REPORT

Fate of the inhaled smoke particles from fire scenes in the nasal airway of a realistic firefighter: A simulation study

Xiaoyu Xu\textsuperscript{a,b,c}, Yidan Shang\textsuperscript{b}, Lin Tian\textsuperscript{b}, Wenguo Weng\textsuperscript{a}, and Jiyuan Tu\textsuperscript{b,c,d}

\textsuperscript{a}Institute of Public Safety Research, Department of Engineering Physics, Tsinghua University, Beijing, China; \textsuperscript{b}School of Engineering – Mechanical and Automotive, RMIT University, Bundoora, Victoria, Australia; \textsuperscript{c}School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, New South Wales, Australia; \textsuperscript{d}Key Laboratory of Ministry of Education for Advanced Reactor Engineering and Safety, Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing, China

\textbf{ABSTRACT}

Understanding the inhalation, transport and deposition of smoke particles during fire missions are important to evaluating the health risks for firefighters. In this study, measurements from Underwriters Laboratories’ large-scale fire experiments on smoke particle size distribution and concentration in three residential fire scenes were incorporated into models to investigate the fate of inhaled toxic ultrafine particulates in a realistic firefighter nasal cavity model. Deposition equations were developed, and the actual particle dosimetry (in mass, number and surface area) was evaluated. A strong monotonic growth of nasal airway dosages of simulated smoke particles was identified for airflow rates and fire duration across all simulated residential fire scene conditions. Even though the “number” dosage of arsenic in the limited ventilation living room fire was similar to the “number” dosage of chromium in the living room, particle mass and surface area dosages simulated in the limited living room were 90–200 fold higher than that in the ventilated living room. These were also confirmed when comparing the dosimetry in the living room and the kitchen. This phenomenon implied that particles with larger size were the dominant factors in mass and surface area dosages. Firefighters should not remove the self-contained breathing apparatus (SCBA) during fire suppression and overhaul operations, especially in smoldering fires with limited ventilation.

\textbf{KEYWORDS}

CFD; firefighter realistic nasal model; firefighter respiratory health; nasal deposition; smoke particle dosimetry

\textbf{Introduction}

Firefighters face hazardous conditions not only for toxic gases, but also for smoke particles that may be inhaled at fires.\textsuperscript{[1]} The combustion products contain toxic particles, which pose potential acute and/or chronic health risks for firefighters as they might induce respiratory and cardiovascular diseases (such as lung cancers and coronary heart diseases).\textsuperscript{[2]} A 7-year study of 5,000 firefighters, who were engaged in the September 11, 2001 rescuing mission, identified that all of the crew had permanent respiratory functional impairment. Persistent symptoms, such as coughing, wheezing, sore throat, and sinus dripping, significantly reduced the quality of life.\textsuperscript{[3]} An estimated 20% of these firefighters would develop permanent respiratory disabilities at the end of their career, due to asthma or chronic bronchitis. Exposure to an elevated level of fire smoke particulates in the working environment poses significant health risks to the firefighters. It is of significant value to investigate the detailed exposure condition and respiratory dosage of firefighters at typical working environment, to help assess the hazardous condition, and to develop mitigation measures.\textsuperscript{[4]}

Research on firefighter exposure to chemical hazards began nearly four decades ago.\textsuperscript{[5–7]} Knowledge of gaseous exposures during fire activities provided profound insight for the design and improvement of self-contained breathing apparatus (SCBA), routinely worn by current firefighters in action.\textsuperscript{[7]} Gases and smoke particulates emitted from residential building and automobile fires during fire suppression processes (knockdown and overhaul) were measured and analyzed.\textsuperscript{[8]} In a separate study, Fabian et al.\textsuperscript{[9]} measured the exposure of residual contamination to firefighters...
during search and rescue operations, using personal protective cascade impactors. In addition, blood concentration of selected metals and perfluorinated chemicals were monitored in California firefighters,[10] and it was determined that the perfluorodecanoic acid concentrations were three times higher in firefighters than that in average U.S. male adults.

