Study on the pressure drop characteristics for the particles across fibres

XL Li 1,*, H Qin 1, ZP You 2, WX Yao 1 and HM Liu 3

1 School of Energy and Safety Engineering, Tianjin Chengjian University, Tianjin, 300384, China
2 Shijiazhuang Tiedao University, Shijiazhuang, 050043, China
3 Tianjin Jinruntian Solar Technology Co. Ltd., Tianjin, 300122, China
*Corresponding author: X L Li, E-mail: lixianliyn@163.com

Abstract. A comparison of the results obtained from typical pressure drop models of fibrous media to experimental values has been done in the paper. Then, the pressure drop characteristics for different structural and operating parameters would be evaluated. The results show that Davies model instead of Kuwabara, Henry and Happel models fits well with the tested data and gives errors of less than 7.0%. Pressure drop across the media increases with increasing solid fraction, superficial velocity and fibre layer thickness, and decreases with increasing fibre diameter. Fibre diameter in the range of smaller values and solid fraction have more significant effects on the air flow resistance than the other factors.

1. Introduction
Filter media coated with polymeric fibres is considered as the most economical and effective way to remove suspended particulates in air. It has been used in a number of commercial air filtration applications, including filters for mining vehicle cabins, turbine-powered military tanks, and automobile air intakes especially personal protection system for people in the outdoor activities in the haze serious day [1-2].

The principles of fibrous filtration theory are based on the work of Kuwabara studying the fluid flow in a unit cell containing a single fibre [3]. Two-dimensional geometries of the fibrous filters are simplified by placing fibres in square or hexagonal arrangements, perpendicular to the flow direction. One of the limitations of the cell model is that it’s only applicable to Brownian particles. Then extensive studies have investigated the effects of various filter conditions on the performance [4-5]. O Preining considered that within this particle size range where the Brownian motion predominates, the particle-fibre interaction was strongly dependent on the fibre diameter configuration parameters [6]. Kirsch, Liu & Wang, Rao & Faghri have made a major improvement for the model as an array of fibres with inline or staggered arrangement [7-9]. Rabiee et al investigated the characteristics of particulate flows through fibrous filters using the lattice Boltzmann method. The Lagrangian form of the equation of motion of a particle was numerically solved to track the path of each particle in the flow field [10]. In recent years, some studies have been conducted to the variations of filtration performance for different dust accumulation [11], for nanofibre media [12] and for ultrafine particles [13]. Because of these pioneering works, pressure drop as a function of parameters relating to fibre structure, fibre property, and airflow characteristics has been semi-empirically derived under certain experimental conditions. In this paper, a comparison of the results obtained from typical pressure up models to
experimental values for the particles of outdoor origin will be done. Furthermore, the pressure drop characteristics for different structural and operating parameters will be evaluated.

2. Theoretical models
Pressure drop obeys Darcy's (Darcy) law at low speed and small Reynolds number. This means that the pressure drop varies linearly with respect to the superficial velocity of air as shown in equation (1).

\[ \Delta P = \frac{\nu \mu H}{d_i^2} f(\alpha) \]  

where \(\Delta P\) is the pressure drop across the fibre media, \(v_s\) is superficial velocity, \(\mu\) is the air viscosity, \(H\) is the fibre layer thickness and \(f(\alpha)\) is the non-dimensional force.

There are a few popular models used for estimating \(f(\alpha)\). Happel has assumed every cylinder (fibre) was surrounded by a coaxial cylinder with radius \(b\) and the surface shear stress was 0, defining \(f(\alpha)\) as [14],

\[ f(\alpha) = \frac{16\alpha}{-0.5 \ln \alpha - 0.5 \left(1 - \frac{\alpha^2}{1 + \alpha^2}\right)} \]  

where \(\alpha\) is fibre volume fraction.

Kuwabara has given on the basis that the surface curl of cylinder was 0, more accurately if the horizontal and vertical distances between fibres are equal [3],

\[ f(\alpha) = \frac{16\alpha}{-0.5 \ln \alpha + \alpha - 0.75 - 0.25\alpha^2} \]  

Goren has modified the Kuwabara formula to apply in the case for higher solid fraction, accounting for the channel walls in an approximate way. And in the case for smaller solid fraction, it can be simplified into the Kuwabara formula [15].

