5.8.   Filter systems

5.8.1   Principle of operation, layout

Filter systems are the main alternative for ESP systems discussed in the previous section. Gases (and also liquids) are separated from dispersed particles by passing it through a fabric or ceramic filter "medium" with a large surface area. Particles that are not able to penetrate the medium will be retained on its surface, forming the so-called "filter cake". Generally this filter cake is equally important to the actual filtration process as the medium.

Filter systems offer very high collection efficiencies of typically above 99%, over rather large size ranges. Operating mostly in the same temperature range (120 - 200EC) they have the advantage over ESPs that the electric resistivity of the particles does not play any role, making them competitive for high-resistivity ashes. A disadvantage when compared with an ESP is the larger pressure drop and the allowable gas velocity: typically the face velocity (= gas flow/filter surface, unit: m/s) also referred to as "air-to-cloth" (A/C) ratio is in the range 0.5 - 5 cm/s. Hundreds or more than a thousand typically cylindrical or tubular filter bags of fabric materials are collected in a "baghouse" in which the filtration process is confined, see Figure 5.33. Alternatively, more rigid "candle" filter elements can be used, depending on the filter medium choice which depends on temperature, gas and particle properties and unit size. Some general characteristics of gas filtration systems are given in Table 5.12.
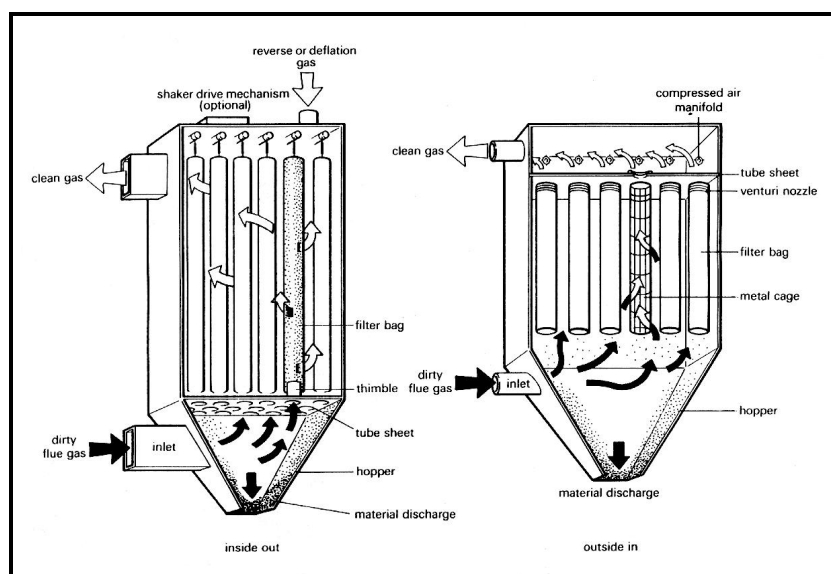

Figure 5.33 shows the two possible modes of operation for baghouse filters. Inside-out filtration implies that the gas passes through the filter from the inside. This "blows up" the bag filters to their maximum volume and produces the cake on the inside of the bag. Outside-in operation involves that the gas

Figure 5.33   Baghouse filter systems based on inside out (*left*) and outside-in (*right*) filtration (picture from Klingspor and Vernon, 1988)

Table 5.12   Types and process quality factors for gas filters

Major type of filters	Factors determining process quality
Bag filters made of fabric fibre materials textile, plastics, ceramic	Removal efficieny
Rigid barrier filters made of metal or of sintered ceramic, powder or fibres	Pressure drop, pressure drop increase
Granular bed filters based on a layer of granular solids	Filtration velocity = flow / filter area
	Medium properties: chemical and physical stability
	Filter clean-up and regenerability

enters the filter from the outside surface where the cake builds up accordingly. In this case a support structure is needed to keep the filters in their shape. The pro's and contra's of the two options depend mainly on the mechanical properties of the filter medium and the method that is used to clean the filter after a certain pressure drop has been reached (see next section). During this filter cleaning stage the cake is to detach from the filter medium and is collected in a hopper which usually comprises the bottom part of the filter unit.
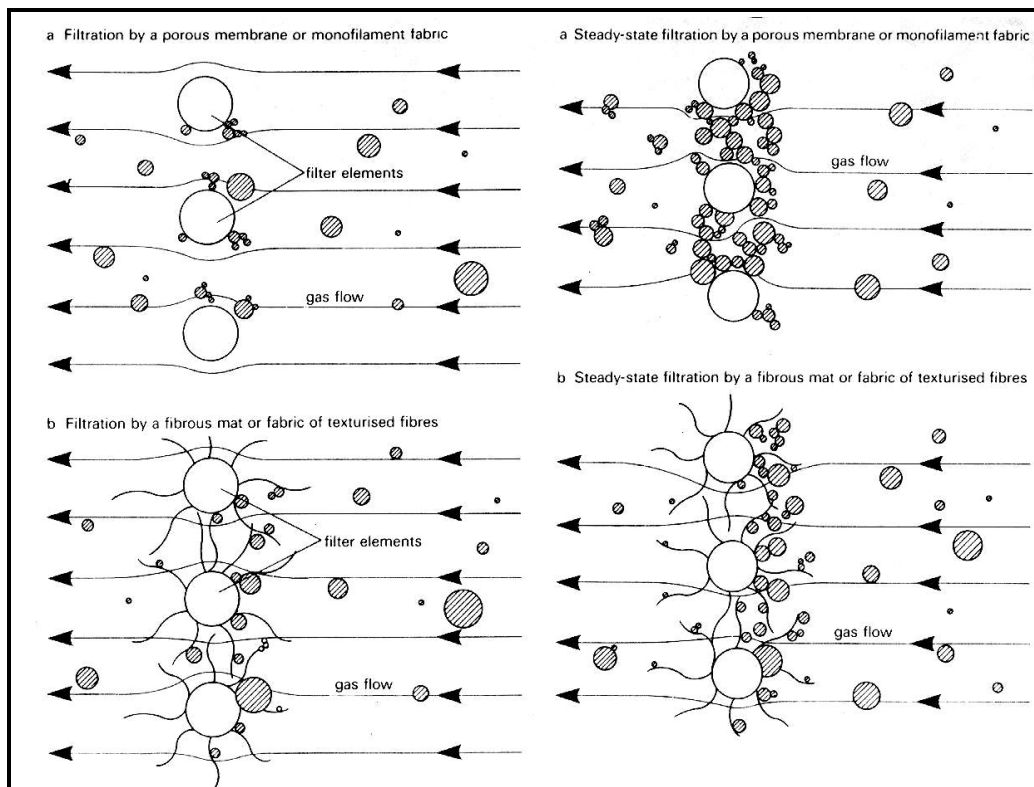

Figure 5.34   Early stages of dust cake build-up (left) and filtration through an established dust cake (picture from Klingspor and Vernon, 1988)

The actual filtration process must be distinguished from filtration on a clean filter and the early stages of filtration until a filter cake has built-up, as shown in Figure 5.34. Filtration efficiency is at its lowest for a clean filter element and the earliest stages of filtration may result in bad filter performance over a longer filter period. Often a pre-coat and pre-heat procedure is used that prevents that the filter medium from acid condensation and from becoming "blinded" by the finest particles present in the gas to be cleaned.

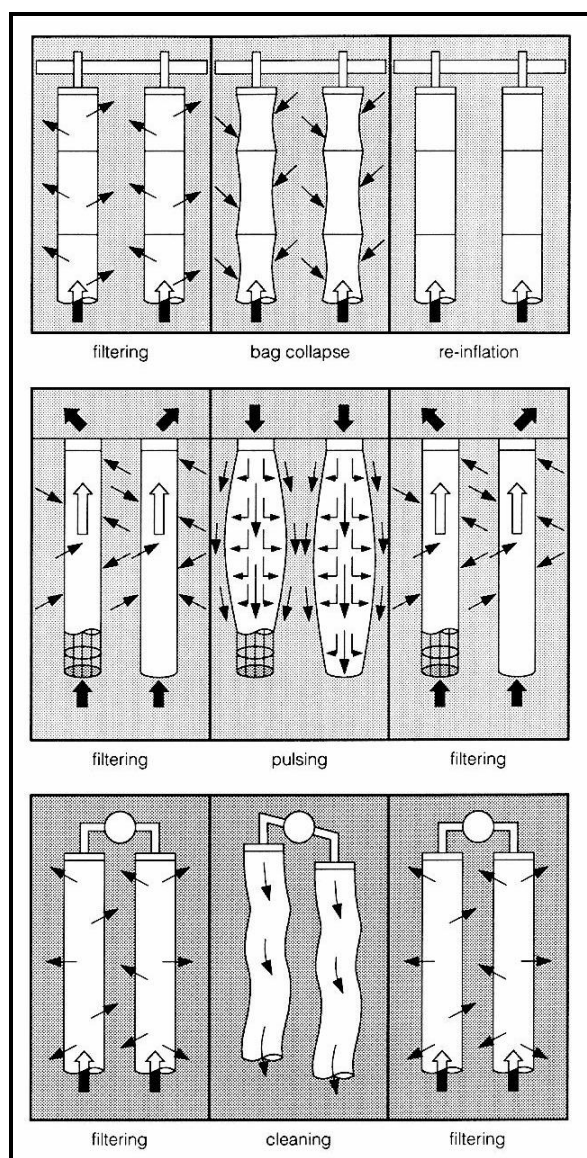### 5.8.2 Filter types and filter cleaning methods

Figure 5.35   Baghouse cleaning methods: reverse-air (*top*), pulse-jet (*centre*) and shake/deflate (*bottom*) (picture from Soud, 1995)

Three types of fabric filter systems can be distinguished, based on the filter cleaning method that is used: 1) reverse air cleaning, 2) pulse-jet cleaning and 3) shake/deflate systems, the principles of which are shown in Figure 5.35.

