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Industrial separation of fine particles with difficult dust properties

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Abstract

This paper describes possibilities to separate particles with difficult dust properties from gases. Difficult dust properties are related to extreme values of particle size and shape and to the flowability, the adhesion properties or the reactivity of the particles. Special emphasis is given to submicron particles. In cyclones, conductive particles such as diesel soot can be removed by means of additional electrostatic forces. Experimental investigations into wet tubular electrostatic precipitators show that the measured separation efficiencies are much higher than theoretically anticipated. This result is explained by higher particle charges than predicted by the existing charging models. For small flow rates where electrostatic precipitators are economically not feasible, a new type of wet scrubber may be an alternative. The critical issue of surface filters is the adhesion of the dust cake at the surface of the filter medium. Regeneration of the dust cake as well as trends for the separation efficiency can be determined by small coupon testers which can be used for lab investigations and for field tests. Surface filters are widely used in industry for the separation of nanoparticles. Even extremely sticky particles such as tar particles can be removed by surface filters if a precoat layer protects the filter medium. It is shown that by looking at the physical fundamentals of particle separation, new and innovative solutions can be discovered. Guidelines for the separation of particles with difficult dust properties are given.

Keywords: Dust properties; Cyclone; Electrostatic precipitator; Wet scrubber; Bag filter; Dry scrubbing

1. What are difficult dust properties?

Widely used industrial separators for particles from process streams are cyclones, electrostatic precipitators (ESP), scrubbers and filters. In each separator, the particles have to be transported to a collecting surface by transport mechanisms, must adhere to this surface due to adhesion forces (with the exception of cyclones where the particles are transported in a boundary layer flow to the hopper) and must be removed from the separator in order to enable a continuous operation. These principles are summarised in Table 1.

This paper discusses how the individual separators can be used for collection of particles with difficult dust properties. Considerable progress was made in this field during the last years. Examples are given how the separators are used or may be used in industrial applications.

Dust particles are difficult to separate or to handle if,

- the flux density of the particles to the collecting surface is low (i.e. the collection efficiency may become too small),
- the particles do not adhere to the collecting surface (i.e. sticking efficiency is small),
- the particles can not be removed from the collecting surface or from the separator (e.g. due to their strong adhesion forces and/or poor flowability),
- the particles have extreme mechanical or chemical properties (e.g. very hard or very soft particles, particles with high reactivity),
- mixtures of solid and liquid particles do occur.

Table 2 summarises difficult dust properties and gives examples how to measure them. A very important parameter is the particle diameter. In inertia-dominated separators (e.g. cyclones, scrubbers), collection efficiency drops sharply for $x < 1$ μm and for very low-density particles. In surface filters, however, even extremely fine particles can be separated with high efficiency due to the sieving

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Table 1
Collecting surface in gas cleaning devices

Collecting surface	Type of separator	Transport mechanisms
Non-permeable wall	cyclone electrostatic precipitator	centrifugal force electrostatic force
Permeable wall	surface filter	mostly sieving
Droplet	wet scrubber	mostly inertia
Granule, fiber	granular bed, fibrous filter	inertia, interception, diffusion, electrostatic forces

mechanism of the dust cake. For fibrous particles, extremely high separation efficiencies may be needed due to the high impact of some type of fibers to human health (e.g. asbestos). Fibrous dust can cause problems due to clogging, an effect which is well-known for instance, in surface filters, when the distance between the individual filter bags is too small. Flowability is an important criteria for the transport of the dust out of the separator. If the particles are sintering, e.g. reactive powder paint particles or particles with chlorine components in high-temperature filtration applications, caking and/or problems due to dust cake removal can occur. Abrasive particles can be harmful in all applications where these particles have a high relative velocity to walls (e.g. near the cyclone apex or near the raw gas inlet in poorly designed bag-houses). Abrasive particles are characterised by specific shapes like sharp edges and high values of their hardness. Typical examples are dusts from grinding or polishing applications or ceramic particles like SiC. In the case of reactive (explosive) particles, special care has to be given to the selection and the design of the individual separators. ESPs, for instance, should generally not be used since spark ignition can hardly be avoided. Hot or glowing particles are a specific problem to fabric filters, which can be solved by keeping an inert protective precoat layer on the filter element surface.

Particles with one or more of these properties occur in a wide variety of applications. These range from the flame synthesis of nanoparticles in the gas phase to condensation aerosols which occur in the wood industry, in soil remediation, in waste recycling processes or in municipal waste incinerators, to name only a few. An overview of the various methods for particle separation can be found in the books from Löffler [1] and Seville [2]. In this paper, some new methods for separating particles in industrial applications are described. The results were obtained during the years the author spent in industry with Hosokawa Mikropul.

2. Cyclones

In cyclones, particles are usually separated by means of centrifugal forces. This limits the applications of cyclones in industrial applications to particles larger than 1–10 μm. Finer particles can only be removed if some additional means are employed. In principle, one possibility is the agglomeration of the particles before or directly in the cyclone. Agglomeration upstream the cyclone, or any other separator, can in principle be realised by employing bipolar charging of the particles by means of electric fields or by using acoustic fields. These methods are so far not very successful in industry. Agglomeration in the cyclone due to hydrodynamic effects is called kinematic agglomeration,

Table 2
Difficult dust properties

Dust property	Characterisation method	Comment
Fine particle diameter, $x < 1$ μm	size measurement, e.g. light scattering, mobility analyser	low separation efficiency in cyclones, scrubbers, ESP, high pressure drop in surface filters
Low particle density	pycnometer	small sedimentation velocity, small inertia effects
Fibrous particles	shape analysis	extremely high separation efficiency may be required, caking
Free flowing particles	shear test (e.g. Jenike, ring shear tester), angle of repose	problems with dust cake formation
Sticky particles, sintering particles	shear test, angle of repose thermal analysis (dilatometer, DSC)	caking, problems with regeneration in fabric filters
Abrasive particles	hardness, shape analysis	erosion in areas with high velocities of the particles
Reactive (explosive) particles	reactivity of the particles in the specific environment, TG/DTA, DSC	requires pressure or pressure shock resistant design
Hot particles	consider upstream process units (e.g. calciner, burner etc.)	destruction of the filter medium