Henry and Ariman calculated a set of numerical solution using computer and obtained the flow field around cylindrical fibres in staggered arrangement, defining \(f(\alpha)\) as,

\[ f(\alpha) = 4(2.44\alpha + 38.16\alpha^2 + 138.9\alpha^3) \]  

Rao et al deduced an empirical formula, in good agreement with the calculated data from Kuwabara formula.

\[ f = 4(2.653\alpha + 39.34\alpha^2 + 144.5\alpha^3) \]  

Davies has obtained a popular used empirical relation by performing many experiments on flat fibrous filters with average fibre diameter as observed in microscope.

\[ f(\alpha) = 64\alpha^{1.5}(1 + 56\alpha^2) \]  

3. Experimental system and results
3.1. Apparatus and method
The experimental apparatus in this work is shown in figure 1. Air duct was made by galvanized steel plate with 0.5mm in thickness, 400mm in width and 400mm in height. Orifice plate was set to ensure the dust-laden air flowing through duct uniformly. Special fixture was made to improve the tightness in the installation of the fibre layer. The pressure drop caused by the fibres filtration, aerosol velocity and fibre layer thickness were respectively measured by Digital micro-pressure gauge, Airdata multimeter electronic micro-manometer ADM-860C connected with pitot tube and vernier caliper T74611. To improve the measuring precision, the velocity testing point was set on the section with area 63 times smaller than that of filtration working section. The sampling point were taken at respectively 4 times and 1.5 times rectangle duct’s width from upstream and downstream local components to achieve uniform airflow before sampling. Choosing 4 grid points on the sampling cross section in the upstream and downstream respectively to ensure not deviate from the average of 10%.
The testing accuracies are listed in table 1. The tests were accomplished at an ambient temperature of 20°C and standard atmospheric pressure.

Table 1. Information about the experiment instruments

| Device                                    | Model       | Full scale | Accuracy         |
|-------------------------------------------|-------------|------------|------------------|
| Airdata multimeter electronic micro-manometer (with pitot tube) | ADM-860C   | 0-25.4m/s  | ±3% or ±0.035m/s |
| Digital micro-pressure gauge              | DP1000-II  | 0~±1999Pa  | ±1%              |
| Vernier caliper                           | T74611      | 0-150mm    | 0.025mm          |

Random arranged fibres with three parameters combinations were referred here, respectively defined as Fibre A, Fibre B and Fibre C. Solid fraction is the ratio of bulk density to real density, in which the former is obtained by dividing the weight by the volume of fibre layer. Various methods to estimate the equivalent diameter for multimodal fibres have been developed [16]. The root mean square value of fibre diameter is more suitable instead of its arithmetic or geometric mean value. Randomly select 10 points on each type of fibre for electron microscopy scanning (SEM). Count the fibre diameters based on the scale in 50 SEM pictures for each point using Image-Pro Plus software and then calculate the fibre equivalent diameter, 1.21 μm for Fibre A, 0.98 μm for Fibre B, and 2.92 μm for Fibre C.

3.2. Comparison of theoretical results with testing data

Random error can be eliminated by repeatedly measurement. All the tests and analysis were carried out with 4 times for each upstream and downstream sampling point and average values were taken. In analysis, spoiled points were picked out in order to avoid parasitic error. The pressure drop of air containing dust particles across the Fibre A, Fibre B and Fibre C is related to velocity as plotted in figure 2. The Kuwabara, Henry and Happel models give large root mean square (RMS) errors calculated by equation(7), respectively 28.69%, 23.84% and 10.85% for Fibre A, 29.52%, 24.99% and 10.10% for Fibre B, and 31.68%, 27.05% and 14.76% for Fibre C.

