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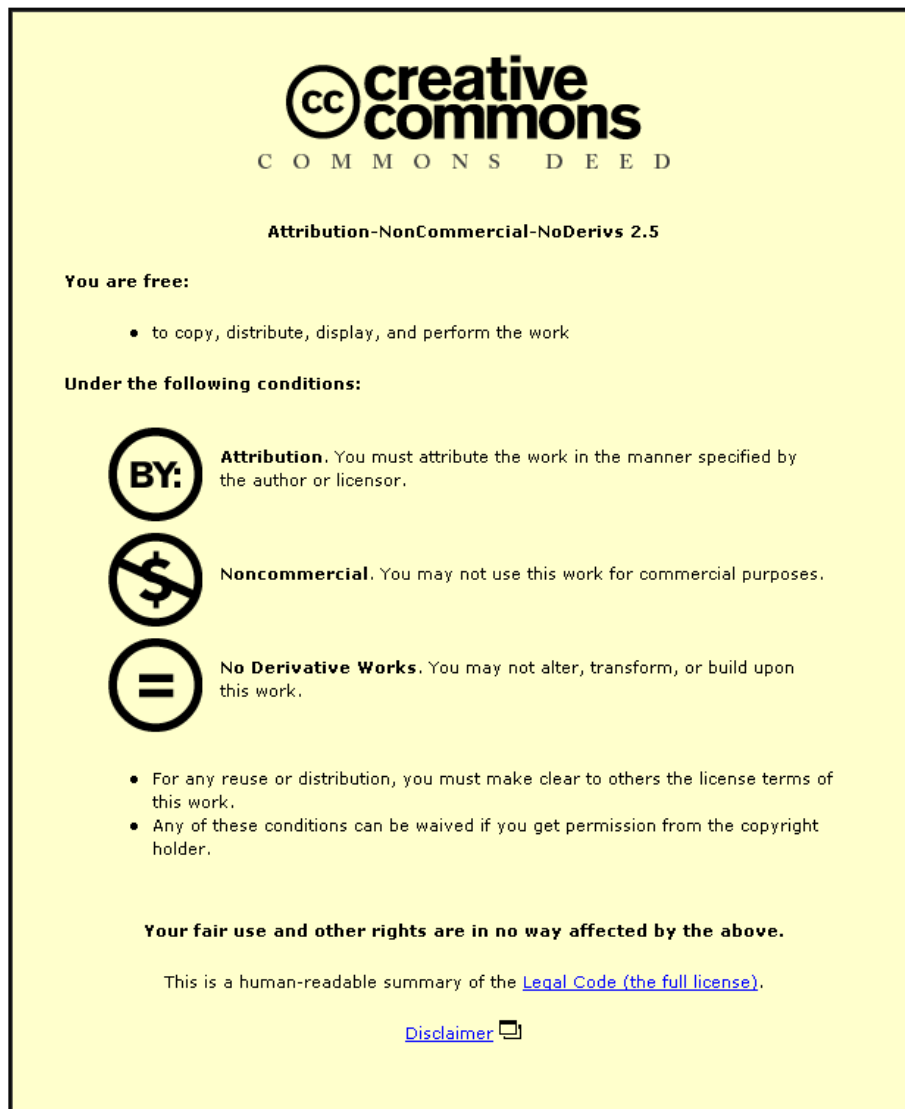
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# PHYSICAL AND CHEMICAL CHARACTERIZATION OF KUWAITI ATMOSPHERIC DUST AND SYNTHETIC DUSTS: EFFECTS ON THE PRESSURE DROP AND FRACTIONAL EFFICIENCY OF HEPA FILTERS

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## ABSTRACT

The importance of clean air to the indoor air quality affecting the well-being of human occupants and rising energy consumption has highlighted the critical role of air filter performance. Actual performance of air filters installed in air handling units in Kuwait tends to deviate from the performance predicted by laboratory results. Therefore, accurate filter performance prediction is important to estimate filter lifetime, and to reduce energy and maintenance operating costs. To ensure appropriate filter selection for a specific application, particulate contaminants existing in Kuwaiti atmospheric dust were identified and characterized. This paper compares the physical and chemical characterization of Kuwaiti atmospheric dust with the available commercial synthetic dusts. It also tests full scale HEPA pleated V-shaped filters used in Heating Ventilation and Air Conditioning (HVAC) and gas turbine applications. The effects of different synthetic dust types and their particle size distributions on the pressure drop and fractional efficiency using DEHS testing according to DIN 1822 is studied.

## KEYWORDS

Air filters; Fractional efficiency; Gas cleaning; Glass fibre; HEPA filter; Permeability; Pressure drop.

## FILTRATION OF AIR

Air filtration is a complex process which is influenced by several factors pertaining to the dust physical and chemical characteristics. To better understand and evaluate the filtration process and influential parameters affecting the filtration performance of air filters, an in-depth analysis of the dust must be conducted.

Although several authors have studied the performance of clean filters<sup>1-3</sup> and other authors have considered dust loaded filters<sup>4-5</sup>, the literature is generally limited to the study of flat filters. Studies have considered loading samples of filters with monodispersed<sup>6</sup> and polydispersed<sup>7</sup> aerosols. Literature on the testing of HEPA pleated filters is limited<sup>8-10</sup>. Other authors have studied the effects of particle size on the pressure rise<sup>11-15</sup> of filters but did not consider a full scale HEPA filter constructed in a V-shape cartridge with variable pleating density. This paper investigates the effect of synthetic polydispersed dust type and pleat density on filter design and performance in terms of fractional efficiency and pressure drop.