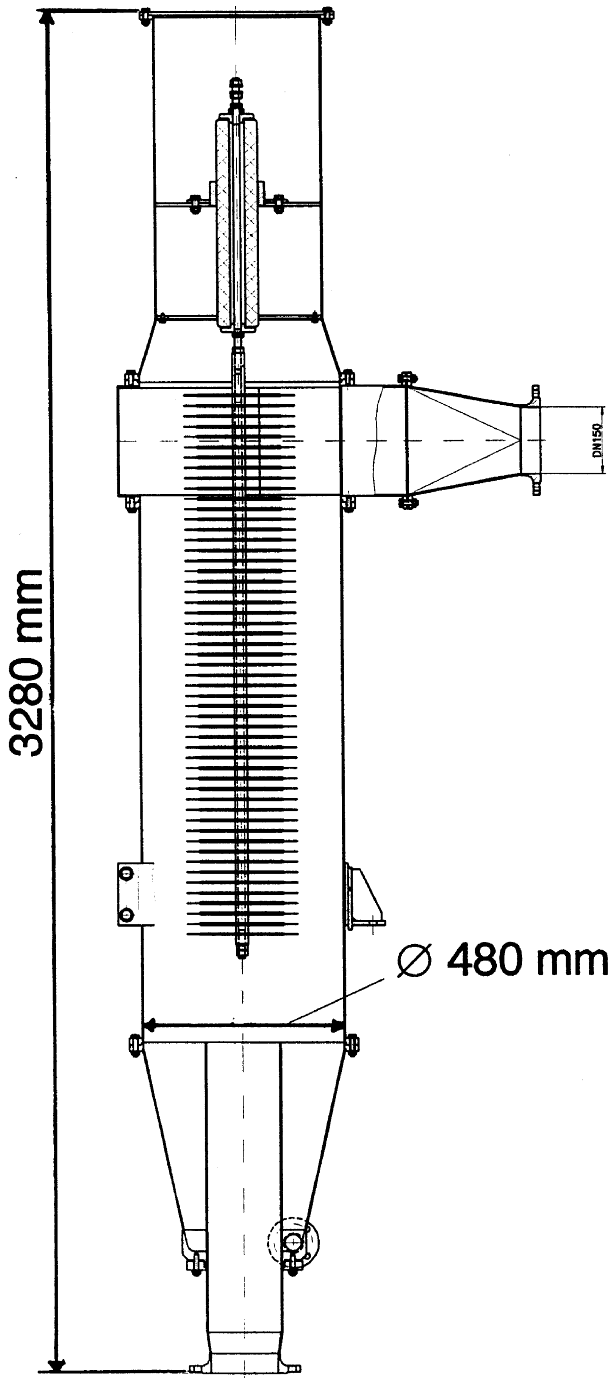

Fig. 1. Schematic drawing of the electrocyclone.

according to Mothes and Löffler [3]. Larger particles settle in the centrifugal field faster than smaller ones and may therefore collect some of the finer particles. Although this effect can, in principle, explain the experimentally well-known observation that the separation efficiency increases with increasing mass concentration in the raw gas, this effect is too weak to separate a high amount of nanoparticles. Iinoya [4] investigated particle separation in small cyclones of 76 mm in diameter, from which a small amount of gas was extracted through the hopper. Iinoya could show that it is possible to separate particles down to 0.3 μm.

Nanoparticles can be separated in cyclones by means of additional electrostatic effects as demonstrated by Wadenpohl in his PhD thesis [5]. This author investigated the separation of diesel soot particles which were emitted from an automotive diesel engine by means of a modified cyclone. This cyclone was equipped with a central electrode. A high voltage was applied between the electrode and the cyclone wall so that particles are charged due to corona discharge. Wadenpohl showed that primary particles of 10–30 nm in diameter are transported to the cyclone wall by means of electric field forces, where they form fairly large aggregates of few microns in diameter. Collected particles may be recharged to the potential of the collecting electrode. Thus, the field lines of the electric field are focused so that the collected particles act as nuclei for dendritic growth of aggregates. The separation of the aggregates from the collecting surface can be explained by two mechanisms. Both image forces induced in the collected structures, which are directed towards the spray electrode and fluid forces in the boundary layer, can lead to the removal of the aggregates from the collecting surface [6]. The particles are then transported in the boundary layer flow to a small outlet where 5–10% of the total flow rate is extracted. This principle was upscaled to flow rates of several 1000 m^3/h (see Fig. 1).

This cyclone was tested after a stationary diesel engine. It was found that the mass specific separation efficiency ranged from 50% to 80%, depending on the flow rate (i.e. on the residence time in the cyclone) and the applied voltage (Fig. 2). These results are similar to that observed in the lab with a geometrically similar cyclone and a flow rate of only 68 m^3/h.

This principle, however, only works for conductive particles. Experiments with fumed silica failed because of two reasons: at low concentration particles can be separated but not removed from the cyclone wall; at concentrations in the order of 1 g/m^3 and higher, the electric field

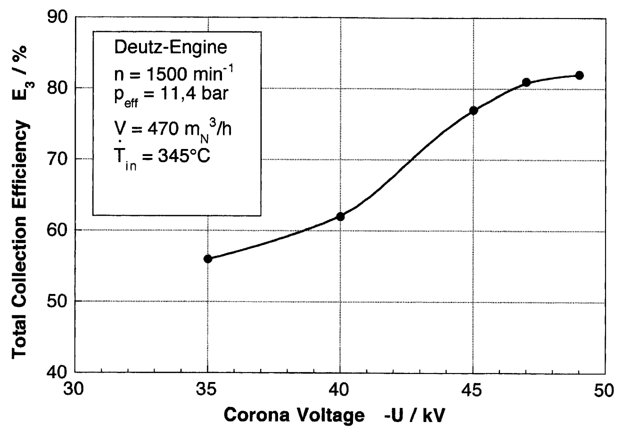

Fig. 2. Total separation efficiency (mass basis) of the electrocyclone.

broke down due to space charge effects. Thus, the separation efficiency for nanoparticles dropped since the centrifugal forces alone are too weak to achieve a substantial separation efficiency. As a conclusion, conducting nanoparticles at mass concentrations below approximately 1 g/m^3 can be separated in electrocyclones. The separation efficiency is determined by the residence time of the particles in the cyclone and by the electric field strength.

3. Electrostatic precipitators

3.1. General remarks

Electrostatic precipitators are mainly used for particles $> 1\ \mu m$, with dust resistivities between approximately 10^4 and $10^{11}\ \Omega$ cm. Particles with very high resistivity cause problems due to back corona effects, whereas conductive particles may reverse their charge and thus do not adhere to the collecting electrode (reentrainment) [7]. When the gas contains condensible components or liquid particles, clogging causes problems in all dry operating separators. As an alternative, wet electrostatic precipitators may be employed, which show outstanding collection efficiencies and moderate power consumption. In this study, a wet tubular ESP is investigated. Tubular ESPs have the advantage that scale-up is straightforward once the operational behaviour in one single tube has been investigated.

A special feature of the electrostatic precipitator (ESP) described in this paper is the continuously irrigated collection electrode by means of a liquid film. The advantages of this technology are as follows. Formation of a dust layer on the collection electrodes is avoided, and thus, there are no problems with reentrainment or arcing. There is no breakdown of the electric field during flushing as it occurs for spray irrigated electrostatic precipitators, which are regenerated intermittently. The danger of clogging is low because contact between particles and the collection electrode is prevented by the liquid film. The liquid film can be grounded and therefore conducts the corona current. This makes it possible to manufacture the electrostatic precipitator from non-conductive materials (e.g. polypropylene, PVC, reinforced plastics), which allows cost-effective design even when the gas streams contain corrosive components. In the following, some results of experimental and theoretical investigations on such a wet wall ESP will be given [8].

3.2. Experimental set-up

Fig. 3 shows the schematic drawing of the experimental set-up. The tubular electrostatic precipitator is made of PVC. This material offers the advantage of high chemical resistance. As discharge electrode, a stainless steel wire is used, which is made taut by a weight. The irrigating liquid is fed in a manner that the whole collection electrode is covered by a thin liquid film. The liquid drains into a sedimentation tank, where the collected particles settle down and the liquid is recirculated into the ESP. Optionally, the ESP can be operated in the condensation mode. In this case, the collection electrode is cooled by a cooling liquid. If the dew point of the gas is sufficiently high, the condensed vapour forms a closed film which drains off the collected particles in the same way as it is described above. In both cases, the liquid film can be grounded and conducts the corona current, which works well with conductivities of the liquid down to 10 $\mu S/cm$. Particles are dosed by a screw conveyer and are dispersed in an eductor.