Reverse-gas and shake/deflate methods operate off-line, *i.e.* the dusty gas stream must be temporarily interrupted or by-passed. The pulse-jet method operates on-line, cleaning a few bags at a time while the rest of the filter bags continue filtration, and is most suitable for outside-in filter systems. Depending on the duration of the pulse that is required high pressure (3 ~ 7 bar over-pressure), intermediate pressure (1 ~ 2 bar over-pressure) or low pressure (0.5 ~ 0.7 bar over-pressure) pulses can be applied. Reverse gas systems are found in inside-out systems, using cleaned gas from another filter unit. Low frequency sound helps removing the cake from the filter.

Shake/deflate systems are based on a shaking force exposed by a mechanical system in combination with reverse air.
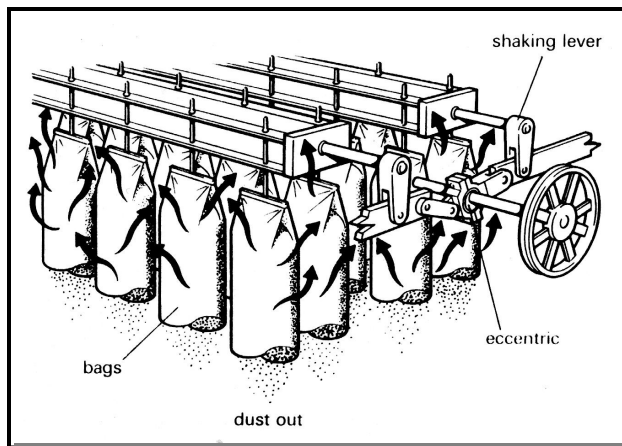
Figure 5.36   A shake/deflate baghouse filter (picture from Klingspor and Vernon, 1988)

The forces that are exerted on the particles that actually removes them from the filter are inertial forces in shake/deflate systems, viscous drag forces in reverse flow systems and a combination of these two in pulse-jet systems.

The filter velocity (or air to cloth ratio) for reverse air systems is ~ 1 cm/s, for pulse-jet systems 1.5 ~ 2 cm/s and for shake/deflate systems 3 ~4 cm/s, giving a comparable pressure drop. Dust cake loads vary from 1~2.5 kg/m² for shake/deflate systems and 2.5~7.5 kg/m² for reverse air systems to 5~10 kg/m² for pulse-jet filters. A typical filter bag has a length of 5~10 m, and a diameter of 0.2~0.3 m, giving a surface of 3~10 m² per bag. Pulse-jet units operate with somewhat smaller bags (Klingspor and Vernon 1988, Soud 1995, Cooper and Alley 1994).

5.8.3   Filtration efficiency, pressure drop

Particles of different size are removed by different physical mechanisms in a baghouse filter and rigid barrier filters. As shown in Figure 5.37, which shows the
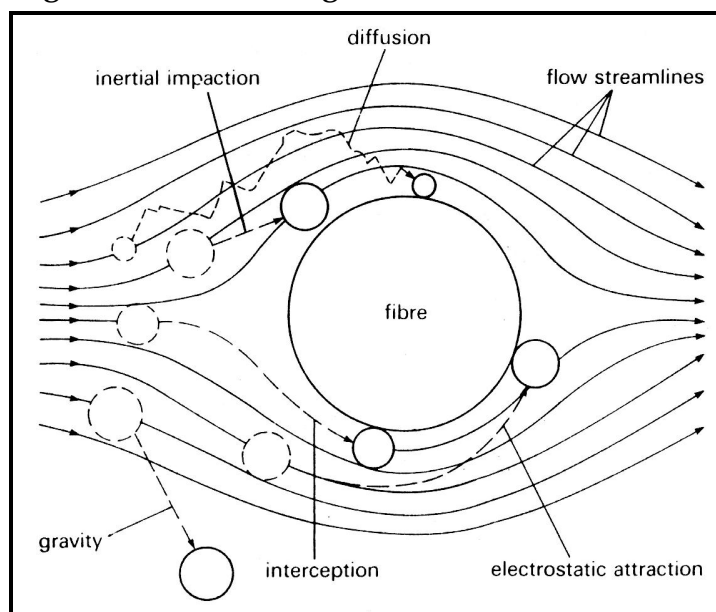

Figure 5.37   Particle capture mechanisms in fabric filtration (picture from Klingspor and Vernon, 1988)

flow around a filter fibre, five mechanisms can be distinguished. The largest particles experience a gravity force that determines their trajectories. Secondly, somewhat smaller particles will be removed by internal impaction, not being able to follow the trajectory of the gas. These particles my also be come in contact with the fibre collector by a third mechanism: the streamlines of the gas flow are contracting when passing
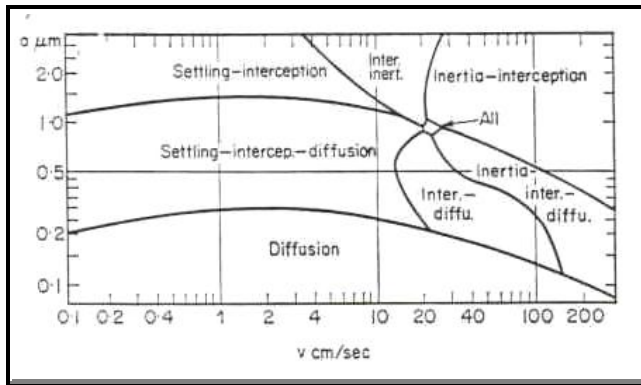
Figure 5.38   Particle capture "domains" for a particle with diameter a, velocity v, on a cylindrical 5 μm fibre in ambient air (picture from Davies, 1973)

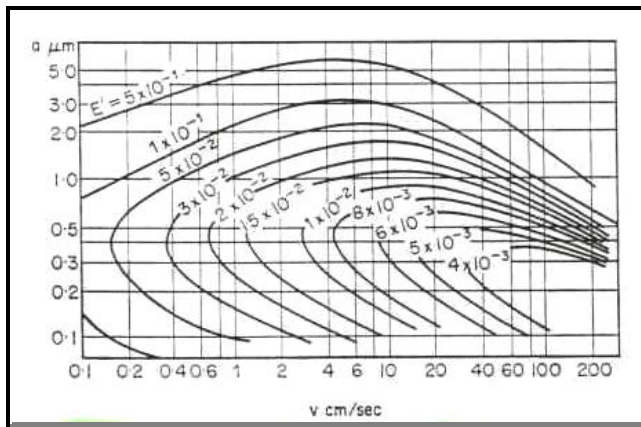**Figure 5.39**   Particle capture efficiency contour-lines for a particle with diameter a, velocity v, on a cylindrical 5 μm fibre in ambient air (picture from Davies, 1973)
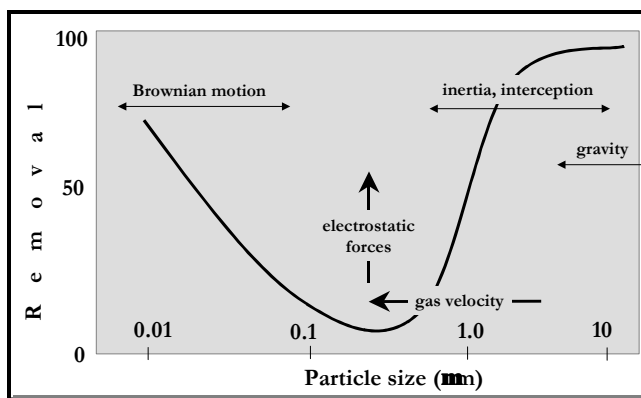

Figure 5.40   Typical filter efficiency as function of particle size (picture from Zevenhoven and Heiskanen, 2000)

the fibre which leads to interception of the particle. The finest particles are removed by a fourth mechanism, which is diffusion as a result of Brownian motion. A fifth mechanism may be effective when electrostatic forces are generated between the particles and the collector. This can be accomplished by an electric field across the filter in combination with a particle charging process.

Which collection mechanism finally will be the most effective depends on particle size and mass, velocity, density and viscosity of the gas, electrostatic forces and the filter used. Moreover, the different mechanisms are not independent but operate simultaneously, as illustrated by Figures 5.38 and 5.39.

The highest removal efficiencies are obtained for the large particles at high gas velocities and for the finest particles at low velocities. The removal efficiency of the intermediate size range of 0.2 to 2 μm, roughly, depends much more on the particle size/collector diameter ratio, and shows a minimum in the size *versus* efficiency curve shown in Figure 5.40. This minimum can be shifted to finer particle sizes by higher gas velocities, it can be alleviated by electrostatic forces (Zevenhoven *et al.*, 1993a, Emi, 1990, Henry *et al.*, 1985).

