Numerical studies on the performance of an aerosol respirator with faceseal leakage

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Abstract. We studied the efficiency of a facepiece filtering respirator (FFR) in presence of a measurable faceseal leakage using the previously developed model of a spherical sampler with porous layer. In our earlier study, the model was validated for a specific filter permeability value. In this follow-up study, we investigated the effect of permeability on the overall respirator performance accounting for the faceseal leakage. The Total Inward Leakage (TIL) was calculated as a function of the leakage-to-filter surface ratio and the particle diameter. A good correlation was found between the theoretical and experimental TIL values. The TIL value was shown to increase and the effect of particle size on TIL to decrease as the leakage-to-filter surface ratio grows. The model confirmed that within the most penetrating particle size range (~50 nm) and at relatively low leakage-to-filter surface ratios, an FFR performs better (TIL is lower) when the filter has a lower permeability which should be anticipated as long as the flow through the filter represents the dominant particle penetration pathway. An increase in leak size causes the TIL to rise; furthermore, under certain leakage-to-filter surface ratios, TIL for ultrafine particles becomes essentially independent on the filter properties due to a greater contribution of the aerosol flow through the faceseal leakage. In contrast to the ultrafine fraction, the larger particles (e.g., 800 nm) entering a typical high- or medium-quality respirator filter are almost fully collected by the filter medium regardless of its permeability; at the same time, the fraction penetrated through the leakage appears to be permeability-dependent: higher permeability generally results in a lower pressure drop through the filter which increases the air flow through the filter at the expense of the leakage flow. The latter reduces the leakage effect thus improving the overall respiratory protection level. The findings of this study provide valuable information for developing new respirators with a predictable actual workplace protection factor.

1. Introduction
Facepiece filtering respirators (FFRs) are used to protect workers from hazardous aerosol exposures. The efficiency of an FFR is generally dependent on the properties of its filter. It has been reported that the protection level offered by a respirator may substantially decrease in the presence of a faceseal leakage due to significant penetration of particle that bypass the filter [1], [2]. The particle flux through a faceseal leakage depends on the particle diameter, leak size, breathing flow rate and permeability of the filter medium. In our recent study [3], we developed a model for predicting the Total Inward Leakage (TIL) of an FFR. This model utilizes the previously validated fluid dynamic
approach to an aerosol flow created by a spherical sampler with suction through a porous layer. In the quoted investigation, the particle penetration into an FFR was calculated for different ratios of the leak area to filter surface area at constant filter permeability which corresponded to a protection level of 95%. The present effort extends our earlier investigation [3] by considering the filter permeability as a variable that makes the model capable of predicting the efficiency of respirators equipped with various filter materials.

2. The problem statement
An idealized model of human head used in this investigation involves a spherical geometry with a circular opening for air suction (Fig.1). The sphere and opening radii are denoted by \( R_h \) and \( R_i \) respectively. The respirator filter is represented by a porous layer located upstream of the orifice. It is a spherical segment of height \( H_f \) and radius \( R_f \). An annular peripheral opening between the sphere and the segment simulates the face seal leakage of width \( W_l \). The air movement in the breathing zone is described by a 2D axisymmetric steady flow passing through the porous layer and the peripheral opening. The air velocity \( U_0 \) far enough from the sphere is assumed constant.

![Figure 1. Schematics and major parameters included in the model.](image)

The influence of aerosol particles on air flow is neglected due to their small concentration. The air motion in the free space and inside the porous medium (filter) approximated by a laminar viscous flow of an incompressible gas is described as follows [4]:

\[
\nabla \cdot \vec{U} = 0 \tag{1}
\]

\[
\rho \vec{U} \cdot \nabla \vec{U} = -\nabla P + \varepsilon_f \mu \Delta \vec{U} - \alpha \varepsilon_f^2 \frac{\mu}{k} \vec{U} \tag{2}
\]

In Eqs. (1)–(2), \( \vec{U} \) is the air velocity; \( \mu \) and \( \rho \) are the coefficients of dynamic viscosity and air density; \( P \) is the pressure; and \( \varepsilon_f \) is the medium porosity. The coefficient \( \alpha \) is defined as being equal to zero outside the porous medium and equal to one inside the layer. Last term in Eq. (2) takes into account the additional air drag in the porous medium. In the latter case, it yields to the extended Darcy-Brinkman equations. To formulate a boundary value problem, the following boundary conditions were adopted for Eqs. (1)–(2): in the left part of the outer circular boundary of the computational domain, the air velocity is \( U_0 \); in the right part, the pressure is assumed to be equal to atmospheric pressure; the no-slip conditions are assumed on the sphere. The air velocity at the suction opening cross-section is defined as inhalation velocity \( U_i \). The axial symmetry condition is applied along the \( x \)-axis.

