Mixture Aerosols Filtration on Filters with Wide Fibre Diameter Distribution - Comparison with Theoretical and Empirical Models

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ABSTRACT

A methodology for calculating aerosol filtration efficiency using non-woven filters with polydispersity distribution of fibre diameters was formulated. In order to verify the results of the calculations experimentally, filters made of polypropylene non-woven fabric were used to filter solid (soot) and liquid (oil) aerosols and their mixtures with different concentrations. In order to increase the accuracy of the calculations, the division of the diameter distribution into several (1–100) ranges of values was considered. The influence of the number of these intervals for theoretical and empirical equations available in the literature was investigated. This effect was found to be significant, and replacing one diameter value representing all the fibres in the filter with twenty diameter ranges, each representing only a fraction of the total fibres, is sufficient to minimize the error due to the underrepresentation of the actual fibre distribution in the filter. Calculation of the mean particle size after the filter was performed using a set of theoretical and empirical equations. The calculations take into account the change in packing density, flow velocity and fibre diameter over time as a result of filling the filter with particles deposited on it. The obtained results were compared with the measurement results. It has been found that such changes in the monofilament performance model are insufficient to properly describe the effects inside the filter.

Keywords: Fibrous filters, Filter clogging, Filtration dynamics, Efficiency models, Mixture aerosols

1 INTRODUCTION

The single fibre efficiency model is widely used to calculate initial filter efficiency. Its simplicity allows it to be used for calculations for different types of particles and filters. At the same time, its accuracy is insufficient in many cases, i.e., filters with polydisperse fibres distribution (Kirsch and Stechkina, 1973; Steffens and Coury, 2007), especially as the area of interest has shifted towards submicron particles and the evolution of filtration efficiency during the process (Löffler, 2004). In addition, the multitude of methods for manufacturing non-woven filters and their widespread use in filtration processes poses the challenge of finding methods to describe as accurately as possible the behaviour of filters with different properties (Hutten, 2007; Mao, 2016).

Many improvements to the single fibre efficiency model have been proposed. These improvements have taken into account both polydispersity of fibrous filters and the formation of particle deposits which could also change the filtration efficiency at later stages of the process.

First group of improved models have assumed that, though the polydispersity of fibrous media, all the fibres may be considered as having the same mean or "effective" diameter (Löffler, 2004; VanOsdel et al., 1990). The next step was the assumption, that the fibre diameter distribution...
has a predetermined form, e.g., log-normal distribution (Jackiewicz et al., 2013; Tronville et al., 2008). The next step was the use of Fully Segregated Flow Model (FSFM) and Perfectly Mixed Flow Model (PMFM) which allowed to consider practically any distribution of fibre diameters (Podgorski et al., 2011). The application of these models has improved reliability and accuracy for particle sizes close to the most penetrating particle size (MPPS) (Jung et al., 2013; Lee and Liu, 1980; Podgorski et al., 2011). Parallelly, approaches based on the numerical description of the fluid flow through the filter medium were used. The classical computational fluid dynamics (CFD) methods were used as numerical methods: finite element method (Kang et al., 2019; Sambaer et al., 2011) or lattice Boltzmann method (Zhou et al., 2017). The consideration of particle deposits formation inside the filter and on the filter surface allowed for a significant increase in accuracy when describing the clogging of the filter with solid particles (Fotovati et al., 2012; Thomas et al., 2019, 1999).

However, all the above research focuses on the use of filters with a polydisperse distribution of fibre diameters, primarily for the filtration of solid particles, less often-liquid particles. However, real-world applications require consideration of the presence of mixture aerosols. In many cases, the filtration process deals with the simultaneous removal of solid particles of different morphology and liquid particles of different wettability towards the filter fibres.

Filtration of mixture aerosols differs from filtration of sole solid or sole liquid aerosols. Interactions between particles in the case of simultaneous filtration of solid and liquid particles lead to changes in the filter structure that have a significant impact on filter efficiency (Agranovski and Shapiro, 2001; Gac et al., 2018, 2016; Mullins et al., 2003). Previous studies carried out for consecutive filtration of solid and liquid particles have partly revealed the mechanisms of formation and degradation of the solid structure formed from the solid particles deposited on the fibres. In earlier studies, solid particle filtration was also investigated when the fibres were pre-coated with liquid (Müller et al., 2014).

