Investigation of Balance of Filtration Mechanisms during the Air Filtration Process to the Fibrous Filters Media

Giorgos P. Kouropoulos

Department of Energy Technology, Technological Educational Institute of Athens, Greece

*Corresponding Author: Email: etmecheng@gmail.com

Abstract

Purpose of the specific study is an investigation of balance of filtration mechanisms during the air filtration process in a fiber filter medium. During the air filtration process three or four filtration mechanisms take place and acting simultaneously, each one of them contribute to the total particles collection efficiency of the filter medium. Initially, the mathematical models of filtration mechanisms will be reported, also the definitions of efficiency and penetration of a filter will be described. Furthermore, the equations that determine the participation rate during filtration for every mechanism, as well as the curves which present the change of participation rate with regard to the particle diameter and total penetration, will be extracted after the case study. The conclusion that arises is that every filtration mechanism has its own participation rate. The fluctuations of the mechanisms are different.

Keywords: Fibrous filter, Filtration, Filtration balance, Filtration mechanism.

Introduction

The filtration mechanisms as well as the way that effect in the aerosol particles are studied by scientists. According to bibliography there are three basic air filtration mechanisms, diffusion mechanism, interception and inertial impaction mechanism. There is still one, the electrostatic charge mechanism. These mechanisms acting simultaneously during filtration process and their contribution shape the total particle collection efficiency or penetration of the filter. The participation rate of every mechanism as a percentage of total filtration process is defined as balance of filtration mechanism.

The electrostatic charge mechanism does not take place in all kinds of filter media. It mainly happens in the air filtration by synthetic materials such as bag filters, fabric filters or paper filters. The mathematical mode of electrostatic charge mechanism has been studied from scientists [1] [2]. In the specific study are examined only with diffusion, interception and inertial impaction filtration mechanisms. According to Lee and Liu, the diffusion mechanism has the larger balance than other two mechanisms. Also, interception with diffusion mechanism has almost same participation rate with inertial impaction and interception mechanism in the air filtration process [3] [4].

The efficiency E of a filter medium is the ability of medium to retain solid microparticles. The filtration efficiency is calculated by inlet and outlet mass flow rate fraction, \( m_o \) is outlet mass of microparticles and \( m_i \) the inlet mass of microparticles that are passed through the filter medium.

\[
E = \left(1 - \frac{m_o}{m_i}\right) \times 100\% \quad (1)
\]

The penetration P of a filter medium is calculated by:

\[
P = 1 - E = \frac{m_o}{m_i} \times 100\% \quad (2)
\]

When the filtration efficiency is 100%, that is, filter retains all solid microparticles that
are passed through the filter medium, the penetration is 0% that means no particle cannot pass the specific filter medium. The efficiency is the difficulty of the particles to pass through the medium and penetration is precisely the opposite of filtration efficiency.

Mathematical Models of Filtration Mechanisms

The efficiency of filter element is analyzed as a function with lots of parameters and physical quantities. Also, there are the available mathematical models that govern the filtration mechanisms and correlate efficiency/penetration as a function of physical quantities of filtered fluid and retained microparticles within the filter [2] [5] [6]. The general equation that calculates the penetration of the filter in relation to the diameter of particles that has been collected by filter medium is given by (3):

\[
P = \exp\left(- \frac{4L \alpha_r \sum n}{\pi d_f}ight)
\]

Where:
- \(L\): The length of filter element (mm).
- \(d_f\): The fiber diameter of filter element (mm).
- \(\alpha_r\): The ratio of fiber volume \(V_f\) to total volume \(V_F\) of filter medium.
- \(\sum n\): Sum of coefficients of diffusion interception and inertial impaction mechanisms.

The sum of coefficient of three filtration mechanisms is equal to:

\[
\sum n_{SUM} = n_D + n_R + n_I = \sum_{i=3} n
\]

Where:
- \(n_D\): Dimensionless coefficient of diffusion mechanism.
- \(n_R\): Dimensionless coefficient of interception mechanism.
- \(n_I\): Dimensionless coefficient of inertial impaction mechanism.