However, limited data were available to assess the relationship between firefighters’ respiratory health conditions and exposure to the airborne ultrafine smoke particles (UFPs). Smoke particles present a high potential health risk to firefighters. Recommendations from the Occupational Safety and Health Administration (OSHA), National Institute for Occupational Safety and Health (NIOSH) and American Conference of Governmental Industrial Hygienists (ACGIH) were used as standards to evaluate safety of firefighters’ exposure to respiratory toxicants (ultrafine particles) during suppressing and overhaul activities.[11,12] Baxter et al.[2] indicated that the UFPs should be considered as a major contributing factor for coronary heart diseases (CHD) among firefighters, including during overhaul when firefighters frequently removed their respiratory protections (SCBA), which put them in direct exposure to fire emissions. Firefighters were also reported to be more likely develop respiratory conditions, such as lung inflammations, as they were routinely exposed to prescribed burning, wildland fire, and bush fire environment.[13–17]

Despite very few studies on firefighter exposure to ultrafine smoke particles, a growing interest has yielded information on the relationship between ultrafine particle exposure and respiratory health conditions in the general population since 1990s.[18–20] Toxic mechanisms in relation to the unique physical and chemical characteristics of the ultrafine particles from air pollution (e.g., PM2.5, PM10, and PM coarse) were investigated. It was found out that inflammation and oxidative stress in the lung were increasingly induced by exposure to ultrafine particles, containing toxics such as metals and polycyclic aromatic hydrocarbons.[21]

Computational fluid dynamics (CFD) techniques have been used to investigate the effect of inhaled particles in human respiratory system, and applications can be found in drug delivery and toxicology studies.[22–25] Examples included the evaluation of carbon and glass composite fiber exposure of an anatomical respiratory system model (including larynx, trachea and lung) in post-crash aircraft fire.[26–28] Air flow, heat transfer, and micron particle deposition, simulating smoke inhalation during fire, were studied in a human upper airway model, focused on trachea tissues. The influence of high temperatures on particle airflow deposition was investigated in the work of Xu et al.[29] Particle agglomerates including long straight chains, branches, and compact shapes in welding fume were simulated in a realistic human nasal airway,[30] where the presence of neurotoxin manganese (Mn) was a known health hazard. Tian et al.[31] demonstrated that particle size distribution played a significant role in evaluating nanoparticle deposition in
human upper airways by conducting a combined experimental and numerical study in a wire-cut electrical discharge machine shop (WEDM). Comparisons of nanoparticle, ultrafine particle, and micron particle deposition in human lung were performed under semi-empirical single breathing, multiple breathing and steady-state breathing conditions.[32–34] Considering the facial feature, Shang et al.[35] investigated the deposition efficiency of mid-inertial particles.

In this study, the connection between fire scene exposure and toxic smoke particle dosimetry (mass, number, and surface area) in an anatomically realistic firefighter nasal cavity model was established. Real-time smoke particle size distribution and concentration in three fire scenes (living room, living room with limited ventilation, and kitchen room) were obtained from experimental measurements.[8] The firefighter nasal cavity geometry model, including facial features and external environment, was reconstructed. The inhalation and fire scene conditions on the smoke particle deposition, in the nasal cavity and middle meatus regions, were investigated. Inhalation health hazards to firefighters due to toxic smoke particle dosimetry (arsenic and chromium) in the three simulated fire scenes were assessed.

Methods

Nasal cavity computational model development

Schematics of the CFD model for firefighters in the fire ground was shown in Figure 1a. The nasal cavity airway, containing facial features, was developed from CT scans of a 20-year-old male and healthy firefighter (Figure 1b). The airway model was connected to form a contiguous path via nostrils, from the external space to the end of nasopharynx. An artificial straight tube extending from the nasopharynx was created to allow sufficient flow recovery and improve numerical convergence in the CFD solution. The nasal airway was added to the face of a realistic firefighter, who was exposed to the external surroundings, containing ultrafine smoke particles emitted from the fire scene.

