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Performance Evaluation of High Efficiency Particulate Filters for the Removal of Sub-Micrometer Radioactive Aerosols in Nuclear Power Reactors. Simulation Study

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***Abstract*:** The removal of radioactive aerosols has always been one of the key issues of air decontamination in a nuclear power plant to reduce both the exposure of the radiation workers inside the NPP and environmental radiation impact. Radioactive aerosols may be removed using nuclear grade High Efficiency Particulate Air filters. The thickness of the particulate filter is function of many parameters like the particle size, the fiber diameter, the face velocity and the ratio volume of fiber/volume of filter. In this work we evaluated, by using a semi empirical model, the effect of different parameters (fiber diameter, particle size, face velocity) on the performance of the HEPA filters to reach an efficiency removal above 99.99%. The results suggest that thin layers of fiber, can work as an efficient and cost-effective filter. This study revealed that the thickness of the filter showed a positive correlation with the face velocity, but negative correlation with fiber diameter and particle diameter. It is also found that the efficiency removal is higher for lower particle velocities in air stream.

***Keywords*:** HEPA filter; Particle filtration efficiency; Particle size; Fiber diameter; Filter thickness

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1. Introduction

Nuclear power plants (NPPs) are designed, constructed, commissioned, operated and later decommissioned under rigorous nuclear safety standards to prevent any potential radiological risks to radiation workers, public and environment. Among these latter are fission and activation products induced in the cooling medium, which in normal operations, are barred from escaping to the NPPs buildings thanks to the concept of defense in depth by the combination of several layers of systems and measures (zirconium alloy tubes enclosing the fuel pellets, positive pressure inside the reactor buildings and the reactor concrete containment). However, they may appear outside the closed system and contaminate the air inside and outside the NPPs buildings by adsorbing on aerosols and dust particles present during the normal operation or decommissioning of NPP's [1]. Table 1 depicts a list of some radionuclides which are typically produced as airborne effluents inside NPPs [2].

Table 1: Main radionuclides, with their respective half-lives and decay modes, which are typically released as airborne effluents from NPPs.

Category	Commonly reported radionuclides
Fission products	^{131}I ($t_{1/2}$=8.05 d, β^- γ), ^{135}Xe ($t_{1/2}$=9.14 h, β^-) ^{140}Ba ($t_{1/2}$=12.8 d, β^- γ), ^{137}Cs ($t_{1/2}$=30.2 y, β^- γ)
Activation products	^{60}Co ($t_{1/2}$=5.2 y, β^-), ^{51}Cr ($t_{1/2}$=27.7 d, EC) ^{26}Al ($t_{1/2}$=7.1 x 10^5 y, β^+), ^{35}S ($t_{1/2}$=87 d, β^-)
Decommissioning products	^{3}H ($t_{1/2}$=12.3 y, β^-), ^{14}C ($t_{1/2}$=5730 y, β^-) ^{55}Fe ($t_{1/2}$=2.7 y, EC), ^{66}Cu ($t_{1/2}$=5.12 m, β^- γ)

m: minute, d: day, h: hour, y: year.
EC: electron conversion, γ: emission of gamma photon, β^+:emission of positron, β^-: emission of electron.

1.1. Air filtration for healthy and sustainable NPP

The dispersion of radioactive aerosols in the workplace and the environment is the major contributor to the internal dose when inhaled by workers and public respectively. The deposition of radioactive aerosols in the human's respiratory track is a function of particle size [3, 4]. Particles smaller than 0.1 µm in diameter are deposited on the surfaces of lungs [5, 6], whereas particles in the range 0.1 -10 µm in diameter are deposited in the various compartments of respiratory tract depending on the size of the particles [1]. The release of airborne radioactive effluents from the operation of a NPP should be kept "as low as reasonably achievable" (ALARA principle) to maintain the internal dose to workers within the limits set by the International Commission on Radiological Protection (ICRP) in its publication 103 [7].

