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Performance Evaluation of Gas Cleaning Industrial Filters using a Bi-Modal Test Aerosol for Dust Loading Studies

Jae Keun Lee, Seong Chan Kim and Benjamin Y.H. Liu*
Department of Mechanical and Precision Engineering Pusan National University Pusan, 609-735, Korea
**Particle Technology Laboratory Mechanical Engineering Department,*
University of Minnesota, Minneapolis, MN 55455, U.S.A.

Abstract—Typical size distribution of emission particulates is bi-modal in shape with particles in the fine mode (< 2.0 μm) and the coarse mode. An experimental study of pressure drop across the industrial gas cleaning filters has been conducted using particle mixture of fine alumina and coarse Arizona dusts with a rotating aerosol disperser to generate the bi-modal test aerosol. Pressure drop increased linearly with increasing mass loading. The pressure drop was found to be strongly dependent upon the mass ratio of fine to coarse particles. The smaller the mass ratio of fine to coarse particles and the higher face velocity are, the faster pressure drop rises. The fine particles and the greater inertia of the particle moving fast would cause a denser cake formation on the filter surface, resulting in a greater specific resistance to the gas flow.

1. Introduction

Typical size distribution of emission particulates from in-plant airborne contaminants such as fly ash and atmospheric aerosols is bi-modal. Fig. 1 shows that the size distribution of fly ash measured upstream of the electrostatic precipitator on a coal-fired utility boiler is usually bi-modal in shape with particles in the coarse (> 2.0 μm) mode and in the fine particle mode consisting of products of combustion[1]. Table 1 shows the modes, mass median diameter, and mass concentration of the typical emissive particulates. Fine mode in the 0.18 to 0.36 μm size range and coarse mode in the 5.7 to 25 μm size range were measured and mass concentration was ranged from 2 to 205 μg/m^3.

High efficiency particulate air (HEPA) filters are successfully used in a multitude of applications such as nuclear, pharmaceutical or semiconductor industries where the dust concentrations are very low. HEPA filters are designed to remove particles from the gas stream with efficiencies of at least 99.97%. HEPA filters are now used in industrial processes that involve higher dust concentrations; under such conditions a rapid increase in pressure drop occurs to a point where the filter replacement is necessary. Therefore the working life and mass loading characteristics of a filter become a challenge of considerable practical and economic importance with typical emission particulates.

In order to determine the industrial gas filter loading, it is necessary to establish the filter efficiency and pressure drop characteristics as a function of particle diameter. A review of previous work revealed that the purpose was to develop a methodology for predicting the mass loading and pressure drop characteristics on a prefilter/HEPA filter system. No previous work has been performed to characterize the filter loading studies with bi-modal test aerosols.

A laboratory generated bi-modal test aerosol is needed to simulate emission particulates and atmospheric aerosols for filter loading studies. The objectives of this study are to develop method for generating bi-modal test aerosols and to study the particle loading characteristics of selected filter media with bi-modal test aerosols. An experimental study of pressure drop across the HEPA and heavy duty industrial filters has been conducted using the particle mixture of fine alumina and coarse Arizona dusts. Pressure drop measurements have been made using a medium flow filter test system and the rotating aero-

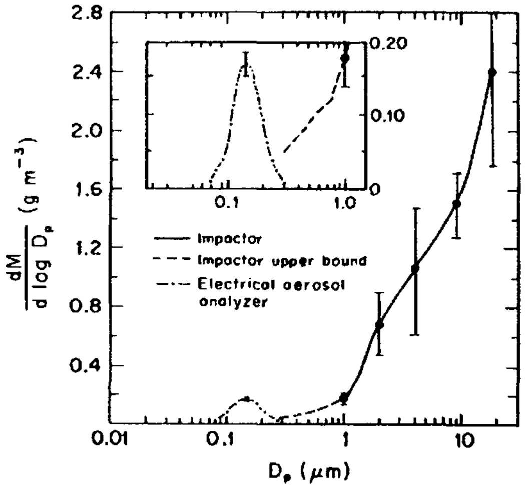

Fig. 1. Fly ash size distribution measured upstream of the electrostatic precipitator on a coal-fired utility boiler.

Table 1. Typical Size Distribution of Emission Particulates.

Particle Type	Mass Mean Diameter (μm)	Geometric Standar Deviation	Mass Concentration (μg/m³)
Fing Mode[1]	01. − 0.5	1.66 − 2.16	2.07 − 38.4
Coarse Mode[1,5]	2.0 − 30	1.5 − 2.0	6.2 − 205

sol disperser to generate the bi-modal test aerosols.