The TIL is calculated as follows [3]:

\[
TIL = \frac{Q_i \eta_i + Q_l \eta_l}{Q_i} \tag{3}
\]
where $Q_i$ and $Q_l$ are the flow rates of air passing through the filter medium and the peripheral opening, respectively; $Q_i = U_i \pi R_i^2 = Q_f + Q_l$ is the air breathing flow rate; $\eta_f$ and $\eta_l$ are the particle penetrations through the filter layer and the peripheral leak, respectively.

As particles move within filter medium, the large ones are deposited on the filter fibers due to mechanisms such as inertia, interception and gravity, and the smaller ones are deposited due to diffusion and electrostatics. The particle penetration $\eta_f$ through the filter medium with a thickness $L$ is calculated as follows [5]:

$$\eta_f = \exp\left(-\frac{4\alpha E_{fiber} L}{\pi d_{fiber}^2 (1-\alpha)}\right) \tag{(4)}$$

where $\alpha$ is the fiber packing density, $d_{fiber}$ is the diameter of a filter fiber, and $E_{fiber}$ is the collection efficiency of a fiber. If the aerosol particles are small enough to make the inertial and gravitational deposition negligibly small, $E_{fiber}$ can be calculated as

$$E_{fiber} = 1 - (1 - E_d)(1 - E_a)(1 - E_q) \tag{(5)}$$

where $E_d, E_a$, and $E_q$ are the collection efficiencies of a fiber by the action of interception, diffusion and electrostatic deposition, respectively. Given a very small depth of the opening (a typical faceseal leakage), no internal particle losses are assumed inside which suggests $\eta_l = 1$.

### 3. Results and discussion

The following geometrical parameters were selected for the numerical study: $R_i=0.09 \, m$, $R_f=0.007 \, m$, $R_L=0.057 \, m$, and $H_i=0.05 \, m$. The filter surface area and the porous layer depth were $S_f=0.018 \, m^2$ and $L=0.003 \, m$, respectively. These values represent a typical European FFP2 or American N95 FFR. An ambient air velocity of $U_i=0.1 \, m/s$ was chosen. The peripheral leakage area $S_l$ (determined by $W_l$) was a study variable. The dimensions of the calculation domain were established so that the influence of the sphere on the ambient flow can be neglected: $R_b=20 \, m$.

For the filter medium, the fiber diameter value was chosen to be $10.07 \, \mu m$, in accordance to [3]. Three filter penetration values (referring to particles in the most penetrating size range) were considered: $\eta_f = 0.1$, 0.05, and 0.01. These represent filter media with collection efficiencies of 90%, 95% and 99%, respectively. Subsequently, the fiber packing densities were calculated to be $\alpha = 0.0479$, 0.069, and 0.0888, respectively, producing permeability values of $k=2.12\times10^{-10} \, m^2$, $9.55\times10^{-11} \, m^2$, and $5.41\times10^{-11} \, m^2$, respectively. In this calculation, we conservatively assumed the inhalation rate corresponding to a high workload.

To numerically solve the fluid flow equations [Eqs.(1)–(2)], ANSYS/FLUENT code was deployed. The second order upwind scheme was applied for the discretization of the air motion equations. The unstructured grid with an increased density in the vicinity of the boundary between the free space and the porous medium was utilized to obtain a numerical solution convergence with a residual of $\sim 10^{-10}$. The flow rate $Q_i$ through leakage was determined from this numerical solution. The value of the flow rate $Q_l$ through the filter was calculated as $Q_l = Q_i - Q_f$.