A filter for gas or liquid processing can be operated with constant pressure (drop), constant velocity or an intermediate of theses two. Two filtration parameters, being medium resistance and specific cake resistance, relate the flow through the filter and pressure drop to time. Assuming that the filter cake is incompressible, Darcy's Law for flow through a packing with thickness L can be used to relate pressure drop, Δp (Pa) to fluid flow per unit area, *i.e.* velocity u (m/s), with fluid viscosity η_{fluid} (Pa.s):

$$u = K \frac{-\Delta p}{L h_{fluid}} \quad \text{with permeability } K \tag{5-18}$$

For a filter cake with porosity ε (-), specific cake resistance, α (m/kg) can be defined:

$$a = \frac{1}{K(1-e)r_{solid}} \tag{5-19}$$

When the deposited cake has a mass w (kg/m²) per unit filter surface, Ruth's equation gives (for filtration along x-axis), with medium resistance R (1/m):

$$d w = (1-e) r_{solid} d x \tag{5-20}$$

$$u = \frac{1}{a(1-e)r_{solid}} \frac{\Delta p}{L h_{fluid}} = \frac{\Delta p}{(a w + R) h_{fluid}}$$

The cake mass, w, depends on the volume V (m/s) of fluid that has been filtered per unit area, the density ρ_{fluid} (kg/m³) of the fluid, and the fractions S_s and S_c (kg/kg) of solids in the incoming fluid and the cake, respectively, as illustrated by Figure 5.41. A mass balance gives

$$w = \left(r_{fluid} V + \frac{w}{S_c}(1-S_c) \right)\left(\frac{S_s}{1-S_s} \right) \tag{5-21}$$

$$= V f(r_{fluid}, S_c, S_s)$$
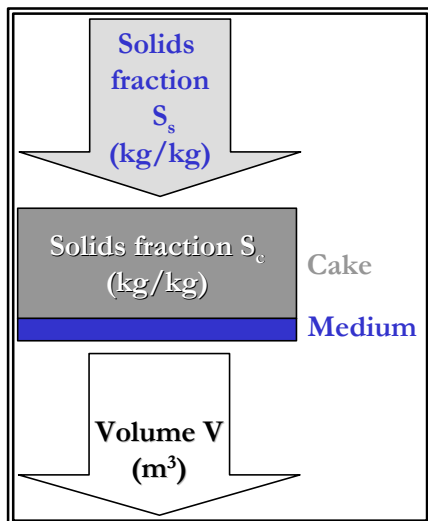
Figure 5.41 Mass balance for a filtration process

with function f defined as

$$f(r_{fluid}, S_c, S_s) = \frac{r_{fluid}}{\left(\frac{1-S_s}{S_s} \right) - \left(\frac{1-S_c}{S_c} \right)} \tag{5-22}$$

For a filtration process that operates under constant pressure (drop), Δp, the relation between time, t, and filtrate volume per unit area V (m/s) is then

$$u = \frac{dV}{dt} \rightarrow \frac{h_{fluid}\, a\, f}{2\,\Delta p}\, V^2 + \frac{h_{fluid}\, R}{\Delta p}\, V = t \tag{5-23}$$

Plotting experimental data as t/V *versus* V produces in this case a line that gives the value for the specific cake resistance, α, from the slope, and the medium resistance, R, from the intercept.

Following similar lines for a filtration process that operates under constant flow, V, the relation between time, t, and pressure drop) is then

$$u = \frac{dV}{dt} = constant \rightarrow \Delta p = h_{fluid}\, (\, a\, f\, u^2\, t + u\, R\,) \tag{5-24}$$

Plotting for this case experimental data as Δp *versus* t produces in this case a line that gives, again, the value for the specific cake resistance, α, from the slope, and the medium resistance, R, from the intercept.

In practice, the filter cake may show some compressibility. In general this can be related to the (average) pressure, Δp, that is exerted on the cake, as

$$a = a_0\, p^b \quad or: \quad a = a_0 + a_1\, p^b \tag{5-25}$$

More detail about filtration theory can be found in (*e.g.*) Ives (1975), Coulson and Richardson (1978).

As with ESP systems the operation of a filter may also be improved by gas conditioning. The composition of the ash has a large effect on its cohesivity, the structure of the filter cake that is formed and whether the ash particles will penetrate the filter medium. This affects the pressure drop but also how well the cake can be removed from the medium during cleaning, *i.e.* the residual pressure drop after cleaning. Conditioning with SO_3/NH_3 improves the quality of the filter cake (section 5.7.8).

Typically pressure drops of the order of 1000-1500 Pa are considered reasonable. Besides the dust load to the filter, particle size distribution is an important factor for how fast the pressure drop increases with time. Especially fine particles can result in rapidly increasing pressure drop and a risk for filter blinding. Usually a somewhat wider particle size distribution is beneficial for filtration operation and performance.

5.8.4　Filter media

Fabric filter performance over longer periods and filtration costs depend very much on the material that constitutes the filter medium. Factors to consider are firstly the temperature of operation that enforces heat resistance, secondly resistance to acidic or alkaline chemicals and thirdly the resistance to erosion, abrasion and other mechanical stresses. Particle characteristics play an important role as well: fly ashes from pulverised fuel combustion differ very much from those from fluidised bed combustion, or gasification (Scott and Carpenter, 1996).

For temperatures below 80EC cotton may be a good choice, whilst polymers such as nylon, polyester and glass may be used at higher temperatures. Teflon™ and Tefair™ (Teflon™ + glass fibre) show excellent performance at up to 260EC - see Table 5.13 for more data. For applications up to ~ 450EC stainless steel can be used under oxidising conditions, under reducing conditions 500-600EC is allowed. At higher temperatures ceramic materials are the best choice which are usually based on alumina, quartz or aluminum silicates. An example is Nextel™ 312, mentioned in Table 5.13. High temperature filtration will be addressed in more detail in section 5.11.

Table 5.13　*Properties of fibre materials for application in filtration (from Klingspor and Vernon, 1988)*

Fibre	Generic name	Aramid	Glass	PTFE	Polyphenylene sulphide	Polybenzi-Midazole	Metal	Ceramic
	Trade name	Nomex	Fibreglass	Teflon	Ryton	PBI	Bekinox	Nextel 312
Recommended continuous operation temperature (dry heat)		204°C	260°C	260°C	190°C	260°C	450°C	1150°C
Water vapour saturated condition (moist heat)		177°C	260°C	260°C	190°C	260°C	400°C	1150°C
Maximum (short time) operation temperature (dry heat)		232°C	290°C	290°C	232°C	343°C	510°C	1427°C
Specific density		1.38	2.54	2.30	1.38	1.43	7.90	2.70
Relative moisture regain in % (at 20°C & 65% relative moisture)		4.5	0	0	0.6	14.0	0	0
Supports combustion		No	No	No	No	No	No	No
Biological resistance (bacteria, mildew)		No effect	No effect	No effect	No effect	No effect	No effect	No effect
Resistance to alkalis		Good	Fair	Excellent	Excellent	Good	Very good	Good
Resistance to mineral acids		Fair	Very good	Excellent	Excellent	Excellent	Very good	Very good
Resistance to organic acids		Fair	Very good	Excellent	Excellent	Excellent	Very good	Very good
Resistance to oxidising agents		Poor	Excellent	Excellent	Attacked by strong oxidising agents	Fair	Very good	Excellent
Resistance to organic solvents		Very good	Very good	Excellent	Excellent	Excellent	Very good	Excellent

5.8.5 Granular bed filters

A third type of filter besides fabric or rigid barrier filters are granular bed filters. Layers or deep beds of solid granules have been used for a long time for the filtration of gases and, more importantly, liquids. An example is the filtration of drinking water by large beds of sand. The principle of filtration is different from what was presented above: for granules with a size larger than ~ 1 mm the fine particles will not be retained on the surface of the bed but will penetrate the packed bed structure. This is referred to as deep bed filtration (Ives, 1975).

When using cheap bulk solids such as sand, silicate or alumina gravel, temperatures up to, say, 450-500EC give good gas filtration performance. At higher temperatures problems arise due to sintering of the fine particles on surface of the granules which may lead to filter blinding at short distances from where the dusty gas enters.

The efficiency of a granular bed filter (GBF) depends on the size distribution and shape of the particles to be filtered and the particle/granule adhesion force. For stagnant beds typical efficiencies are ~ 99%, for moving bed filters ~ 95%, for fluidised bed GBF systems typical efficiencies are ~ 80%. The friction between granules in moving GBFs and the particle collisions in fluidised GBF systems explains the lower efficiency compared to a fixed bed GBF.

Granular bed filters are very well suitable for high temperature gas filtration - see section 5.11.

5.9   Wet scrubbers

Before wet scrubbers were first applied to flue gas desulphurisation (FGD, **7** chapter 3) in the mid-1970s they were already in use for particulate emissions control. Figure 5.42 shows some possible configurations for wet particulate removal from gas streams. Although not as powerful as filters and ESPs when it comes to removal efficiency for sub-micron particles, wet scrubbers are able to effectively remove fine particles and also certain gaseous components from a gas stream by selecting a proper washing liquid. By far the most common is the venturi scrubber (see also Figure 3.9).
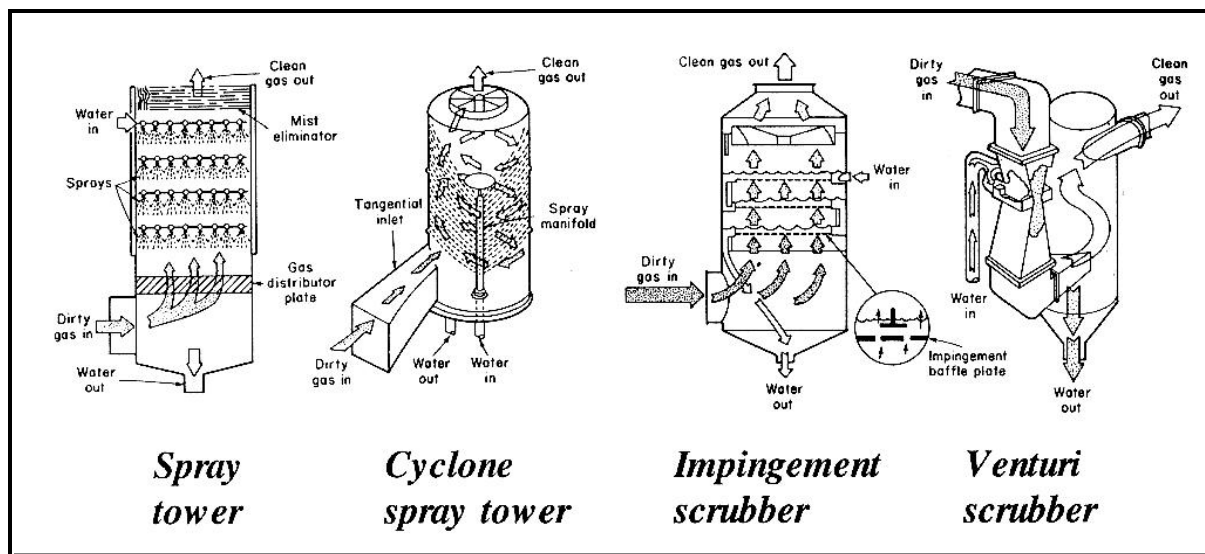
Spray tower   Cyclone spray tower   Impingement scrubber   Venturi scrubber