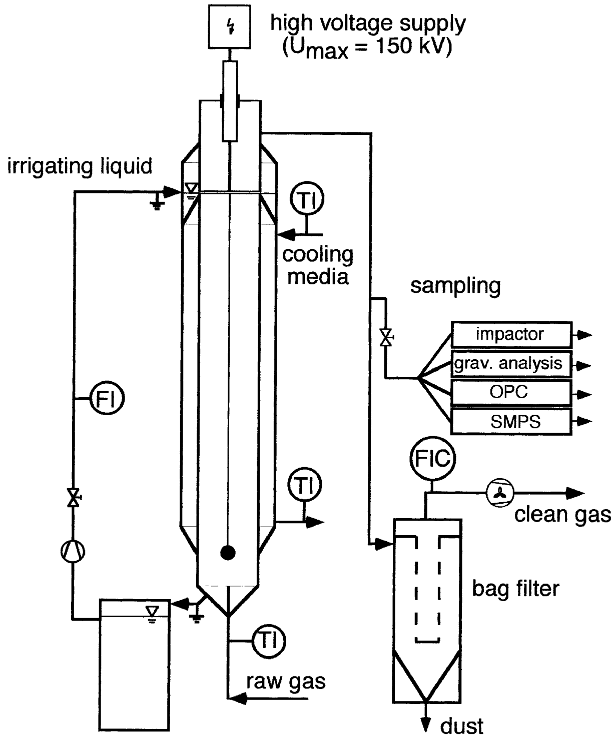

Fig. 3. Schematic drawing of the experimental set-up.

An adjustable fan generates the gas flow through the ESP. Particle analysis is done by isokinetic sampling. To measure the dust concentration, a gravimetric method is used. For measuring the particle size distribution, different devices have been used. A light scattering analyser (Palas) covers the size range between 0.3 and 40 μm. A scanning mobility particle sizer (TSI) is used for particles with a diameter between 10 nm and 0.5 μm. For some tests, a cascade impactor (Anderson Mark III) was used, which was provided kindly by Prof. Büttner of University of Kaiserslautern. Collection efficiency of the ESP is determined by first measuring the particle concentration without high voltage. Afterwards, a second measurement is done under same conditions but with high voltage applied to the ESP. Relating the particle concentration in the clean gas to that in the raw gas, without high voltage, enables the calculation of collection performance.

3.3. Results

The decisive design parameter for ESPs is the specific collection area (SCA), which is defined as the ratio of flow rate $\dot{V}$ and surface area A_{CE} of the collecting electrodes.

$$\mathrm{SCA} = \frac{A_{CE}}{\dot{V}} \tag{1}$$

For tubular ESPs of length L_{CE} and diameter D_{CE}, it results in,

$$\mathrm{SCA} = \frac{4L_{CE}}{D_{CE}v}, \qquad v = \frac{\dot{V}}{A_{CE}}. \tag{2}$$

The specific collection area is related to the grade efficiency of the ESP $T(x)$ by the well known Deutsch equation [9],

$$T(x) = 1 - e^{-w_{th}(x)\mathrm{SCA}} \tag{3}$$

w_{th} is the migration velocity of the particles, of diameter x, in the electric field E_{CE} near the collection electrode. η is the gas viscosity, Cu denotes the Cunningham correction factor.

$$w_{th}(x) = \frac{q_p(x)E_{CE}Cu(x)}{3\pi\eta x} \tag{4}$$

The particle charge $q_p(x)$ can be calculated from the equation of Cochet [10].

$$q_p = \left[\left(1+\frac{2\lambda}{x}\right)^2 + \left(\frac{2}{1+\frac{2\lambda}{x}}\right)\left(\frac{\varepsilon_{r,p}-1}{\varepsilon_{r,p}+2}\right)\right]\pi\varepsilon_0 x^2 E \tag{5}$$

λ is the mean free path of the gas, $\varepsilon_{r,p}$ and ε_0 denote the permittivity of the particle and of vacuum, respectively, E is the electric field strength. From Eq. (3), it can be seen that collection efficiency improves with increasing specific collection area. This can be understood easily, looking at Eq. (2). An increase in SCA can be achieved either by increasing the residence time of the particles in the electric field (increasing length of the ESP or reducing gas velocity) or by reducing the tube diameter, which results in a shorter distance that particles have to travel for reaching the collection electrode. Fig. 4 shows grade efficiencies for different values of SCA measured with the light scattering analyser. For these experiments, the flow rate was varied at a constant area of the collection electrode. As it was discussed above, an increase in SCA leads to significantly higher collection efficiencies. Depending on the required clean gas concentration, the ESP can be dimensioned for each application appropriately. At a value of 58 s/m for SCA, a nearly complete collection even for particles below 1 μm is observed, so that even strongest emission requirements can be met. SCA values determine

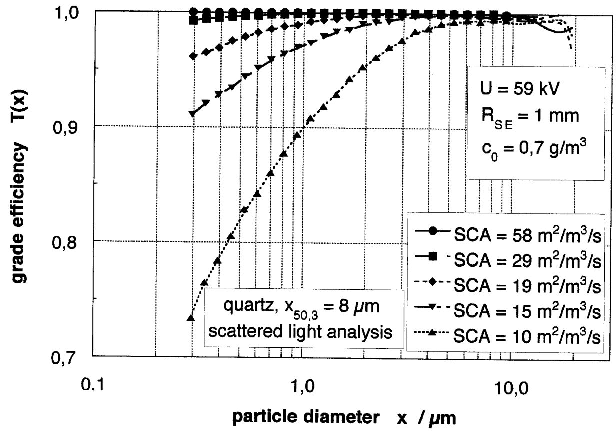

Fig. 4. Grade efficiency depending on specific collection area.

the collection efficiency completely if the theoretical migration velocity is given.

A comparison between measured and calculated grade efficiencies is shown in Fig. 5. It is surprising that the measured values are considerably higher than the calculated ones using the Deutsch equation [11]. This result is, however, in accordance with the investigations of Riehle [12] and Schmid [13]. Riehle studied particle transport in a laboratory plate-type ESP, in a way that collection efficiency is not influenced by secondary effects (e.g. rapping losses, back corona). Under these conditions, which are comparable to the situation in a wet wall ESP, he also found a significantly better efficiency than predicted by theory. Schmid came to the same conclusion by measuring particle flux densities near the collecting electrode of the ESP. In order to verify the above shown results obtained by a light scattering analyser, additional measurements with a cascade impactor were done and led to similar grade efficiencies. Obviously, the simple Deutsch model in combination with Cochet's law are not able to describe particle collection correctly. An explanation may be seen in the fact that calculations of particle trajectories, including the inhomogenous distribution of the electrical field, led to a distinct increase of grade efficiencies [12]. Additionally, it may be anticipated that the particles may carry higher charges than those assumed by Cochet's model. Effects due to the electrical wind can probably not explain the measured data since the experiments were performed in a cylindrical geometry, i.e. under axial symmetry.