1.2.HEPA filters

Ventilation air from different units of a NPP is usually filtered, to remove particulate material, in a single section outside the containment prior to stack discharge. This sort of system usually involves a significant number of filters to adapt the high-volume of air to be filtered. uropean Classification categorizes particle filters into three types: course, fine and HEPA. This latter (made of randomly arranged dense structure of micro-fiberglass, of diameters between 0.1 to 3.0 μm) could achieve an efficiency of 99.97% for particles ≧ 0.3 μm in diameter such as dust, bacterial, fungal, and other micro-organisms [8, 9]. HEPA filters can resist to an intense heat with temperature up to 500°C [10]. They are waterproof and have a good efficacy of trapping dust in high humidity environments. Besides all these important properties, they are chemically inert to most chemicals and corrosive liquids. This makes them widely used in nuclear power plants to remove radioactive aerosols from their effluent exhaust streams [11].

However, HEPA filters have some drawbacks which frequently limit them from copping with several of the filtration difficulties in the nuclear power industry; they cannot block other pollutants such as gases and odors [12]. HEPA filters are mounted inside the air ducts in the ventilation and air cleanup systems and typically last three to five years. After filtration and monitoring air is released, into the environment via stacks. The key aspect of air filtration in NPP, is a balance of the following [13]:

- Air flow to assure adequate ventilation
- Efficiency to block a large size range of radioactive aerosols,
- Ability to allow for acceptable cost-effective maintenance programs without negatively impacting airflow and efficiency.

The physics behind trapping aerosols by fibrous HEPA may be divided in three main mechanisms: interception, Brownian diffusion and impaction (Figure 1):

- In the interception process, an airborne particle coming within one particle radius of a fiber is trapped by the fiber. Particles that are beyond than one particle diameter will not be trapped by this process. This process is dominant in the range 0.1-1μm.
- In Brownian diffusion (dominant for particles ≤ 0.1μm), the particles carried away by the gas stream will collide with gas molecules creating a random motion through the media. This random motion increases the probability of the particle being in contact with a fiber.
- The impaction process (dominant in the range 0.5-5μm) occurs when large particles make head on collisions with filter fibers and are captured.

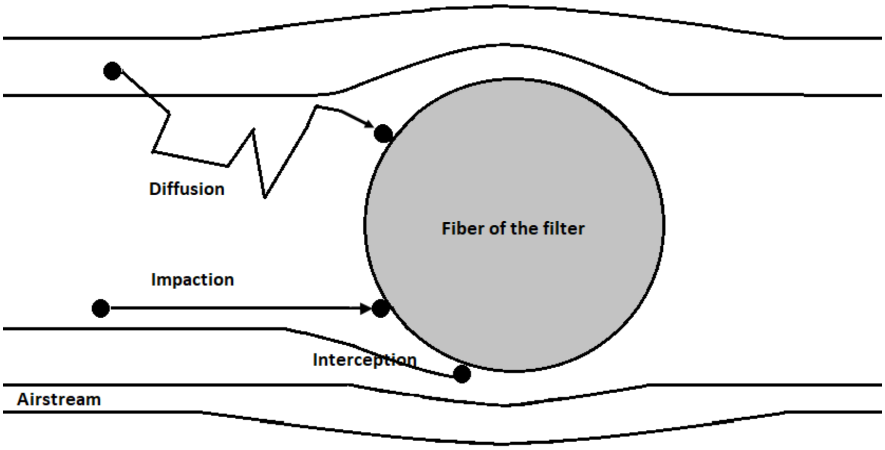

Fig. 1: Brownian diffusion, impaction and interception mechanisms in the air filtration

These three mechanisms or one or some of them will take place during the particle filtration depending significantly on parameters such as the particle size, density, fiber thickness, packing density (the ratio of the fiber volume over the total volume) and air velocity.

