ANALYSIS OF BASIC PROBLEMS OF AIR FILTRATION

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ABSTRACT

Air filtration is a problem related to the mechanics of two-phase flow in porous materials which finds unlimited applications. In the aeronautical and aviation fields, air filtration at the entrance of gas turbines , compressors and engines of airports construction equipment is essential for reliability improvement. Industrial, transport and medical applications are other examples. Effective air filtration necessitates the theoretical analysis and the experimental verification.

The paper presents a survey for the fundamentals and basic definitions concerning the porous media, dust-air disperse system, mechanisms and techniques of filtration with the necessary principles from fluid mechanics and other subjects. An experimental investigation of the performance of two types of filters operating on different principles was introduced for the purpose of interpretation and comparison of the characteristics of basic techniques of filtration (surface and volume). Analysis of results and conclusions are included.

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THEORETICAL ANALYSIS

Air filtration is the process of dust separation by flowing the dust-air disperse system, under a pressure gradient, through a porous medium which retains the dust particles (solid phase) and let passing the air (gaseous phase). It is a process related to the mechanics of fluids in porous materials, associated with a set of particular phenomena.

The characteristics of filtration process are essentially influenced by the properties of porous medium, dispersed dust and dispersing fluid (air). Filtration is realized through several mechanisms whose intensity defines the "efficiency" of the porous filtering medium (filter) which is the fraction of incoming dust flux captured by the filter. The "pressure drop " across the filter is a significant criterion. The effectiveness of filtration process is evaluated according to the performance characteristics of filters determined experimentally.

Porous Medium

It is a solid contaning voids either interconnected or non-connected. If the voids are interconnected throughout the medium thickness, they form "Open Pores", otherwise " Closed Pores" are formed. The fibrous, vacuol and granulated porous media are widely used for filtration.

The porous medium is characterized by its porosity, specific surface, permeability, size and distribution of structural units, dimensions, chemical composition and electrostatic properties.

The total porosity ε is the fraction of the bulk volume V of the medium occupied by voids:

$$\varepsilon = \frac{V_p}{V} = \frac{V-V_s}{V} = 1 - \frac{V_s}{V}$$

V_p : Volume of voids
V_s : Volume of solids

In addition, the partial porosity χ (fraction of the total porosity ε for each pore size) and porosity spectrum should be determined for defining the "Filtration Threshold " expressed by the size of the largest open pores (figure 1). It corresponds to the minimum size of dust particles that the medium could separate.

The specific surface S_o is the interstitial surface area of pores S per unit bulk volume V :

$$S_o = \frac{S}{V}$$

For fibrous media, S_o depends on the total porosity ε and radius of fibers r_f according to Sulliven equation |4| :

$$S_o = \frac{2(1-\varepsilon)}{r_f}$$

The permeability K is the fluid conductivity of porous medium. As a macroscopic quantity, K is defined by D'Arcy law:

$$K = \frac{\mu\ U\ L}{\Delta p}$$

μ : dynamic viscosity of fluid
U : fluid velocity
L : Thickness of porous medium
Δp: pressure gradient applied to the medium

K as a function of medium properties is defined by Kozeny relation |1| :

$$K = \frac{C\ \varepsilon^3}{S_o^2}$$

C : constant depending on the shape of pore cross section

Disperse System

The dust particle is characterized by its size (diameter), shape, density, chemical composition and electrostatic properties (charge and dielectric constant). The assembly of dispersed dust particles is characterized by the concentration in the dispersing medium (weight or number of particles per unit volume of air) and the size distribution (fraction by weight or by the number of particles of each particle diameter).

The fluid (air) flow through the porous medium is characterized by its velocity, viscosity, density, pressure and temperature. The fluid velocity U defines the discharge (flow rate) through the porous medium and determined by Kozeny equation:

$$U = \frac{1}{5\mu}\ \varepsilon\ \lambda_h^2\ \frac{\Delta p}{L}$$

$\lambda_h = \frac{\varepsilon}{S_o}$ hydraulic radius

Pressure drop

The pressure drop Δp across the porous medium is a basic parameter from the point of view of energy absorbed by the medium.