## FILTER PROPERTIES

The experimental work involved the testing of glass fibre pleated cartridges of HEPA Class H10 according to DIN 1822<sup>16</sup>. Eight filters were manufactured by EMW Filtertechnik with pleating densities varying from 28 to 34 pleats per 100 mm. Table 1 lists all the filters used for testing with their corresponding surface areas. The manufactured filters were divided into two groups, A and

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B. Both groups underwent similar testing procedures and were challenged with DEHS to give data for the initial fractional efficiency. Figure 1 shows the face dimensions of 592 x 592 mm with a depth of 400 mm. The filter cassette has a V-shape bank which contains eight pleated media panels.

The glass fibre media used in these filters is shown in Figure 2. Glass fibre filtration media was selected for all experiments as it exhibits better resistance to high temperatures and has smaller fibre size compared to synthetic media. Glass fibre media are highly porous with a low resistance to air flow. Filter performance is affected by several variables such as filter medium thickness, permeability, packing density, fibre diameter as well as the design of the filter module itself. Operating conditions such as filtration velocity and temperature also affect the filter performance, in addition to the characteristics of the aerosol such as particle size distribution, particle shape and density. The properties of the media are listed in Table 2.

## Dust Characterization

Kuwaiti and synthetic dusts were characterized physically and chemically to better understand their behaviour in the filtration process. The physical and chemical characteristics of synthetic dust were examined to choose one that represents Kuwaiti atmospheric dust.

### *Chemical Characterization – EDAX*

The three synthetic dusts, ASHRAE, SAE Fine and SAE Coarse, were analyzed using Energy Dispersive Analysis X-ray (EDAX) to determine their chemical composition. Analysis showed that Kuwaiti atmospheric dust is mainly silica and also contains aluminium, calcium, iron and some traces of potassium and magnesium. On the other hand, ASHRAE and SAE Coarse dust contain carbon and also consist of mainly silica. SAE Fine dust contains aluminium, calcium and traces of potassium. From such chemical analysis the ASHRAE dust seems to be closest to the Kuwaiti dust from a silica content standpoint. However, analysis of ASHRAE dust does not show any presence of aluminium, calcium and traces of potassium which are found in Kuwaiti dust. SAE Fine and Coarse on the other hand, contain aluminium, calcium and traces of potassium, but have higher silica content than Kuwaiti dust. In all Kuwaiti dust samples, the silica contents were higher than that of the ASHRAE content. Furthermore, ASHRAE dust contains cotton lint as shown in Figure 3 which is absent in Kuwait dust.

While it is difficult to decide on the most representative dust using EDAX analysis, the SAE Fine dust seems to be the closest to Kuwaiti atmospheric dust from a chemical composition standpoint. Table 3 lists the chemical composition of samples of Kuwait atmospheric, ASHRAE, SAE Fine and SAE Coarse dusts.

### *Particle Size Distribution*

While it is hard to obtain a commercially produced dust that fits the physical and chemical characterization of Kuwaiti atmospheric dust, particle size analyses can give the particle size distribution of Kuwaiti samples. Ten samples of Kuwaiti atmospheric dust were obtained from the Kuwait Scientific Research Centre (KISR). The dust samples were sized using a Malvern MasterSizer in order to determine the particle size distribution. Each sample was inserted into an ultrasonic bath for one minute to ensure that the dust was dispersed. A 300RF lens was used to provide measurements in the size range between 0.05 and 880  $\mu\text{m}$ . Since the Kuwaiti atmospheric dust was found from EDAX analysis to be mainly silica, a refractive index of 1.5 was used. The same refractive index was used for the synthetic dusts. Figure 4 shows the particle size distribution comparison between Kuwaiti atmospheric dust and the commercial synthetic dusts selected for analysis.

Sizing measurements revealed that the dust size distribution of ASHRAE dust was dissimilar to the all of ten Kuwait dust samples as shown in Table 4. The size distribution of SAE Coarse dust was also different from the Kuwaiti particle size distribution. This signified that each dust has different settling velocities, which increase rapidly with particle size and density. The particle size distribution of the SAE Fine seems to be the closest to Kuwaiti atmospheric dust. It can also be noticed that SAE Coarse and Fine dust can be considered as upper and lower limits in terms of size distribution in comparison to Kuwaiti atmospheric dust. Therefore, those two types were used for this study to conduct the comparisons of filter performance.

Table 4 lists the measured values of the mean diameters, volume mean diameters and surface area mean diameters of synthetic dusts in addition to the Kuwaiti dust. The measured specific surface area mean diameter of ASHRAE and SAE coarse dust particles by Malvern MasterSizer are 1.84  $\mu\text{m}$  and 1.75  $\mu\text{m}$ , respectively. Both measurements are lower than the surface area mean diameter of the Kuwait dust which has a range of 3.22 to 5.74  $\mu\text{m}$ . The drag force is affected by the surface area of the particle which in turn means the drag force created by ASHRAE dust particle is lower than the Kuwait one. The mean surface area of SAE fine dust particles is 3.73  $\text{m}^2/\text{g}$  which falls within the Kuwait atmospheric dust range of specific surface area mean diameter.

#### *Kuwaiti and Test Dusts*

Most of the filters used in Kuwait are evaluated using ASHRAE dust and hence this dust was considered in the study in order to assess its appropriateness for filter performance via its similarities in physical and chemical characteristics to Kuwaiti atmospheric dust. The synthetic dusts selected were ASHRAE, SAE 726 Coarse, and SAE 726 Fine to include two different size distribution dusts. ASHRAE synthetic dust is composed by weight of 72% standardized SAE 726 Fine dust (Arizona road dust), 23% powdered carbon and 5% cotton linters. Standardized air cleaner test dust is classified from dust gathered in a desert area in Arizona. It is predominantly silica and has a mass mean diameter of approximately 7.7  $\mu\text{m}$ , a geometric standard deviation of approximately 3.6, and density of approximately 2.7  $\text{g}/\text{cm}^3$ .