Figure 5.42 Wet particulate collectors (pictures from Flagan and Seinfeld, 1988)

The capital costs of a wet scrubber are lower than for a baghouse filter or ESP. Operation and maintenance costs, however, are much higher due to high pressure drops and problems related to corrosion, abrasion, solids build-up, failure of rotating parts and re-start problems after a shut-down. Despite the advantage of high inlet gas velocities of ~ 100 m/s, a collection efficiency of ~ 99% overall is obtained with system pressure drops of the order of 1 bar. The latter is less problematic when used in high pressure processes such as PFBC-CC or IGCC (**7** chapter 2).

Table 5.14   Typical operating conditions for wet particulate scrubbers
(from Klingspor and Vernon, 1988)

Category	Particle capture mechanism	Type of scrubber	Number of stages	Pressure drop per stage, Pa	Liquid-to-gas ratio 1/m^3
Preformed spray	Inertial impaction	Spray towers	1	800–1100	1.3–1.7
		Cyclone spray towers		1000–2000	0.7–1.3
		Vane type cyclonic towers			
Packed bed	Inertial impaction	Standard packed-bed scrubber	1	1300–1600	1.3–2.0
		Moving-bed scrubber	3-5	800–1300	2.0–8.0
		Cross-blow scrubbers	4	~2500	~2.5
		Fiber-bed scrubbers		50–800	
Tray-type scrubbers	Inertial impaction Diffusional impaction	Perforated plate		~400	
		Impingement-plate		250–2000	0.4–0.7
		Horizontal impingement plate			
Mechanically aided scrubbers	Inertial interception	Wet fans	1	1000–2000	
		Disintegrator scrubbers			
Venturi and Orfice scrubbers	Inertial impaction Diffusional impaction	Standard venturi scrubber	1	1000–18000	0.8–2.0
		Variable throat venturi (flooded disc, plumb bob, movable blade, radial flow, variable rod)	1		
		Orfice scrubbers	1	800–400	

For conventional power plants as much as 3% of the net output may be needed to operate the wet scrubber, which is also due to the re-heat of the outlet gas to stack conditions.

The major drawback of wet particulate scrubbers is that a gas cleaning problem is transformed in a water treatment problem. Table 5.14 lists the features of different wet particulate scrubbers - see also Flagan and Seinfeld, § 7.6 (1988).

5.10   Cost comparison ESP, filter, cyclone

A cost comparison for particulate emission control equipment at 10 MW$_{thermal}$ coal-fired boilers in the UK (made in the early 1980s) is given in Table 5.15.

Table 5.15   *Cost comparison for particulate control equipment at 10 MW$_{thermal}$ (data from Klingspor and Vernon, 1988)* *

	Efficiency %	Capital cost US$ 1982	Operation cost US$/ton removed
High efficiency cyclone	87	10500	1.68
ESP	98.3	96500	2.84
Reverse air baghouse	99.9	49000	3.14

* Assumptions: coal ash, electricity costs 0.0614 US$/kWh, 8000 h/year, filter bags lifetime 2 years

Although ESPs have higher capital costs (~ twice) than those for baghouse filters, operation costs for baghouses are ~ 10% higher. The actual costs for dust control depends also on the costs or benefits of ash disposal or selling.

5.11   High temperature, high pressure (HTHP) particulate control

5.11.1 Process description, gas purity requirements

The renewed interest for solid fuel-based power generation after the oil crisis of 1973 has resulted in clean coal technologies and related projects worldwide. Processes based on combined cycle (CC) operation of gas turbines and steam turbines offer a high thermal efficiency (**7** chapter 2) that is also possible when solid fuels such as coal or peat are used. Pressurised combustion or gasification of solid fuels may be integrated with a CC power generation system, but only when a powerful gas clean-up system is used the hot pressurised gases can be directly sent to a gas turbine or expansion turbine. A typical set-up for high temperature, high pressure gas (HTHP) clean-up for a gasification product gas is shown in Figure 5.43. Typical conditions are 500EC or higher at 15-25 bar for the particulate removal. Sulphur- and nitrogen species removal is discussed in Chapters 3 and 4, respectively.
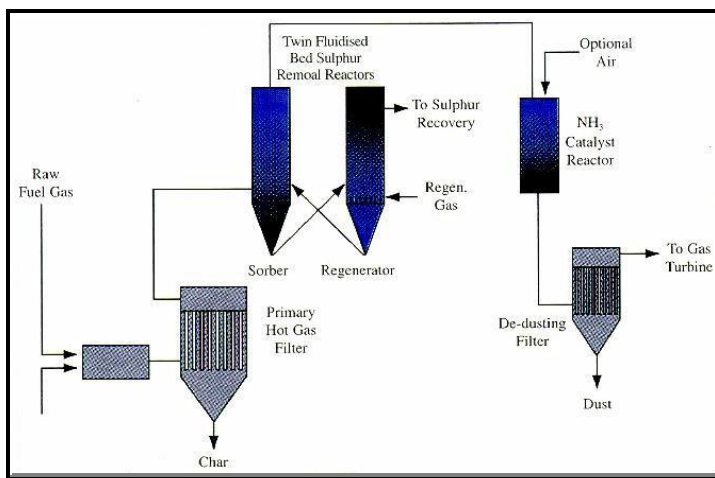

Figure 5.43   Typical HTHP gas cleaning system for gasification product gas (picture from ETSU, 1998)
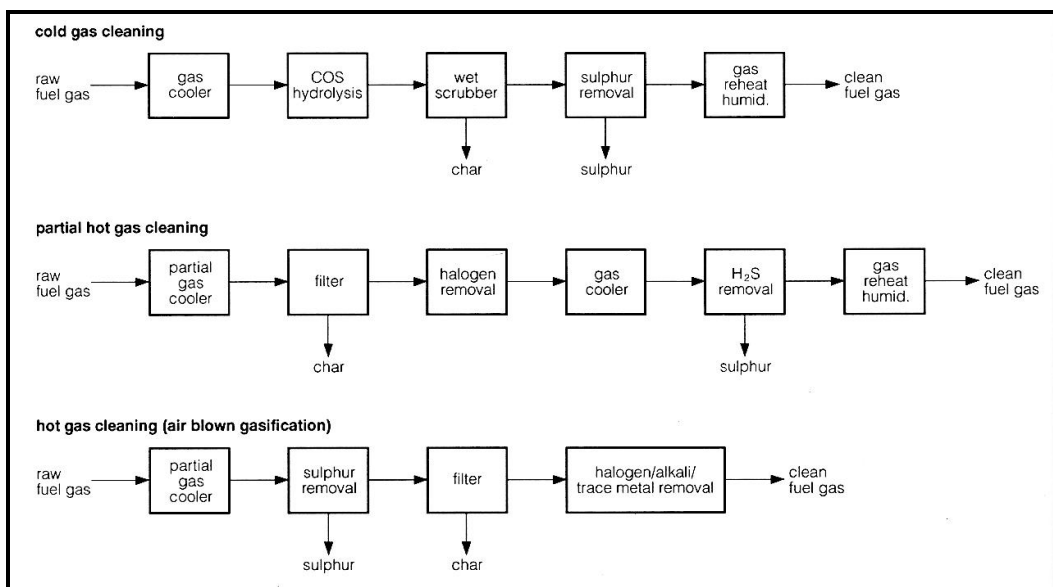

Figure 5.44   Options for HTHP gasification fuel gas cleaning (picture from Mitchell, 1997)

A comparison between conventional cold gas cleaning (below 200EC), partial hot gas cleaning (260-540EC) and hot gas cleaning (above 550EC) is given in Figure 5.44. Currently HTHP particulate control conditions are determined by the temperature for desulphurisation with regenerable sorbents (**7** section 3.14) and the control procedure for alkali metals (**L** chapter 8). Above 600EC most alkali will reside in the gas phase (Mitchell, 1997).

A recent gas turbine specification for maximum concentrations of contaminants is given in Table 5.16 for the Siemens Westinghouse VX4-3A gas turbine. Particles are allowed up to 2 ppmw with further specification of the size distribution: less than 7½ %-wt should be larger than 2 μm. These values, aiming at preventing erosion and fouling of the turbine blades are more stringent that current emission standards, which are typically in the order of 30 - 50 ppmw in countries where these new technologies are being implemented (Scott, 1997).