The Lawrence Livermore National Laboratory (LLNL) required that HEPA filters must be replaced whenever the efficiency becomes less than 99.97% or 10 years after the date of manufacturing but stated that any filter that becomes wet must be replaced promptly [14]. Their replacement is based on the actual operational requirements such as obstruction by aerosols and dust, mechanical degradation due to aging. These alterations eventually result in the failure of the reliability and efficiency of the HEPA filters. These filters must be monitored at regular intervals as a fundamental part of the safety protocol of the NPP promptly replaced when damaged [15]. Acidic or alkaline aerosols as well as high temperature can reduce their lifetime [16]

To the best of our knowledge, no study has been done for a removal efficiency of 99.99%. The objective of this work is to evaluate the optimal thickness of a HEPA filter to retain 99.99% of radioactive aerosols (this means that for every 10,000 particles, 1 will pass through the filter, and the rest will be trapped). We will use a currently available semi empirical model based on the theoretical aspects of air filtration considering the following parameters: diameter of the fiber, packing density of the filter and particle size.

2. Materials and Methods

2.1.Materials

To generate optimum thickness of the HEPA filter, calculations were performed using a designed program based on MATLAB software (The MathWorks, Inc., Natick, MA, USA)

The mechanisms of radioactive aerosol fixation and buildup on fiber filters are generally empirical and depend on numerous parameters affecting the contact of particles with a fiber.

The small particles (especially those below 0.1 µm in diameter) stick to a fiber through the Brownian diffusion as the main capture mechanism [17]. The inertial impact is the main capture mechanism for large particles [17].

2.2.Theoretical backgrounds for air filtration

Filtration performance of HEPA air filters can be described by two related parameters, the penetration coefficient and the efficiency. The relationship between the particle concentrations before and after the filter (N_0 and N respectively) is called the penetration coefficient K:

$$K = \frac{N}{N_0} = e^{-2aL\eta} \qquad (1)$$

In addition, $1 - K$ is called the efficiency of the filter. N is the downstream particle concentration (particles/m^3), N_0 is the upstream particle concentration (particles/m^3), a is the radius of the fiber (mm), η is the capture coefficient (dimensionless) which characterize the process of particle deposition on fibers

L is the total length of the fiber per unit area $\left(L = \frac{\alpha H}{\pi a^2}\right)$ (mm^{-1}), α is the dimensionless packing density i.e. the ratio of the fiber volume over the total volume of the filter $\left(\frac{V_{fiber}}{V_{filter}}\right)$, and H is filter thickness (mm).

Inserting the expression of L into Eq. 1, we get

$$K = \frac{N}{N_0} = e^{-2\frac{\alpha H}{\pi a}\eta} \qquad (2)$$

It is noticed that as thickness H increases, the penetration coefficient decreases exponentially. Usually, the ratio of the fiber volume over the total volume of the filter varies between 5 to 70 % [19]. As stated by Stechkina et al., [17] and Lee and Liu, [20], it can be assumed that particle impaction can be neglected due to the low gas velocity and the small particle size. Therefore, the two major filtration mechanisms are Brownian diffusion and interception (see Figure 1), the efficiency of the HEPA filter is the sum of two components [20]:

$$\eta_{total} = \eta_d + \eta_i \qquad (3)$$

η_d is the trapping coefficient of the particles by diffusion

η_i is the trapping coefficient of the particles by interception

η_{total} is the total trapping coefficient of the fiber filter.

The efficiency η_d is given by the following equation [21]:

$$\eta_d = 1.6\left(\frac{1-\alpha}{k_u}\right)^{\frac{1}{3}} (Pe)^{\frac{-2}{3}} \qquad (4)$$

k_u is the dimensionless Kuwabara hydrodynamic factor and is given by the relationship [10]

$$k_u = -\frac{1}{2}\ln\alpha - \frac{3}{4} + \alpha - \frac{\alpha^2}{4} \qquad (5)$$

Pe is the Peclet dimensionless number (ratio of convectional transport to diffusive transport) and is given by the following relationship [22]

$$Pe = \frac{uD_f}{D} \qquad (6)$$

u is the face velocity (defined as the airflow velocity passing the cross section of air filter) in the range 5 - 100 cm/s [23]