The powdered carbon is carbon black in powder form, with ASTM D3765 CTAB surface of  $27\pm 3$   $\text{m}^2/\text{g}$ , ASTM D2414 DBP adsorption of  $0.68\pm 0.7$   $\text{cm}^2/\text{g}$ , and ASTM D3265 tint strength of  $43\pm 4$ . The SAE 726 Fine test dust is composed of mineral dust, predominantly silica with other oxides present. It has a specific gravity<sup>17</sup> 2.6-2.7  $\text{g}/\text{cm}^3$ . On other hand, SAE 726 Coarse dust is a naturally occurring mineral, which is predominantly  $\text{SiO}_2$  with other oxides present. It has a mass mean diameter of approximately 7.7  $\mu\text{m}$ , a geometric standard deviation of approximately 3.6, and density between 2.6 and 2.7  $\text{g}/\text{cm}^3$ .

#### *Reasons for Dust Selection*

The particle shapes of the Kuwaiti atmospheric dust along with ASHRAE synthetic, SAE 726 Coarse, and SAE 726 Fine dusts were examined using a scanning electron microscope. Figures 5-7 show that SAE Coarse and Fine dusts as well the Kuwait atmospheric dust are mainly non-spherical particles. The drag force varies with the particle shape which in turn affects the aerodynamic behaviour. A spherical particle has higher velocity than an irregular particle with the same weight<sup>18</sup>. The aerodynamic behaviour of particles affects the filtration performance of air filters. Therefore, the angular velocity of irregular dust particles should be considered, and a modified equation of motion for spherical particles may be used to describe the non-spherical particle dynamics with more accuracy.

Clearly, the ASHRAE dust is not representative of Kuwaiti atmospheric dust as far as the particle shape is concerned. The SAE 726 Coarse and SAE 726 Fine dusts seem to be closer in this regard. However, particle shape similarity is not sufficient to select a representative dust since particle size distribution and density measurements will also play a role in the verification process.

The true densities of all dusts were measured using a pycnometer. From a true density standpoint, all synthetic dusts have different densities when compared to the Kuwait atmospheric dust. However, SAE 726 Fine dust may be closer in terms of density than ASHRAE dust. The true densities of the dusts are listed in Table 5.

For the scope of this experimental work, a series of filters (series A) were challenged by SAE Fine dust while the series B filters were challenged by SAE Coarse dust. Scanning electron microscope images at the same scale are shown of both dusts in Figures 6 and 7 for comparison purposes. It is evident that the SAE Fine contains finer particles when compared to the SAE Coarse dust. Dust particles of both dusts seem to have similar shape.

#### *Particulate Matter in Kuwait Atmosphere*

Several filter samples from different locations in Kuwait were examined using a scanning electron microscope to identify common air contaminants existing in the Kuwaiti atmosphere. Figure 8 shows SEM examination which revealed pollen grains deposition on the surface of the filter media. Pollen grains discharged by weeds, grasses and trees are capable of causing hay fever<sup>19</sup>, and most are hygroscopic and therefore vary in mass with humidity<sup>20</sup>. A pollen count of 10 to 25 may make hay fever sufferers experience the first symptoms. The pollen grain found in the SEM examination of the filter media used in Kuwait ranged in size between 10 and 60  $\mu\text{m}$ .

#### **Filter Efficiency Using Test Dusts**

Description of initial filter behaviour constitutes a small part of filter lifetime. While the study of clean filter performance is important, it does not predict the behaviour of the same filter during dust loading. When particle deposition begins to take place within the filtration medium, the filter's inner mechanical structure changes causing the overall efficiency and pressure drop to (generally) increase. Eventually, particles collect other particles leading to dendrite formation which would finally lead to dust cake formation. To better understand dust loaded filter performance, filter series A and B were loaded with SAE Coarse and SAE Fine dust, respectively. Fractional efficiencies were measured after each dust feed, i.e. every 500  $\text{m}^3/\text{h}$  increment, starting at 500  $\text{m}^3/\text{h}$ . On the other hand, the pressure drop responses were measured every five minutes at a single flow rate of 3500  $\text{m}^3/\text{h}$ .

#### **EFFECT OF PLEATING DENSITY ON PRESSURE RISE**

A filter with 28 pleats per 100 mm was loaded with AC coarse dust. 1000 g of dust was loaded in four increments of 250 g. The pressure rise was always linear with time. The 1000 g was mainly deposited within the depth of the filter without a significant dust cake formation. Figure 9 shows the pressure drop response for different pleating densities for filter group A after each dust loading stage.

As dust starts to be fed into the filter by means of a dust feeder, dust settlement into the depth of the filtration medium around the fibre and the rise in pressure drop is negligible. This is the so called the stationary filtration stage and it is represented by a linear response as shown in Figure 10. Filter 34A has the lowest pressure drop and a linear response which could mean that the 1000 g of dust was not enough to make the filter depart from stationary depth filtration to non-stationary filtration and finally to dust cake formation. Furthermore, filter 34A has the highest losses in surface area whilst filter 38A has the least losses in surface area. However, filter 28A satisfies the efficiency requirement and its pressure drop response is acceptable and a linear response is still exhibited. In other words, the 1000 g also did not form dust cake on the filter surface. This indicates that filter 28A is more economical from a cost point of view as well as from efficiency and pressure drop standpoints.