Table 5.16   Gas quality specifications for a gas turbine* (from Mitchell, 1997)

Contaminant	Chemical formula	Emission limit†	Comment
Particulates		2 ppmw	Grain size: 10 μm: 0 2-10 μm: 7.5% 0-2 μm: 92.5%
Hydrogen halides	HCl + HF	1 ppmw	
Sulphur compounds	$H_2S + COS + CS_2$	20 ppmv	Emissions‡ Only corrosive in combination with alkalis
Alkalis	Na + K	0.03 ppmw	
Heavy metals	V	0.05 ppmw	
	Pb	1 ppmw	
Calcium	Ca	1 ppmw	

*   Specifications for Siemens Model VX4-3A gas turbine
†   Based on a lower heating value of 4 MJ/kg$_{fuel}$
‡   In order to reach very low SO_2 content in the flue gas of about 25 mg/m^3 (6% O_2, STP (0°C (273 K), 101.3 kPa))

An entrained bed coal gasifier such as marketed by Shell or Texaco produces ~ 50 % bottom slag, ~ 50% fly ash. Typical fly ash particle distributions can go up to 200 μm, with a typical mass average of 20-50 μm and ~10% smaller than 6 μm (Klein-Teeselink and Alderliesten, 1990). Achieving the standards defined in Table 5.16 may be accomplished with some of the techniques discussed in this chapter so far. How successful these methods may be under HTHP conditions is tabelised in Table 5.17.

It is clear that cyclones may remove the largest particles but won't be able to match the turbine standards. Also the application of ESPs is questionable at temperatures above 450EC. Most suitable appear to be the ceramic rigid barrier filters, although the alternative methods are still under development as well. They will be discussed below in this order.

Table 5.17   Techniques for hot gas particulate control and their status (from Mitchell, 1997)

Device	Capture mechanism	Rejection mechanism	Pressure drop	Flow capacity	Particle removal	Status
Cyclones	Inertial concentration	Gravity flow of fly ash (continuous)	High	Moderate	Moderate	Commercial
Electrostatic precipitators	Particle charging and migration to plates	Mechanical rapping of plates (intermittent)	Very low	Moderate	Moderate	Pilot scale
Bag filters	Cake formation	Back pulse with clean gas (intermittent)	Low	Moderate	High	Demonstration scale planned
Granular beds filters	Impact/diffusion	Gravity flow of granules; granule cleaning (intermittent)	Moderate	Low	High	Demonstration scale planned
Metallic filters	Cake formation	Back pulse with clean gas (intermittent)	Moderate	High	High	Demonstration scale planned
Rigid barrier filters	Cake formation	Back pulse with clean gas (intermittent)	Moderate	High	Very high	Commercial

5.11.2 Ceramic rigid barrier filters

Ceramic barrier filters can be divided in three types: 1) candle filters, 2) tube filters and 3) cross/parallel flow filters. A further division can be made of a fibrous or granular material. The ceramics that are used for fibrous filter media are usually alumina or aluminosilicate fibres with a silicon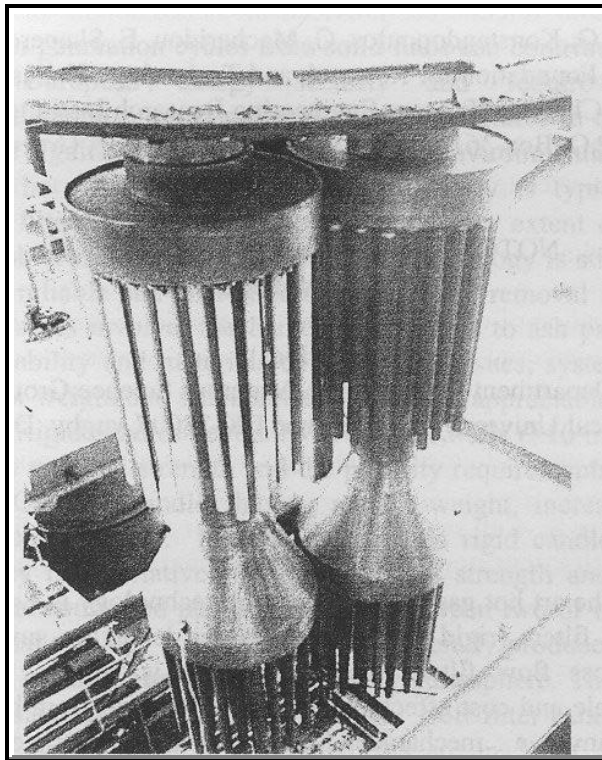-based binder, the granular filter media are usually silicon carbide (SiC), alumina or aluminosilicates. (Mitchell, 1997, ETSU, 1996).

Candle filters are cylindrical tubes closed at one end with a typical length and diameter of 1~1.5 m and 5~10 cm, respectively. They are typically operated "outside-in" (see Figure 5.33) at face velocities of 1~ 4 cm/s although the

Figure 5.45   Siemens Westinghouse filter system of Southern Company in the US (picture from LeCostanouec, 1999)
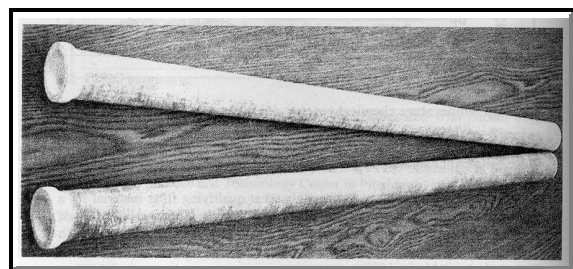

Figure 5.46   Filter candles for HTHP particulate control (picture from LeCostanouec, 1999)

goal is 10 cm/s. They have been and are still being tested at full scale operation at 300-550EC at several IGCC demonstration projects in Europe and the US. For a 300 MW_{elec} IGCC plant the number of typical candles to be used at 400EC/25 bar is 800 or 1500 for an oxygen/steam blown or air blown gasification process, respectively. At the 335 MW_{elec} IGCC unit at Puertollano, Spain, 1036 filter candles (14 groups of 74) were installed in 1997 (which took 80 hours to accomplish including checks *etc.*) and is supposed to clean 500000 m^3_{STP}/h at 220-265EC/25 bar. Filter cleaning is done by backpulsing with nitrogen at 180EC, 50 bar (Krein, 1999). Tests are also ongoing in a sidestream of the Escatron PFBC in Spain. For PFBC flue gas processing at 850EC, 15 bar, the number of candles for a 300 MW_{elec} power unit would be 9600 (Mitchell, 1997, ETSU, 1996).

As an illustration filter candles that are being tested in the US in a Siemens Westinghouse filter system are shown in Figures 5.45 and 5.46.
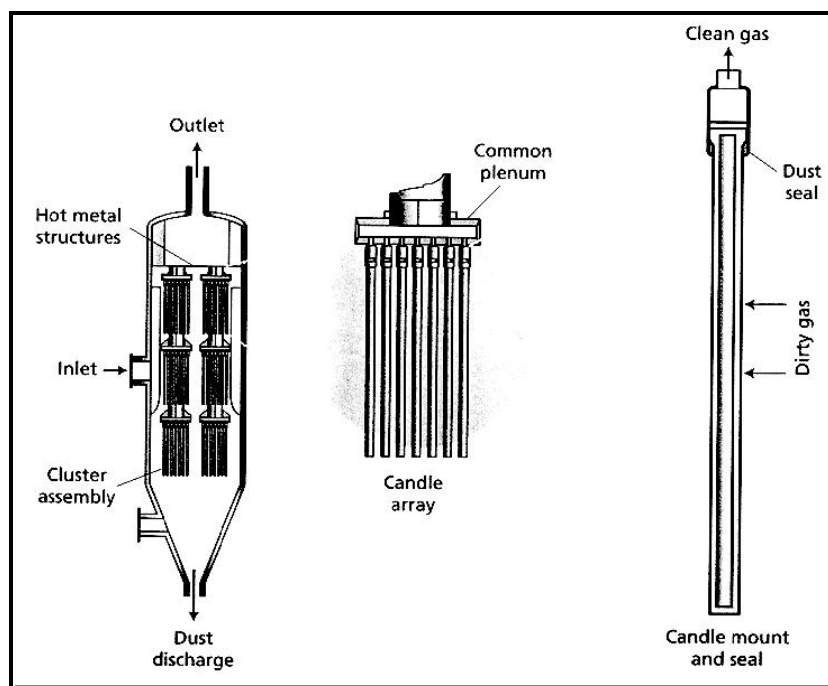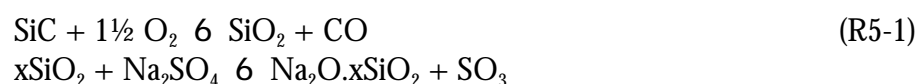

Figure 5.47   Ceramic candle filter system by Siemens Westinghouse (picture from ETSU, 1996)

Some more detail of a candle filter system is given in Figure 5.47. These systems have shown to be capable of cleaning pressurised gases at up to ~ 400EC - clearly much development work is needed before full scale application in a PFBC flue gas at 850EC will be an option.