For a porous medium of known permeability, Δp can be determined by D'Arcy law:

$$\Delta p = \frac{1}{K}\ \mu\ U\ L$$

Concerning the structural properties of fibrous medium, Δp can be determined by Carman equation |1| :

$$\Delta P = -\ 180\ \frac{\mu\ M\ L}{\rho d_f^2}\ \frac{(1-\varepsilon)^2}{\varepsilon^3}$$

M : mass rate of flow per unit surface area of porous medium
ρ : density of fluid
d_f : diameter of the medium fibers

Mechanisms of filtration

Dust is separated by the porous medium under the action of several mechanisms. The intensity of each mechanism is described by a dimensionless quantity called the " characteristic parameter". The rate of settlement (separation) of dust particles by each mechanism is given by its "Capture coefficient " which is a function of the characteristic parameter. The filter efficiency is a function of the capture coefficients of the mechanisms acting simultaneously. Several formulae for the functions of capture coefficients and efficiency are given by different investigators |4| . The important mechanisms in case of fibrous media are as follows.

1- Direct Interception : When the trajectory of the center of a dust particle approaches the fiber of porous medium at a distance less or equal to the particle radius, the particle is intercepted on the fiber surface. The characteristic parameter N_R of this mechanismis given by |4| :

$$N_R = \frac{d_p}{d_f}$$

d_p : diameter of dust particle

A special case of this mechanism is the " Sieve action" where the particle is intercepted if the pore size (or the distance between fibers) is smaller than the particle diameter.

2- Inertial Settlement : Flowing of the disperse system through the filter fibers results in a curvature of the streamlines in the neighbourhood of fibers. The dust particles due to their inertia are deviated from the curved streamlines and projected against the fiber surface (their trajectory reaches the fiber). For Stokes particles (spherical particles obeying Stokes law) the characteristic parameter is the Stokes number Stk |4| :

$$S_{tk} = \frac{\rho_p \, d_p^2 U}{18\mu \, d_f}$$

ρ_p : density of particle

3- Gravitational Settlement : A dust particle in an air flow of a certain velocity has a settling velocity due to gravity (Stokes relation). This leads to the deviation of particle trajectory from the fluid streamlines. Owing to such deviation the particle may touch and settle on the medium fibers. The intensity of this process increases for larger particles and for smaller flow velocity. Ratio of settling velocity V_s to the flow velocity U defines the characteristic parameter N_G of this mechanism, given as |4| :

$$N_G = \frac{V_s}{U} = \frac{\rho_p \, d_p^2 \, g}{18\mu \, U}$$

g: gravity acceleration

4- Diffusion Settlement : When the disperse system flows close to the fibers of porous medium the trajectories of submicron particles are deviated from the fluid streamlines due to the Brownian motion and may settle on the fibers surfaces. The intensity of this process increases with the decrease of the size of particles and the velocity of flow and the increase of the specific surface of filtering medium. The characteristic parameter N_D of this mechanism is the reciprocal value of Peclet number P_e |4| :

$$N_D = P_e^{-1} = \frac{D}{d_f\ U}$$

D : diffusion coefficient of the particle

The mass fraction X_D of flowing particles of certain size d_p which may settle by diffusion can be determined by the simple formula |3| :

$$X_D = \frac{1.35 \times 10^{-2}}{\sqrt{U}\ d_p\ d_f} \qquad U \text{ in } (\text{m/s}),\ d_p \ \&\ d_f \text{ in } (\mu\text{m})$$

5- Settlement due to Van der Waals Forces : When the distance between a particle and a fiber is very small, the particle may settle under the influence of molecular interaction (Van der Waals) forces between the particle and fiber . The characteristic parameter N_M of this mechanism is given by |4| :

$$N_M = \frac{Q_o\ r_p^2}{9\ \pi\ \mu\ U\ r_f^4}$$

Q_o : Hamaker's constant of interaction

6- Electrostatic Settlement : One or both of the dust particle and fiber may carry electrostatic charges and consequently the particle may settle on the fiber due to the forces of interaction between charges. Ratio of the interaction force to the viscous medium resistance is the characteristic parameter N_{ES} of this mechanism. When the particle carries a charge q and the fiber carries a charge Q per unit length, N_{ES} is defined as |4| :

$$N_{ES} = \frac{4\ Q\ q}{3\pi\ \mu\ d_p\ d_f\ U}$$

Other formulae for N_{ES} are derived for the cases when either the particle or the fiber is charged only |4|.