Figure 10a illustrates the pressure drop response after the fourth dust feed for filter 28 A and B for SAE Coarse and Fine dust, respectively. It is evident that the pressure drop response is higher for SAE Fine dust which indicates that fine particles tend to penetrate further through the filter medium compared to the coarse particles of the SAE Coarse dust. SAE Fine dust particles settling into the depth of filtration medium effectively cause the fibre diameter to increase and consequently changes to the depth of the filter as well as the porosity. This leads to increases in the drag force for the filter matrix. Since the drag force is directly proportional to the pressure drop, an increase in the latter is expected and was in fact observed experimentally as shown in Figure 10b. Similar observation and comment can be made for filter 30A and B as shown in Figure 10, however, the difference in the pressure drop response are smaller. This is attributed to the fact that the pleats are closer to each other in the 34 pleats/100 mm density compared to the 28 pleats/100 mm density.

Figure 11 shows pressure drop response versus mass deposited per surface area for filters from series A which indicates that a higher pleating density yields a lower pressure drop (this does not consider the losses of surface area during operation). Filter 28A exhibits the highest pressure drop response when compared with the other pleat densities. On the other hand, the response of filter 34A show the least response in pressure drop due to the high surface area provided. Figure 11 shows pressure drop response versus mass deposited per surface area for filter series B using the Fine test dust; the differences in pressure drop with varying pleating density are smaller when compared with the Coarse dust used with series A filters. This is due to the fact that finer particles are more penetrating and are capable of occupying interstitial spaces inside the filter medium which is responsible for the rise in pressure drop of the filter.

The pressure drop response for the 34A and B filters are shown in Figure 12, which illustrates that the pressure drop response is smaller compared to the 28 pleat filters shown in Figure 11. It can be concluded that solid particles depositing within the fibrous structure change the geometry of the porous matrix which leads to substantial variations in the pressure drop and filtration efficiency.

## **EFFECT OF MASS OF COARSE DUST LOADED ON FILTER EFFICIENCY FOR DIFFERENT PLEATING DENSITIES**

The fractional efficiencies were plotted versus particle size for filter 28A after each dust feed of 250 g. All dust loading and efficiency measurements were measured at 3500 m<sup>3</sup>/h. Figure 13 illustrates the increase of efficiency for each dust feed of SAE Coarse dust as particle size and dust mass loading increases. Clearly, as more dust is loaded into the depth of the filter medium so additional changes in the inner structure occur. Consequently, permeability decreases and as a results the pressure drop response increases. Furthermore, such effect is associated with an increase in efficiency and the fourth dust feed records the highest efficiency.

Figure 14 illustrates the effect of mass loading on efficiency for different pleating densities after the first dust feed. In addition, filter 32A recorded the lowest dust loaded efficiency after the fourth feed. This excludes filter 32A from the competition for an optimal pleat count selection. Filter 34A recorded the highest dust loaded efficiency among other filters in its series, however, as the particle size increases so its efficiency recorded the lowest dust loaded efficiency. Furthermore, Filter 34A recorded the highest losses in surface area prior to dust loading.

## **CONCLUSIONS**

- ASHRAE dust is not representative of Kuwaiti atmospheric dust, due to differences in its physical and chemical characteristics. SAE 726 Fine dust is more representative of Kuwaiti dust.

- Kuwaiti atmospheric dust is mainly non-spherical particles and silica based. It also contains other contaminants such as pollen.
- The particle size distribution of Kuwaiti dust falls between the SAE Fine and SAE Coarse size distributions. Therefore, these synthetic dusts effectively act as lower and upper size distribution limits for the Kuwaiti atmospheric dust, respectively.
- The pressure drop response of SAE Fine dust was higher than that of the SAE Coarse particles. This suggests that the smaller particles are more penetrating than coarse particle for a given filtration medium which is in this case the H10<sup>12</sup> with fibre size range between 0.8-6 µm. This is in agreement with previous studies<sup>11-14</sup>.
- The MPPS (Most Penetrating Particle Size) decreases with increasing filter face velocity for all pleating densities of a given surface area and filter medium. The MPPS increases slightly or remains the same as the pleating density increases.
- Filter class H10 efficiency requirement according to Standard DIN 1822 was achieved at flow rates of 2000-2500 m<sup>3</sup>/h for most filters. On the other hand, a higher filter class (H11) was achieved for a flow rate of 500 m<sup>3</sup>/h for filters with 28 pleat/100 mm density.

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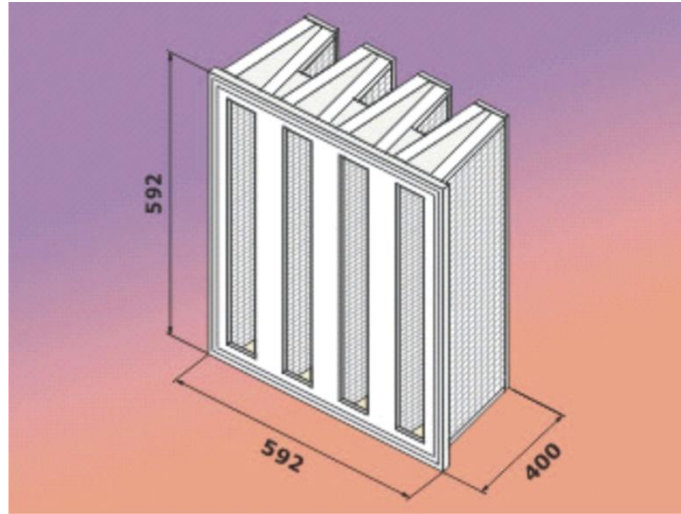
**FIGURES AND TABLES**

Figure 1: Pleated filter with V shape design (EMW Filtertechnik).