This study investigates the changes in an average particle size downstream from the filter during filtration of sole solid, sole liquid and simultaneous solid and liquid particles. For solid particles, soot-like graphite particles were utilised due to their presence in the air as a common pollutant (Löffler, 2004). For liquid particles, di-ethylhexyl-sebacate (DEHS) oil was utilised due to the stability of the formed aerosol and its widespread use as a research material, which enables easy verification of the results and data comparison (Mead-Hunter et al., 2014). The data obtained from experiments were compared with simulation performed for two sets of equations. The simulation of filter loading with deposited particles took changes in packing density, flow velocity and fibre diameter into account. For that reason, chosen equations had to be reliable in a wide range of parameter changes. Additionally, the influence of the number of diameters taken for the single fibre efficiency model calculations was investigated.

2 METHODS

2.1 Experimental Setup

Measurements were performed utilising the setup presented below in Fig. 1. The filter samples were disc-shaped with a diameter of 100 mm, with only a segment of 80 mm in diameter being exposed to aerosol flow. Based on measured aerosol flow from generators, the flow of air was adjusted to keep the face velocity on the filter surface at 0.2 m s⁻¹ for each aerosol. The soot particles were generated from a graphite electrode with a density of 2090 kg m⁻³ by means of a spark aerosol generator GFG 1000 (Palas, Germany). The liquid particles were generated from DEHS oil with a density of 914 kg m⁻³ by means of Laskin nozzle based generator PLG-2010 (Palas, Germany). Each measurement cycle was 64 min long. Although some filter loading happens during the first 4 min, they are omitted on graphs due to instability in initial readings provided by the particle counter UCPC 3776 (TSI Inc. USA). Utilised experimental setup allowed the concentration measurements for particles with sizes ranging from 32.2–735.6 nm. The temperature of aerosols was about 295 K, and the relative humidity of air was 5%.

2.2 Filters

The properties of filters utilised in experiments are listed in Table 1. Filters were made of polypropylene using the melt-blown technique. The filters utilised in experiments were not
Fig. 1. Experimental setup utilised for efficiency and filter loading investigation.

Table 1. Properties of filters utilised in the experiments.

<table>
<thead>
<tr>
<th>Filtration layer</th>
<th>Mean fibre diameter (µm)</th>
<th>Layer thickness (mm)</th>
<th>Packing density (−)</th>
<th>Initial pressure drop (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F6</td>
<td>6.04 ± 2.75</td>
<td>0.913 ± 0.074</td>
<td>0.127 ± 0.010</td>
<td>120 ± 17</td>
</tr>
<tr>
<td>2F6</td>
<td>2.050 ± 0.086</td>
<td>0.115 ± 0.005</td>
<td>200 ± 20</td>
<td></td>
</tr>
<tr>
<td>F8</td>
<td>7.64 ± 3.25</td>
<td>0.953 ± 0.080</td>
<td>0.126 ± 0.011</td>
<td>60 ± 10</td>
</tr>
</tbody>
</table>

Fig. 2. Fibre diameter distribution for utilised filters.

charged with static charges. Filters F6 and F8 have similar packing density and layer thickness. Their main difference is mean fibre diameter. Filter 2F6 is made of the same fibres as F6, but its thickness is double that of F6. Fig. 2 shows that the distribution of fibre diameters cannot be described precisely by standard statistical models.

2.3 Aerosols

Eight different types of aerosol were utilised in the experiments, four pure (soot_h, soot_l, oil_h, oil_l) and four mixture aerosols (soot_h + oil_h, soot_h + oil_l, soot_l + oil_h, soot_l + oil_l). Fig. 3(a) shows the pure aerosols consisting of either solid soot particles or liquid DEHS oil
Fig. 3. Concentrations of (a) pure and (b) mixture aerosols.

Table 2. Aerosol properties.

<table>
<thead>
<tr>
<th>Aerosol</th>
<th>Mean particle diameter (nm)</th>
<th>Total concentration (particles cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>soot(_h)</td>
<td>107.62</td>
<td>8.46E6</td>
</tr>
<tr>
<td>soot(_l)</td>
<td>80.16</td>
<td>4.44E6</td>
</tr>
<tr>
<td>oil(_h)</td>
<td>231.50</td>
<td>7.63E6</td>
</tr>
<tr>
<td>oil(_l)</td>
<td>242.67</td>
<td>4.12E6</td>
</tr>
<tr>
<td>soot(_h) + oil(_h)</td>
<td>90.1</td>
<td>201.9</td>
</tr>
<tr>
<td>soot(_h) + oil(_l)</td>
<td>87.1</td>
<td>163.3</td>
</tr>
<tr>
<td>oil(_h) + soot(_l)</td>
<td>212.5</td>
<td>227.7</td>
</tr>
<tr>
<td>oil(_l) + soot(_l)</td>
<td>227</td>
<td>211.3</td>
</tr>
<tr>
<td>soot(_l) + oil(_h)</td>
<td>76.9</td>
<td>238.9</td>
</tr>
<tr>
<td>soot(_l) + oil(_l)</td>
<td>79.4</td>
<td>238.9</td>
</tr>
</tbody>
</table>