2. Pressure Drop Theory

A general model describing the pressure drop across the filters as a function of mass loading has been developed by many investigators[2,3]. For high levels of particle mass loading on filters, a simple model describing the total pressure drop (ΔP) across the filter due to mass loading can be written as the sum of the pressure drop (ΔPo) across the clean filter plus the pressure drop (ΔPc) across the filter cake due to particle loading as follows.

$$\Delta P = \Delta Po + \Delta Pc \qquad (1)$$

This simple model is appropriate for solid particles and for high efficiency filters because their high collection efficiency causes a particle cake to rapidly form on the surface of the filter. From Darcy's law, ΔPo is proportional to filter face velocity (U) through the filter as follows.

$$\Delta Po = K_1 U \qquad (2)$$

The constant (K_1) depends upon the various morphological features such as the fiber diameter, filter porosity and thickness. Pressure drop across the filter cake due to mass loading (ΔPc) can be described as follows[2,3].

$$\Delta Pc = K_2 U \frac{M}{A} \qquad (3)$$

where K_2 and M/A are the constant and the particle mass loading per unit filter area, respectively. The constant (K_2) is the specific resistance of loading material on the filter and depends primarily upon the particle diameter and cake porosity. K_2 can be experimentally correlated with the parameters that are known or easily estimated. Accurate predictions can be made for the pressure drop across a given filter as a function of mass loading[4].

Methods of determining specific resistance of a filter (K_2) require a knowledge of the porosity of the particle cake. However, the porosity can only be determined with experimental measurements of the thickness of the deposited cake and the total mass of particles in the cake. The specific resistance (K_2) can be obtained from Equations 1, 2, and 3 as follows.

$$K_2 = \frac{(\Delta P - \Delta P_0)}{U} \frac{A}{M} \qquad (4)$$

Experimental values for the specific resistance with bi-modal aerosols will be discussed in the section describing the results of the filter loading tests.

3. Experimental

3-1. Filter Test Systems

Fig. 2 is a schematic diagram of the filter test system used in this study. The system consists of the bi-modal aerosol generator to produce both fine and coarse particles, a test chamber consisting of mixing and test sections, and a blower and flow control damper to pull air through the test chamber and filters.

Basic design concept for the filter loading test system is that it should both minimize transport loss of large particles and enhance mixing of test particles. Also the test system should be designed to straighten the flow, monitor continuously filter pressure drop, and be compatible with loading of bi-modal test aerosols.

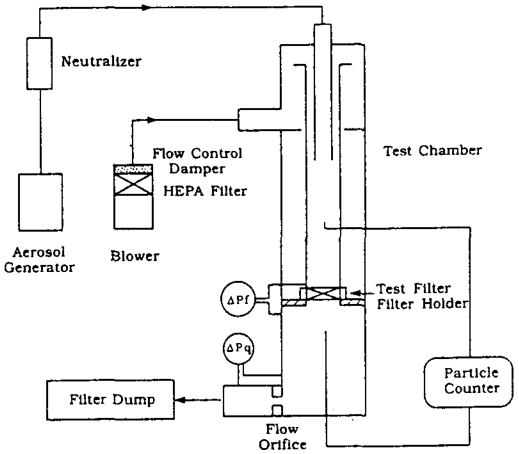

Fig. 2. Schematic diagram of the medium flow filter test system.

The bi-modal test aerosol mixed with the fine and coarse particles, generated by the rotating aerosol disperser, is passed through a Kr-85 ionizer to achieve a Boltzmann equilibrium charge on the particles[5]. The bi-modal aerosol is then mixed with clean air to obtain the proper flow rate needed for the test. The test chamber is divided into two sections. The test aerosol introduced into the top mixing section, where the clean air flow is directed to generate large eddiès to promote mixing and obtain a uniform particle concentration over the entire cross-sectional area of the chamber. The test section consists of a filter holder to accommodate various thickness filters, a pair of pressure taps for pressure drop measurement across the filters, a pair of sampling probes for measuring the aerosol concentration upstream and downstream of the filter, and a flow orifice and a pair of pressure taps for measuring flow rate through the filters.