Basic techniques of filteration

Referring to the nature of the different mechanisms mentioned earlier, two basic filtration techniques are distinguished:

- Surface filtration
- Volume filtration

In surface filtration, the dust particles are separated on the surface of porous medium mainly due to direct interception. In this technique, the settlement and accumulation of the initial dust particles on the surface of filtering medium results in the formation of a "Dust Cake" whose porosity is smaller than that of the original filter (porous medium) . The cake formation imporoves the filter efficiency but a higher pressure drop develops. Surface filtration is a typical for thin filtering media like paper.

In volume filtration dust particles are separated within the whole volume of filtering medium whereas the different mechanisms act simultaneously with adequate probabilities . It is a typical for thick filtering media like the cartridges of metallic wire, graded fibers and polymers.

Testing of air filters

The aim of the testing is to determine experimentally the " basic performance characteristics" of air filter:

- Resistance characteristics : evolution of pressure drop Δp in dependence of discharge Q (flow rate through filter) with the filter cleaned.
- Efficiency characteristics : variation of filter efficiency η with the weight of retained dust (by filter) at a certain discharge.
- Clogging characteristics: evolution of pressure drop with the weight of retained dust at certain discharge.

The weight of dust retained before reaching a certain pressure drop, defines the "Filter Capacity".

Different arrangements for test rigs of air filters exist |5|.

EXPERIMENTAL WORK

For the experimental investigation and comparison of the characteristics of the two basic techniques of filteration (surface and volume), two different types of filters were tested:

- Cartridge of paper (undulated) which operates on the principle of surface filtration.
- Cartridge of polypropylene(olefin-based polymer rolledin spiral), oiled. It operates by the technique of volume filtration.

Both filters have similar basic dimensions.

Test equipment

Measurements were conducted on the test rig given schematically in figures 2,3 . Air is sucked into the filter 8 through the piping by means of the centrifugal fan 2 (figure 2) driven by the electric motor 1. The discharge through filter is controlled by the shutter 3 and measured by the orifice-meter (4,12). Pressure drop across the filter and subsequent piping A is measured by the manometer 10. For measuring the efficiency and clogging characteristics , the filter was installed in the chamber 16 (figure 3) where dust is supplied by the dust feeder 15 and an absolute filter 18 (of efficiency 100% theoretically) is mounted after the filter to be tested. Besides the test rig,a high accuracy balance was used for weighing the filters. Ambient conditions were measured by thermometer, barometer and hygrometer.

Test procedure and conditions

The test included the measurement of performance characteristics for the two filters.

For measuring the resistance characteristics the assembly of test rig indicated in figure 2 was used . First, the filter was dismounted from the rig and the pressure drop across the piping A (Δp_A) was determined (by manometer 10) at different values of discharge Q. Next, the filter (cleaned) was mounted and the pressure drop across the filter and piping A (Δp_{tot}) was measured for different Q. Hence the pressure drop across the filter Δp was determined as :

$$\Delta p = \Delta p_{tot} - \Delta p_A \quad \text{for each } Q \quad , \quad \text{or :}$$

$$\Delta p = f(Q)$$

For measuring the efficiency and clogging characteristics, the assembly of test rig shown in figure 3 was utilized. The weights of tested filter (cleaned) W_1 and absolute filter W_{a1} were determined prior to mounting into system. The discharge was adjusted to the prescribed value. Dust was injected into the chamber 16 at a rate corresponding to the required dust concentration in the air sucked into filter. After each specific time interval, weights of filters (tested and absolute) W_2 and W_{a2} were determined and the pressure drop Δp across the filter was recorded.

