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Lessons learnt over 30 years of air filtration in the nuclear industry

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Abstract. The more than 30 years since the inception of the High Efficiency Particulate Air filters (HEPA) provide an incredible story. The filter’s application to nuclear air cleaning and reciprocal effect on nuclear programme upon its development is even more interesting. The HEPA filter provided the capacity needed to intercept extremely small particulate matter in the airstreams of nuclear plants and laboratories. When some of the particulate matter potentially might be plutonium or other alpha radiation bearing particles in the air exhausted to the environment, the critical importance of the filter becomes obvious. From a crude and weak initial concept, the HEPA filter has developed into the backbone of particulate air cleaning for nuclear ends and has become most essential to environmental cleaning for other industrial pursuits as well.

In the nuclear industry, High Efficiency Particulate Air filters (HEPA) were the need for the containment of radioactive aerosols within the nuclear facilities. Air filtration theory has been very important in the development of HEPA filters. The early air filtration theories model air filters as the air flow around single fibres and the particle capture by these single fibres. The single fibre theories included the interference effect of neighbouring fibres by using cell flow models. Equations were derived to describe particle capture efficiency as function of system variables (air flow temperature and pressure), particle variables (size, density…) and filter characteristics (fibre diameter, fibre volume fraction, filter thickness…).

1. Mechanisms of filtration

In the viscous flow conditions which obtain in HEPA filters, the major mechanisms are considered to be diffusion, interception and inertia. The flow lines around the fibre are deflected and the three main collection mechanisms can be described as follows. A massive particle approaching the fibre deviates from the flow lines because of its inertia, the deviation being greater the more massive the particle and the higher the velocity. The particle centre needs only approach to a distance equal the particle radius from the fibre for interception capture to take place. This is more important for larger particles and does not depend on air velocity. Smaller particles are subject to molecular bombardment and diffuse across the flow lines increasing the likelihood of capture. The smaller the particle size and the lower the gas velocity, the greater is the importance of the diffusion.

The penetration of a fibre filter according to the different parameters which govern the particle filtration can be calculated with the following equation (Dorman, 1964):
where \( e \) is the filter thickness, \( d_f \), the fibre diameter, \( \alpha \) the packing density and \( \eta_f \) the single fibre efficiency.

The single fibre efficiency is generally taken equal as the sum of each elementary mechanism of particle collection on a fibre:

\[
\eta_f = \sum J f f
\]

where \( J \) is the elementary collection mechanism.

In the case of the fibre filter, the elementary collection efficiency of a single fibre can be written as:

\[
\eta_f = \eta_{f_{df}} + \eta_{f_{int}} + \eta_{f_{inc}}
\]

- \( \eta_{f_{df}} \) : elementary collection efficiency by diffusion,
- \( \eta_{f_{int}} \) : elementary collection efficiency by interception,
- \( \eta_{f_{inc}} \) : elementary collection efficiency by inertia.

2. Collection efficiency

2.1. Elementary collection efficiency by diffusion

As shown on the Figure 1, the particle capture efficiency is due to Brownian motion of the particles which have a probability to reach a fibre and to stick at the surface.

The particle collection by diffusion is governed by a characteristic number which is the Peclet number (\( Pe \)). The Peclet number is given by the following equation:

\[
P_e = \frac{d_f U}{D_l},
\]

where \( U \) is the flow velocity far away of the fibre and \( D_l \), the coefficient of diffusion for the particle.

The coefficient of diffusion for a spherical particle is given by:

\[
D_l = \frac{kT Cu}{\pi \mu d_p},
\]

where \( k \) is the Boltzmann’s constant, \( \mu \) the gas dynamic viscosity, \( d_p \) the particle diameter and \( Cu \) the Cunningham slip factor.

The elementary particle collection efficiency by diffusion can be written (Stechkina and Fuchs, 1966) as:
This relation shows that if the flow velocity or the particle diameter increases the elementary collection efficiency is decreasing.

2.2. Elementary collection efficiency by interception
As shown on the Figure 2, the particle collection by interception is a purely geometrical phenomenon. The particles, which follow trajectories such as they flow nearby the fibre, will be intercepted and collected by the fibre.

\[
\eta_{f,\text{int}} = \left( \frac{1 - \alpha}{\frac{1}{2} \ln \alpha - 0.75 + \alpha - \frac{\alpha^2}{4}} \right)^{1/3} \rho e^{-2/3}.
\]

This relation shows that the particle collection by interception is independent of the flow velocity and the efficiency is increasing when the particle diameter is bigger.

2.3. Elementary collection efficiency by inertia
As shown on the Figure 3, the particle collection by inertia is due to the fact that the particles, according to their mass and velocity, will be able to follow or not the streamlines around the fibre. When the particle inertia will be too high, the particles will impact the fibre.

\[
\eta_{f,\text{int}} = \left( \frac{1 - \alpha}{\frac{1}{2} \ln \alpha - 0.75 + \alpha - \frac{\alpha^2}{4}} \right) \frac{R^2}{1 + R}.
\]

This relation shows that the particle collection by interception is independent of the flow velocity and the efficiency is increasing when the particle diameter is bigger.
where \( \rho_p \) is the particle density.

The elementary particle collection efficiency by inertia can be written (Davies, 1973) as:

\[
\eta_{\text{int}} = \frac{\eta}{4 \left( \frac{1}{2} \ln \alpha - 0.75 + \alpha - \frac{\alpha^2}{4} \right)^2}
\]

This relation shows that if the flow velocity or the particle diameter increases, the elementary collection efficiency is increasing.

2.4. Total collection efficiency

As it is mentioned in the equation giving the filter penetration, the total collection efficiency of a fibre results from the sum of each elementary collection efficiency. So, according the evolution of the different mechanisms with the particle diameter, the penetration of a fibre filter corresponding to the ratio between downstream and upstream concentrations, reaches a maximum as it is shown on the Figure 4.

3. Experimental results

It is well established that at constant velocity, the penetration of particles larger than 300 nm decreases as particle size increases, while theories predict that particles much smaller penetrates less easily due to diffusion collection. Much effort has been expended on testing of the theories and on attempts to find the most penetrating particle size (MPPS). Examples of experimental results are given on figure 5 (decontamination factor is defined as the inverse of the penetration). For HEPA filters the MPPS is important, a test at the MPPS would guarantee a minimum efficiency for any unknown particle size challenge. So, the HEPA filters are tested with particles between 30 nm and 300 nm.
4. Conclusion
In the frame of the development of HEPA filters a large effort has been put on the air filtration theory. It continues to be important, mainly due to the availability of CFD codes, for improving the performance of HEPA filters because of the large time and cost savings from reducing the number of tests required to optimize the filter and media design parameters.

The lessons learnt in the frame of the development of HEPA filters show that the particle collection efficiency reaches a minimum for particle diameter around 100-300 nm and demonstrate that there is no problem to filter nanoparticles which size is over 40 nm. So, efforts would be emphasized to demonstrate that the filtration theories would be extended to particle sizes of few nanometres.

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