In this study, particles were uniformly released from a hemisphere (of radius 3 cm) with respect to the nose tip.[31,36] A high-quality mesh with polyhedral meshing elements filled the nasal airway passage. Seven prism layers were applied to the bounding respiratory walls to resolve the viscous sub-layer. The first grid point above the wall surface was given in wall units with \( y^+ \) less than or equal to 1.0. The final model consisted of 1.7 million cells, achieved mesh independency (Figure 1c, with supporting details in online supplementary materials, Figure S1). A workstation with 64GB RAM, 4GB video card and 20 processor cores was used for the CFD simulations.

Turbulence fluid flow simulation

The cardiac load of male firefighter in the fire scene was assumed to be moderate, with inspiration flow rates being 30–50 L/min. In this circumstance, male firefighters would be presumed to mainly inhale through the nose.[30,37] At these flow rates in the nasal cavity, airflow was transition to turbulent condition. The effect of breathing pattern on ultrafine deposition was not fully understood. For simplicity, current study employed a steady inhalation condition, assuming that particle deposition mainly occurred during the inhalation process.[24] Transition Shear Stress Transport (SST-transition) turbulence model was employed in the current study, emphasizing prediction of the turbulence kinetic energy profiles in transition flows. The airflow was simulated using Ansys-Fluent v18.0 (Ansys Inc., Cannonsburg, PA). Second-order upwind schemes were used to improve the computational accuracy, and the SIMPLE method was used to handle the pressure-velocity coupling. A double-precision solver was employed. External surroundings were assumed to be at the atmospheric pressure, and inhalation was initiated by a negative pressure difference between the surrounding environment and the outlet at nasopharynx. This allowed the ambient flow to be influenced only by inhalation. For brevity, SST-transitional turbulent model is not repeated here, but can be found in the work of Menter et al.[38]

Particle trajectory modeling

Lagrangian particle tracking was used to trace dispersion of airborne spherical smoke particles. The trajectory of each simulated particle was modeled until it either deposited on the boundary surface or escaped from the airway outlet. Neglecting collision between particles, particle equation of motion is given as:

\[
\frac{du_p}{dt} = \frac{1}{C_c} F_D + \frac{g(p_p - p_g)}{\rho_p} + F_s + F_B
\]

(1)

where \( u_p \), \( \rho_p \), \( t \), and \( \rho_g \) are the particle velocity, particle density, time, and the air density, respectively; and \( g \) is the gravitational constant. \( F_D \) is the drag given as:

\[
F_D = \frac{18\mu_p(u_p - \bar{u}_p)}{\rho_p d_p^2}
\]

(2)
where \( d_p \) is the particle diameter and \( \mu_g \) is the molecular viscosity of the air. \( C_c \) is the Cunningham correction, given as:

\[
C_c = 1 + \frac{2\lambda}{d_p} \left( 1.257 + 0.4e^{-1.1d_p/2\lambda} \right),
\]

(3)

\( \lambda \) is the molecular mean free path of air, defined as:

\[
\lambda = \frac{\mu_g}{p} \sqrt{\frac{\pi k_B T}{2m}}
\]

(4)

Here \( m \) is the molecular mass, \( k_B \) is the Boltzmann constant \((1.38 \times 10^{-23} \text{J/K})\), \( p \) is the pressure, and \( T \) is the absolute temperature of the inspiratory air.

\( F_s \) in Equation 1 is the Saffman force and \( F_B \) is the Brownian diffusion force. The Brownian diffusion force is negligible for micron particles; however, it is significant for the nanoparticles. \( F_s \) is given as:

\[
F_s = 1.6(\mu_g \rho_g^{1/3})^2 d_p |u_g - u_p| \cdot \frac{du_g}{dx_{pi}}^{1/3}
\]

(5)

where \( x_{pi} \) is the particle position. Amplitudes of the Brownian force components at every time step are evaluated as:

\[
f_B = \zeta \sqrt{\frac{\pi S_0}{\Delta t}}
\]

(6)

where \( \zeta \) is a zero-mean, unit variance independent Gaussian random number, \( \Delta t \) is the time step for particle integration, and \( S_0 \) is the spectral intensity function, defined as:

\[
S_0 = \frac{216 \mu_g k_B T}{\pi^2 \rho_g^5 d_p^5 \left( \frac{\rho_g}{\rho_i} \right)^2 C_c}
\]

(7)

The simulation used the discrete phase model (DPM). The particle Equation 1 was solved by step-wise integration over discrete time steps yielding a new particle velocity at each time step.