D_f is the fiber diameter (mm)

D is the particle diffusion coefficient and can be determined from the Stokes-Einstein relationship [21]:

$$D = \frac{k_B\, T\, C}{3\pi\mu D_p} \text{ (mm}^2\text{.sec}^{-1}\text{)} \qquad (7)$$

k_B	is the Boltzmann constant for ideal gas (1.38 x 10^{-23} J.s)
T	is the absolute ambient temperature in Kelvin (^{0}K)
μ	is the dynamic air viscosity at ambient temperature and pressure (Pa.sec)
D_p	is the particle diameter (mm)
C	is the Cunningham correction factor (for small particle sizes where Brownian diffusion is prevalent), and is given by the following relationship [24]

$$C = 1 + 2a\frac{\lambda}{D_p} + 2b\frac{\lambda}{D_p}\exp\left(-c\frac{D_p}{\lambda}\right) \quad (8)$$

a, b and c are three coefficients which can be determined experimentally [25], a = 1.23, b = 0.41 and c = 0.44, λ is the mean free path (distance traveled by the particle between 2 successive collisions with air molecules equal to 67.3 nm at 25 ºC and 101.3 kPa [26]. It should be noted that the performances of the HEPA filter are affected only for ambient humidity greater than 90%which is not the case for almost all NPPs [16]. Table 3 below illustrates some fiber filters dimensions [27].

Table 3: Sources of experimental data for some fiber filter

Commercial name	**Diameter of fiber D_f (µm)**	**Diameter of particle D_p (µm)**
Fiber glass HEPA	0.7	0.07-0.29; Hetero
Fiber glass HEPA	0.7	<0.121- >11.0; Hetero
Fiber glass FG-50, AAF	1.5	0.25-11.0; Homo
Fiber glass “B” glass	3.0	0.15-0.72; Homo
Fiber glass Aero-solve 95	0.85	0.02-0.7; Hetero

The efficiency η_i of interception of airborne particle by the fiber filter is given by the following relationship [20]:

$$\eta_i = \left(\frac{1-\alpha}{k}\right)\frac{R^2}{R+1} \quad (9)$$

The total efficiency η_{total} of the HEPA filter is then

$$\eta = \eta_d + \eta_i = 1.61\left(\frac{1-\alpha}{k}\right)^{\frac{1}{3}}(Pe)^{\frac{-2}{3}} + \left(\frac{1-\alpha}{k}\right)\frac{R^2}{R+1} \quad (10)$$

R is the ratio $\frac{D_p}{D_f}$

3. Results and discussion

3.1. Effect of particle diameter on the thickness of the filter

A high removal efficiency is accomplished by finding the optimum balance of different the filter parameters such as its packing density, fiber diameter and thickness. In this work, fiber diameter of the HEPA filter varies from 0.7 to 50 µm and packing density α between 0.01 and 0.6. The effect of the diameter of the particles for a 99.99% efficiency removal on the thickness of the filter was computed at six different D_f and six different α values. As expected, the calculations show that the filter thickness correlates inversely with particle diameter *i.e* larger particle diameters D_p resulted in smaller filter thickness H (Figures 2 and 3) as previously reported by Gao and al. [28]. This dependence does not significantly change for D_f and α in the range 10 to 50 µm and 20 to 60% respectively (Figure 2). However, when D_f and α are in the range 0.7 to 2.5 µm and 0.01 to 0.09 respectively, the dependance of the thickness of the filter on the diameter of the particle and the packing density appears to be strong especially for particles with diameters less than 0.3µm (Figure 3) which are trapped by Brownian diffusion and interception. With the increase of particle size, the effect of diffusion decreases gradually, and the thickness becomes independent of fiber diameter and the packing density (Figure 3). It should be noted that these results showed that the thickness of the filter was negatively associated with the fiber diameter and the packing density for a given particle diameter (i.e the smaller the fiber diameter and packing density, the greater filter thickness).