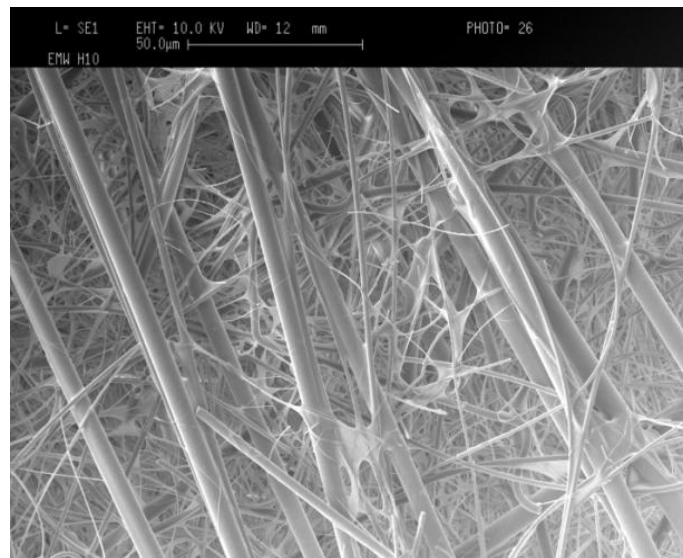


Figure 2: Image of the glass fibre HEPA filter medium (Class H10 according to DIN 1822).

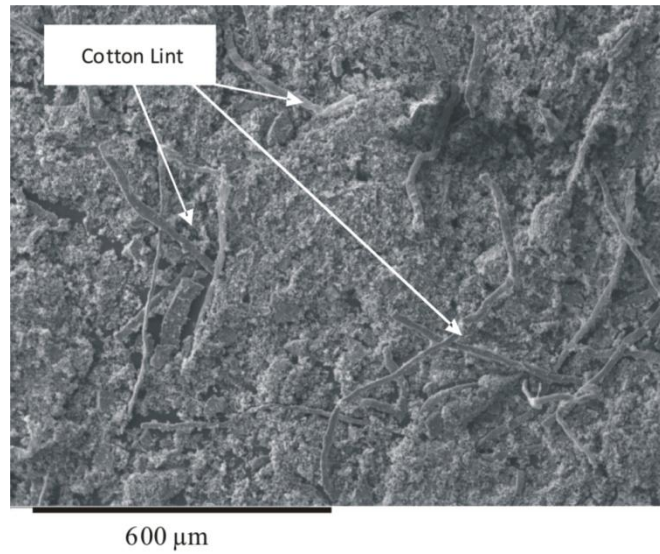


Figure 3: The existence of cotton lint in ASHRAE dust.

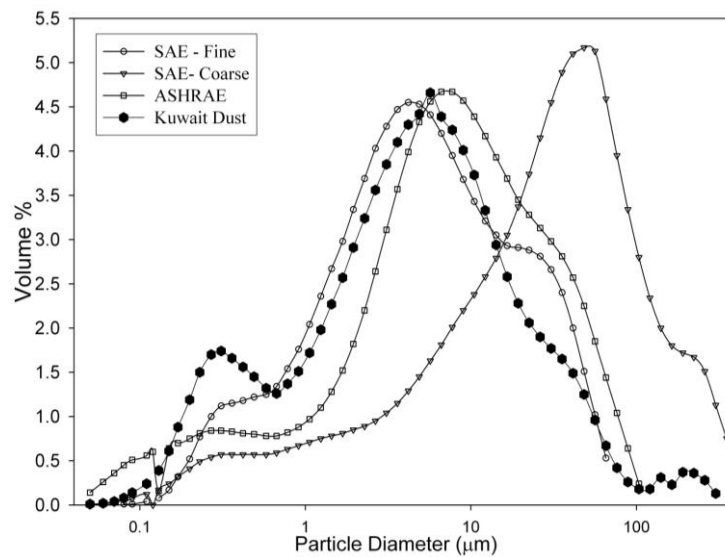


Figure 4: Particle size distribution comparison between Kuwaiti atmospheric dust (Sample 1) and commercially available dusts.

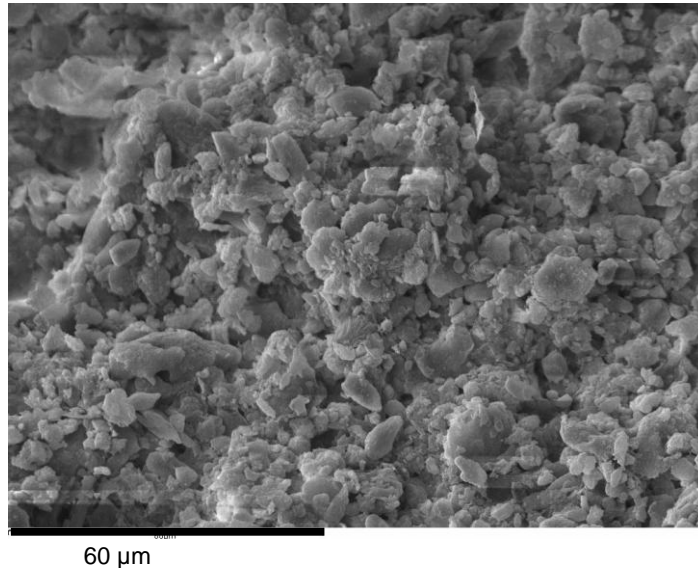


Figure 5: Scanning electron micrograph (SEM) of Kuwait atmospheric dust.

