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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 the Kuwaiti atmospheric dust were identified and characterized both physically and chemically and compared to the synthetic dust used in laboratories. This paper compares the physical and chemical characterization 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 to study the effect of different synthetic dust types and their particle size distributions on the pressure drop and fractional efficiency using DEHS testing according to DIN 1822.

KEYWORDS

Air Filters, Fractional Efficiency, Gas Cleaning, Glass Fibre, HEPA filter, Permeability, Pressure Drop.

1 Filtration of Air

The process of air filtration is a complex process which is influence 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 [1-3] and other authors considered dust loaded filters [4-5], the literature was limited to the study of flat filters. Studies have considered loading samples of filters with monodispersed [6] and polydispersed [7] aerosols. Literature on the HEPA pleated filter is limited [8-10]. Other authors studied the effect of particle size on the pressure rise [11-15] 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.

2. Filter Properties

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

FILTER	PLEAT DENSITY (Pleats/100 mm)	SURFACE AREA (m^2)
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 µm
Average fibre diameter	2.1 µm
Media Thickness	500 µm
Packing Density	0.06 µm
Porosity	94%
Fibre Shape	Circular

Table 2: Properties of the filter medium.

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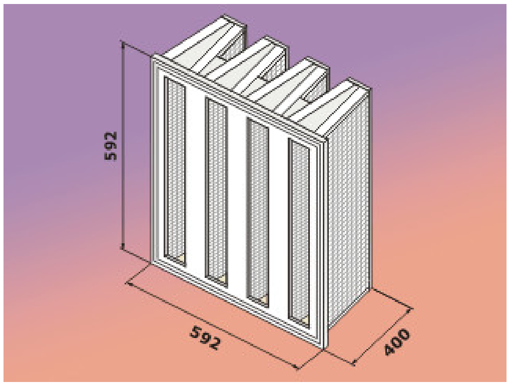


Figure 1: Pleated filter with the V shape design (EMW Filtertechnik).

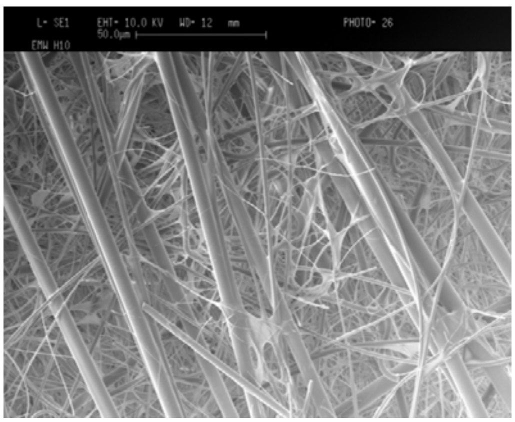


Figure 2: Image of the glass fibre HEPA filter medium (Class H10 according to DIN 1822).

The glass fibre media used in these filters is shown in Figure 2. Glass fibre filtration media was selected for all experiments in this work 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. 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.

1.1 Dust Characterization

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

1.1.1 Chemical Characterization – EDAX

The three synthetic dusts; ASHRAE, SAE Fine and SAE Coarse were analyzed using *Energy Dispersive Analysis X-ray* (EDAX) to determine the chemical composition. The analysis shows that the Kuwaiti atmospheric dust is mainly silica and also contains aluminium, calcium, iron and some traces of potassium and magnetism. On the other hand, ASHRAE and SAE coarse dust contains carbon and they 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 the closest to the Kuwaiti dust from silica-content standpoint. However, analysis of the ASHRAE dust does not show any presence of aluminium, calcium and traces of potassium which are found in the Kuwaiti dust. SAE fine and coarse on the other hand, contain aluminium, calcium and traces of potassium but have higher silica content than the 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 the Kuwait dust.

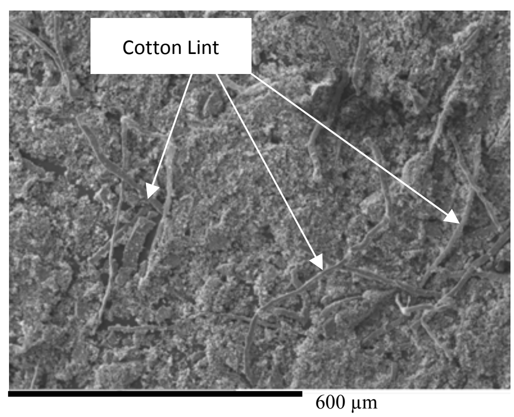


Figure 3: The existence of cotton lint in the ASHRAE dust.