3.2.Effect of the face velocity of the particles on the filter thickness and removal efficiency

Face velocity is an essential factor to reflect the structural peculiarity of air an air filter. For a collection efficiency of 99.99%, the filter thickness has been computed for a face velocity up to 100 m/s. The calculated results, given in Figure 4, show that the thickness of the filter increases non-linearly with the increase of filtration velocity. For face velocity below 40 cm, it is common that the thickness of the filter decreases with decreasing face velocity. This characteristic is more pronounced for smaller particle sizes and may be caused by the intense diffusion effect of smaller particles at small filtration velocity as already reported by Leung and co-workers [29]. However, the thickness of the filter gradually reaches a plateau region as the face velocity increases. It should be noted that the plateau value correlates negatively with the particle diameter.

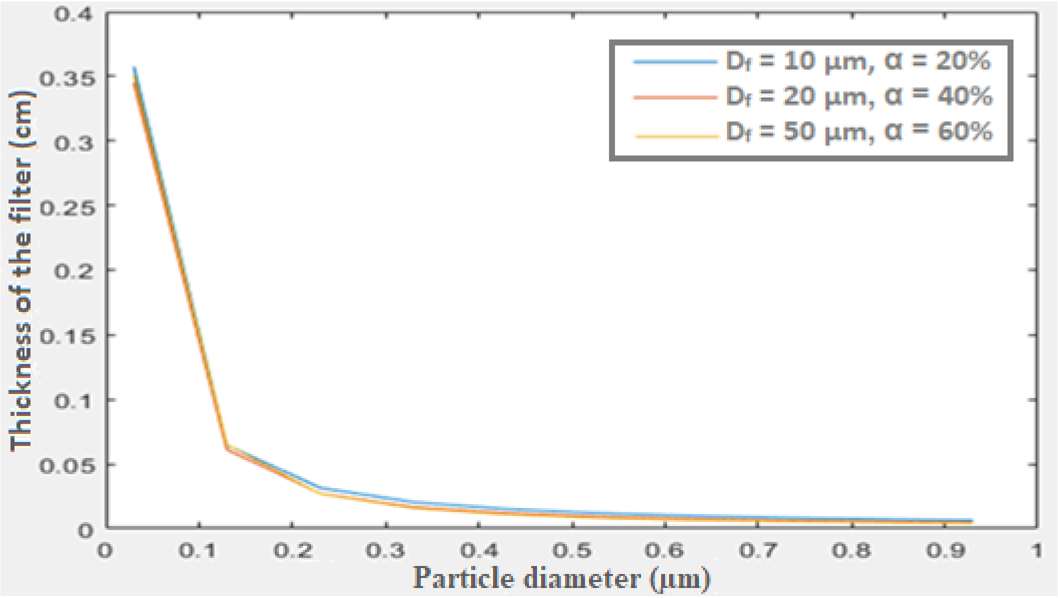

Fig. 2: Effect of the diameter of the particles on the thickness for 10 µm < D_f < 50 µm and 20% < α < 60%. Filter efficiency: 99.99%