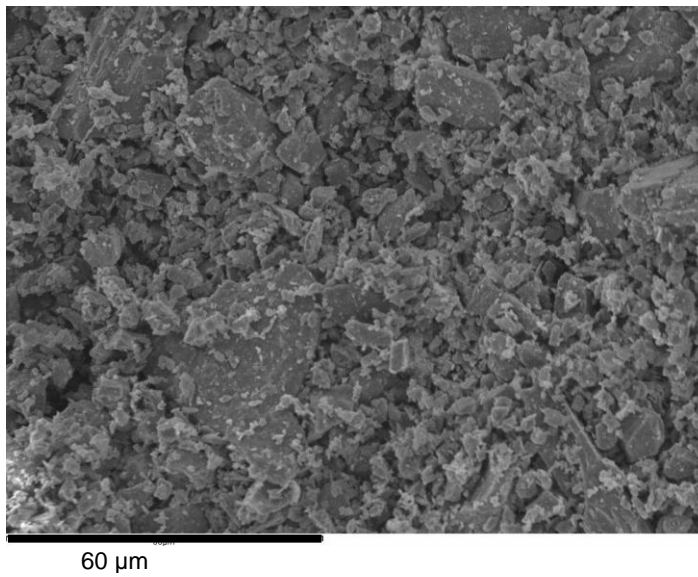


Figure 6: SEM of SAE Fine dust.

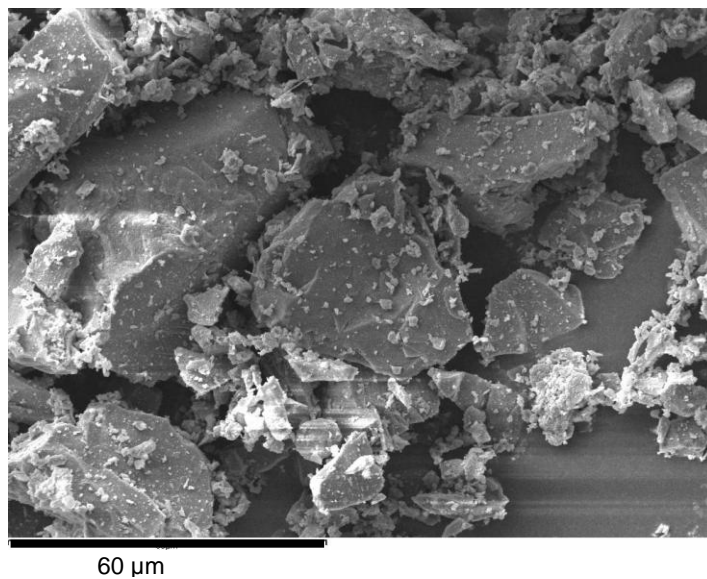


Figure 7: SEM of SAE Coarse dust.

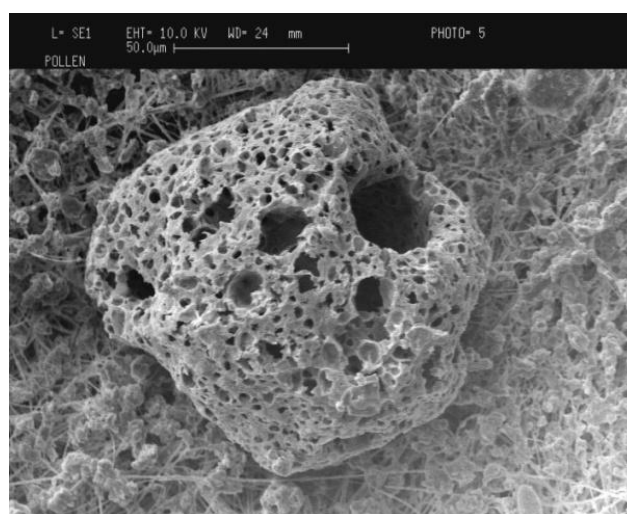


Figure 8: SEM of air filters used in air conditioning units in Kuwait.

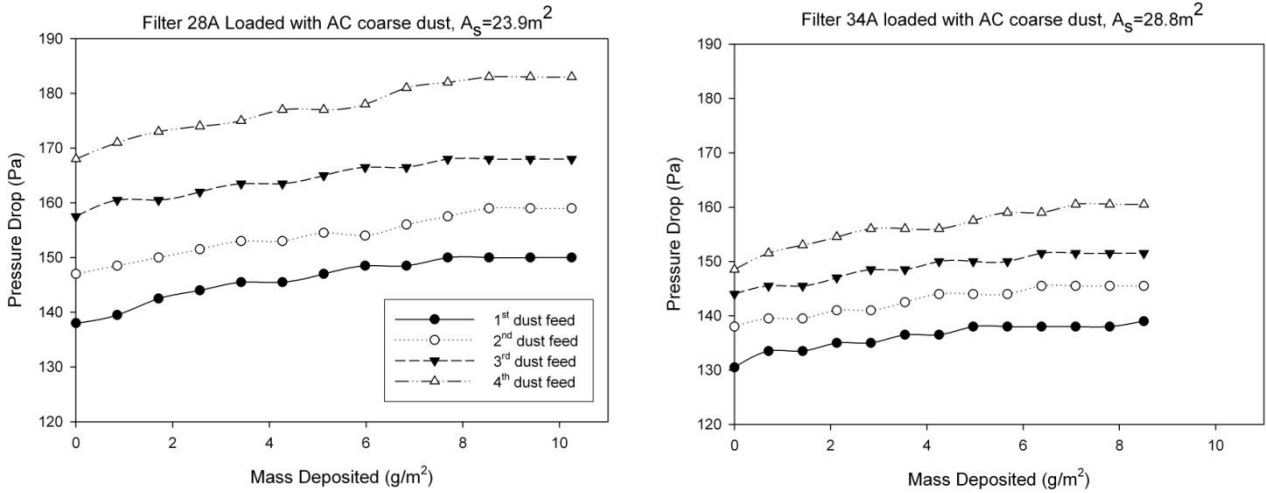


Figure 9: Behaviour of the time dependent particle deposition in different pleating density filters (series A) at a flow rate of  $3500m^3/h$ .