The weight of dust (W) retained by the filter was given by :

$$W = W_2 - W_1 \quad , \text{ and}$$

The efficiency η was calculated as :

$$\eta = \frac{W_2 - W_1}{W_2 - W_1 + W_{a2} - W_{a1}} \times 100 \quad (\%)$$

The required characteristics were obtained by tracing the functions :

$$\left.\begin{matrix} \eta = f(W) \\ p = f(W) \end{matrix}\right\} \quad \text{at constant discharge } Q$$

During these tests, the discharge Q ought to be preserved at the prescribed value (by the control shutter in the test rig), since it tended to decrease due to continuous contamination of filter.

Testing of filters was developed at the following conditions:

Dust used for testing : SAE standard dust with the particle size distribution shown in figure 4

Concentation of dust: 200 (mg/m^3)
Temperature : 20 ± 2 °C
Humidity : 55 ± 5 RH

The maximum permissible pressure drop Δp_{max} was fixed to 150 mm H_2O for both filters.

Clogging and efficiency characteristics of filters were measured at constant discharge 240 (m^3/h)

RESULTS AND DISCUSSIONS

The results for the two tested filters are presented in figures 5,6,7.

Resistance characteristics (figure 5) :

The figure shows an increase of pressure drop for both filters as a function of the discharge. This is due to the increase of friction losses through the pores of filtering media caused by the increase of fluid (air) velocity. The rate of augmentation of pressure drop is higher in case of paper filter operating on the principle of surface filtration due to smaller pore size in comparison with that of the polypropylene filter operating on the principle of volume filtration.

Clogging characteristics (figure 6):

The figure shows an increase of pressure drop with contamination of filters (increase of quantity of retained dust) but with higher rate for the paper filter which means that it gets clogged quickly. As a result, the capacity of paper filter is found to be smaller, about 0.63 of that for the polypropylene one, which limits the service duration of paper filters.

Efficiency characteristics (figure 7):

The results indicate a higher efficiency of paper filter during operation within the prescribed range of pressure drop. The efficiency of both filters increases for small quantities of retained dust. That is due to cake formation in the paper filter (surface filtration) and the change of pore dimensions in case of polypropylene unit (volume filtration). From the figure, a sudden drop in the efficiency of paper filter behind the permissible limit of pressure drop is noticed. This is a typical phenomenon for paper filters which could be referred to the mechanical deformation of pores due to excessive contamination.

CONCLUSIONS

1. The exact determination of the dependence of the basic parameters of filtration (efficiency and pressure drop) on the properties of disperse system and porous media considering only theoretical informations is not yet precise . This is due to the difficulty of complete definition of the participating criteria such as the global effect of the different mechanisms of dust separation and the geometry of pores. The theoretical results found in literatures concerning this subject were derived for particular cases with certain assumptions. This dictates the necessity of experimentation for the complete solution of the problem.
2. The results of the experimental comparative study for filtration techniques indicate the higher efficiency of paper filters operating on the principle of surface filtration within the design range of pressure drop. Prolonged utilization of such filters behind the pressure drop limit should be strictly prevented in order to avoid the sudden loss of efficiency. Due to quick clogging, the application of this type of filters should be limited to the conditions of low dust concentration. On the other hand, the filters operating on the principle of volume filtration could be applied for the conditions of medium and heavy dust concentration due to their greater capacity. Efficiency of certain types of these filters could be improved by oiling.