The dimensionless coefficient of diffusion mechanism \(n_D\) [5] is equal to:

\[
n_D = 1.61 \left(1 - \frac{\alpha_r}{Ku}\right)^{\frac{1}{3}} \frac{1}{P_e} \frac{2}{3}
\]

Where:
- \(P_e\): The dimensionless Peclet number.
- \(Ku\): The Kuwabara hydrodynamic factor, dimensionless.

Kuwabara hydrodynamic factor is equal to:

\[
Ku = \frac{4a_r - a_r^2 - 3}{4} - \frac{lna_r}{2}
\]

The Peclet number is equal to:

\[
P_e = \frac{3 \times 10^{-12} \pi \mu d_f d_r}{kT} \left[1 + \left(\frac{0.067}{d_r}\right)^2 (2.492 + 0.84 \exp(-6.49d_r))\right]
\]

Where:
- \(u\): The flow velocity of passed fluid within the filter element (m/sec).
- \(\mu\): The absolute viscosity of air (Kg/mXsec).
- \(k\): Boltzmann constant (1.3708 × 10^{-23} J/ºK).
- \(T\): The absolute temperature of air (ºK).

The dimensionless coefficient of interception mechanism \(n_R\) [2] [5], is equal to:

\[
n_R = \frac{(1 - \alpha_r)N_R^2}{Ku(1 + N_R)}
\]

Where:
- \(N_R\): Dimensionless factor. Is the ratio of particles diameter \(\mu m\) to the average fiber diameter of fiber filter medium \(\mu m\).

The dimensionless coefficient of inertial impaction mechanism \(n_I\) [2] [6], is equal to:

\[
n_I = \frac{Stk \times J}{2Ku^2}
\]

Where:
- \(Stk\): The dimensionless Stokes number.
- \(J\): Dimensionless coefficient that is depended by \(N_R\) factor.

The dimensionless coefficient \(J\) is calculated according to the equations below:

\[
J = (29.6 - 28a_r^{0.62})N_R^2 - 27.5N_R^{2.5}
\]

\[
J = 2 \quad \text{if} \quad N_R < 0.4
\]

\[
J = 2 \quad \text{if} \quad N_R > 0.4
\]

The Stokes number is equal to:

\[
Stk = \frac{\rho d_r^2 u C_D}{18 \mu d_f}
\]

With \(C_D\) the dimensionless drag factor which is selected and calculated as a function of the Reynolds number for air flow through the filter [7].
To summarize, the combination of equations (3), (4), (5), (8), (9), gives the final equation which calculates the penetration of the filter during air filtration process as a function of diameter \( d_p \) of retained microparticles. So we are able to extract the characteristic curve of a filter, that is, the function of efficiency or penetration in relation to the particle diameter.

\[
P_d = \exp \left[ \frac{4 \alpha_0 \eta_p}{ \pi d_f \sum_{n=1}^{n} \eta_n \left( \frac{n}{n_0 + n + n_j} \right) \right]
\]

(16)

**Extracting Model Equations of Balance of Filtration Mechanisms**

\( P_D \) is defined as the percentage rate or balance of diffusion mechanism. \( P_D \) is equal to:

\[
P_D = \exp \left( \frac{4 \alpha_0 \eta_p}{ \pi d_f \sum_{n=1}^{n} \eta_n \left( \frac{n}{n_0 + n + n_j} \right) \right) \]

(17)

\( P_R \) is defined as the percentage rate or balance of interception mechanism. \( P_R \) is equal to:

\[
P_R = \exp \left( \frac{4 \alpha_0 \eta_p}{ \pi d_f \sum_{n=1}^{n} \eta_n \left( \frac{n}{n_0 + n + n_j} \right) \right) \]

(18)