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

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	-
Si	**29.18**	**20.82**	**38.80**	**34.93**
Ca	9.39	-	3.02	-
Fe	7.80	-	-	-
K	-	-	4.07	-
Totals	100.00			

Table 3: The chemical composition of Kuwait atmospheric dust.

1.1.2 Particle Size Distribution

While it is hard to obtain a commercially produced dust that fits the physical and chemical characterization of the Kuwaiti atmospheric dust, particle size analyses can give the particle size distribution of the Kuwaiti samples. Ten samples of Kuwaiti atmospheric dust were obtained from Kuwait Scientific Research Centre (KISR). The dust samples were then sized to obtain the particle size distribution using a Malvern MasterSizer. Each sample was inserted into an ultrasonic bath for one minute to ensure that the dust was dispersed. A 300RF lens was used which provides a size range between 0.05 and 880 μm. 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 the analysis.

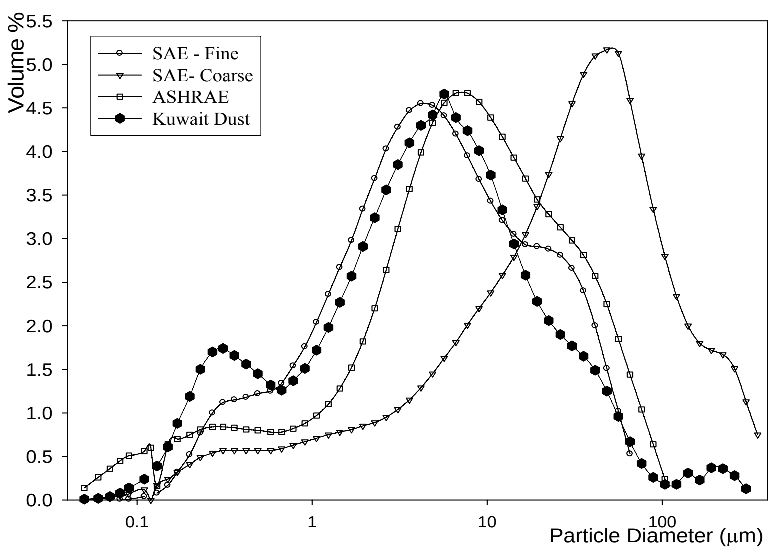


Figure 4: Particle Size distribution comparison between Kuwaiti Atmospheric Dust (sample 1) and commercially available dusts.

Sizing measurements revealed 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 theSAE fine seems to be the closest to the 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 to Kuwaiti atmospheric dust. Therefore, those two types were used for this study to conduct the comparison of the 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 one. The obtained specific surface area mean diameter of ASHRAE and SAE coarse dust particles by Malvern MasterSizer are 1.84 µm and 1.75 µm 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 µm. 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 m^2/g which falls within the Kuwait atmospheric dust range of specific surface area mean diameter.

	Mean Particle Size (µm)	**Volume Mean Diameter (µm)**	**Surface Area Mean Diameter (µm)**	**Specific Surface Area (m^2/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 under study.

1.1.3 Kuwaiti and Test Dusts

Prior to loading the filters under test with solid aerosol, it is imperative to characterize physically and chemically the commercially available dusts. Since most of the filters used in Kuwait are evaluated using ASHRAE dust, this dust was selected for this 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 dessert area in Arizona. It is predominantly silica and has a mass mean diameter of approximately 7.7 µm, a geometric standard deviation of approximately 3.6, and density of approximately 2.7 g/cm^3.

The powdered carbon is carbon black in powder form, with ASTM D3765 CTAB surface of 27± 3 m^2/g, ASTM D2414 DBP adsorption of 0.68± 0.7 cm^2/g, and ASTM D3265 tint strength of 43 ± 4. The SAE 726 fine test dust is composed of mineral dust predominantly silica with other oxides present. It has a specific gravity 2.6 – 2.7 g/cm^3 [17]. On other hand, SAE 726 coarse dust is a naturally occurring mineral, which is predominantly SiO_2 with other oxides present. It has a mass mean diameter of approximately 7.7 µm, a geometric standard deviation of approximately 3.6, and density between 2.6 and 2.7 g/cm^3.