The test filter holder is designed for face sheet filters and effective filter area of 100 cm². The test is performed at the face velocities of 2, 5 and 10 cm/s, 5 cm/s representing the typical face velocity in many industrial processes. The filter holder and clean test filter are weighed and then the mass loading tests each have to be started from initial pressure drop (ΔPo). The filter holder and loaded filter assembly are removed and weighed at the next target ΔP, and the same test filter is loaded with test particles for the next target ΔP. This procedure to weigh both the filter holder and test filter assembly is required to avoid the change in particle cake structure of particles caused by handling the filter itself.

Table 2. Summary of Test Conditions for Filter Loading Studies.

Parameters	Specification
Test Particles	• Fine Particle: Alumina -Alcoa S-11 -Mass Median Diameter: 0.25 μm -Specific Gravity: 2.42 -Composition: $Al(OH)_3$(99%), Na_2O -Moisture Content: 0.6% -Refractive Index: 1.57 • Coarse Particle: Dust -PTI 0-10 μm -Mean Volume Diameter: 4.16 μm -Particle Size: 0.5-10.08 μm -Specific Gravity: 2.65 -Composition: SiO_2(65-75%) Al_2O_3(11-17%), Fe_2O_3(2-5%), Na_2O_3, CaO, MgO, TiO
Ratio of Fine to Coarse Particle Mass	• Fing Only • 50%:50% • 25%:75% • 10%:90% • Coarse Only
Bi-Modal Aerosol Generation Method	• Rotating Aerosol Disperser
Test Media	• HEPA Filter (Gelman Type A/E Filter) • Heavy Duty Industrial Air Filter
Face Velocity	2-10 cm/s (4-20 fpm)
Flow Rate	12-60 lpm (0.424-2.12 cfm)
Filter Face Area	100 cm² (0.107 ft²)
Relative Humidity	55%
Room Temperature	20.5°C

3-2. Bi-Modal Test Aerosols and Test Filters

A laboratory generated bi-modal test aerosol is needed to simulate emission particulates and atmospheric aerosols for filter loading studies. Test particles for the fine mode can be made using solid particles such as NaCl, alumina, uranine, and carbon black and liquid particles such as DOP (di-octyl phthalate) and sodium hydrooxide. Tests are made using bi-modal aerosols of alumina particles for the fine mode and Arizona road dusts for the coarse particles as shown in Table 2. Physical properties of alumina particles obtained from Alcoa Industrial Chemicals (Model: SpaceRite S-11)

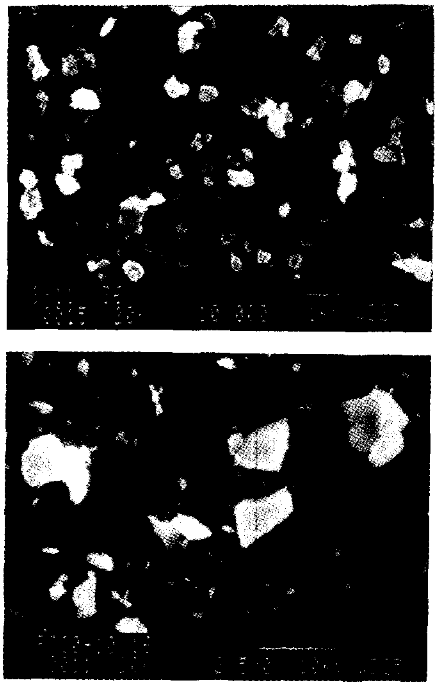

Fig. 3. Test aerosols generated by the rotating aerosol disperser (Top: fine alumina only, bottom: coarse Arizona dusts).

Fig. 4. Test filters (Top: HEPA filter, bottom: heavy duty industrial filter).

are an aerodynamic mass median diameter of 0.38 μm and a specific gravity of 2.42. The chemical compositions of alumina particles are $Al(OH)_3$ (99%), Na_2O (0.1-0.25%), and moisture (0.6%). Physical properties of Arizona dusts for the coarse particles obtained from Powder Technology Inc. (Model PTI 0-10 μm) are a mean volume diameter of 4.16 μm, a typical size distribution ranging from 0.5 to 10.08 μm, and the specific gravity of 2.65. The chemical compositions of Arizona dusts are SiO_2 (65-75%), Al_2O_3 (11-17%), Fe_2O_3 (2.5-5%), Na_2O (2-4%), CaO (2-5%), MgO (1-2%), and TiO (0.5-1%).