An important question, of course, is the scale-up. The cylindrical geometry is not only advantageous for the formation of the liquid film on the inner surface, but also, realisation of ESPs with different throughput (and same collection efficiency) is no problem by varying the number of collection tubes, depending on the amount of gas that has to be cleaned. In addition to this way of scaling up or down, the diameter of the pipes is an important parameter when designing a wet ESP. Based on an existing approach for plate-type ESPs [3], a method was developed to predict

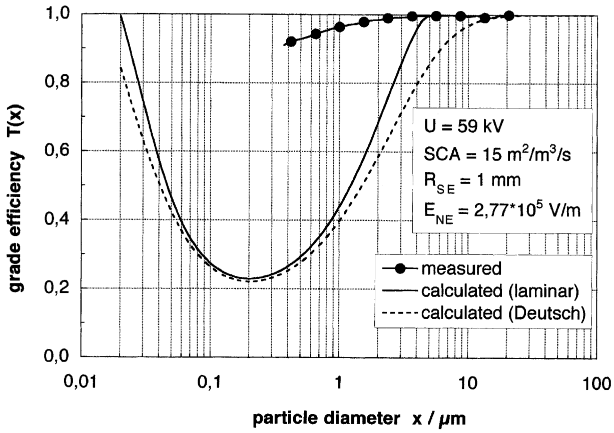

Fig. 5. Comparison between measured and calculated grade efficiencies.

the collection efficiency of tubular ESPs with different diameters. When two ESPs of different diameter are similar from a geometrical point of view and when they are operated at constant velocity, a non-dimensional voltage, $U' = U/(ER_{SE})$ (U: applied voltage, R_{SE}: radius of the spray electrode, E: electric field strength), must be kept constant to get identical grade efficiency curves. This method makes it possible to design ESPs of any diameter on the basis of experimental results obtained from measurements at one fixed geometry.

Apart from collection efficiency, the energy consumption is of interest for the characterisation of a dust collector. Well investigated is the relationship between specific energy consumption and cut size (particle size which is collected with an efficiency of 50%) for wet scrubbers. The general trend is that energy consumption increases with decreasing cut size. A comparison with the empirical optimum curve according to Wicke and Holzer [14] shows that the performance of the ESP is superior to all types of wet scrubbers, from the point of view of collection efficiency as well as from energy consumption.

The above shown results point out that continuously irrigated tubular ESPs show an outstanding performance, in combination with a moderate energy consumption. Due to this, they are advantageous for collection of finest particles, especially when they are sticky or suspended in humid gases and when highest efficiencies are required. Some typical applications are, for example, automotive recycling plants, incinerators for hazardous or medical waste, pigment production plants, sulphuric acid plants, tar collection, fiberglas forming lines, soil regeneration, and sinter plants.

4. Wet scrubber

Wet scrubbers separate according to inertia effects when the droplet approaches a dust particle due to the relative velocity, v_{rel}, between particle (density ρ_p) and droplet with diameters x and d_c, respectively. The decisive parameter is the inertia parameter,

$$\psi = \frac{Cu\,\rho_p\,x^2\,v_{rel}}{18\eta d_c}. \tag{6}$$

With decreasing Ψ, i.e. for submicron particles, the separation efficiency drops to unacceptable small values. Various means were proposed to overcome this effect. Schmidt

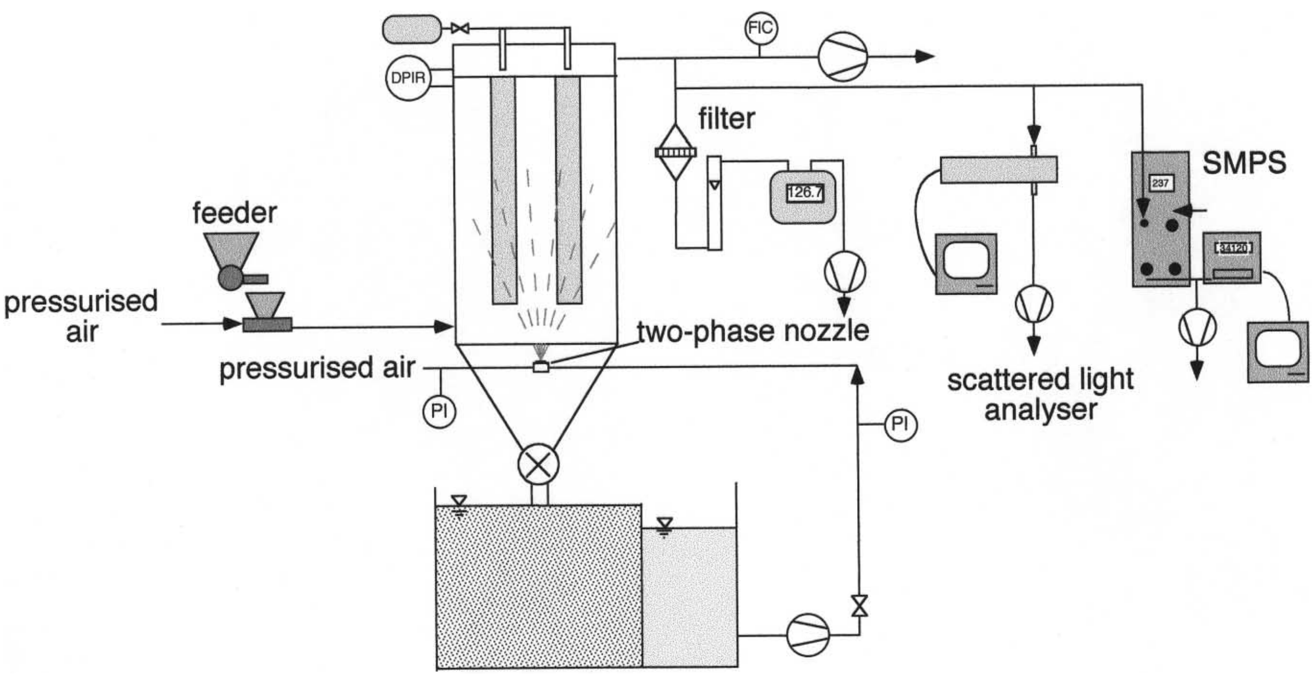

Fig. 6. Experimental set-up of the wet bag filter.

and Löffler [15] as well as Ebert et al. [18] investigated the effect of additional electrostatic effects by charging the particles and/or the droplets electrostatically, whereas Krames and Büttner [16] explained the enhanced separation efficiency for particles, < 1 μm, in cyclone scubbers by turbulent diffusion. Ebert et al. [17] also investigated the effect of heterogeneous condensation in order to generate larger, i.e. easier to collect particles with larger inertia parameters. Although a wet ESP can be used for applications where solid and liquid particles or extremely sticky ones have to be separated, a certain disadvantage of the wet ESP may be seen in the relatively high investment costs for the high voltage supply, which are almost independent of the size of the system. Therefore, an alternative for small flow rates of a few 1000 m^3/h was investigated, which may be supplied in similar applications as the wet ESP.

A pilot bag-house with six filter elements of 1.8-m length, which is operated under wet conditions, was investigated. In the bag-house, a two-phase nozzle located below the filter elements generates small droplets. The droplets are collected simultaneously with dust particles on the surface of the filter bags. A stable operation of this configuration depends on the type of filter medium, on the filter rate (air/cloth ratio) and on the ratio of the gas to liquid flow rate. The droplets collected on the surface of the filter bag form a discontinuous liquid film which removes the collected dust particles. The experimental set-up is shown in Fig. 6. Dust and droplet size distribution were measured gravimetrically, by means of a scattered light analyser and a TSI SMPS-system. Samples were taken isokinetically. Experiments were conducted with quartz dust with a mass median size of $x_{50.3} = 8$ μm and with TiO_2 nanoparticles ($x_{50.3} = 0.3$ μm). Fig. 7 shows that the grade efficiencies do only weakly depend on the air/cloth ratio. Since the flow rate of the liquid through the nozzle was kept constant, the ratio of liquid to gas flow rates, L/G, changed accordingly.