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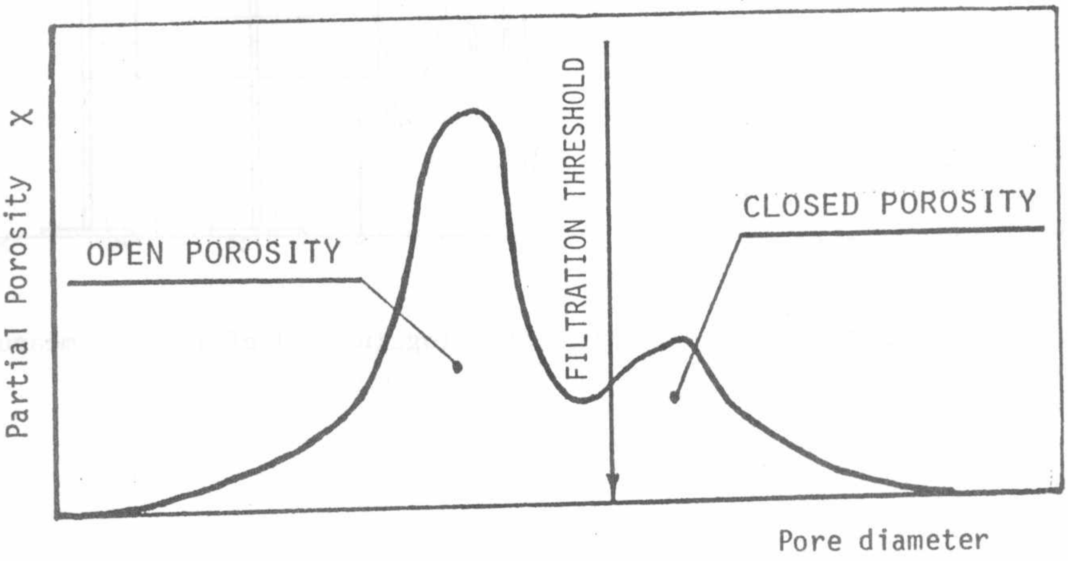