particles of different concentrations (h—high concentration, l—low concentration, where high concentration is approximately two times greater than the low one). The mixture aerosols were their respective mixtures, as shown in Fig. 3(b).

Table 2 shows the mean particle diameter and total concentration for each aerosol. The total concentration of mixture aerosol is lower than the sum of concentrations for pure aerosols it consists of. It is due to interactions between solid and liquid particles in aerosol. The mean particle diameter for mixture aerosol components is based on their expected share in mixture aerosol and is calculated as weighted average of the shares of each size. These values are utilised in efficiency and average particle size downstream calculations.

2.4 Calculations

The calculations of efficiency were based on the single fibre efficiency method. In our calculations, we took into account mechanisms of diffusion, interception and impaction. Due to the nature of our analysis, the primary selection criterion was a wide range of parameter variability so as not to affect the applicability and reliability of the equations. Two sets of equations were utilised. The first one consists of theoretical equations (Eqs. (1), (2) and (3)).

Diffusion (Lee and Liu, 1981):

\[
\eta_{\text{diff}} = 2.6 \left( \frac{1 - \alpha}{Ku} \right)^{\frac{1}{3}} Pe^{\frac{1}{3}}
\]  

Interception (Givehchi and Tan, 2014):
\[ \eta_{\text{int},t} = \frac{1 + R}{2 \cdot K u} \left( 2 \cdot \ln (1 + R) - 1 + \alpha + \left( \frac{1}{1 + R} \right)^3 \left( \frac{1 - \alpha}{2} - \frac{\alpha}{2} (1 + R)^2 \right) \right) \]  \hspace{1em} (2)

Impaction (Stechkina et al., 1969):

\[ \eta_{\text{imp},t} = \left( \frac{\text{Stk}}{4 \cdot K u^2} \right) \left( 29.6 - 28 \cdot \alpha^{0.62} \right) \cdot R^2 - 27.5 \cdot R^{2.8} \]  \hspace{1em} (3)

The second one of empirical equations (Eqs. (4), (5) and (6)).

Diffusion (Wang et al., 2007):

\[ \eta_{\text{dif},e} = 0.84 \cdot \text{Pe}^{-0.43} \]  \hspace{1em} (4)

Interception (Lee and Liu, 1982):

\[ \eta_{\text{int},e} = 0.6 \left( \frac{1 - \alpha}{K u} \right) \left( \frac{R^2}{1 + R} \right) \]  \hspace{1em} (5)

Impaction (Gougeon, 1994):

\[ \eta_{\text{imp},e} = 0.0334 \cdot \text{Stk}^{1.5} \]  \hspace{1em} (6)

The efficiency of each mechanism was then utilised to calculate the resultant efficiency of all the mechanisms (Eq. (7)) and total efficiency of the filter (Eq. (8)). The equations utilised for calculating the parameter values are listed in the appendix section.

Resultant efficiency of all the mechanism (Thomas, 2017):

\[ \eta = 1 - (1 - \eta_{\text{dif}})(1 - \eta_{\text{int}})(1 - \eta_{\text{imp}}) \]  \hspace{1em} (7)

Total filter efficiency (Thomas, 2017):

\[ E = 1 - \exp \left( \frac{4 \cdot \eta \cdot \alpha \cdot Z}{(1 - \alpha) \cdot \pi \cdot d_f} \right) \]  \hspace{1em} (8)

\( \eta_{\text{dif}} \)–diffusion mechanism efficiency, \( \eta_{\text{int}} \)–interception mechanism efficiency, \( \eta_{\text{imp}} \)–inertia mechanism efficiency, \( \eta \)–calculated single fibre efficiency, \( E \)–filter efficiency, \( \alpha \)–packing density, \( Z \)–filter thickness, \( d_f \)–fibre diameter.