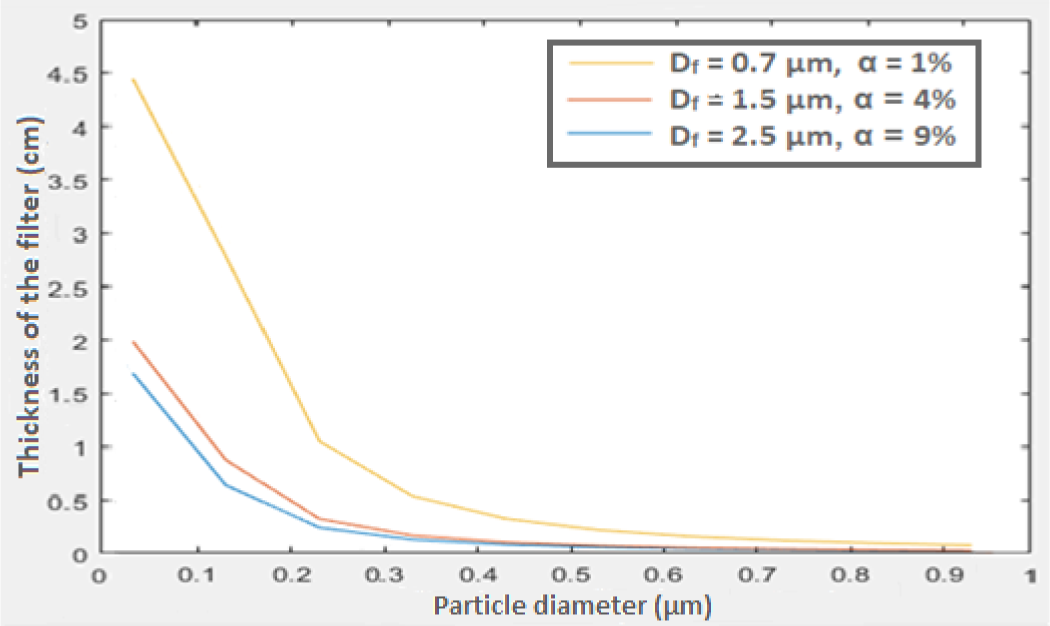

Fig. 3: Effect of the diameter of the particles on the thickness for 0.7 µm < D_f < 2.5 µm and 1 < α < 9%. Filter efficiency: 99.99%

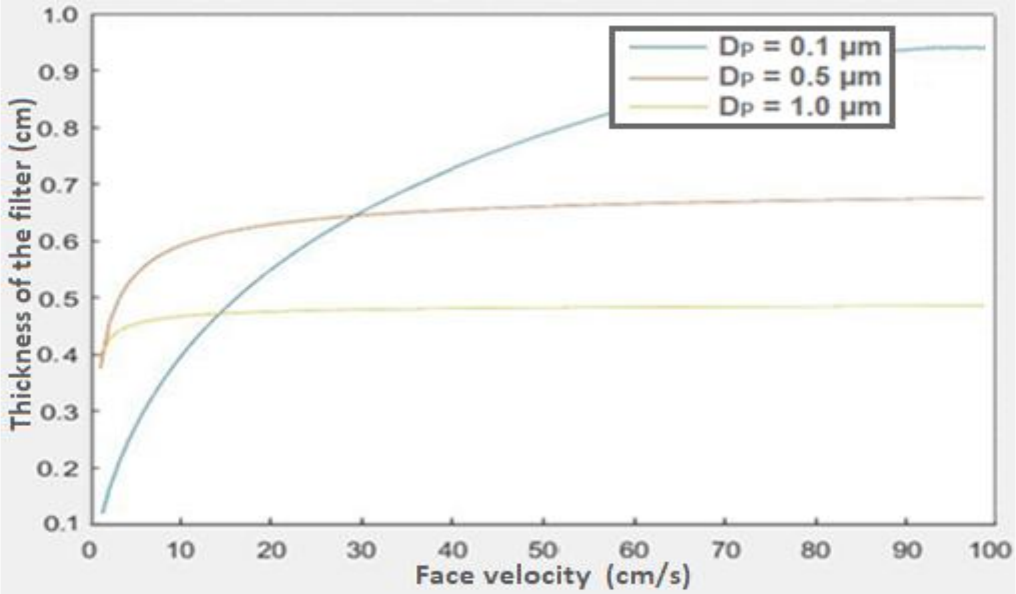

Fig. 4: Effect of the face velocity on the thickness of the filter when the efficiency of removal of particle is fixed to 99.9%

Figure 5 shows the filter removal efficiency, for 0.1 µm particle diameter, versus face velocity for different diameter fiber. The filter removal efficiency decreases with increasing particle face velocity. Furthermore, it should be emphasized that the removal efficiency showed a decrease with decreasing fiber diameter as expected. This is explained by the fact that for a given face velocity:

i) filter resistance inside towards the particles (friction) is proportional to the square of the fiber diameter (and thus to the packing density) [30, 31],

ii) as fiber diameter decreases, the fiber-to-fiber distance decrease and particles can pass through the filter without being trapped air as reported by many authors [32, 33].