1.1.4 Reasons for Dust Selection

The particle shape of the Kuwaiti atmospheric dust along with ASHRAE Synthetic, SAE 726 coarse, and SAE 726 fine dusts was examined using a scanning electron microscope. Figures 5, 6 and 7 show that SAE coarse and fine dust as well the Kuwait atmospheric dust are mainly nonspherical 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 [18]. 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. 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 one. 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.

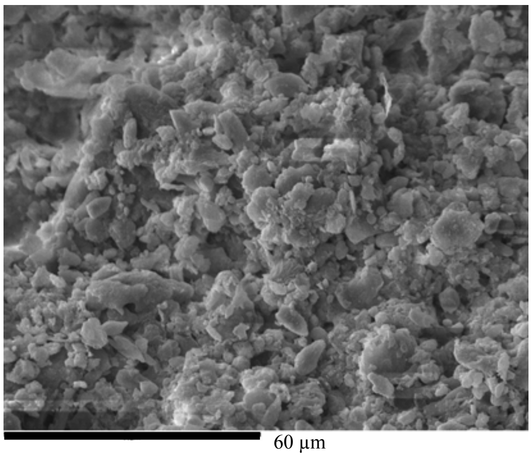


Figure 5: Scanning electron micrograph of Kuwait atmospheric dust.

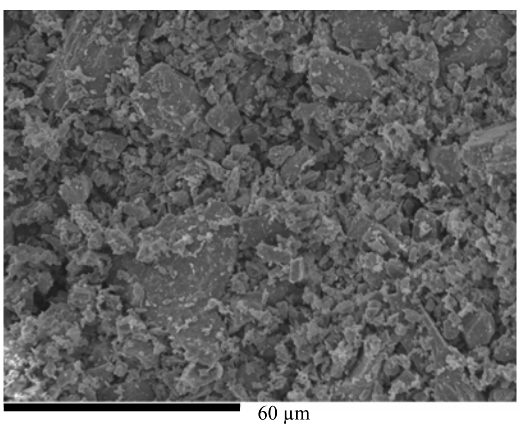


Figure 6: Scanning electron microscopic images of SAE fine dust.

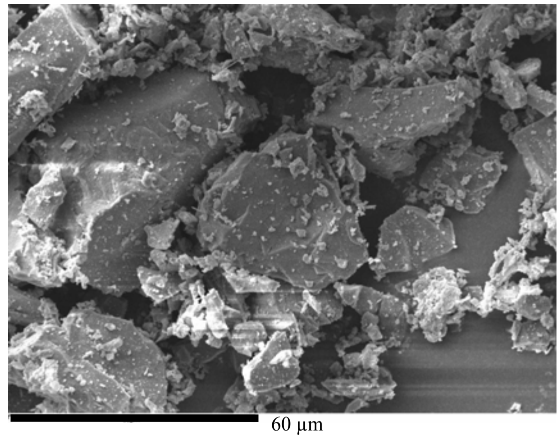


Figure 7: Scanning electron microscopic images of SAE coarse dust.

Dust	**Mean Measured Density (g/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 measurement for Kuwaiti and Synthetic dust under study.

For the scope of this experimental work, a series of filters (filter series A) was challenged by SAE fine while the series B filters were challenged by SAE coarse dust. Scanning electron microscope images of 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 particle when compared to the SAE coarse dust. Dust particles of both dusts seem to have similar shape.

1.1.5 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 [19], and most are hygroscopic and therefore vary in mass with humidity [20]. 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 µm.

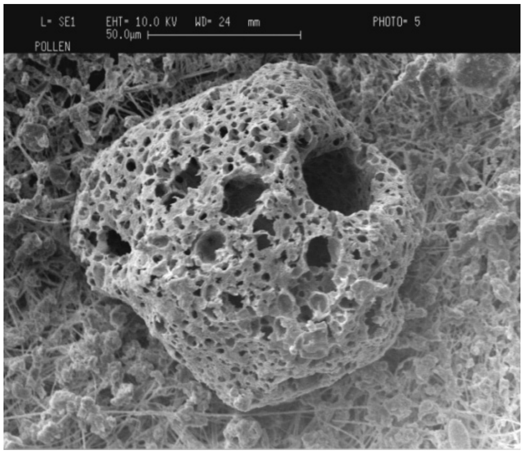


Figure 8: SEM examination of air filters used in air conditioning units in Kuwait.