For efficiency calculations, there is usually the classical filtration theory (CFT) applied (Brown, 1993; Dorman, 1966). According to this method, the efficiency of the filter is computed by assuming that all the filtration fibres have the same diameter which is set to equivalent fibre diameter. The equivalent fibre diameter may be interpreted as arithmetic or geometric mean (VanOsdell et al., 1990), volume-surface diameter (Podgórska, 2009) or effective Davies diameter (Japuntich et al., 2007; Li et al., 2012; Löffler, 2004). The distribution of fibre diameters can deviate significantly from a standard statistical distributions, this can be seen in Fig. 2. In opposite to this standard method, for cases involving wide fibre size distribution, we propose the concept of effective fibre diameters distribution, which is as follows. Instead of using one single fibre diameter to describe all the fibres in the filter, we use some different values of fibre diameters. In this paper we decided to compare the use of 1, 2, 5, 10, 20, 50, 100 values of diameters. For this purpose, the images were taken with a scanning electron microscope, and the measurements of 100 fibres diameters were performed for each filter. The obtained diameters were then set in ascending order and divided into groups containing mentioned above number of diameters. For each group, the average value representing it was calculated. These average diameters were then utilised for efficiency calculations, and the total efficiency of the filter was determined based on the share
of individual groups. For example, in the case of “20 diameters”, the 100 measured fibres diameter were divided into 20 groups, each containing 5 diameters, then the average value for each of the groups was calculated, filter efficiency for each average diameter and total filter efficiency with a share of each group being 0.05. This procedure is similar to that presented by Frising et al. (2003)—defined there as “parallel approach”. The main difference is that the group of Frising et al. (2003) assumed the log-normal distribution of fibre diameters while the method presented in our work can be successfully applied for any kind of distribution. The exact values of fibre diameter are listed in supplementary data.

In calculations, we implemented the effective density concept. Its aim is to improve the efficiency calculations for solid particles. Especially in the case of soot-like particles, we are dealing with the advanced spatial structure of particles built with smaller particles. This structure affects the effective density of particles and can be a source of calculation errors. The effective density of solid particles was calculated with Eq. (9) (Maricq and Xu, 2004). The primary particle diameter was \( D_{pp} = 5 \) nm, the fractional dimension \( f = 2.3 \), the initial particle density \( \rho_0 = 2090 \) kg m\(^{-3} \) and the particle diameter \( D_p \) as measured by the particle counter. The obtained effective density was then utilised in efficiency calculations.

\[
\rho_e = \rho_0 \left( \frac{D_p}{D_{pp}} \right)^{f-3} \tag{9}
\]

Fig. 4 shows block diagram of the calculation procedure. To simulate the filter being clogged with deposited particles for each time step \( t = 1 \) s, the current total filter efficiency was calculated. For the known aerosol particle size distribution, the number of particles captured by the filter was calculated. The number of particles captured on the filter was then converted to volume based on their density and effective density in the case of solid particles. This volume was then utilised to calculate the new packing density of the filter:

\[
\alpha = \frac{V_f + V_d}{V_t} \tag{10}
\]

and with new packing density, flow velocity:

\[
u = \frac{u_0}{1 - \alpha} \tag{11}\]

and fibre diameters:

\[
d_f = d_p \left( \frac{\alpha}{\alpha_p} \right)^{0.5} \tag{12}\]

In Eqs. (10), (11) and (12) the meaning of the symbols is as follow: \( \alpha \)–packing density, \( \alpha_p \)–clean filter packing density, \( V_f \)–fibres volume, \( V_d \)–deposits volume, \( V_t \)–total clean filter volume, \( u \)–average flow velocity in filter with deposits, \( u_0 \)–average flow velocity in clean filter, \( d_f \)–calculated fibre diameter and \( d_p \)–clean fibre diameter.

The calculations were carried out for 64 minutes of constant filtration, with first 4 being omitted on graphs, to make the comparison with experimental measurements easier (due to instability in initial readings provided by particle counter). In the case of more than one diameter utilised for efficiency calculations, each diameter changes proportionally. We did not introduce new fibres built with solid particles as a concept to describe filter loading because of limitations of theoretical equations and the presence of liquid particles in the case of mixture aerosols.