3.3.Effect of the packing density on filter thickness

The packing density of the filters is a one of the main parameters impacting the filter removal efficiency by provide more surface area for aerosol deposition. As shown in Fig. 6, the required thickness to block 99.99% of the particles decreases with increasing packing density for all particle sizes (D_p = 0.1, 0.3 and 0.7 µm) since interstitial space between the mesh of fibers and decreases and impaction and interception are more prone for trapping particles [29]. Therefore, high packing density filters perform better for larger particles from the point of view of filter because there are more materials providing sites for particle deposition.

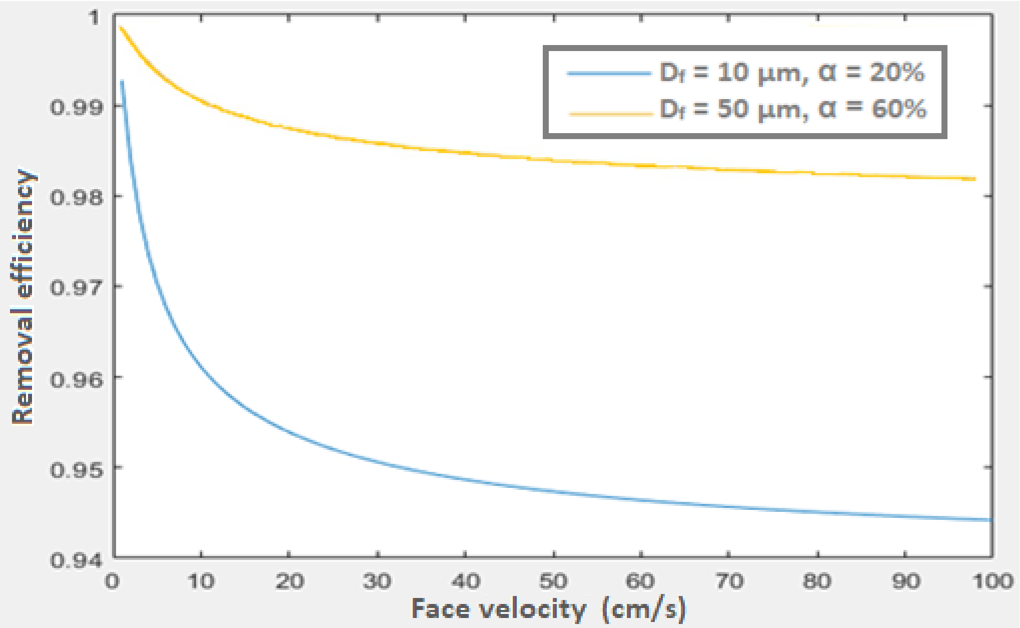

Fig. 5: **Efficiency of removal as function of face velocity for very thin filters.**