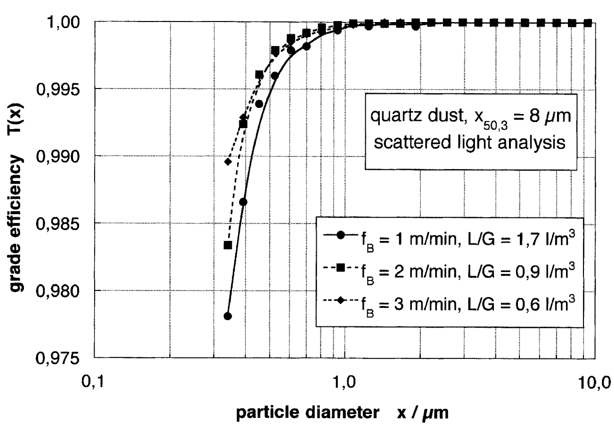

Fig. 7. Influence of the air to cloth ratio f_B on the grade efficiency of the wet bag filter.

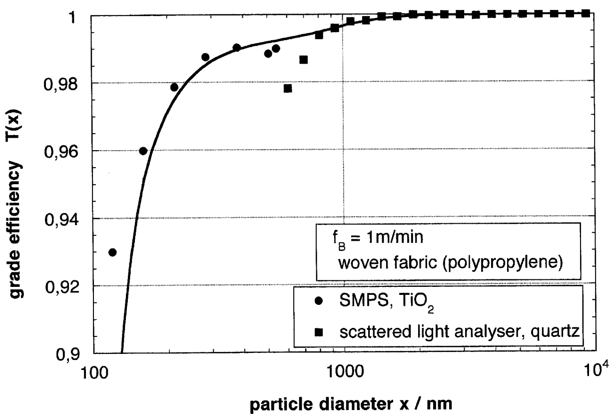

Fig. 8. Grade efficiencies obtained with the wet bag filter.

Fig. 7 shows that the grade efficiencies are surprisingly high even for submicron particles. Additional measurements with TiO_2 nanoparticles, which were analysed by the SMPS-system, coincide quite well with the results obtained for quartz particles with optical measuring system (Fig. 8). However, the grade efficiencies for particles smaller than 300 nm drop sharply, leading to even negative values of the separation efficiency. This effect can be explained by the fact that small droplets evaporate so that a high number of residual salt particles are formed. This effect is known from experiments with scrubbers, where it could be shown that the observed particle sizes relate to the salt concentration in the water used in the experiments. This assumption also coincides with measurements of the droplet size distributions after the filter. It was found that the drop size distribution is shifted to smaller particles and that the total number of droplets increased with increasing filter rate.

This example shows that the performance of scrubbers is only as good as the droplet separator. The performance of the filter depends also on the selection of the filter medium. More than 20 filter media were tested over a period of several days. Currently, it is too early to define guidelines for the selection of the filter media. Both needle felts and nonwoven fabrics can be used. Filter media equipped with a membrane, however, led to high pressure drops above 100 mbar and cannot be recommended.

5. Fabric filters

5.1. Fabric filters for separation of nanoparticles

Fabric filters are built for the separation of particles from gases with flow rates of a few cubic meters per hour, up to several million cubic meters per hour, whereby practically all available materials of construction can be used. Dust concentrations in the raw gas may vary between below 1 g/m^3 up to several 100 g/m^3. Clean gas concentrations below 5 mg/m^3 can be achieved even for submicron particles. In individual cases, even values far below 1 mg/m^3 are possible. The operational behaviour of bag filters depends on geometry of the bag house, on fluid flow distribution in the raw gas part, on the kind and geometry of filter media, on gas composition, on temperature and pressure and on particle properties. Particles are transported with the gas to the filter elements where the gas flows through the porous filter medium. The particles are separated after a short initial period on the surface of the filter medium. A dust cake is formed, leading to an increase of pressure drop so that the filter element has to be regenerated periodically, i.e. the dust cake has to be removed. Since the dust cake itself is a very effective filter medium, emissions are highest immediately after regeneration and decrease usually upon dust cake build-up. The excellent book of Löffler et al. [19] gives an overview of the field. Fig. 9 shows schematically the principal operational behaviour of fabric filters.

Fabric filters can be employed for the separation of dust particles with difficult properties. Usually, separation of the particles is not a major point of concern. Only if extremely free flowing dust particles (e.g. surface modified alumina powders) have to be separated, which do not form a dust cake, problems due to unsatisfactory clean gas concentrations or due to clogging of the filter medium may occur. With extremely fine particles, two main topics have to be considered. Firstly, the gas flow in the raw gas section of the bag-house should assist sedimentation of the fine particles to the hopper, i.e. a down-flow configuration has to be realised. Secondly, the adhesion forces of the dust cake must be overcome by the separating forces during regeneration (see Fig. 10). A proper design of the regeneration system (pulse-jet regeneration for instance) enables high separation forces due to the pressure wave moving along the filter bag. Systems working according to these principles are already in operation for several years. Fig. 11 shows an example of a filter which is used for the separation of TiO_2 particles after a steam-jet mill operated at approximately 130°C, in a gas atmosphere of almost 100% water vapour. The operational conditions are: flow rate, 50 000 m^3/h; particle concentration, 150 g/m^3 TiO_2 with 100% of the particles smaller than 1 μm. Emissions in continuous operation are smaller than 20 mg/m^3. The raw gas inlet is from top through the clean gas chamber to bottom so that an almost ideal downflow configuration is realised. The bag-house is heated and insulated so that condensation of water vapour is avoided. Regeneration of the filter medium is realised online during operation by means of a pulse-jet regeneration system. The pulse gas has to be heated in order to avoid condensation in the pulse-jet [30].

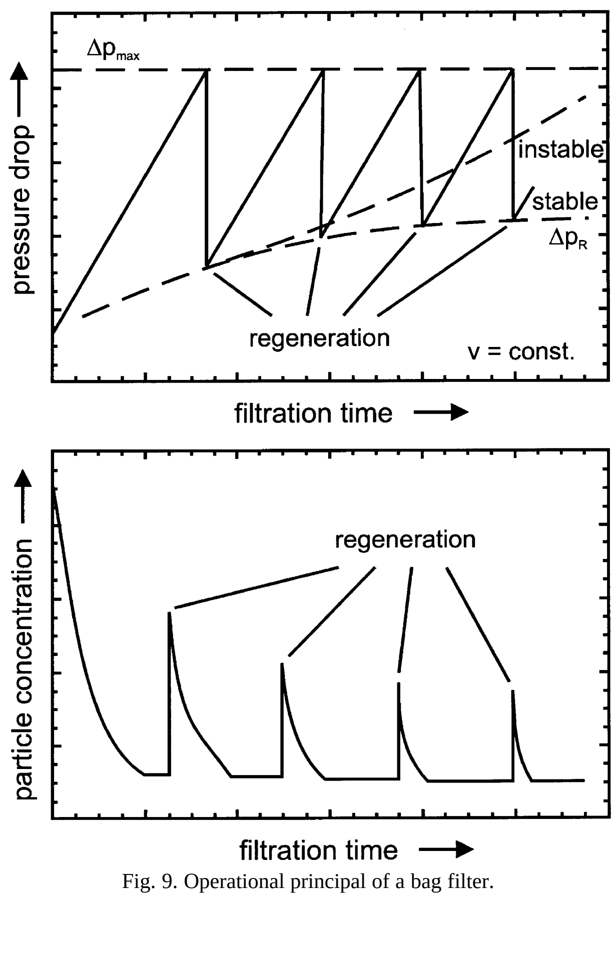

Fig. 9. Operational principal of a bag filter.