Uniform smoke particles were assumed in the breathing zone. In the current study, ultrafine particles of 1, 1.2, 1.5, 2, 5, 10, 20, 30, 50, 70, 100, 150, 300, and 500 nm and 1, 2, 3, 5, 7, 10, 15, 20, 30, and 50 \( \mu \text{m} \) were included. Approximately 70,000 monodisperse independent airborne smoke particles for each particle size were released into a hemispheric profile in front of the nose tip. The particle independency was assessed (see online supplementary materials, Figure S2). Particles were considered deposited onto the respiratory walls when they were within \( d_p/2 \) distance from the surface.

Discrete Random Walk (DRW) model was used for stochastic tracking in turbulence. The instantaneous velocity of the turbulence air consists of two components: the averaged speed \( u_i \) where \( i = x, y, z \) and the fluctuation velocity \( u_i' \). The time scale \( \tau_e \) associated with each eddy (eddy life time) is given as:

\[
\tau_e = 2C_1 \frac{k}{\varepsilon}
\]

(8)

where \( C_1 \) is a constant, \( k \) is the turbulent kinetic energy, and \( \varepsilon \) is turbulence dissipation. In addition to the eddy lifetime, the particle eddy crossing time \( t_{cross} \) is defined as:

\[
t_{cross} = -\frac{\tau}{\pi \ln \left[ 1 - \left( \frac{L_e}{\tau |u_g - u_p|} \right) \right]}\]

(9)

Here, \( L_e \) is the eddy length scale and \( \tau \) is the particle relaxation time, defined as:

\[
\tau = \frac{\rho_p d_p^2 C_c}{18 \rho_g v}
\]

(10)

The frequency of the particle encountering turbulence eddies is the reciprocal of the lesser of \( \tau_e \) and \( t_{cross} \).

**Smoke particle from fire scenes**

Experimental data of smoke particle concentration and size distribution in three residential fire scenes were obtained from Underwriters Laboratories’ large-scale fire tests [8]. These investigators used full-scale testing facilities representing typical fire scenes designed and built and characterized the size and count distribution of smoke particle using a Wide-range Particle Spectrometer (WPS). The various
inorganic elements contained in airborne particles were measured and analyzed by Inductive Coupled Plasma Mass Spectroscopy (ICP-MS) with the specimen collected from firefighters’ glove, hood and MSP Corporation MDI 129 personal cascade impactor. Dissolved sample material was injected into the ICP where the liquid carrier was evaporated and any dissolved solids were atomized. It could then be separated and detected by the mass spectrometer based on their mass to charge ratio. Figure 2 displays the measured smoke particle size distribution in each of the three fire scenes.

For the vented living room case, the living room was outfitted with a sofa, love seat, end table, coffee table, TV stand, flat screen TV, carpeting, and a lamp with lightbulb. The small open flame fire was initiated by ignition of the upholstered furniture, and the door was open to ensure full ventilation. The ultrafine smoke particle number concentration at the 12.97th min was chosen as the representative scenario, where overhaul activities began and when particle count density was the highest, therefore, representing the worst scenario. A mixture of iron, zinc, and chromium were detected in the particle composition. For simplification, particle density of $\rho = 7190 \text{ kg/m}^3$ which is approximately the same as chromium, is harmful to human health and was assumed for particles in the living room. According to the report, chromium accounted for 0.005% of the total number of particles in the living room fire scene. The measured particle size ranged from 10 nm to 1.28 \text{um}.