Fig. 1 : Porosity Spectrum

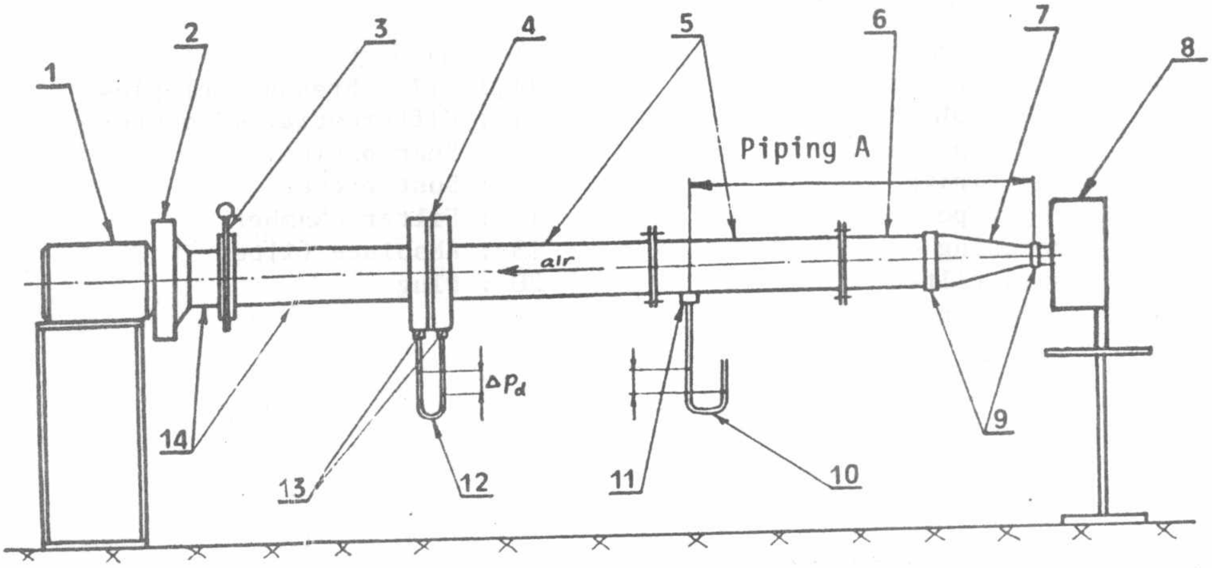

Fig. 2 : Air filter Test Rig-Assembly for resistance measurements

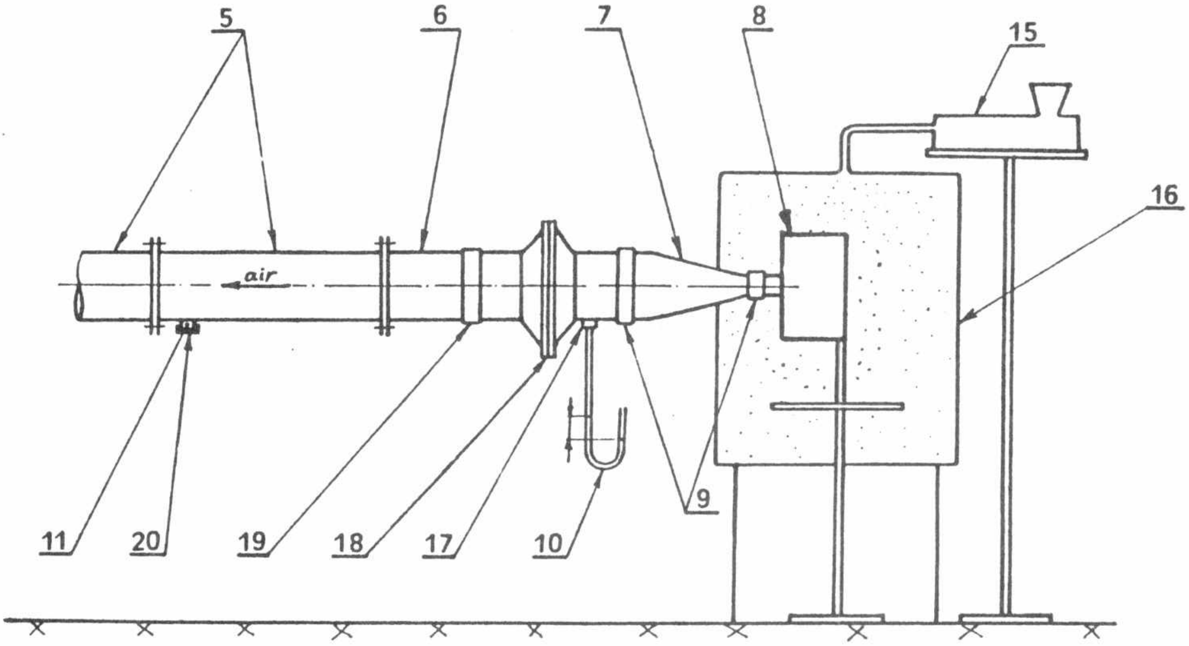

Fig. 3 : Air Filter Test Rig - Assembly for clogging and efficiency measurements

Description of figures 2,3

1 : Electric motor
2 : Centrifugal fan
3 : Control shutter
4 : Orifice plate
5 : Front piping
6 : Glass pipe
7 : Connecting cone
8 : Tested filter
9,19 : Rubber hoses

10 : Manometer
11,13,17 : Pressure nipples
12 : Differential manometer
14 : Rear piping
15 : Dust feeder
16 : Filter chamber
18 : Absolute filter
20 : Plug