TiO_2 in a flame hydrolysis process can also be collected directly after the flame reactor. In this case, a high-temperature filter, operated at about 400°C, can be used. Surface filters are also employed to separate fumed silica, carbon black and a variety of other nanoparticles produced in the gas phase.

5.2. Selection of filter medium for demanding applications

Physical models for the determination of filtration velocity, and thus for the size of a bag-house have for the time being no relevance in industrial practice. The design depends on the experience of suppliers and users. In those cases where physical design models are not available, simple experimental techniques for determination of relevant parameters are required. Based on the results of Sievert [20], Gäng and Löffler [21], a new VDI guideline [22] was developed by Gäng for the characterisation of regenerable filter media. In this test, particles are fed, well-dispersed, into the vertical raw gas duct and transported to a filter element, which is mounted at the end of the horizontal clean gas duct. This arrangement allows simulation of the filtration process by using a flow rate of only 5 m^3/h. The measured parameters are pressure drop, residual pressure drop directly after regeneration, regeneration efficiency in dependence of over-pressure during pulsing, and clean gas concentration. It becomes thus possible to select a filter medium for the collection of a specific dust. Sievert showed that results, with regard to regeneration efficiency in dependence of over-pressure obtained

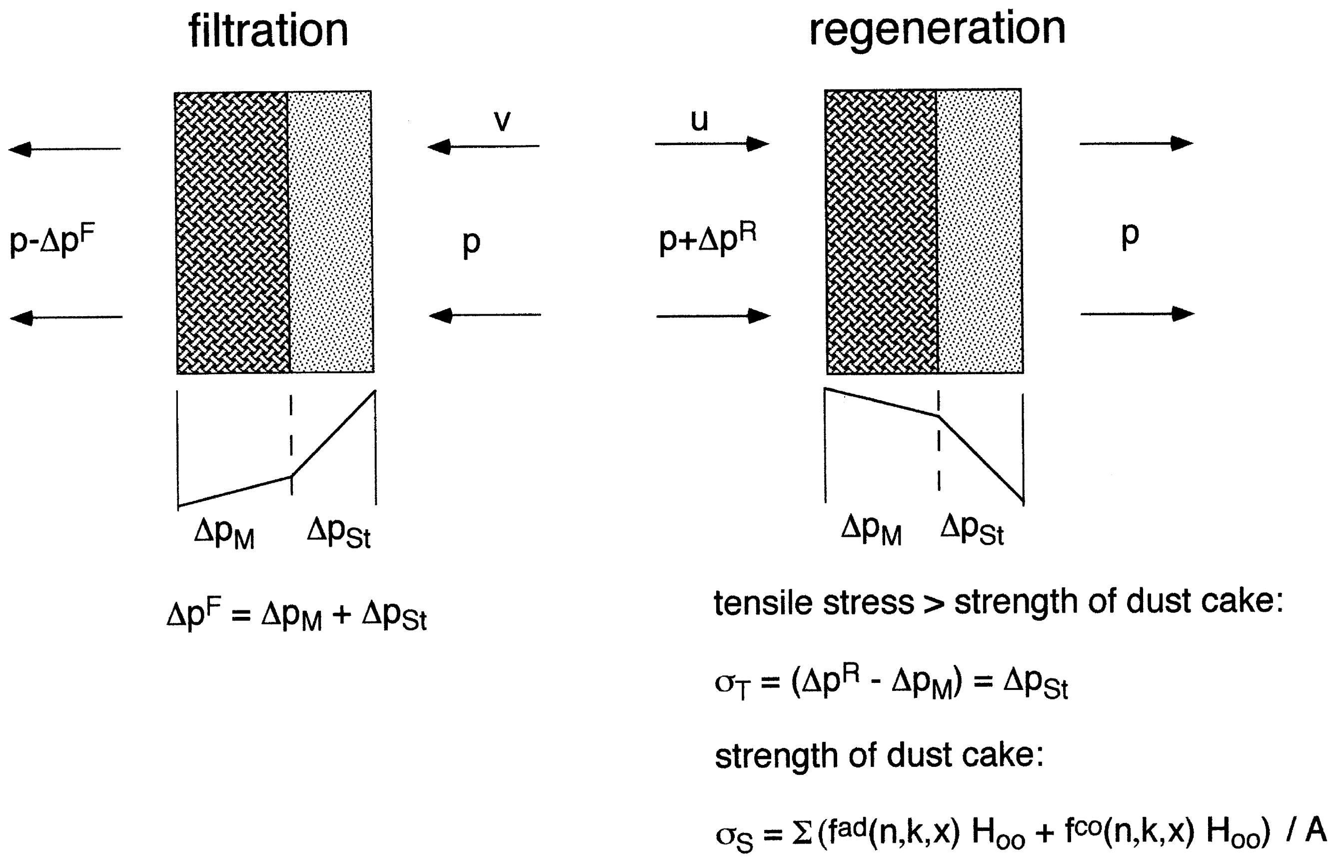

Fig. 10. Cake removal in surface filtration.

with the coupon tester, are comparable to those measured locally at the surface of a filter bag.

In order to compare the results obtained from the VDI-unit with the filtration behaviour of a larger industrial pilot filter, the clean gas part of the VDI-system was installed in a bag-house with 40 bags of 2.4-m length. One filter bag was removed and the clean gas duct of the VDI-tester was mounted in the bag-house according to Fig. 12. The small filter sample was operated with the filtration velocity corresponding to the mean filter rate of the bag house. Regeneration was triggered simultaneously to row 4 of the bag house. The maximum over-pressure at the filter sample was similar to the value in the filter bag at the position of the filter sample. Fig. 13 shows a comparison of the pressure drop gradient of the bag house and the filter sample in dependence of filtration rate.

Both curves are similar, indicating that dust cakes structures on the filter sample and on the filter bags are comparable. Particle size distribution of the dust (limestone) on the filter sample and on various locations on the bag surface were found to the similar, i.e. no segregation occurred. However, maximum filtration velocity for the bag-house cannot yet be determined by the VDI-tester. At filter rates above 2.2 m/min, residual pressure drop of the bag-house began to increase (i.e. operation became unstable), whereas the operation of the VDI-tester was found to be stable up to a filtration velocity of 2.8 m/min, even though the over-pressure during pulse-jet regeneration was similar in both arrangements. One reason for this difference is supposed to be in fluid flow distribution in the bag-house. The coupon tester gives the maximum value of the filter rate for which the medium can still be regenerated without taking fluid flow distribution into consideration. These results show, however, that the small filter tester can conveniently be used in applications with difficult dust properties. The tests give reliable data on the pressure drop to be expected and if the dust cake can be removed. The design of the bag-house regeneration system can be based on a preliminary test with the VDI-system [23].

