_L are unstable while flowing through the pressure jump and will be divided into smaller drops with diameters less than d_L .

Liquids can thus be atomized with a given (or required) maximum drop diameter. The maximum drop diameter is controlled by the pressure jump at the outlet of the nozzle.

Design of the nozzle

The pressure jump Δp_j at the end of the nozzle is given by

$$\Delta p_j = 8\sigma/d_L \quad (16)$$

The pressure at the end of the nozzle is

$$p_E = p_\infty + \Delta p_j \quad (17)$$

The sonic (critical) velocity at the end of the nozzle is given by [8]

$$\frac{1}{a_c^2} = \frac{\alpha}{a_g^2} \left[1 + (1-\alpha) \left(\frac{\rho_L}{\rho_g} - 1 \right) \right] + \frac{1-\alpha}{a_L^2} \left[1 + \alpha \left(\frac{\rho_g}{\rho_L} - 1 \right) \right] \quad (18)$$

α represents the void fraction at the nozzle outlet. The properties of the liquid and gas phases such as ρ_L or ρ_g correspond to the pressure p_E at the outlet of the nozzle.

The intensity of the critical mass flow rate is

$$\dot{m}_c = a_c \cdot \rho_{loc} \quad (19)$$

with the local density

$$\rho_{loc} = \alpha \rho_g + (1-\alpha) \rho_L \quad (20)$$

With f as the cross-sectional area at the outlet of the nozzle, the total mass flow rate is

$$\dot{M} = \dot{m}_c \cdot f \quad (21)$$

If x is the quality of the mixture, the liquid mass flow rate is

$$\dot{M}_L = \dot{M}(1-x) \quad (22)$$

and the gas mass flow rate

$$\dot{M}_G = \dot{M} \cdot x \quad (23)$$

The void fraction α is a function of the intensity of the mass flow rate \dot{m}_c and the quality of the mixture x .

Calculation procedure

Any value of α is assumed and a_c , ρ_{loc} and \dot{m}_c are calculated. α and \dot{m}_c lead to the quality of the mixture x and to the required flow cross-section for given \dot{M}_L .

Energy consumption

The frictional pressure loss in the nozzle is negligible compared with the acceleration pressure drop which is

$$\Delta p_0 = \dot{m}_c \cdot a_c \quad (24)$$

The liquid and gas pressure p_A required at the entrance of the nozzle is

$$p_A = p_E + \Delta p_0 \quad (25)$$

The energy E required for the atomization is

$$E = E_g + E_L \quad (26)$$

The energy required for the compressed air is

$$E_g = \dot{M}_g \frac{\kappa}{\kappa-1} p_\infty v_\infty \left[1 - \left(\frac{p_A}{p_\infty} \right)^{\kappa/(\kappa-1)} \right] \quad (27)$$

and for the water pump

$$E_L = \dot{V}_L (p_A - p_\infty) \quad (28)$$

Figure 4 shows the outlet velocity (critical velocity of air-water mixture) as a function of the pressure at the entrance of the nozzle.

The water droplets have this velocity while leaving the nozzle. The air-water jet has a throw of about 3m.

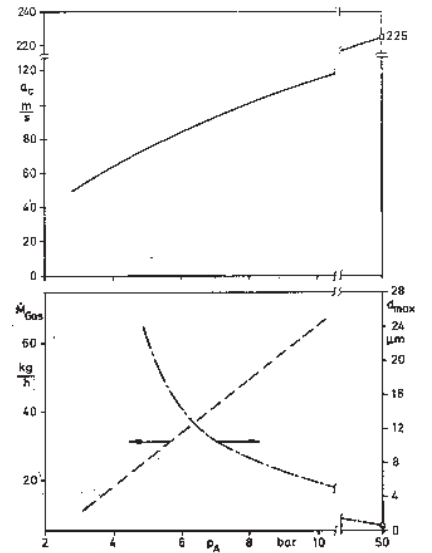


Fig.4: Critical sonic velocity a_c at the nozzle outlet for different pressures at the inlet of the mixing chamber. The Figure also shows the amount of air pressure required for the atomization of 100kg/h of water and the largest water droplet achieved as a function of the pressure at the nozzle inlet.