\( P_i \) is defined as the percentage rate or balance of inertial impaction mechanism. \( P_i \) is equal to:

\[
P_i = \exp \left( \frac{4 \alpha_0 \eta_p}{ \pi d_f \sum_{n=1}^{n} \eta_n \left( \frac{n}{n_0 + n + n_j} \right) \right) \]

(19)

The total penetration may be extracted as a function of balance of every filtration mechanism. I.e., in equation (17) for diffusion mechanism, if we try to solve as total penetration then we will have the following expressions:

\[
P_d \quad 0 < Re < 0.1 (13)
\]

\[
C_D = \left( \frac{24}{Re} + 0.5407 \right)^2 \quad 0 < Re < 6000 (14)
\]

\[
C_D = 0.44 \quad 500 < Re < 100000 (15)
\]
We apply equations (17) (18) and (19) for participation rate of each filtration mechanism. The results are presented in Fig. 2.

Table 3: The values of participation rate for every filtration mechanism in relation to the total penetration and efficiency of the filter during air filtration.

<table>
<thead>
<tr>
<th>Particle diameter (μm)</th>
<th>Total penetration P (%)</th>
<th>Total efficiency E (%)</th>
<th>Diffusion balance $P_D$ (%)</th>
<th>Interception balance $P_R$ (%)</th>
<th>Inertial imp. balance $P_I$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>0.25</td>
<td>70</td>
<td>30</td>
<td>0</td>
<td>40</td>
<td>64</td>
</tr>
<tr>
<td>0.5</td>
<td>40</td>
<td>60</td>
<td>8</td>
<td>0</td>
<td>58</td>
</tr>
<tr>
<td>1.0</td>
<td>5</td>
<td>95</td>
<td>61</td>
<td>0</td>
<td>52</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>98.5</td>
<td>84</td>
<td>0</td>
<td>47</td>
</tr>
<tr>
<td>2.0</td>
<td>1</td>
<td>99</td>
<td>91</td>
<td>0</td>
<td>44</td>
</tr>
<tr>
<td>2.5</td>
<td>1</td>
<td>99</td>
<td>95</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>3.0</td>
<td>1</td>
<td>99</td>
<td>96</td>
<td>0</td>
<td>37</td>
</tr>
<tr>
<td>3.5</td>
<td>1</td>
<td>0.99</td>
<td>97</td>
<td>0</td>
<td>34</td>
</tr>
<tr>
<td>4.0</td>
<td>1</td>
<td>99</td>
<td>98</td>
<td>0</td>
<td>31</td>
</tr>
<tr>
<td>4.5</td>
<td>0.5</td>
<td>99.5</td>
<td>98.5</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>5.0</td>
<td>0.5</td>
<td>99.5</td>
<td>99</td>
<td>0</td>
<td>26</td>
</tr>
</tbody>
</table>

The values of Table 3 were selected by curves of Fig. 1 and Fig. 2. The values will be imported in the software so that the change curves of balance of filtration mechanisms in relation to the total filtration efficiency and penetration will be exported. With applying of equation (20) and values from Table 3 will have the following curves.

Fig. 3: The change of the balance of diffusion interception and inertial impaction with regard to the total penetration of the filter.

Fig. 4: The change of the balance of diffusion interception and inertial impaction with regard to the total filtration efficiency of the filter.

Conclusions

Every filtration mechanism has its own contribution as well as participation with different percentage rate and balance during the air filtration process. From Fig. 2 we conclude that the diffusion and inertial impaction mechanisms have the larger participation rate of air filtration process. It follows the interception mechanism which has lower participation rate that the other mechanisms in relation to the particles diameter. These conclusions are confirmed by Lee and Liu [3].

The mathematical model in equation (20) is confirmed by Fig. 3 and Fig. 4 which were exported by regression analysis. Eq. (20) explains the change of balance of filtration...
mechanisms with regard to the total penetration or filtration efficiency during the air filtration process.

References