Bi-modal test aerosols are made from the mixture of fine and coarse particles based on the particle mass. The mass ratios of fine particles to coarse particles used in this study are fine particles only, 50% : 50%, 25% : 75%, 10% : 90%, and coarse particles only. Fig. 3 shows the test aerosols produced by the rotating aerosol disperser, such as alumina only, Arizona dust only, and mixed particles of 50% : 50%. Test aerosols are found to be appeared separate and well disperse in all cases.

Tests are conducted using flat sheet HEPA filters obtained Gelman Instrument Co. (Model: Type A/E) and heavy duty industrial filters obtained from Donaldson Co. Both filters are made from a fibrous material and used for industrial air pollution applications. Fig. 4 shows the structure of test filters. The fiber diameter of HEPA filters is submicron size, a value which is approximately a tenth that of heavy duty industrial filters.

4. Results and Discussion

Tests are conducted to investigate filter loading characteristics as a function of pressure drop across the flat sheet HEPA and heavy duty industrial filters and develop a methodology for predicting the mass loading and pressure drop effects with bi-modal test aerosols. The measured specific resistance of the filters is also investigated.

4-1. Pressure Drop Characteristics

Fig. 5 shows the pressure drop across the clean test filters as a function of face velocites between 1 and 17.3 cm/s. The pressure drop across the filter at the face velocity of 5 cm/s was measured to be 443 and 83 Pa for the HEPA and heavy duty industrial filters, respectively. The pressure drop was found to be proportional to the face velocity. For the HEPA filter, the proportional constant (K_1) was approximately equal to 90.9 Pa per cm/s face velocity, a value which was approximately five times that of the heavy dust industrial filters.

Fig. 6 shows the results of the pressure drop across the loaded HEPA filter as a function of mass loading with bi-modal test aerosols. Pressure drop characteristics of Y-axis are expressed as a pressure difference to the initial pressure drop, which is defined as (ΔP-ΔPo)/ΔPo, where ΔP is the total pressure drop at a given mass loading, and ΔPo is the initial pressure drop. Tests were carried out with the face velocity of 5 cm/s and the initial pressure drop of 443 Pa. Pressure drop increased linearly with increasing mass loading in various particle mixtures. The pressure drop was found to be strongly dependent upon the ratio of fine to coarse particles based on the particle mass. The smaller the mass ratio of fine to coarse particles is, the faster pressure drop rises. The mass loading became greater as the mass median diameter of the test aerosol was increased at a given pressure drop across the filter. Filter mass loading until the pressure drop reached twice the initial pressure drop was found to be 1.5, 3.0, 3.8, 6.7, and 15 mg/cm² for the mass ratio of fine to coarse particles such as fine particle only, 50% : 50%, 25% : 75%, 10% : 90%, and coarse particle only, respectively. Therefore, the fine particle mixture had an effect on the increase of the pressure drop across the loaded filter due to dense cake to form on the filter surface. Similar pressure drop characteristics for the heavy duty industrial filters have been obtained as shown in Fig. 7. The increase of pressure drop at a given mass loading for the heavy duty industrial filter was much higher than that for the HEPA filter.

Investigations in pressure drop characteristics according to the bi-modal test aerosols deposited in the filter have been carried out at various face velocities. Fig. 8 shows the pressure drop of loaded HEPA filters as a function of face velocity. The mass ratio of fine to coarse particles is 50% : 50%. The pressure drop across the loaded filter increased with increasing face velocity. The greater inertia of the particle moving fast would cause a denser cake formation on the filter surface. Similar pressure drop characteristics for

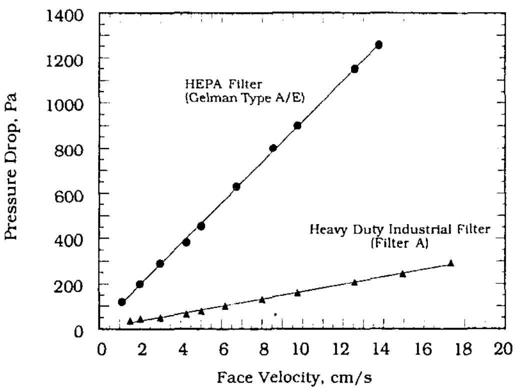

Fig. 5. Pressure drop characteristics of clean filters.