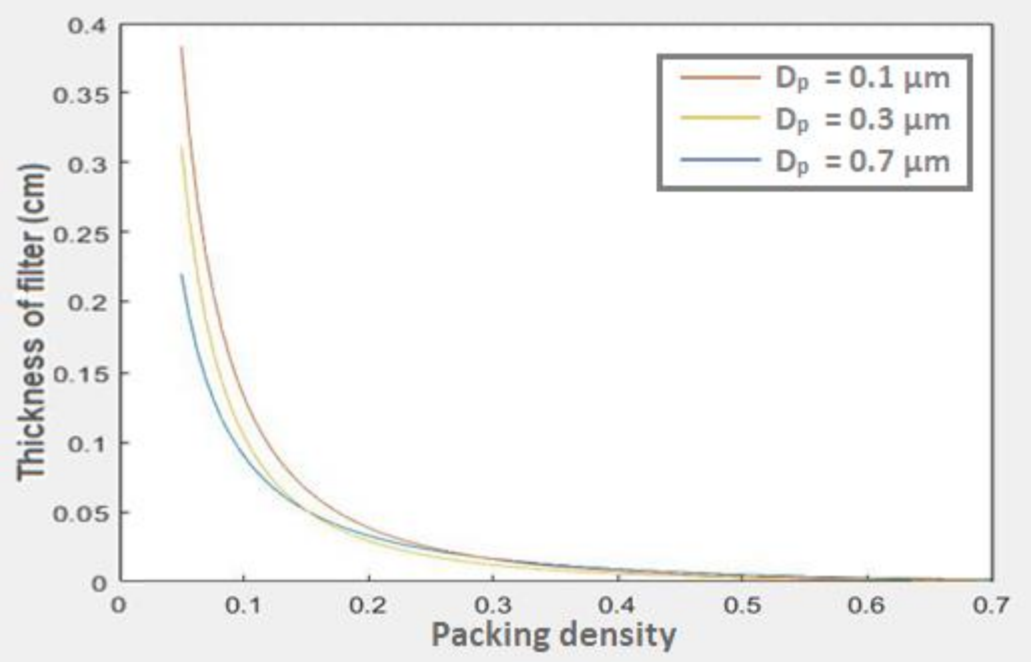

Fig. 6: Effect of the face velocity on the thickness of the filter when the efficiency of removal of particle is fixed to 99.9%

4. Conclusion

The ventilation system of a NPP plays a vital role in ensuring that the air in working areas remains free from radioactive contamination. In NPP's, reduction in particulate matter is achieved successfully through efficient HEPA air filters. In this work we simulated, using semi-empirical formulae, a model to determine the optimal thickness of a HEPA filter for a 99.99% efficiency removal of air particles up to 1 µm diameter, considering different physical parameters (fiber diameter, particle diameter, packing density of the filter, face velocity of the particle). For HEPA filter, for a 99.99% efficiency removal of particles up to 1 µm, the filter thickness correlates positively with the face velocity, and negatively with particle diameter and fiber diameter. It was also found that the efficiency is reached at low particle velocities in the air stream.

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تقييم أداء مرشحات الجسيمات عالية الكفاءة لإزالة الهباء الجوي المشع في مفاعلات الطاقة النووية. دراسة المحاكاة

فتحي جويدار

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ملخص

تعتبر إزالة رذاذ الهوائية المشعة واحدة من القضايا الرئيسية لإزالة تلوث الهواء في محطة الطاقة النووية لتقليل كل من تعرض عمال الإشعاع داخل محطة الطاقة النووية وتأثير الإشعاع البيئي. يمكن إزالة هذه الحلالات باستخدام مرشحات عالية الكفاءة (filters HEPA). سمك المرشح يعتمد على العديد من العوامل مثل حجم الجسيمات ، قطر الألياف ، سرعة الهواء وحجم نسبة الألياف / حجم المرشح. خلال هذ البحث تمت دراسة تأثير العوامل المختلفة (قطر الألياف ، قطر الجسيمات ، سرعة الهواء) على سمك المرشح للوصول إلى كفاءة إزالة أعلى من ٩٩,٩٩٪ باستخدام مرشحات HEPA. تشير النتائج إلى أن الطبقات الرقيقة من الألياف يمكن أن تعمل كمرشح فعال وفعال من حيث التكلفة. وجدنا أيضًا أن كفاءة إزالة الحلالات الهوائية المشعة تكون أعلى لسرعات الجسيمات المنخفضة في تيار الهواء.

الكلمات الرئيسية: مرشح HEPA ؛ كفاءة ترشيح الجسيمات ؛ حجم الجسيمات؛ قطر الألياف؛ سمك المرشح