Typical problems that are encountered during the testing is the "creep" of the candles at temperatures above ~ 750EC, and bending. Another problem is alkali attack which occurs with oxide as well as non-oxide ceramics: examples of chemical reactions that can take place at as low as 650EC are (Seville *et al.*, 1996):
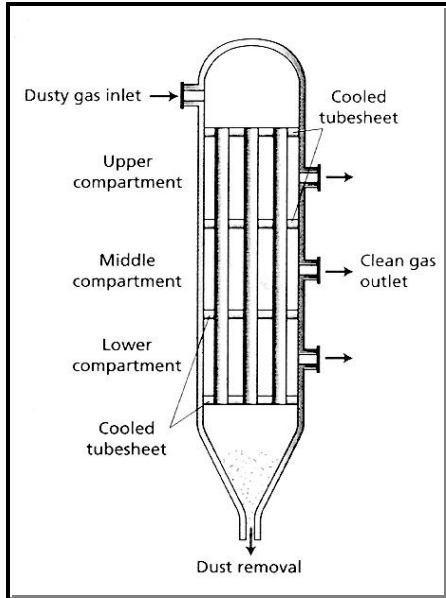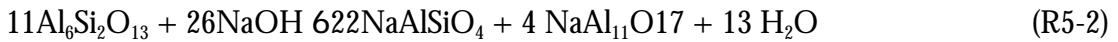
$$SiC + 1\frac{1}{2} O_2 \ 6 \ SiO_2 + CO \qquad\qquad (R5\text{-}1)$$
$$xSiO_2 + Na_2SO_4 \ 6 \ Na_2O.xSiO_2 + SO_3$$

or

$$11Al_6Si_2O_{13} + 26NaOH \; 622NaAlSiO_4 + 4\, NaAl_{11}O17 + 13\, H_2O \qquad \text{(R5-2)}$$

Figure 5.49 Ceramic cross-flow filter of Siemens Westinghouse (picture from ETSU, 1996)

Figure 5.48 Tube filter by Asahi Glass Co., Japan (picture from ETSU, 1996)

Ceramic tube filters are operated inside-out: the clean gas enters on one end, after reverse pulsing the dust leaves via the other end. An impression of a tube filter system as is being used at up to 900EC at the Wakamatsu PFBC in Japan is shown in Figure 5.48.

The third type of filter is a compact structure of thin ceramic plates that can be cleaned by a reverse pulse of clean gas - see Figure 5.49. They offer a ~ 5 times larger filtration area per unit volume than a candle filter. Problems related to cleaning and degradation of the laminar structure need to be tackled before large scale use in *e.g.*

Table 5.18 Short-term and long-term degradation of ceramic HTHP filters (taken from Mitchell, 1997)

| Mechanism	Source
Short-term	
Mechanical shock	Filter vessel ash filling or ash bridging
Thermal shock	High gas temperature excursion
Chemical shock	Low permeability coating formation during off-design conditions
Long-term	
Thermal exposure	Continuous degradation such as flow of the binder phase
Temperature transients	PFBC startups and shutdowns; hot spots
Bulk gas reactions	Pulse clean cooling
Gas phase trace contaminants	Oxidation of non-oxide ceramics
Fly ash interactions	Gas phase moisture
	Volatilisation
	Alkali vapour, and others, reacting with amorphous phase and weakening material strength
	Adherence along amorphous glass phase, and subsequent pore plugging
	Reaction of fines with ceramic material
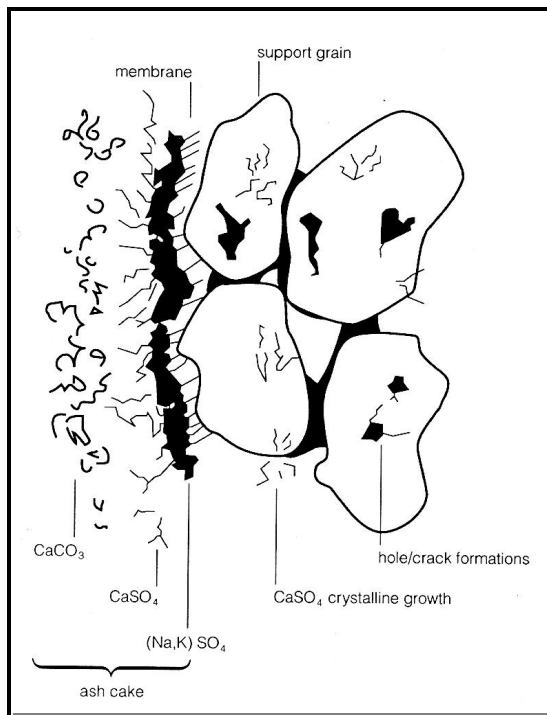
Figure 5.50   Chemical interaction between a dust layer and a ceramic candle filter matrix (picture from Mitchell, 1997)

coal-fired power generation will be possible (Mitchell, 1997, ETSU, 1996).

The three types of ceramic rigid barrier filters for HTHP particulate control all suffer from various kinds of short-term and long-term problems, the most important of which are listed in Table 5.18.

An example of the chemical interactions between ash deposit and filter matrix, leading to degradation, is shown in Figure 5.50. More detail on the progress that is being made within this field can be found in the enormous literature on this: see *e.g.* Dittler *et al.* (1999), Mitchell (1997), ETSU (1996), Schmidt *et al.* (1996), Saxena *et al.* (1985).

5.11.3 High temperature cyclones

High temperature cyclones suffer from the drawback that the dynamic gas viscosity decreases with temperature, roughly as $T^{2/3}$. From eq. (5-4) it is readily seen that this increases the value for cut size d_{50}. Wall cooling gives improved performance due to a lower viscosity, and reduced stickiness of the collected particles (Klein-Teeselink and Alderliesten, 1990).

Nevertheless, a series of two or three cyclones is so far used for the set-up for the Ahlstom Power PFBC units: ceramic barrier filters have been tested for HTHP cleaning but are not yet considered sufficiently reliable and powerful. For IGCC systems HTHP cyclones are very useful pre-collectors that facilitate the return of unburned char and sulphur capture sorbent to the gasifier. Cyclones are being used up to and over 1000EC, up to 100 bar, for particles larger than 5 μm. (See also Bernard, 1992).
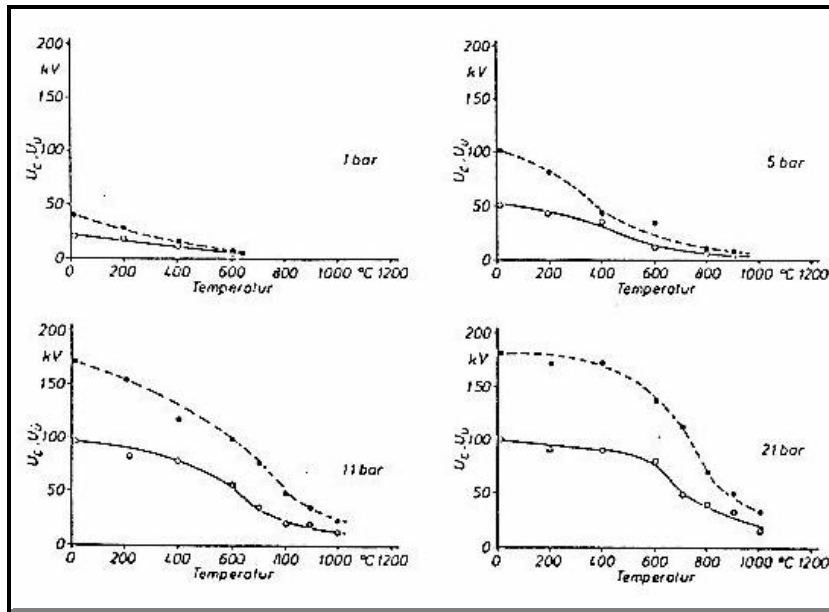
5.11.4 High temperature ESPs

Figure 5.51   Stable corona onset (solid line) and sparkover voltages (striped line) in ESP at HTHP (picture from Weber, 1984)
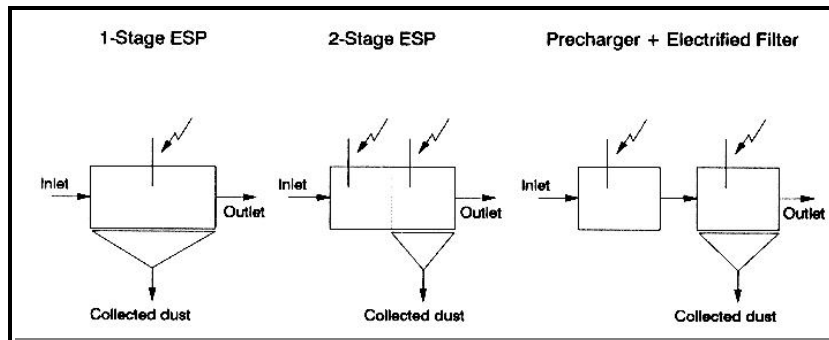
Typically, ESPs are used at 1 bar, 120-450EC, giving overall efficiencies of ~ 99.5 %. At higher temperatures the range of operating with a stable electric field becomes more narrow, since the voltage needed for corona generation approaches the voltage where sparkover occurs, especially when operating at negative potential (electrons are faster than positive ions).

Figure 5.52   New concepts for advanced ESP (picture from Zevenhoven, 1992)

This is illustrated by data from Weber (1984) in Figure 5.51. Increasing the pressure as well widens the operation range for voltage: comparing the results from 1 bar, 100EC and 21 bar, 1000EC shows roughly the same voltages for corona onset and for sparkover. For PFBC flue gas at 400-700EC, 5-15 bar the use of ESP has been thought of as an option, supported by good ash properties as well. Since the early 1990s very little progress has been reported on this area, though. Other systems for high temperature are based on separate optimisation of the particle charging process and the particle removal process - see Figure 5.52. A serious disadvantage are the considerable heat losses when operating these rather large devices at elevated temperatures.

5.11.5 High temperature fabric filters

Fabric filters based on textile or polymer fibres are commonly used up to ~ 300EC. A process where a baghouse filter is applied at high temperature is the Babcock and Wilcox (B&W) SOx-NOx-ROx-BOx (SNRB™) process. In this process a baghouse which is operated at 440-480EC, removes fly ash and SO_2, which reacts with dry-injected limestone, (**7** chapter 3) and NO by reaction with NH_3 (**7** chapter 4) which is injected upstream of the filter as well. The SCR catalyst is located inside the filterbags (US DOE, 1999).