Environmental air is drawn from all sides and mixes with the free jet, thus diminishing its velocity. A linear velocity reduction may be assumed from an initial value of about 100ms^{-1} to smaller values equal to the residual gas flow velocities. The mean velocity of the jet and also of the liquid droplets is about 50ms^{-1} . The residual gas entering the jet carries aerosols which are scrubbed by the water droplets. The inertial collection is a function of the impaction parameter, the efficiency per impact being 0.28. A number of droplets impact with aerosols within the jet.

Figure 4 also shows the pressure p_A required to generate water droplets of diameter d_{max} . An air and water pressure of 50bar is needed to produce pure water droplets with diameter $0.6\mu m$, whereas an absolute pressure of only 9bar is needed to produce $6\mu m$ droplets.

Design of aerosol scrubber

A layout of the scrubber is shown in Fig.5. Residual gas enters the scrubber at the point A. Pure water is atomized through the nozzle N_1 with a maximum droplet diameter of $6-26\mu m$. Gas is saturated and cooled down to the wet bulb temperature. The aerosols present in the gas stream are enlarged to $0.24\mu m$. Gas now enters the second

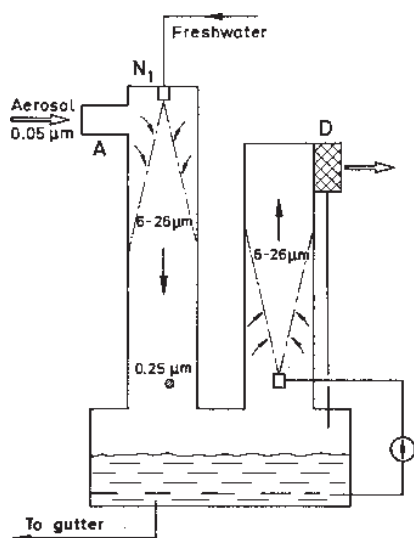


Fig.5: Layout of the scrubber

column from below and process water is atomized by the nozzle N_2 . The enlarged aerosols are collected by impaction with water droplets. The water droplets are finally separated from the gas stream in the demister D.

This system has been employed in industrial plants in various components. A few typical applications are described here.

(1) Carbon black fumes are separated from the hot chimney gases originating in the gold recovery process of 'Hereaus' in Hanau. The gases are quenched and the aerosols are enlarged in the first stage. A second nozzle in series scrubs the enlarged aerosols. The fumes were visible at the chimney outlet before installation of the 'CAS' system. This plant has been working since 1980.

(2) A venturi scrubber was installed by Wiegand to clean the residual gases from an incinerator of the company Wacker-Chemie in Burghausen. The dust load at the entrance to the venturi was about $200\text{mg}/\text{m}^3$ gas. Dust loads at the outlet of the venturi scrubber were $90\text{mg}/\text{m}^3$ gas without aerosol enlargement and $12\text{mg}/\text{m}^3$ gas with aerosol enlargement by the

'CAS'-system. This plant has been in operation since 1985.

(3) Ammonia aerosols as described above were generated in a demonstration plant for the Walther process at the power plant in Mannheim. The dust load was about $250\text{mg}/\text{m}^3$. Aerosols of approximately 30wt.% less than $0.4\mu\text{m}$ were enlarged and separated in a plastic demister. The dust load was less than $10\text{mg}/\text{m}^3$ after scrubbing.

(4) This system is employed regularly in combination with the Waterloo scrubber. Many such plants are in operation in Canada, U.S.A. and elsewhere.

The energy consumption of this system is approximately 50% less than that of systems like the venturi scrubber [9] according to experiments performed at Hoechst AG in Frankfurt.

Nomenclature

a	sonic velocity
d	diameter
f	cross-sectional area at nozzle outlet
i	number of ions per molecule of salt
\tilde{M}	molecular weight
m	mass
\dot{m}	mass flow rate
p	pressure
Δp	pressure drop
R	universal gas constant
T	absolute temperature
t	time
u	velocity
x	quality of mixture
α	void fraction
δ	diffusivity
η	dynamic viscosity
κ	coeff. of adiabatic compression
ν	kinematic viscosity
ρ	density
σ	surface tension

Subscripts

A	nozzle entrance
c	critical
E	nozzle outlet
g	gas
j	jump
L	liquid
loc	local
R	relative
s	saturation
so	solid

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