The calculations of average particle size in aerosol upstream and downstream of the filter were based on aerosol particle size distribution. The average size was calculated as weighted arithmetic mean with a share of individual size fraction as weights. The change in average particle size over...
time, with a constant and unchanging aerosol particle size distribution upstream of the filter, was due to a change in filter efficiency due to aerosol particle interaction and deposition on the filter.

3 RESULTS

3.1 Number of Diameters and Accuracy for Initial Particle Size

Fig. 5(a) shows the results of filtration efficiency calculations for various aerosols for filter F8. It is representative of the results obtained for all the other filters. The increased number of diameters utilised in efficiency calculations results in increased efficiency for all considered cases. The change is rapid for the first four cases (1, 2, 5, 10 diameters) and stabilises for ten diameters and more. The relative difference between efficiency for a given number of diameters and reference, which is the result for 100 diameters, falls below 0.1% for the number of diameters
Fig. 5. Efficiency calculated with set of theoretical equations for (a) various aerosols and various number of diameters for F8 filter and (b) the initial average particle size for F8 filter for various aerosols.

For that reason, all further calculations are being carried out with 20 diameters being used to calculate filter efficiency. For exact values for each efficiency data point and difference between them, please refer to supplementary data.

Fig. 5(b) shows comparison between measured and calculated initial average particle size downstream from the filter and initial average particle size upstream from the filter (by initial size we mean size after first four minutes). Results for both theoretical and empirical models agree well with measurements. The average particle size downstream does not differ substantially from the upstream. The difference between measured upstream and downstream values for soot_h aerosol can be explained by the presence of the filter and the mentioned understanding of the initial value as that 4 min after the start of filtration. Filter clogging with soot particles leads to increased filtration efficiency for large particles due to formation of secondary fibres made out of soot particles. At the same time in case of mixture aerosols the presence of oil prevents such effect from occurring.

3.2 Aerosol Deposition over Time

Figs. 6 and 7 shows that the measured change in average particle size downstream from filters is much higher than the calculated one for the theoretical set of equations (Figs. 8(a), 9(a), 10(a)) and empirical set of equations (Figs. 8(b), 9(b), 10(b)). Note the same range on the graphs for measured values and a variable range for calculated values.

Fig. 6. Measured change in average particle size downstream from 2F6 filter as a fraction of initial size downstream.
In the case of measured values (Figs. 6 and 7), significant changes for soot_h aerosol are observed for F6 and 2F6 filters. Moreover, for the 2F6 filter, significant changes occurred for all mixture aerosols. For both F6 and 2F6, the decrease in average particle size downstream for soot_h aerosol reached 90% of the initial value. Based on the curve for the F6 filter, it can be concluded that a similar plateau on the curve will occur as for the 2F6 filter.

The presence of only soot particles and their deposition on fibres leads to the formation of secondary fibres made out of soot particles. The contribution of these secondary fibres to the total filter efficiency increases with time. This structure can grow above the surface of the filter and be responsible for the majority of filtration efficiency (Thomas et al., 2019). It results in stabilisation of packing density, flow velocity and fibres diameter in the zone where the majority of deposition happens.

In the case of theoretical equations (Figs. 8(a), 9(a), 10(a)), for F6 and F8 filters, the decrease in average size occurs for all aerosols containing oil, for 2F6 filter only for aerosols: soot_h, soot_l, soot_h + oil_l, soot_l + oil_l (Table 2; aerosols influenced by the presence of oil in a limited way).

In the case of empirical equations (Figs. 8(b), 9(b), 10(b)) for 2F6 and F8 filters, the increase in average size occurs for all tested aerosols, for F6 filter only for aerosols influenced by the presence of oil in a limited way.

The measured values for the 2F6 filter for mixture aerosols the initial decrease followed by an increase in average particle size downstream from the filter can be observed. The average particle size downstream from (a) F6 filter and (b) F8 filter as a fraction of initial size downstream.

**Fig. 7.** Measured change in average particle size downstream from (a) F6 filter and (b) F8 filter as a fraction of initial size downstream.

**Fig. 8.** (a) Calculated theoretical and (b) empirical change in average particle size downstream from 2F6 filter as a fraction of initial size downstream.
size decrease over time, downstream from the filter, can be explained by increased filtration efficiency for large oil particles and lowered efficiency for small soot particles. Such a change is the result of particle deposition in the surface filter layer, leading to an increase in packing density and flow velocity. The following increase in average particle size can be explained by the surface layer being filled with liquid deposits, a state of dynamic equilibrium is reached, the oil is transported deep inside the filter structure. At that point, the flow velocity does not change significantly, while the increase in packing density and fibre diameter still occurs, leading to increased filtration efficiency for small particles.