Filter bags made of 3M's Nextel™ material (see Table 5.13), based on boronsilicate should allow for continuous operation at 1170EC, with a maximum of 1340EC (ETSU, 1996). Tests at ~ 550EC under oxidising and reducing conditions showed removal efficiencies of ~ 99% at face velocities ~ 1 cm/s.

5.11.6 High temperature metallic filters

Stainless steel suffers from severe corrision under oxidising conditions at above ~ 450EC, under reducing conditions it may be used up to 600EC. In gasification product gas the corrosion is directly related to the chromium (Cr) and nickel (Ni) content, with nickel producing Ni_3S_2 with the sulphur in the gas (H_2S). Preferably metallic filters are used in gasification product gas below 400EC, H_2S below 300 ppm, and no chlorine in the gas (**⌐** chapter 7). New sintered alloys such as Fe_3Al, with 2 or 5% Cr are currently being tested for IGCC and PFBC projects in the US.

5.11.7 High temperature granular bed filters

Granular bed filters (GBFs) for hot gas cleaning are basically a stagnant or moving bed of coarse (~ 3 mm) granular solids, made of basically the same materials as ceramic candle and tube filters are made of. In principle the granules are chemically inert, although it has been considered to remove particulates and alkali from PFBC flue gases simultaneously using a GBF or apply ammonia dehydrogenation catalysts (Zakkay *et al.*, 1989, McDaniel *et al.*, 1995). Filter velocities can be relatively high, of the order 0.1 - 1 m/s. Some pro's and contra's of GBFs for hot gas cleaning application are given in Table 5.19.

Fixed bed GBFs offer high efficiencies under HTHP conditions but need a cleaning /regeneration stage, whilst moving bed GBF systems may remove only 90-95% of the

Table 5.19   Pro's and contra's of granular bed filters for hot gas filtration

Advantages	Disadvantages
High filter velocity	Efficiency is not high enough: 90 - 95 %
Cheap granular materials can be used	Attrition and abrasion of the medium
Also gases may be removed: HCl, SO$_2$, alkali	Problems with dust sintering / agglomeration
Catalytically active filter material can be used	Dust re-entrainment
Continuous operation is possible.	Reliability
	Medium regeneration problems

fly ash downstream of a cyclone from a PFBC flue gas. Friction between the granules leads to some re-entrainment of the ash, moreover attrition and abrasion fines are released with the clean gas as well (Zevenhoven, 1992, Zevenhoven *et al.*, 1993b). GBF filters are still considered to have good potential for HTHP gas cleaning in relation to clean coal technologies, a typical example of a powerful design is the screenless moving bed GBF by Combustion Power Co., as shown in Figure 5.53.
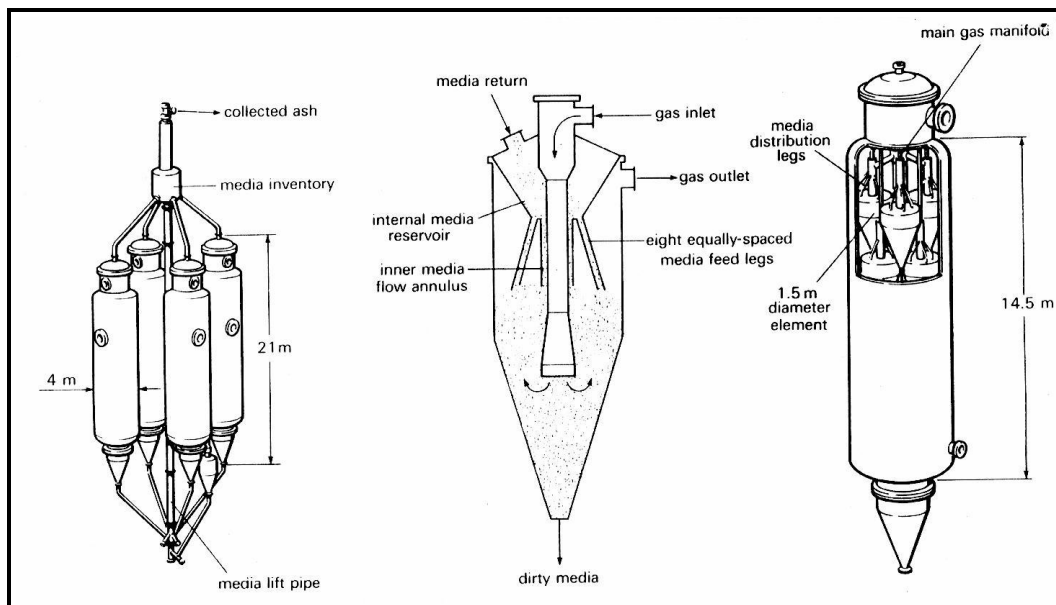

Figure 5.53   The Combustion Power Company's screenless moving granular bed filter: 1 unit (*centre*), a module (*right*) and total filter system (*left*) (picture from Klingsport and Vernon, 1988)

5.11.8 Comparison between high temperature particulate control methods

The performance of different particulate control techniques for application at HTHP conditions is shown in Figure 5.54. The need for 99+ % removal efficiency points to the direction of filter systems. Moving granula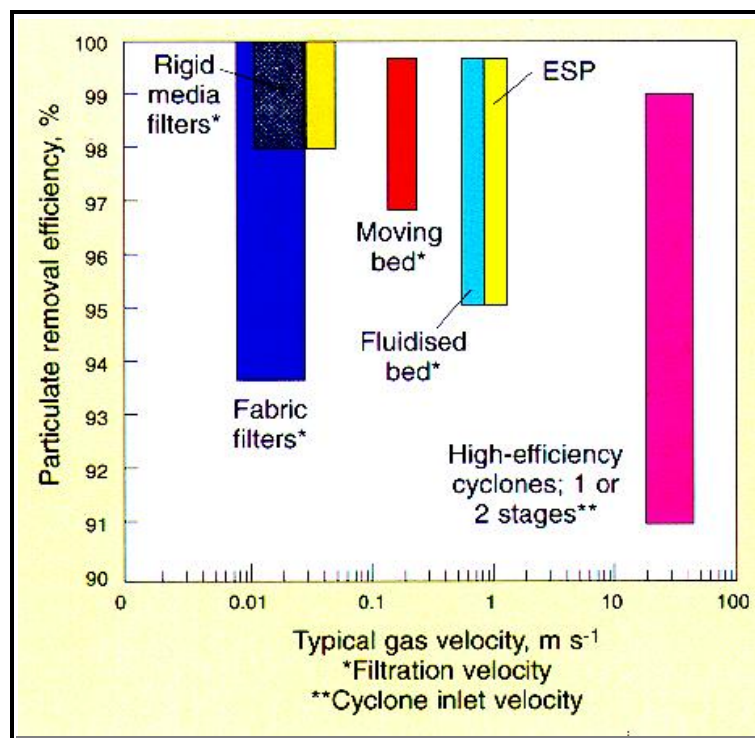r bed filters seem to be on the boundary between a sufficiently high efficiency and a gas velocity of the order of 0.2 m/s. For ESPs it is uncertain whether they will be able to operate under HTHP conditions; cyclones can only act as pre-separator for relatively large particles. (ETSU, 1996, Saxena *et al.*, 1985).

The costs of these systems increases with efficiency and decreases with gas speed, *i.e.* lowest cost corresponds to the lower right corner of the diagram, highest cost to the upper left corner.

Figure 5.54   Comparison of techniques for high temperature, high pressure particulate control (picture from ETSU, 1996)

5.12   Particulate emissions control for vehicles

Particulates are released from spark-ignition and, more importantly, from diesel engines of on-road and off-road vehicles and ships. Current EU regulations (**7** Table 4.13) allow for 500 ppm particulates from passenger car diesels, with 250 ppm as the regulation as of 2005 (Euro IV regulation). Nevertheless, quite significant air pollution is generated by diesel engines. Estimates from the US are that 25-30 % of the NOx and 60-65% of the particulate matter (PM) emissions are from heavy-duty diesel engines (Yanowitz *et al.*, 2000). Up to 0.5 % of a diesel fuel may be released as fine particles, mainly as $PM_{2.5}$ composed of agglomerates of 10-80 nm carbonaceous particles (Morawska *et al.*, 1998). The most important compounds in vehicle exhaust PM are organic particulates being soot (*i.e.* insoluble organic fraction) and unburnt

fuel, sulphates and nitrates, and lead (for leaded gasoline).

PM emissions from spark-ignition engine (without a exhaust gas catalyst) are ~ 20 mg/km for unleaded low-sulphur gasoline. With leaded fuels the emission of lead-based particles is 100-150 mg/km: in modern fuels lead has been replaced by other anti-knocking agents, however (Heywood, 1988). Diesel PM emissions are typically of the order 0.2 - 1 g/km composed mainly of carbonaceous particles smaller than 1 µm. Depending on the engine operation (speed, power, temperature) the soluble organic part is 5-40%, the rest being soot and a small amount of sulphate/nitrate (Morawska *et al.*, 1998). Recent measurements showed that for a modern heavy duty diesel engine the fraction of sulphate and nitrate in the PM is 1 -11 %-wt and 1-4 %, respectively, (both decreasing with engine load), the remainder being about equal amounts of elemental carbon and organic carbon, and very little (less than 0.1 %-wt) polyaromatic hydrocarbons (PAHs), however (Shi *et al.,* 2000).