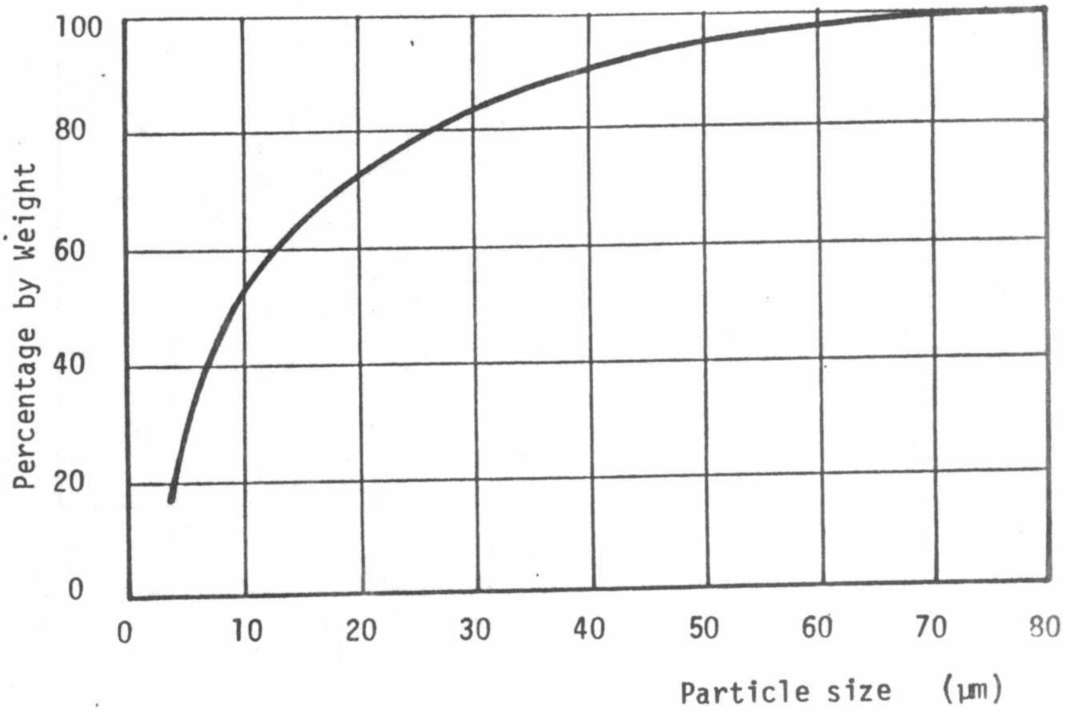

Fig. 4 : Particle size distribution (comulative) of SAE fine dust

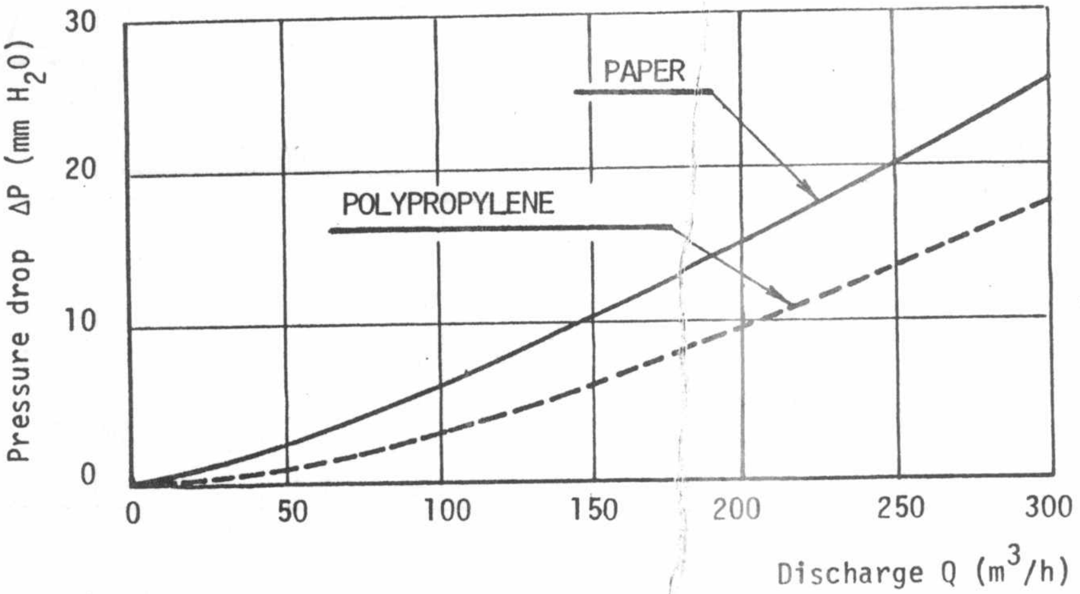

Fig. 5 : Resistance characteristics