2.2 Filter Efficiency Using Test Dusts

Description of initial filter behaviour constitutes a small part of the filter life time. 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 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 every 500 m^3/h increment, stating at 500 m^3/h. On the other hand, the pressure drop responses were measured every five minutes at a single flow rate of 3500 m^3/h.

3 Effect of Pleating Density on Pressure Rise

A filter with 28 pleats per 100 mm was loaded with AC coarse dust. The 1000 g of dust was loaded in four increments each 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.

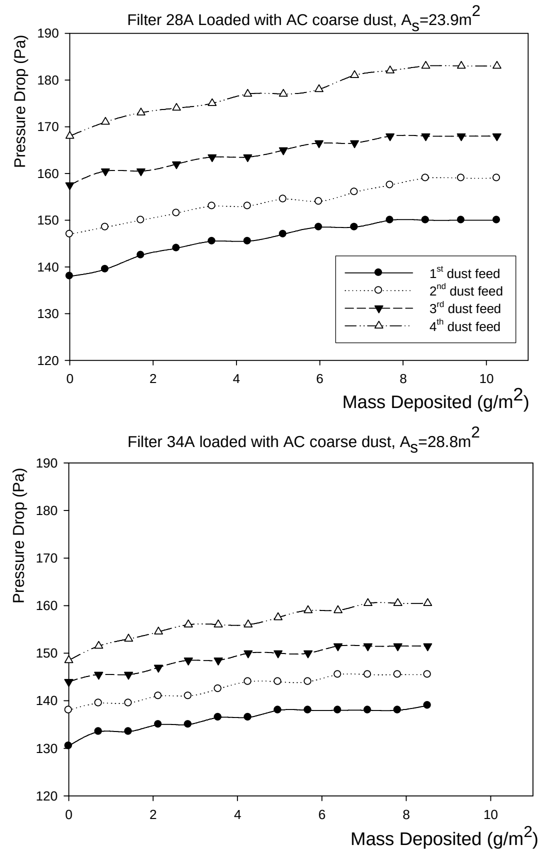
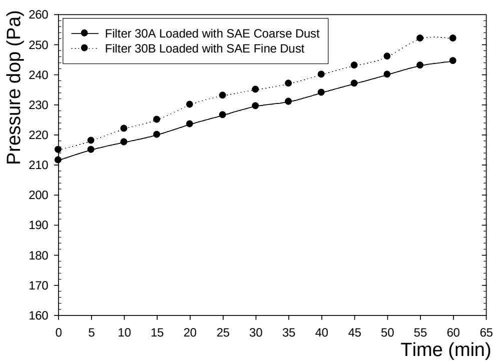


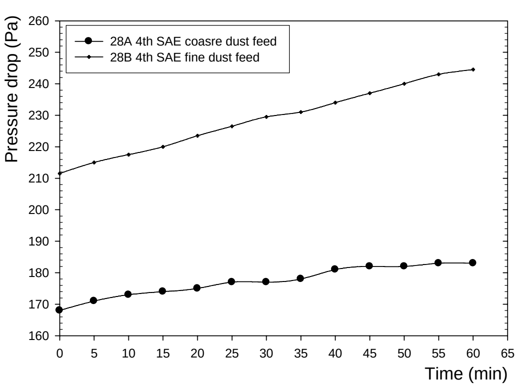
Figure 9: Behaviour of the time-dependent particle deposition in different pleating density filters (Group A) at a flow rate of 3500m^3/h.

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 show in Figure 10. Filter 34A has the lowest pressure drop and a linear response which could be that the 1000 g of dust were not enough to make the filter depart from the stationary depth filtration to non-stationary filtration and finally to the dust cake formation. Furthermore, Filter 34A has the highest losses in the surface area and filter 38A has the least losses in the surface area. However, Filter 28A satisfies the efficiency requirement and its pressure drop response is acceptable and still a linear response. In other words, the 1000 g also did not form dust cake on the surface on the filter surface. This indicates that Filter 28A is more economical from cost point of view as well as from efficiency and pressure drop standpoints.

Figure 10(a) illustrates the pressure drop response after the fourth dust feed for 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 causes the fibre diameter to increase and consequently changes to the depth of the filter as well as the porosity and as results increasing the drag force in 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 10(b). Similar observation and comment can be made for filters 30A and B as shown in Figure 10, however, the difference in the pressure drop response are smaller. This is reasoned to the fact the pleats are closer to each in the 34 pleats/100 mm density compared to the 28 pleats/100 mm.