PM emission control for diesel engines concentrates mainly on soot and other organic compounds, which will be addressed in the next chapter. Most important there is the so-called CRT (Continuously Regenerating Trap) system which is based on a catalyst and a particle filter - ∟ chapter 6. The sulphate level will continue to drop with the sulphur level in the fuel, *e.g.* from 200 ppm to 50 ppm in so-called city diesel.
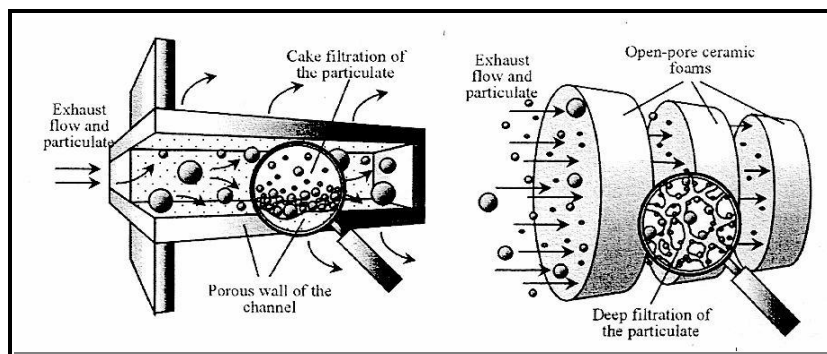

An example of a diesel PM filter system is shown in Figure 5.55 - the basic idea is to collect the particulates, followed by catalytic combustion.

Figure 5.55　　　Diesel exhaust gas particle traps (picture from Saracco, 1999)

5.13　References

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APPENDIX   Calculating the terminal settling velocity of particles

The velocity of a solid particle or droplet in a steady, non-fluctuating fluid flow will eventually level off at an equilibrium value. A particle or droplet that experiences the influence of gravity will, when moving in a stagnant medium, ($\underline{u}_F=\underline{0}$) speed up or slow down to what is referred to as the terminal settling velocity, $\underline{u}_t$. This is illustrated by Figure 5A-1 for a spherical particle in a vertical flow.
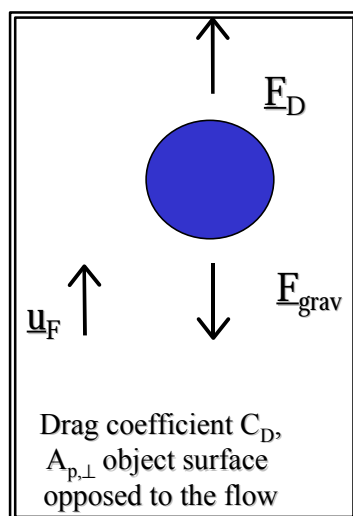

Figure 5A-1 Forces on a spherical particle in a fluid flow

The drag force $\underline{F}_D$ on a particle moving in a fluid flow, opposite to the direction of the flow is given by

$$\underline{F}_D = C_D \, A_{p,\perp} \, \boldsymbol{r}_F \, (\, \underline{u}_F - \underline{u}_p \,) \, \left\| \underline{u}_F - \underline{u}_p \right\| \qquad (5A\text{-}1)$$

with drag coefficient C_D. Being determined by the particle size d_p and the fluid flow, C_D can be related to the particle Reynolds number Re_p. For a spherical particle some widely

used expressions are, besides Stokes' Law:

$$C_D = \frac{24}{Re_p} \qquad Re_p = \frac{r_F \, d_p \, \|u_F - \underline{u}_p\|}{h_F} < 0.2 \qquad Stokes$$

$$C_D = \frac{24}{Re_p} \left(1 + \frac{3}{16} Re_p \right) \qquad 0.2 < Re_p < 2 \qquad Oseen$$

$$(5A\text{-}2)$$

$$C_D = \frac{24}{Re_p} \left(1 + \frac{1}{6} Re_p^{2/3} \right) \qquad 2 < Re_p < 800 \qquad Klyachko$$

$$C_D = 0.44 \qquad\qquad 800 < Re_p < 10^5$$

The terminal settling velocity u_t of a spherical particle follows from a force balance in the vertical direction, and equating the acceleration of the particle to zero:

$$m_p \, g - V_p \, r_F \, g = c_D \, \tfrac{1}{2} \, r_F \, u_t^2 \, \tfrac{1}{4} \, p \, d_p^2 \;\rightarrow\; u_t = \left(\frac{4}{3} d_p \frac{\left(\dfrac{r_S}{r_F} - 1 \right) g}{c_D} \right)^{\!\!\frac{1}{2}} \qquad (5A\text{-}3)$$

where m_p and V_p are the mass and volume of the particle, respectively, gravity g and fluid and particle densities ρ_F and ρ_S. The problem of calculating u_t whilst C_D is itself a function of u_t can be solved by considering the parameter $C_D Re_{p,t}^2$ ($Re_{p,t}$ is Re_p with velocity $u = u_t$) instead, which is also known as the Archimedes number:

$$Ar = C_D \, Re_{p,t}^2 = d_p^3 \, \frac{r_F \, (r_S - r_F) \, g}{h_F^2} \qquad (5A\text{-}4)$$

with fluid dynamic viscosity η_F. For a spherical particle, the relation between Ar and $Re_{p,t}$ is given in Figure 5A-2.

Based on the properties of the fluid and the particle the value for Ar can be calculated which allows for evaluating Re_p from Figure 5A-2. The value for the terminal settling velocity is then readily calculated as

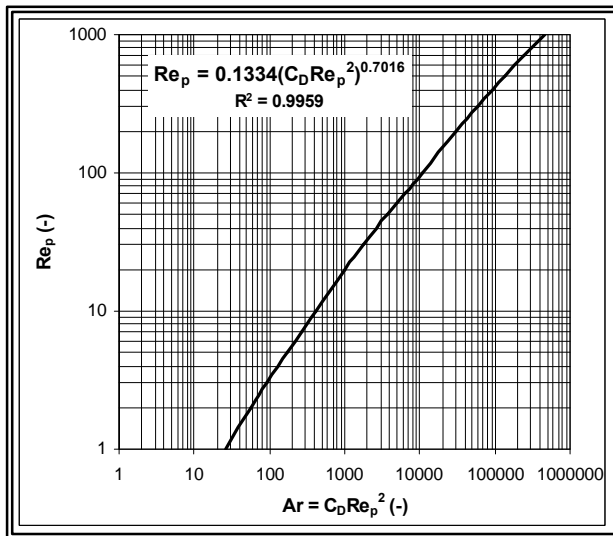$$u_t = Re_{p,t} \, \frac{h_F}{d_p \, r_F} \qquad (5A\text{-}5)$$

$Re_p = 0.1334(C_D Re_p{}^2)^{0.7016}$
$R^2 = 0.9959$

Figure 5A-2 Relation between Ar and Re_p for a spherical particle

Figure 5A-3 Cunningham correction factor for fine spherical particles dispersed in ambient air (picture from Hinds, 1982)

For low Reynolds numbers, *i.e.* $Re_{p,t} < 0.2$, Stokes' Law applies :

$$\underline{F}_D = 3\,p\,h_F\,(\,\underline{u}_F - \underline{u}_p\,)\,d_p \qquad (5A\text{-}6)$$

for which' case the value for u_t can be calculated according to

$$u_t = \frac{r_p\,d_p^2}{18\,h_F}\,g \qquad (5A\text{-}7)$$

For particles smaller than $5 \sim 10\ \mu m$ in a gas, a correction should be made for molecular slip, considering the mean free path of the gas molecules, Λ_G. Then Stokes' Law is corrected to:

$$\underline{F}_D = \frac{3\,p\,h_F\,(\,\underline{u}_F - \underline{u}_p\,)\,d_p}{C_c} \qquad (5A\text{-}8)$$

with Cunningham correction factor C_c, which can be calculated by the Knudsen-Weber equation:

$$C_c = 1 + \frac{\Lambda_G}{d_p}\left(2.49 + 0.84\exp\left(-0.44\frac{d_p}{\Lambda_G}\right)\right)$$

with for air : $\Lambda_G(\,p,T\,) = 2.26\text{x}10^{-3}\,\dfrac{T\,(K)}{p(Pa)}$

$$(5A\text{-}9)$$

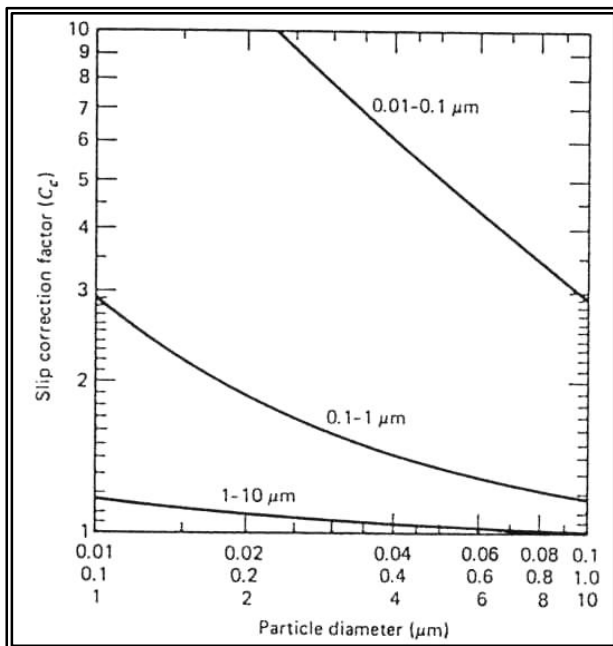Values for the Cunningham correction factor for spherical particles in ambient air are given in Figure 5A-3.

More detail is found in textbooks on transport phenomena and aerosol science:

Bird, R.B., Stewart, W.E., Lightfoot, E.N. (1960) "Transport phenomena", Wiley & Sons, New York, Chapter 6

Hinds, W.C. (1982) "Aerosol technology" Wiley & Sons, New York