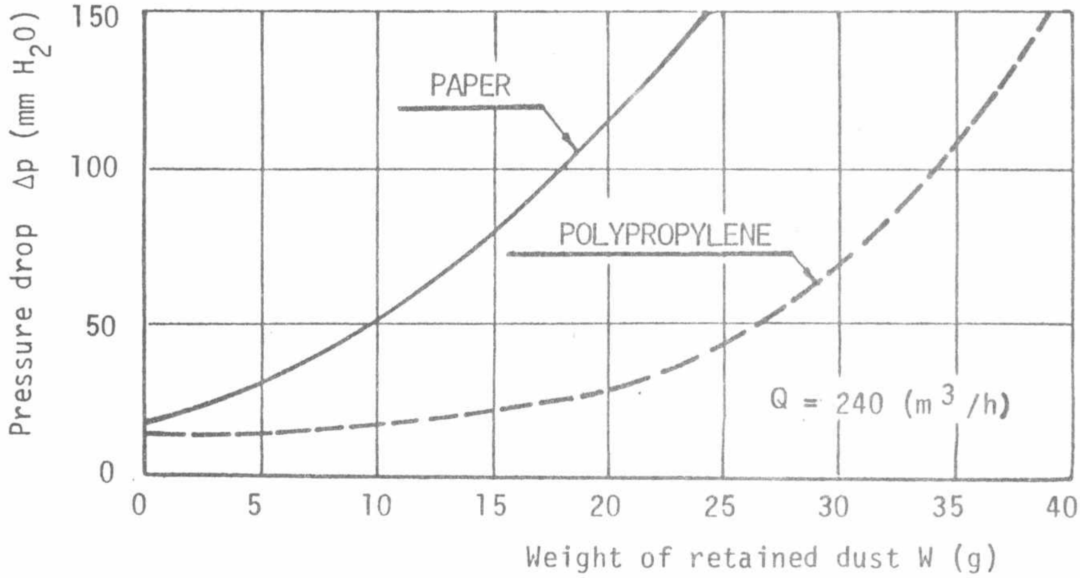

Fig. 6 : Clogging characteristics

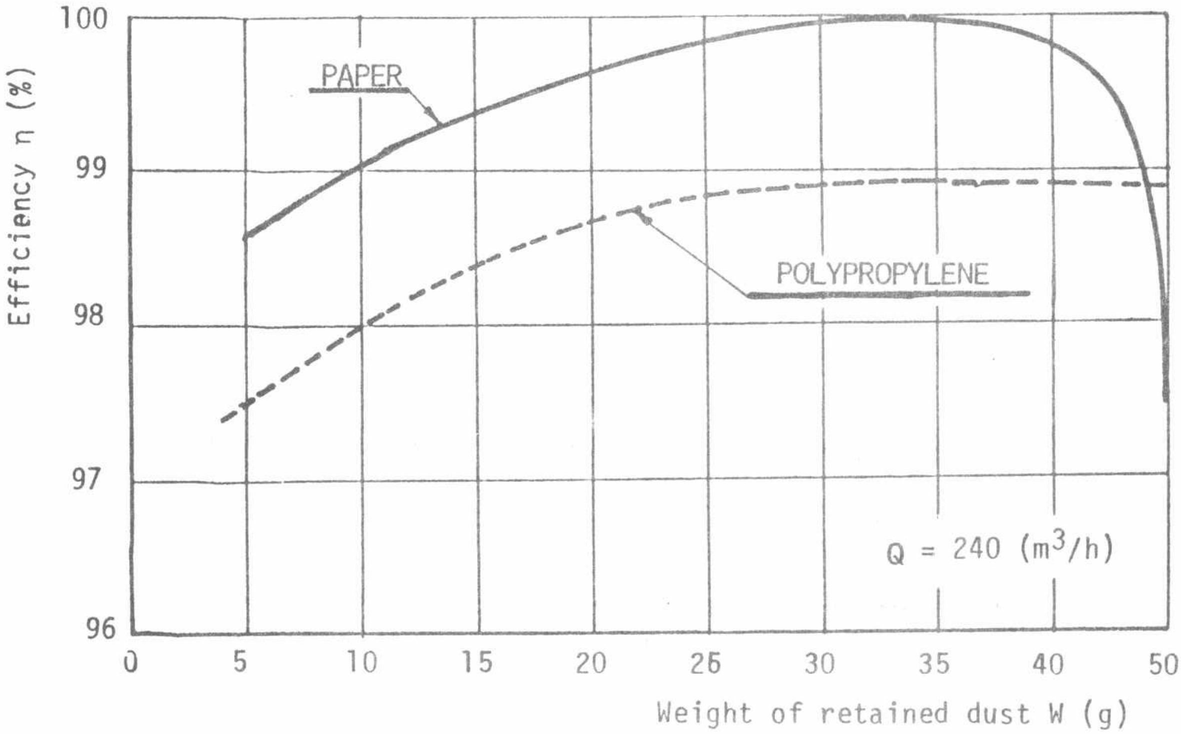

Fig. 7 : Efficiency characteristics