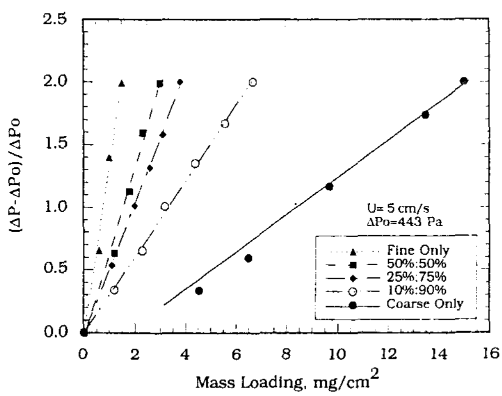

Fig. 6. Pressure drop of loaded HEPA filters as a function of particle mixture.

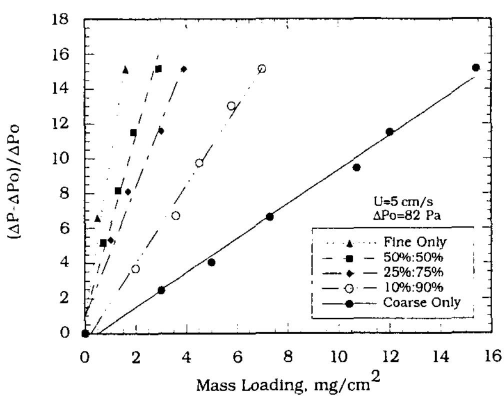

Fig. 7. Pressure drop of loaded heavy duty industrial filters as a function of particle mixture.

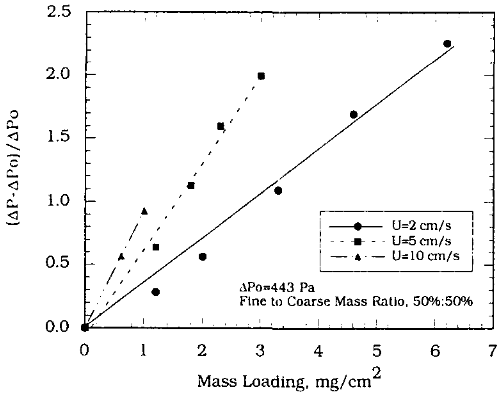

Fig. 8. Pressure drop of loaded HEPA filters as a function of face velocity.

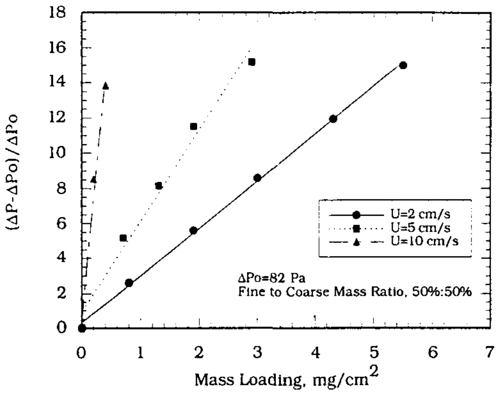

Fig. 9. Pressure drop of loaded heavy duty industrial filters as a function of face velocity.

the heavy duty industrial filters as a function of face velocity have been obtained as shown in Fig. 9.

4-2. Specific Resistance of the Filters

The pressure drop across the filters with bi-modal aerosols is found to be dependent upon the mass ratio of fine to coarse particles and face velocity as shown in Figures 6 through 9. As discussed previously, it is very useful to define the specific resistance (K_2) of a filter as the increase in pressure drop difference for a given particle mass loading per unit filter area at a given face velocity, so that comparisons between filters can be obtained.

Table 3 shows the specific resistance of the HEPA and heavy duty industrial filters as a function of face velocity and particle mixture. The measured specific resistances of HEPA filters at a given face velocity of 5 cm/s were 1.18×10^6, 5.89×10^5, 4.67×10^5, 2.65×10^5 and 1.18×10^5 s^{-1} for the mass ratio of fine to coarse particles of fine only, 50% : 50%, 25% : 75%, 10% : 90%, and coarse particles only, respectively. The fine particles would cause a denser cake formation on the filter surface, resulting in a greater specific resistance to the gas flow. The specific resistance of the heavy duty industrial filters measured a little higher than that of the HEPA filters as shown in Table 3. The increase of pressure drop for the previous work at the mass median diameter of 0.61 and 0.66 μm was similar to that of fine particles only[2,3]. The specific resistance for the face velocity of 10 cm/s might have slight error due to small mass loading with fast increase of the pressure drop.

Figures 10 and 11 show the change in pressure drop noted at various face velocity, (ΔP-ΔPo)/U, as a function of the filter mass loading. The measured

Table 3. The Measured Specific Resistance (K_2) of the Filters.