The limited ventilation living room had similar structure; although, there were more pieces of furniture than that in the living room. Additional furnishings included crown molding, throw rug, electric slot-car racing set on the coffee table, a plastic rocking horse, blankets draped over one of the sofa arms, cigarettes, plastic cups, color magazines, a desk, a computer with CRT monitor, and a plastic plant in the room corner. The ventilation was controlled by an open or closed door and the reduced oxygen resulted in the smoldering fire. Data at the 17th min, corresponding to the end of first growth fire, were chosen in current simulation, as it covered the widest range of particle size, from 0.01 to 3.98 \text{um}. Various inorganic elements, such as calcium, aluminum, iron, potassium, sodium, magnesium, and arsenic were detected. In the simulation, particle density in the limited ventilation living room fire scene was assumed to be $\rho = 2000 \text{ kg/m}^3$ similar to that of arsenic, a known toxic to human. Arsenic was about 0.04% of the measured particle count in the limited ventilation living room.

The kitchen scenario involved a furnished floor and wall cabinets (stocked with food items), plastic dishes and cups, a refrigerator, a table, and chairs. The kitchen fire was induced by a candle inadvertently positioned close to a paper roll with the door open. The representative fire scene was chosen at the 16th min, when firefighters usually took off their SCBA and particle concentration was the highest at beginning of the overhaul. Iron, zinc, chromium, calcium, aluminum, potassium, sodium, magnesium, and titanium were found in the ultrafine smoke particles. Particle density of $\rho = 7190 \text{ kg/m}^3$ was assumed, resembling that of chromium, accounting for 0.15% of particle counts in the kitchen. The particle size range was identified from 0.01 to 2.15 \text{um}.

At the beginning of the overhaul in a fire scene, the air temperature was assumed to be 100°C. The temperature boundary conditions of the nasal cavity wall were assumed to be the same as the body core temperature (37°C). The molecular mean free path of air ($\lambda$) was 72.5 nm and $\mu_g = 2.18 \times 10^{-5} \text{kg/m} \cdot \text{s}$. In the current simulation, particle densities of 1000, 2000, and 7190 $\text{kg/m}^3$ were included.

**Deposition fraction and particle dosimetry**

Particle deposition in human nasal airways can be quantified in terms of the deposition fraction ($DF_p$), defined as:

$$DF_p = \frac{N_d}{N_i} \times 100\%$$

where $N_d$ is the number of trapped particles in a specific region, and $N_i$ is the number of particles entering human nasal airway. The deposition fraction is an important parameter, which is closely related to transport mechanism. For nanoparticles, particle size, diffusivity, and airflow rate are identified as the dominant parameters. For microparticles, particle size, density, and airflow rate mainly influence the deposition fraction. Empirical fitted deposition equations are frequently used to relate the deposition fraction to the governing parameters, by employing MATLAB curve fitting function. When the coefficient of determination ($R^2$) reached up to 0.985, the parameters of the equation were assumed the best fit.

Environment of a fire scene contains polydisperse particles at various number concentration (number of particles per unit volume) given by the particle size distribution function $n(d, \bar{r}, t)$. Here $\bar{r}$ is the particle position vector, $t$ is the time, and $d$ is the particle
diameter. Assuming spherical, the toxic particle dosimetry by number, surface area, and mass can be obtained by integrating the product of $n(d, \tau, t)$ and $DF$, over the exposure time at the specified flow rate, taking account of the percentage of toxic particles and the aspiration ratio $AR$, defined as:

$$AR = \frac{A_c V_c}{A_n V_n}$$

where $A_c$ is the upstream critical area, $A_n$ is the total area of the nostrils, $V_c$ is the upstream freestream velocity within in the critical area, and $V_n$ is the average velocity at nostrils. In current fire scenarios, where the particle sizes were less than 4 $\mu$m, the $AR$ was 98–99%, which indicated that nearly 99% of airborne particles were inhaled into the nose in the three fire scenes.