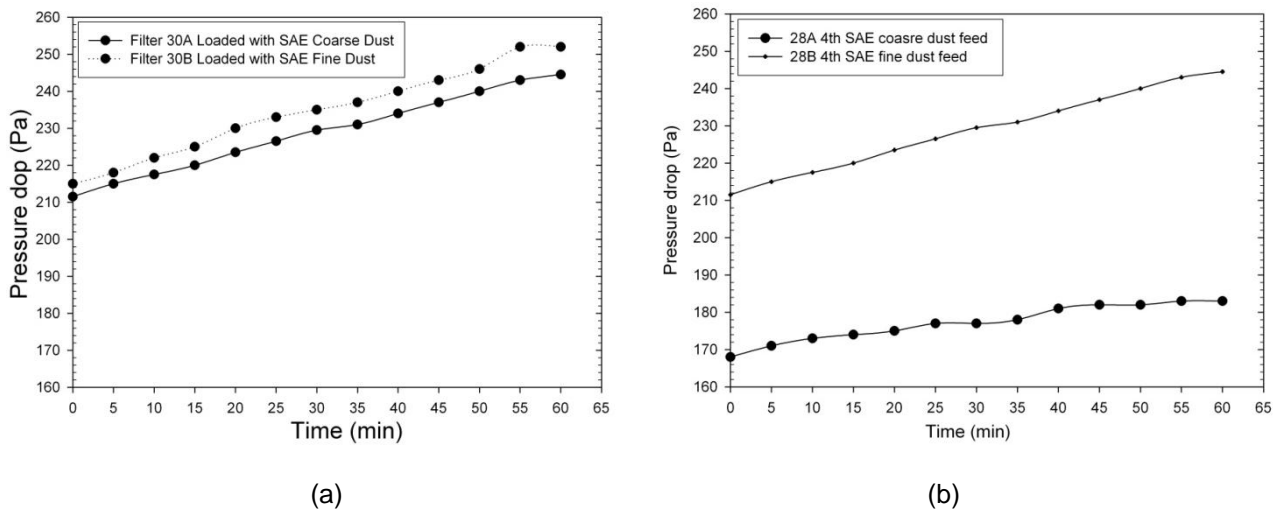


Figure 10: Pressure drop responses for filter 28 A (Coarse dust) and B (Fine dust) after the fourth dust feed.

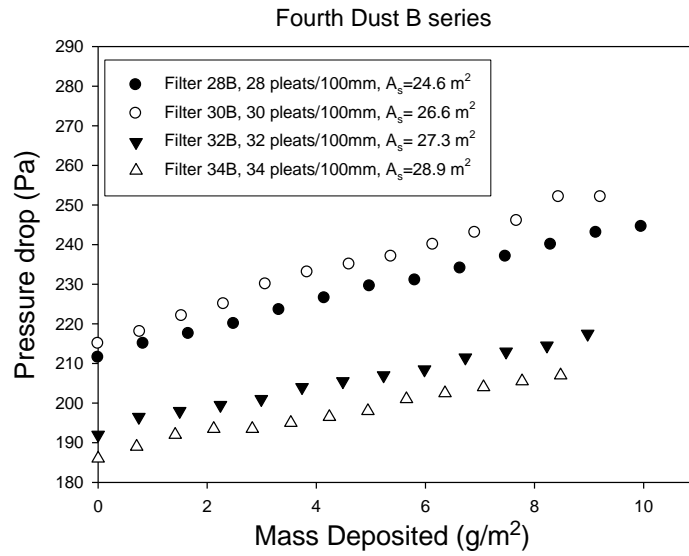


Figure 11: Pressure drop response versus mass deposited per surface area for filter series B using SAE Fine dust.

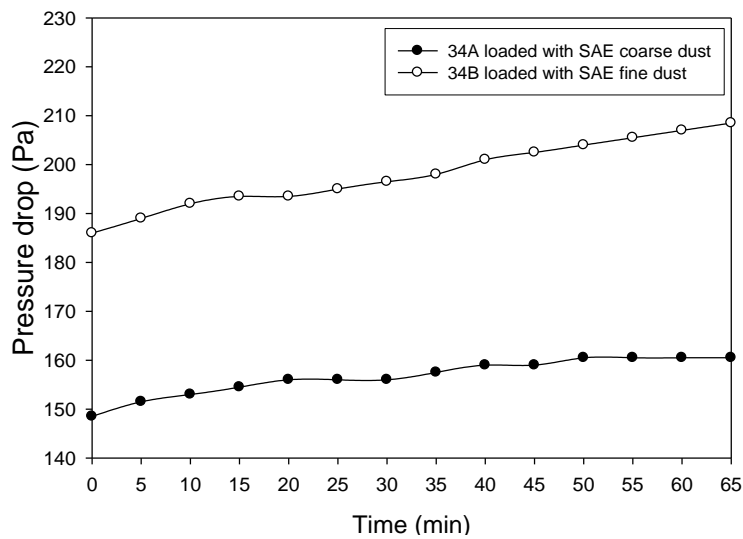


Figure 12: Pressure drop response for filter 34A and B after the fourth dust feed.