5.3. Dry scrubbing

Dry scrubbing systems consist of an entrained flow reactor and a subsequent collection device, e.g. a bag filter in which both particulate matter and gaseous components are collected simultaneously. The adsorbent particles are fed into the reactor, whereby dispersion is essential in order to achieve maximum mass transfer of the gaseous pollutants to the surface of solid adsorbent particles. Adsorption takes place during transport to the bag filter and on the surface of the bags where the solid particles are

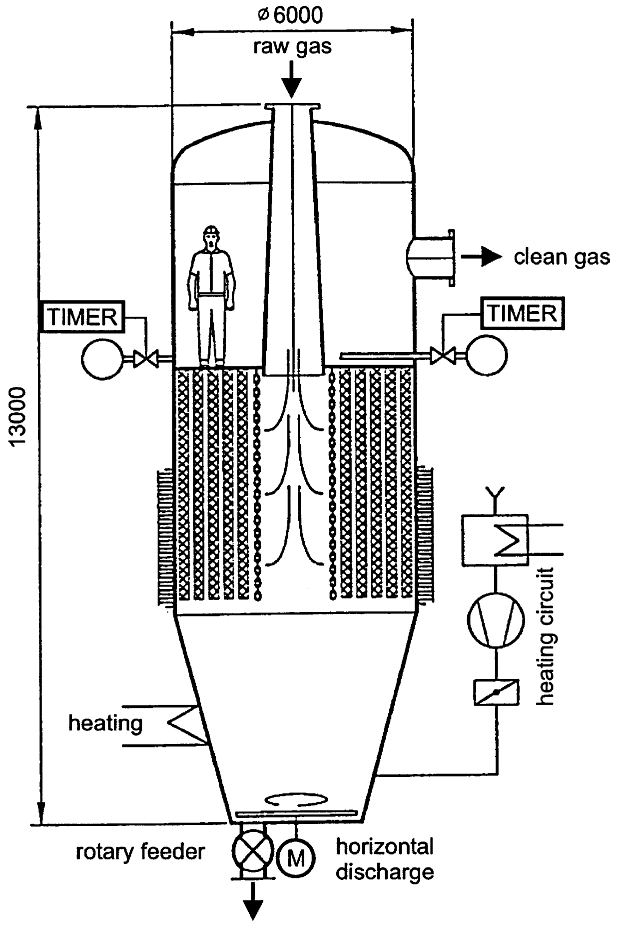

Fig. 11. Filter after a steam-jet mill for TiO_2 removal.

collected. The adsorbent particles are usually smaller than 50–100 μm, so that a dust cake is formed during separation with pores in the μm-size range. The dust cake is then used as a highly efficient fixed bed reactor with very short diffusion distances.

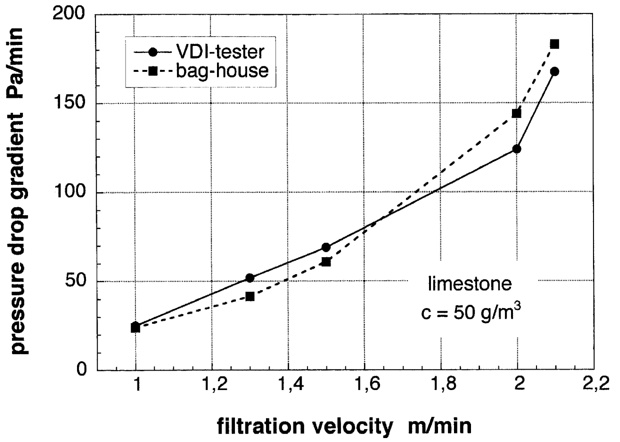

Fig. 13. Comparison of pressure drop gradients of a bag-house and a small filter sample.

In the following, an example for separating extremely sticky solid and liquid particles is given. Carbon in form of coke, pitch and tar is an important raw material in the fabrication of electrodes. These electrodes are used, for instance, in the aluminium industry as anodes for electrolysis. Fumes from anode baking furnaces contain, besides SO_2 and HF, substantial concentrations of solid, liquid and gaseous polyaromatic hydrocarbons (PAH), which are extremely sticky. Traditionally, fume treatment systems consisted of evaporative cooling towers with subsequent electrostatic precipitators. The evaporative coolers lower the gas temperature in order to condense the hydrocarbons, which are collected as droplets in the electrostatic precipitators. Fume treatment plants are not only evaluated by its emissions but also by the residues which are produced by the cleaning process itself. A decisive progress in fume treatment technology for closed-ring type baking furnaces is the concept which is schematically represented in Fig. 14 [24].

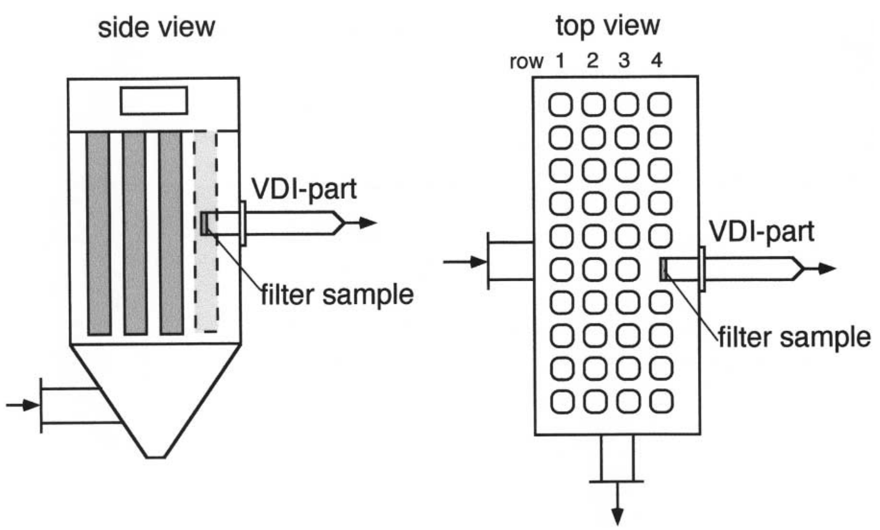

Fig. 12. Arrangement of the filter sample in the bag-house.