**Results and discussion**

**Model validation**

Figure 3 compares the nanoparticle and micron particle deposition (water droplets of $\rho = 1000kg/m^3$) in human nasal cavity at room temperature between present study and the experiments. Nano particle deposition in the nasal cavity is mainly governed by diffusion, closely related to particle size and flow rate. The Péclet Number ($Pe$) is defined as:

$$Pe = \frac{Lu}{D}$$

where $L$ is the characteristic length of nostrils, $u$ is the airflow velocity at nostrils, and $D$ is the mass diffusion coefficient, given as:

$$D = \frac{k_B T C_c}{3\pi \mu d_p^2}$$

where $T$ is the temperature and assumed to be 300K. For micron sized particles, deposition fractions were related to the inertial parameter $I$, which considered particles mass to the square power, and the averaged fluid momentum. The inertial parameter is defined as:

$$I = d_p^2 Q$$

where $Q$ is the volume flow rate ($cm^3/s$) and $d_p$ ($\mu$m) is the particle aerodynamic diameter. Deposition fraction of micron particles (defined as the ratio of deposited particles to the total number of particles entering nostrils) at flow rates of 30 L/min agree well with the experiments (Figure 3b). While for nanoparticles, despite that the Péclet number has taken different respiratory flow rates into account, experimental deposition data is twice as large as numerical data (Figure 3a). The under-predicted nanoparticle deposition may be attributed to the variation in nasal geometry model and the length of the airway. The Adult-Nasal-Oral-Tracheal (ANOT) nasal replica used in the experiment (from the nostril to the upper trachea) was longer than the firefighter nasal model (from the nostril to the nasopharynx) used in the current work. Therefore, the particle deposition in the lower respiratory tract has not been counted, as current research focused on particle dosimetry in the nasal cavity. The discrepancies for the total nasal cavity nanoparticle deposition are acceptable considering the shorter airway in the simulation.
Airflow patterns

Moderate cardiac load at breathing rates of 30 and 50 L/min were included in the simulation. Key features of the airflow pattern were similar at the two flow rates, conforming to the geometric details of the airway. Figure 4 shows the streamlines as well as velocity contours in the nasal airway model at selected cross sections. Ambient air enters the nostril with an upward direction and turns nearly 90° at the middle and inferior nasal meatus. Airflow enters the posterior nasopharynx with a second 90° turn downward. Peak velocities occur at the nostril entrance and downstream of the nasal valve, indicating the preferential pathways. Bulk air was largely found in the middle regions of the nasal passages, while very low velocity passes the superior meatus region. The flow patterns provide potential deposition sites for inhaled micron particles, which is driven by inertial mechanism. Spots with peak velocities and locations where flow directions change and imply higher potential for larger particles to deposit. This suggests that larger particle deposition might occur at the entrance of the nasal cavity, inferior meatus, and the posterior of the nasopharynx where a sudden contraction of the cross-sectional area occurs.

Particle deposition equations

The simulated particle size range was slightly expanded to allow a wider coverage of the developed deposition equations. Figure 5 presents the nanoparticle (1–500 nm) deposition fraction in the nasal cavity and middle meatus in variation to particle density, diffusivity, and airflow rate. It shows that flow rates have significant impact on deposition (especially for smaller or high diffusion particles), and the deposition is proportional to the mass diffusion coefficient in the nasal cavity and middle meatus. The smaller the nanoparticle (or higher diffusion) is, the higher is the deposition fraction. Based on the simulation, deposition in the nasal and middle meatus, as a function of flow rate \( Q \) (m\(^3\)/s) and particle diffusivity \( D \) (m\(^2\)/s) is analyzed. We find that \( D_{\text{nasal}}^{0.6701}/Q^{0.5180} \) provides the best fit for nasal deposition of particles from 1 to 500 nm, breathing rates of 30 and 50 L/min, and densities from 1000 kg/m\(^3\) to 7190 kg/m\(^3\) (Figure 6a), with a coefficient of determination \( R^2 = 0.9997 \). Figure 6b show that \( D_{\text{meatus}}^{0.6154}/Q^{0.4884} \) provides the best fitting for middle meatus deposition, with a coefficient of determination \( R^2 \) of 0.9994. The fitted empirical equations are:

\[
DF_{\text{nasal--nm}} = \left[ 1 - 0.9916 \exp\left( -33.04 \cdot D^{0.6701}/Q^{0.5180} \right) \right] \times 100
\]