	Face Velocity	K_2, s^{-1} HEPA Filter	K_2, s^{-1} Heavy Duty Industrial Filter
Mass Ratio of Fine to Coarse Particles			
Fine Only	5 cm/s	1.18×10^6	1.56×10^6
50% : 50%	2 cm/s	8.15×10^5	1.18×10^6
50% : 50%	5 cm/s	5.89×10^5	8.58×10^5
50% : 50%	10 cm/s	4.10×10^5	2.84×10^5
25% : 75%	5 cm/s	4.67×10^5	6.37×10^5
10% : 90%	5 cm/s	2.65×10^5	3.55×10^5
Coarse Only	5 cm/s	1.18×10^5	1.62×10^5

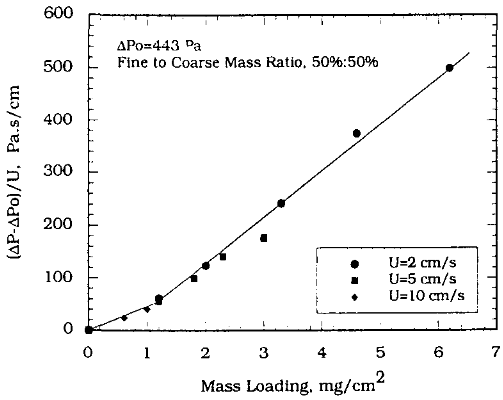

Fig. 10. Specific resistance of loaded HEPA filters as a function of face velocity.

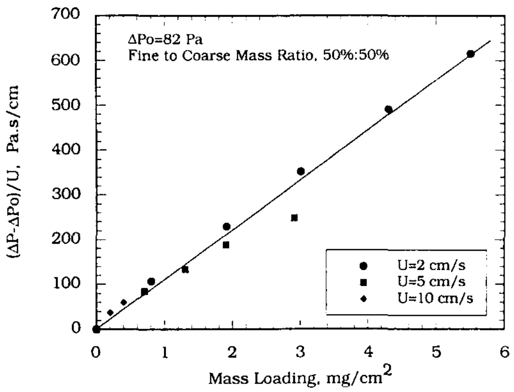

Fig. 11. Specific resistance of loaded heavy duty industrial filters as a function of face velocity.

specific resistance of the filters as a function of face velocity can be measured. Tests are conducted using the mass ratio of fine to coarse particles of 50% : 50%. It can be seen in Figures 10 and 11 that the experimental data corresponding to the various face velocities agree closely with the single line. Also this representation can be stated that (ΔP-ΔPo)/U is approximately linear relationship with filter mass loading for both filters.

5. Summary

A bi-modal aerosol filter test system for flat sheet media has been designed. The effect of fine and coarse particles loading on the HEPA and heavy duty industrial filters and pressure drop characteristics is investigated as a function of mass loading. Also the measured specific resistance of the filters is investigated and compared with previous work.

The filter test system consists of the bi-modal rotating aerosol disperser to produce both fine and coarse particles, a test chamber consisting of mixing and test sections, and a blower and flow control damper to pull air through the test chamber and filters. Bi-modal test aerosols are made from the mixture of fine and coarse particles based on the particle mass. The mass ratios of fine particles to coarse particles used are fine particles only, 50% : 50%, 25% : 75%, 10% : 90%, and coarse particles only.

Pressure drop increased linearly with increasing mass loading in various particle mixtures. The pressure drop was found to be strongly dependent upon the mass ratio of fine to coarse particles. The smaller the mass ratio of fine to coarse particles is, the faster pressure drop rises. The fine particles would cause a denser cake formation on the filter surface, resulting in a greater specific resistance to the gas flow. The pressure drop across the loaded filter increased with increasing face velocity. The greater inertia of the particle moving fast would cause a denser cake formation on the filter surface.

The measured specific resistances of HEPA filters at a given face velocity of 5 cm/s were 1.18×10^6, 5.89×10^5, 4.67×10^5, 2.65×10^5 and 1.18×10^5 s^{-1} for the mass ratio of fine to coarse particles of fine only, 50% : 50%, 25% : 75%, 10% : 90%, and coarse particles only, respectively. Similar pressure drop characteristics for the heavy duty industrial filters have been obtained, except the specific resistance of the heavy duty industrial filters measured a little higher than that of the HEPA filters.

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