![Figure 1. Experimental setup for pressure drop measurement](image)

Predictions of fibres layered model by Kuwabara are the highest, followed by two-dimensional model by Henry and fibres regular arranged model by Happel. However, Davies model fits the data well, with RMS error 3.47% for Fibre A, 5.16% for Fibre B and 6.90% for Fibre C. As can also be seen in figure 2, in same filtration velocity, the pressure drop across Fibre B is the largest, followed by Fibre A and Fibre C. That’s because the solid fraction of Fibre B is bigger than that of Fibre A and Fibre C, and the fibre diameter of Fibre A is nearly two times smaller than that of Fibre C.
4. Discussion

4.1. Volume fraction and fibre layer thickness

The variations of pressure drop due to volume fraction for particle size of 0.5μm at superficial velocity of 0.03m/s and fibre diameter of 2.0μm, can be predicted by equations (1) and (6). Varying the volume fraction would affect the velocity distribution in the neighborhood of the fibres. As shown in figure 3, the pressure drop across the filter increases rapidly for $\alpha$ from 0.04 to 0.16. Similarly, it increases significantly for $H$ from 0.3mm to 0.9mm, due to a longer path through the media. It can be seen from figure 3 that the resistance increases to 611.82Pa at volume fraction of 0.16 for the thickness 0.9mm.

Figure 2. Changes of pressure drop in response to superficial velocity for Fibre A (a), Fibre B (b) and Fibre C (c)
4.2. Superficial velocity and fibre diameter

Figure 4 illustrate the pressure drop of the fibrous media as a function of superficial velocity. It is intuitive to see that the pressure drop varies monotonously with respect to the superficial velocity of air, from 11.51Pa to 126.61Pa for fibre diameter of 2.5μm. That’s because the streamlines spread outwards to pass around the cylinder much more suddenly at high values of Reynolds numbers than those at low values. With the increase of fibre diameter, the air streamlines inside the fibrous media become smooth due to fibres number decreasing and then the energy loss decreases. In view that the resistance in the fibrous media is proportional to the inverse square of the fibre diameter, the decreasing trend is more obviously for smaller values of \( d_f \).

5. Conclusions

A comparison of the results obtained from typical pressure up models to experimental values for the particles of outdoor origin has been done. It is observed that pressure drop predictions of layered fibres model by Kuwabara are the highest, followed by that of two-dimensional model by Henry and regular arranged fibres model by Happel. The three models give errors of more than 10%. However, Davies model fits well with the tested data and gives errors of less than 7.0%. Then a parametric analysis is conducted for a range of key parameters, including volume fraction, fibre layer thickness, superficial velocity and fibre diameter.
Acknowledgments
This work was supported by the National Natural Science Foundation of China [grant number 51506141] and the Science and Technology Project of MOHURD [grant number 2017-K1-015].

References
[1] Huang H K, Wang K and Zhao H B 2016 POWDER TECHNOL 292 232-41.
[2] Huang S H, Chen C W, Kuo Y M, Lai C Y, McKay R and Chen C C 2013 AEROSOL. AIR. QUAL. RES. 13 162-71.
[3] Kuwabara S 1959 J. PHYS. SOC. JPN. 14 527-32.
[4] Arouca A M M, Gerkman G C, Arouca F O, Vieira L G M and Damasceno J J R 2014 MATER. SCI. FORUM. 802 220-25.
[5] Fotovati S, Tafreshi H V and Pourdeyhimi B 2010 CHEM. ENG. SCI. 65 5285-93.
[6] Preining O 1998 J. AEROSOL. SCI. 29 481-95.
[7] Kirsch V A 2007 SEP. PURIF. TECHNOL. 58 288-94.
[8] Liu Z G and Wang P K 1997 AEROSOL. SCI. TECH. 26 313-25.
[9] Rao N and Faghri M 1988 AEROSOL. SCI. TECH. 8 133-156.
[10] Rabiee M B, Talebi S, Abouali O and Izadpanah E 2015 PARTICUOLOGY 21 90-98.
[11] Xu B, Wu Y and Cui P 2014 PARTICUOLOGY 13 60-65.
[12] Hosseini S A and Tafresh H V 2010 CHEM. ENG. SCI. 65 2249-54.
[13] Azimi P, Zhao D and Stephens B 2014 ATMOS. ENVIRON. 98 337-46.
[14] Happel J 1959 AICHE J 2 527-32.
[15] Goren S L 1987 AEROSOL. SCI. TECH. 6 199-205.
[16] Brown R C and Thorpe A 2001 POWDER TECHNOL 118 3-9.