(16)

\[
DF_{\text{Middle--Meatus--nm}} = \left[ 1 - 0.9981 \exp\left( -4.993 \cdot D^{0.6154}/Q^{0.4884} \right) \right] \times 100
\]

(17)

For micron sized particles, deposition fractions are mainly influenced by inertial forces. The Stokes number is used to correlate the deposition to length scale, particle density, size, and flow rate. It is defined as:
The deposition fraction of the nasal cavity and middle meatus, for particles ranging from 0.5 to 50 μm are plotted against the Stokes number in Figure 7. When the Stokes number is below 0.009, the deposition fraction in the nasal cavity is under 1%. Following a sharp increase, the deposition fraction was stable at 100% when the Stokes number reached 0.23. Peak depositions occurred for the middle meatus at the Stokes number around 0.825 and 1.79, where the deposition fractions were 27.6% and 1.48%, respectively. For the deposition in the nasal cavity, an improved fitting was obtained with

\[
St = \frac{\rho_p d_p^2 u}{18 \mu L}
\]  

For particle sizes from 0.5 to 50 μm, breathing rates of 30 and 50 L/min, and particle densities from 1,000–7,190 kg/m³ (Figure 8), with a coefficient of determination (R²) of 0.9971. The empirical deposition equations for the middle meatus are not fitted well with the Stokes number and are not developed. The empirical equation for micron particles in the nasal cavity is given as:

\[
DF_{nasal, \mu m} = \left[1 - 0.9883 \exp(-116.0 \cdot St^{1.188})\right] \times 100
\]

**Toxic particle dosimetry in human nasal airway in three residential fire scenes**

Based on measured data from typical residential fire scenes (Figure 2), human nasal cavity and middle meatus dosages were calculated by using deposition equations and linear interpolation, as presented in Table 1 and 2. The presented dosages are calculated based on 10 min and 60 min exposure duration, typical for the firefighters to perform activities in the fire scenes. Breathing rates of 30 and 50 L/min were
considered. Particle penetration, closely related to the lower airway and deep lung dosimetry, is provided in Table 3.

In number, mass and surface area metrics, a strong monotonic increase of human nasal airway dosages of toxic smoke particles together with the airflow rate and fire activity duration in all fire scenes is shown in Tables 1 through 3. This is the result of a growing particle exposure due to large air exchange rate. The slight decline of nanoparticle deposition at higher flow rate in the diffusion region (Figure 6) is statistically insignificant to the real dosimetry.

Comparing the three fire scenarios, the dosimetry (in number, mass, and surface area) varies significantly in all studied regions. Firefighters inhale the largest “number,” “mass,” and “surface area” dosages of arsenic smoke particles in the limited ventilation living room fire than that in the other two scenarios. The inhaled “number” dosage of arsenic particles in the limited ventilation living room is nearly the same as chromium “number” dosimetry in the living room (Table 1); however, particle mass and surface area dosages in the limited ventilation living room are much higher than that in the living room (about 90–200 fold). The limited ventilation living room fire generated larger size range of smoke particles due to smoldering. Nearly 99% of the mass dosage in the smoldering living room is caused by micron particles (1–3.89 μm). On the other hand, only 50% of the mass dosage in the flaming living room is from the micron range particles (1–1.28 μm). The results imply that particles with larger sizes were dominant in mass and surface area dosages, which is also confirmed in comparing the dosages in flaming kitchen room and the living room. In spite of the higher “number” dosage of toxic chromium smoke particles in the living room, the mass and surface area dosages in the kitchen exceeds 24–110 fold to that in the living room.

As shown in Table 2, at the breathing of 30 L/min, mass dosimetry in the middle meatus areas in the kitchen are about 20 times higher than that in the living room. At higher breathing rate (50 L/min), over 50 times greater dosimetry was observed. Prolonged air exchange and inhalation of increased number of larger sized particles at flow rate of 50 L/min could be the cause. Particle deposits onto firefighters’ face could penetrate into the skin and cause deep tissue damages,[47] which will be discussed in further studies.