4 CONCLUSIONS

The calculations of the effect of the number of fibre diameters on total filter efficiency showed that in all examined cases, there is a significant effect for all utilised filters and aerosols. The increase in the number of diameters leads to increased calculated efficiency, and the use of twenty diameters is sufficient to reach satisfactory accuracy.

These conclusions are in line with the discussion that has existed for some time in the scientific literature, whether and to what extent it is possible to calculate the filtration efficiency based on the average value of the diameter of the fibres. In most cases and computation, it is a typical default assumption. Already Kirsch and Stechkina (1973) analysed the efficiency of filtration of
small particles numerically at the filter with fibres with nonequal diameters. To simplify the calculations, they considered the diffusion mechanism of a deposition only (as it is dominant for particles smaller than a few hundred nanometers in diameter). They concluded that the particle deposition efficiency and pressure drop could be calculated from the mean fibre diameter even when the diameters differ several times. This result then was subjected to criticism by other authors. For example, Steffens and Coury (2007)—who also considered the filtration of solid nanoparticles but not limited themselves to the diffusion mechanism—noted that the heterogeneities in the filter structure (the differences in fibres diameters) have a strong effect on the filter performance. Also, Frising et al. (2003) noted the influence of fibre diameter distribution on filtration efficiency. By comparing with experimental results, they observed that the real penetration of the filter as well as the penetration obtained while taking into account the fibre diameter distribution is less than that computed by assuming one fibre diameter value. That means taking into consideration the distribution of fibre diameter leads to the higher value of filtration efficiency (while the relationship between efficiency and penetration is \( E = 1 - P \))—what is consistent with our results. The influence of fibre diameter distribution on filtration efficiency has also been considered by Podgórski et al. (2011).

All the above-mentioned works did not deal with the mixture solid-liquid aerosols. They also did not consider the dynamics of efficiency in time. We have shown that it is possible to include polydispersity of the fibres into the consideration on mixture aerosol filtration. The results of such calculations are in good agreement with experimental measurements result for the initial moment of the filtration process. However, the simulation results do not agree with measurements in case of filter clogging with particles.

The single fibre efficiency model for predicting filter efficiency is not a sufficient way to describe the behaviour of filters utilised for mixture aerosol filtration, even if the mathematical description takes into account the effect of the volume of deposits on flow velocity, packing density and multiple fibre diameters. Further improvements to the model are required.

The difference between measured and calculated changes for both theoretical and empirical sets of equations can be explained by changes in the internal structure of the filter due to the deposition of particles.

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**APPENDIX A**

Parameter utilised in efficiency calculations were obtained with following equations (Thomas, 2017):

\[
R = \frac{d_p}{d_f} \tag{A1}
\]

\[
Ku = \frac{4 \cdot \alpha - \alpha^2 - 3}{4} - \frac{\ln(\alpha)}{2} \tag{A2}
\]

\[
Pe = \frac{u \cdot d_f}{D} \tag{A3}
\]
\[ D = \frac{K_u \cdot T \cdot C}{3 \cdot \pi \cdot \mu \cdot d_p} \quad (A4) \]

\[ Kn = \frac{2 \cdot \lambda}{d_f} \quad (A5) \]

\[ Stk = \frac{\rho_e \cdot u \cdot d_p^2 \cdot C}{18 \cdot \mu \cdot d_f} \quad (A6) \]

Cunningham correction factor (Allen and Raabe, 1985):

\[ C = 1 + Kn \left( 1.142 + 0.558 \cdot \exp \left( -\frac{0.999}{Kn} \right) \right) \quad (A7) \]

\( R \)–interception parameter, \( d_p \)–particle diameter, \( d_f \)–fibre diameter, \( K_u \)–hydrodynamic factor of Kuwabara flow, \( \alpha \)–packing density, \( Pe \)–Peclet number, \( u \)–average flow velocity in filter, \( D \)–diffusion coefficient, \( k_B \)–Boltzmann constant, \( T \)–temperature, \( C \)–Cunningham slip correction factor, \( \mu \)–fluid viscosity, \( Kn \)–Knudsen number, \( \lambda \)–mean free path, \( Stk \)–Stokes number, \( \rho_e \)–effective particle density.

**SUPPLEMENTARY MATERIAL**

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220039

**REFERENCES**