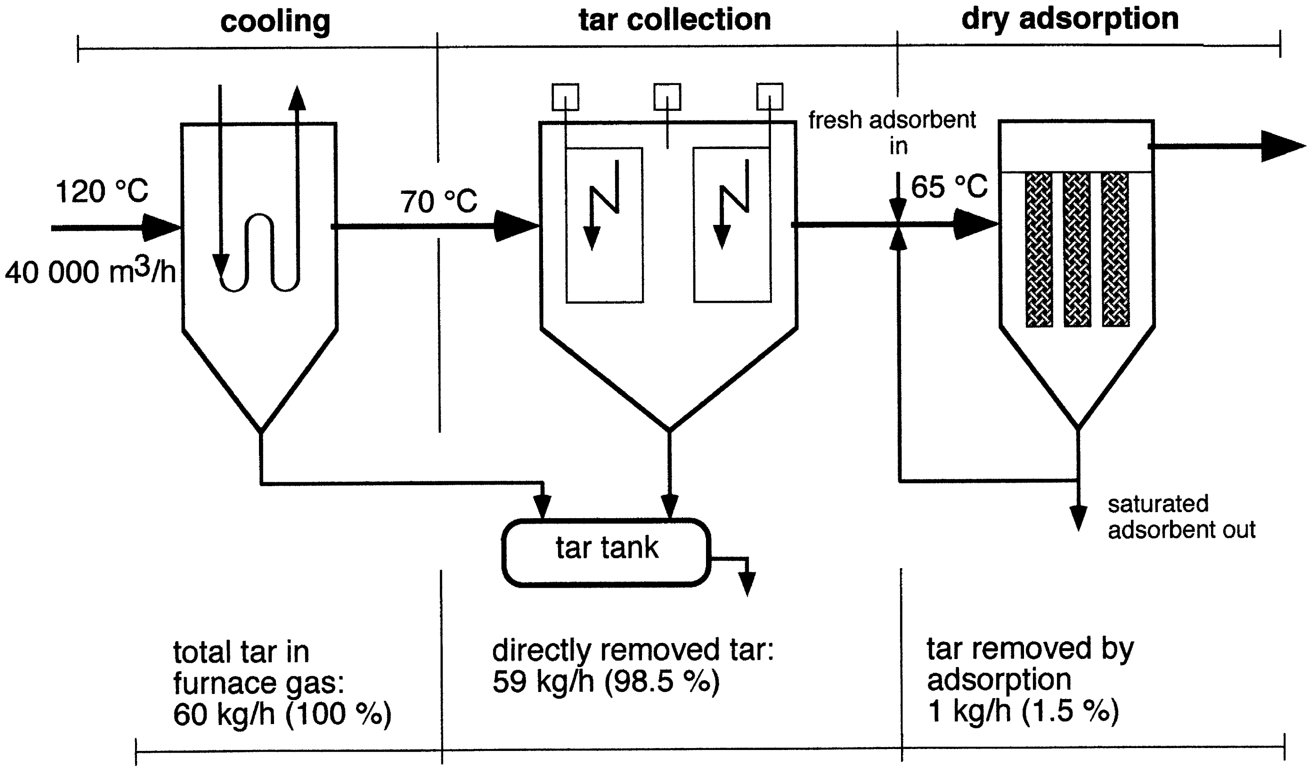

Fig. 14. System with indirect cooling and gas adsorption for closed type ring furnace.

The flue gas is cooled with an indirect cooler down to 70°C. A considerable amount of hydrocarbons is condensed on the outside of heat-exchanger pipes. The droplets are collected together with solid dust and tar particles in the electrostatic precipitator. After the closed-ring baking furnaces, the viscosity of the dust/tar mixture is high enough to ensure sufficient flowability. After the electrostatic precipitator, a dry adsorption unit is used for collection of the remaining particles and the adsorption of gaseous components. Petrol coke, ball mill dust or alumina may be used for adsorption. These materials originate from the process (either from electrode production or aluminum electrolysis), and can be recycled back into the process so that no additional materials have to be used. Essential for a long-term stable operational behaviour is a sufficiently thick dust layer of the precoating material that protects the filter medium from clogging due to the extremely sticky tar particles. The industrial experience shows that even under these extreme conditions, a reliable operation is possible over several years without changing the filter bags.

Results of measurements in a fume treatment plant are presented in Fig. 15. Concentrations of PAH components have been measured in the raw gas, after the electrostatic precipitator and after the dry scrubber in the clean gas. Analytical determination was done by GC–MS analysis. The vapour pressure of the components decreases from left to right, the lowest boiling component being phenanthrene (PHE) and the highest boiling one being dibenzopyrene (DBP). Generally, it can be said that collection becomes easier with decreasing vapour pressure of the components.

Components up to chrysene (CHR) like Benzo(a)pyrene (BaP) are therefore reduced to levels below the detection limit. The dry scrubber, which was operated with petrol coke, reduces components up to pyrene (PYR) below the detection limit. The two components with the highest vapour pressure, i.e. phenantrene (PHE) and anthracene (ANT), cannot be removed at all with the given adsorbent. This example shows that even extremely sticking tar particles can be reliably removed by fabric filters. Emissions of particulate matter are below 5 mg/m^3.

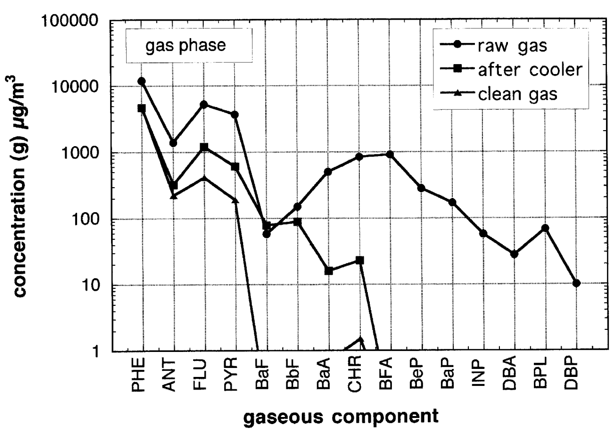

Fig. 15. Concentrations of gaseous PAH components measured in a fume treatment with indirect cooler after a closed type ring furnace.

6. High-temperature filtration

Due to space limitations, high-temperature filtration will be only briefly touched in this paper. High-temperature gas cleaning technology is reviewed in several conference proceedings [25–27]. Effect of dust properties on gas cleaning using rigid ceramic filters is described in Ref. [28]. Generally, application of high-temperature filtration technology is limited due to two important factors:

- high costs for materials of construction and filter media,
- difficult dust properties.

At high temperatures, dust particles may sinter and therefore irreversibly clog the filter medium. This was observed, for instance, by Pilz and Löffler [29] who investigated the filtration behaviour of fly ashes at temperatures up to 900°C. They found that small amounts of chlorides in the ashes (e.g. NaCl, $CaCl_2$) affected the regeneration behaviour considerably. Therefore, the sintering behaviour of dust particles should be carefully considered. Dilatometer tests, as shown in Table 2, can indicate the danger of sintering. As a rule of thumb, sintering influences strongly the flowability of the powder above approximately 60% of the melting temperature. When mixtures occur, low melting eutectica have also to be taken into consideration. Problems due to sintering particles can be overcome by means of precoating the filter medium with an inert dust layer. Integration of precoating into a high pressure and high-temperature filter system is, however, nontrivial and expensive. Another solution is the use of granular filters, which is the only available option above 1000°C, when ashes are actually melting.

High-temperature filter elements can be distinguished into glass, ceramic and metal filter media made of fibres or granules. For ceramic and metal materials, different structures in the form of fibre fleeces, woven tissues and sintered granules, are available. Maximum operational temperature for metal elements, depending on the steel grade, ranges up to 600°C. With ceramic elements, the operational temperature range can exceed 850°C. Most of the commercially available filter media show excellent separation characteristics, and to some extent, also a reliable long-term filtration behaviour. Gravimetrically determined clean gas dust concentrations are often far below 1 mg/m^3. Clean gas concentration, determined by using optical particle analysers, may be in the range of micrograms per cubic meter ($\mu g/m^3$). Excellent separation efficiencies were also found for nanoparticles like fumed silica. Specific cake resistance of fumed silica were about three orders of magnitude higher than those obtained for quartz [31].

The economical disadvantages of high-temperature filtration technology due to high prices, not only for filter elements but of course also for the materials of construction, limits the introduction of high-temperature filtration in a broader way. Therefore, efforts were undertaken to develop an efficient but economically viable filter medium. This goal was achieved by using glass fiber woven media, coated with a thin ceramic layer and supported by a specially designed retainer. This new filter medium shows excellent chemical resistance against most atmospheres, with exception of fluorine and strong alkaline. First experiences (recovery of catalyst dust), at a temperature of 300 to 400°C, are positive [32].

7. Summary

There is a variety of solutions to separate solid and liquid particles with difficult dust properties. By looking at the physical fundamentals of particle separation, new and innovative solutions can be found. Careful examination of the dust properties in the process is a precondition for the design of a gas cleaning process. The principal ways to reach this goal are:

- enhance efficiency of transport mechanisms by introducing additional forces on the particles (e.g. electrocyclone),
- change the particle properties so that they can be collected easier (e.g. heterogeneous condensation in scrubbers),
- avoid clogging of filter media by means of precoating (e.g. tar collection),
- investigate systematically the mechanism of separation; there may be still surprising results to be discovered (e.g. ESP),
- in case of sintering, changes in the process technology may be unavoidable.

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