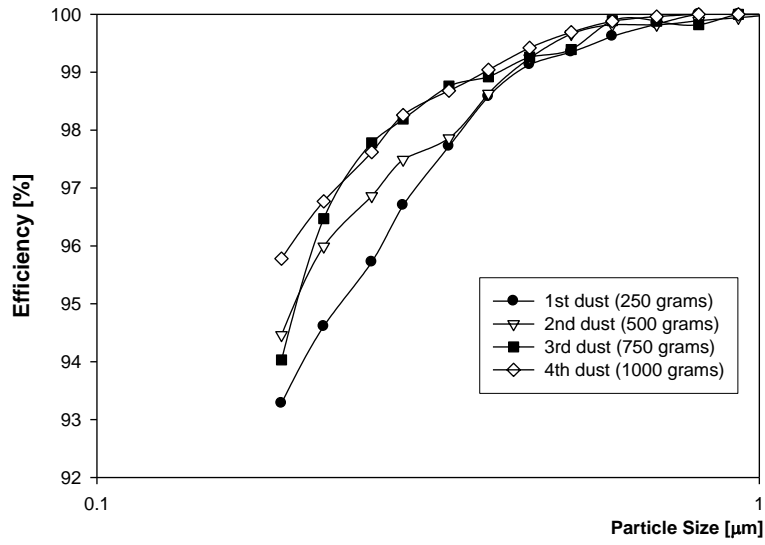


Figure 13: Efficiency after each SAE Coarse dust feeding stage.

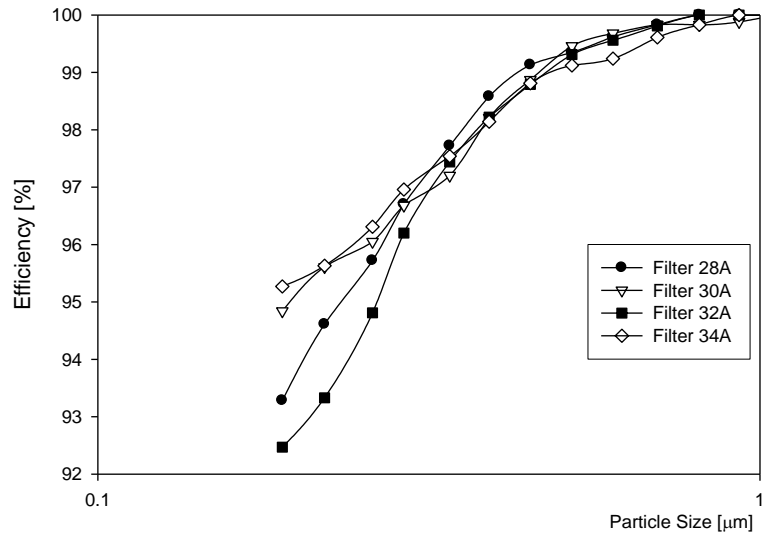


Figure 14: Efficiency after the fourth SAE Coarse dust feeding stage for different pleating density.

Filter	Pleat density (pleats/100 mm)	Surface area (m <sup>2</sup> )
28A	28	23.9
28B	28	24.6
30A	30	26.6
30B	30	26.6
32A	32	27.3
32B	32	27.3
34A	34	28.8
34B	34	28.9

Table 1: The filters tested and their surface areas.

HEPA (H10) filter medium	
Fibre diameter range	0.5-8.5 $\mu\text{m}$
Average fibre diameter	2.1 $\mu\text{m}$
Media thickness	500 $\mu\text{m}$
Packing density	0.06 $\mu\text{m}$
Porosity	94%
Fibre shape	circular

Table 2: Properties of the filter medium.

Element	Kuwait atmospheric	ASHRAE	SAE Fine	SAE Coarse
O	42.25	23.30	49.80	45.37
C	-	55.88	-	19.70
Mg	3.62	-	-	-
Al	7.75	-	4.31	-
<b>Si</b>	<b>29.18</b>	<b>20.82</b>	<b>38.80</b>	<b>34.93</b>
Ca	9.39	-	3.02	-
Fe	7.80	-	-	-
K	-	-	4.07	-
Total	100.00			

Table 3: The chemical composition of Kuwait atmospheric dust.

	Mean particle size ( $\mu\text{m}$ )	Volume mean diameter ( $\mu\text{m}$ )	Surface area mean diameter ( $\mu\text{m}$ )	Specific surface area ( $\text{m}^2/\text{g}$ )
KWT 1	5.03	14.14	1.34	4.47
KWT 2	5.11	25.85	1.21	4.94
KWT 3	4.94	27.63	1.04	5.74
KWT 4	8,54	35.52	1.31	4.58
KWT 5	6.94	21.44	1.54	3.54
KWT 6	13.24	31.09	1.69	3.22
KWT 7	6.43	34.20	1.16	4.71
KWT 8	6.26	18.15	1.35	4.43
KWT 9	6.36	26.86	1.45	4.13
KWT 10	7.32	26.86	1.53	3.93
ASHRAE	5.63-8.00	51.15	3.27	1.84
SAE Fine	10.24	36.23	1.61	3.73
SAE Coarse	33.18	57.18	3.41	1.75

Table 4: Various experimental relevant diameters and properties of the Kuwaiti and synthetic dusts studied.

Dust	Mean measured density ( $\text{g}/\text{cm}^3$ )	Standard deviation of the three samples
ASHRAE 52/76	2.233	0.0416
SAE 726 Coarse	2.593	0.0611
SAE 726 Fine	2.613	0.0681
Kuwait atmospheric	2.436	0.0737

Table 5: True density measurements for the Kuwaiti and synthetic dusts.