(a)



(b)

Figure 10: Pressure drop response for Filters 28 A (coarse dust) and B (fine dust) after the fourth dust feed.

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

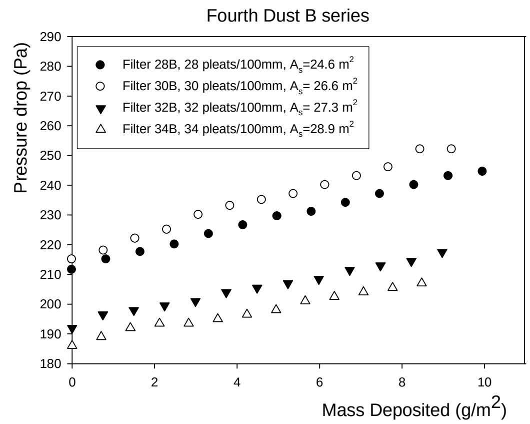


Figure 11: Pressure drop response versus mass deposited per surface area for filter group B using SAE fine dust.

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 pleats filters shown in the previous figure. 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.

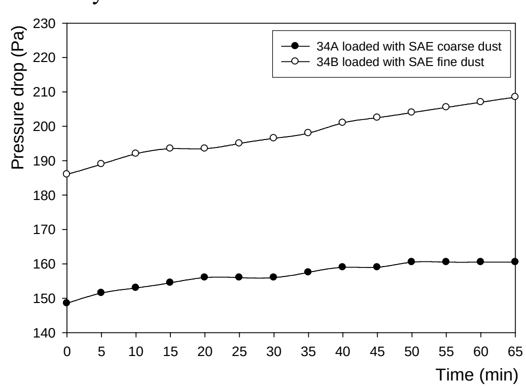


Figure 12: Pressure drop response for filters 34A and B after the fourth dust feed.

4 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^3/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 filtration medium, 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 in efficiency according to Figure 13.

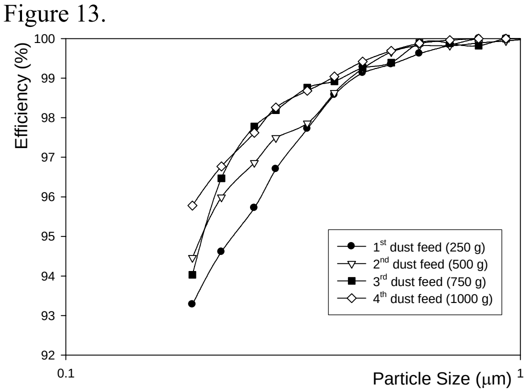


Figure 13: Efficiency after each SAE coarse dust feeding stages.

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 group, however, as the particle size increases; its efficiency recorded the lowest dust loaded efficiency. Furthermore, Filter 34A recorded earlier the highest losses in surface area prior to dust loading.

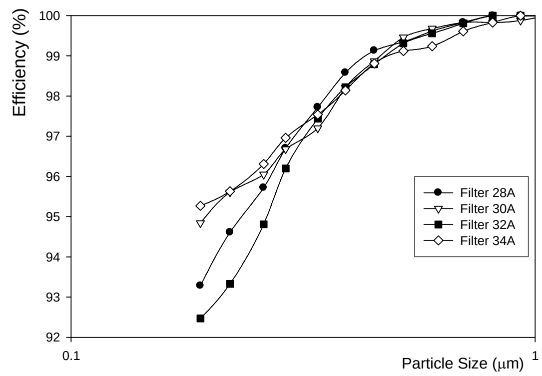


Figure 14: Efficiency after the fourth SAE coarse dust feeding stage for different pleating density.

5 Conclusions:

- ASHRAE dust is not representative dust of Kuwaiti atmospheric dust, due to differences in physical and chemical characteristics. SAE 726 fine dust is more representative of Kuwaiti dust.
- Kuwaiti atmospheric dust is mainly non spherical particles and is 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 of 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 [12] with fibre size range between 0.8-6 µm. This is in agreement with previous studies by [11-14]
- The MPPS (Most Penetrating Particle Size) decreases with the increase of filter face velocity for all pleating densities 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 for flow rates 2000-2500 m^3/h for most filters. On the other hand, higher filter class (H11) was achieved for a flow rate of 500 m^3/h for filters with 28 pleat/100 mm density.

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