The data produced by the above model using a correction factor of 2 [3] were compared to the experimental data reported earlier in [1], [6], and [7] on TIL as a function of the leakage-to-filter surface ratio, $S_l/S_i$, obtained at $Q_i=30 \, L\, min^{-1}$ and the porous layer permeability of $k=9.55\times10^{-11} \, m^2$. The results of this comparison are shown in Fig. 2 for two particle diameters. It is seen that the model is capable of predicting the experimentally obtained TIL values. For both particle sizes, the value of TIL increases as $S_l/S_i$ increases. Solid horizontal lines represent the value of TIL = 0.05 (which corresponds to $\eta_l = 0.05$ representing a commonly used N95 FFR). The TIL value exceeds 0.05 at $S_l/S_i$ in excess of approximately $5\times10^4$. A good agreement is seen between the theoretical findings [curves...
TIL\((S_l/S_f)\) and the published experimental data. For \(d_p = 50\) nm, as \(S_l/S_f\) decreases down to zero (sealed respirator, i.e. no leakage) TIL becomes constant (dotted line) and fully determined by the filter medium properties and the breathing condition. It is noted that the experiments and the model produced plateaus at different TIL\((S_l/S_f)\) values at \(S_l/S_f\) approaching zero. It can be explained given that the model assumes a steady inhalation flow while the experimental design adopted in [6] and [7] established a cyclic breathing.

Figure 3 presents TIL\((d_p)\) for \(k=2.12\times10^{-10}, 9.55\times10^{-11}, \) and \(5.41\times10^{-11}\) at different \(S_l/S_f\) and \(Q=30\) L min⁻¹. At \(S_l/S_f = 0\) and \(8\times10^{-5}\), the peak TIL was observed for \(d_p=50\) nm that falls in the range of the most penetrating particle sizes for fibrous respirator filters [8]. As \(S_l/S_f\) increases, TIL increases as well, and the effect of particle size on TIL becomes rather weak due to increase of the flow rate through the leak. It is also seen that at \(S_l/S_f=0\) the TIL\((d_p)\) curve lies higher for a higher permeability, i.e. the model produces a well anticipated result for perfectly fit respirator facepiece (no faceseal leakage): a filter with lower permeability makes the respirator perform better. At the same time, as \(S_l/S_f\) increases (see \(S_l/S_f=8\times10^{-4}\) and greater, Fig. 3), the model predicts that a better performance, i.e. a lower TIL, corresponds to a higher permeability suggesting an increasing flow rate through the leakage. For \(S_l/S_f\) as high as \(4\times10^{-3}\), TIL exceeds 0.1 for all permeabilities considered in this study. This allows us to conclude that filter permeability does not produce a major effect on the respirator performance once the non-dimensional ratio of \(S_l/S_f\) exceeds a certain value.

Figure 4 presents the data predicted by our model in a form of TIL as a function of \(S_l/S_f\) for the same \(k\)-values, \(Q=30\) L min⁻¹, and two very distinct particle sizes, 50 and 800 nm. The trends are similar, and a reasonable quantitative agreement is achieved for different permeabilities, except for the case of smaller particles (\(d_p = 50\) nm) penetrating at relatively low \(S_l/S_f\) (as explained above). For the particles as large as \(d_p = 800\) nm, a lower TIL\((S_l/S_f)\) curve corresponds to a larger \(k\) in the entire tested range of \(S_l/S_f\) which may seem counter-intuitive. The following explanation is suggested. In contrast to ultrafine particles, the larger ones entering a typical high- or medium-quality respirator filter are almost fully collected by the filter medium regardless of its permeability while the leakage penetration is permeability-dependent: higher permeability is generally associated with a lower pressure drop through the filter thus increasing \(Q_l\) at the expense of \(Q_t\). Lowering \(Q_t\) reduces the leakage effect thus improving the overall respiratory protection level.

The results of this study help assess relative contributions of the two particle penetration pathways – the filter and the faceseal leakage. The findings provide valuable information for the development of new respirators with a predictable actual workplace protection factor.

\[\text{Figure 2. TIL as a function of } S_l/S_f \text{ for } d_p = 50 \text{ nm (a) and 800 nm (b). The solid horizontal lines represent the value } TIL = 0.05 \text{ the dotted horizontal lines represent a “perfect fit” respirator (with no faceseal leakage).}\]
Figure 3. TIL as a function of $d_p$, calculated for $Q_i = 30$ L min$^{-1}$ and various $S_l/S_f$.

Figure 4. TIL as a function of $S_l/S_f$ calculated for $Q_i = 30$ L min$^{-1}$ for $d_p = 50$ nm (a) and 800 nm (b).

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