The majority of the smoke particles penetrated the nasal cavity into the lower airways (Table 3). Both flow rates and the inhalation duration have negligible influence on the proportional dosimetry of penetrated particles.
Table 1. Firefighter nasal cavity dosages of particles in three residential fire scenarios during various fire event time.

| Time of exposure (min) | Q (L/min) | Number $(10^7/\text{#})$ | Mass (µg) | Surface Area $(\times10^{-4} \text{m}^2)$ |
|------------------------|-----------|---------------------------|-----------|----------------------------------------|
| Living room fire       |           |                           |           |                                        |
|                       | 10        | 30                        | 0.092     | 0.012                                  | 0.180                                |
|                       |           |                           |           |                                        |
|                       | 50        | 0.134                     | 0.027     | 0.350                                  |                                       |
|                       | 60        | 0.550                     | 0.073     | 1.081                                  |                                       |
|                       | 50        | 0.805                     | 0.163     | 2.097                                  |                                       |
| Limited ventilation living room fire |           |                           |           |                                        |
|                       | 10        | 0.092                     | 0.012     | 0.180                                  |                                       |
|                       |           |                           |           |                                        |
|                       | 50        | 0.134                     | 0.027     | 0.350                                  |                                       |
|                       | 60        | 0.550                     | 0.073     | 1.081                                  |                                       |
|                       | 50        | 0.805                     | 0.163     | 2.097                                  |                                       |
| Kitchen fire          |           |                           |           |                                        |
|                       | 10        | 0.092                     | 0.012     | 0.180                                  |                                       |
|                       |           |                           |           |                                        |
|                       | 50        | 0.134                     | 0.027     | 0.350                                  |                                       |
|                       | 60        | 0.550                     | 0.073     | 1.081                                  |                                       |
|                       | 50        | 0.805                     | 0.163     | 2.097                                  |                                       |

Table 2. Firefighter middle meatus dosages of particles in three residential fire scenarios during various fire event time.

| Time of exposure (min) | Q (L/min) | Number $(10^7/\text{#})$ | Mass (µg) | Surface Area $(\times10^{-7} \text{m}^2)$ |
|------------------------|-----------|---------------------------|-----------|----------------------------------------|
| Living room fire       |           |                           |           |                                        |
|                       | 10        | 0.092                     | 0.012     | 0.180                                  |                                       |
|                       |           |                           |           |                                        |
|                       | 50        | 0.134                     | 0.027     | 0.350                                  |                                       |
|                       | 60        | 0.550                     | 0.073     | 1.081                                  |                                       |
|                       | 50        | 0.805                     | 0.163     | 2.097                                  |                                       |
| Limited ventilation living room fire |           |                           |           |                                        |
|                       | 10        | 0.092                     | 0.012     | 0.180                                  |                                       |
|                       |           |                           |           |                                        |
|                       | 50        | 0.134                     | 0.027     | 0.350                                  |                                       |
|                       | 60        | 0.550                     | 0.073     | 1.081                                  |                                       |
|                       | 50        | 0.805                     | 0.163     | 2.097                                  |                                       |
| Kitchen fire          |           |                           |           |                                        |
|                       | 10        | 0.092                     | 0.012     | 0.180                                  |                                       |
|                       |           |                           |           |                                        |
|                       | 50        | 0.134                     | 0.027     | 0.350                                  |                                       |
|                       | 60        | 0.550                     | 0.073     | 1.081                                  |                                       |
|                       | 50        | 0.805                     | 0.163     | 2.097                                  |                                       |

Table 3. Firefighter penetrate dosages of particles in three residential fire scenarios during various fire event time.

| Time of exposure (min) | Q (L/min) | Number $(10^7/\text{#})$ | Mass (µg) | Surface Area $(\times10^{-7} \text{m}^2)$ |
|------------------------|-----------|---------------------------|-----------|----------------------------------------|
| Living room fire       |           |                           |           |                                        |
|                       | 10        | 0.092                     | 0.012     | 0.180                                  |                                       |
|                       |           |                           |           |                                        |
|                       | 50        | 0.134                     | 0.027     | 0.350                                  |                                       |
|                       | 60        | 0.550                     | 0.073     | 1.081                                  |                                       |
|                       | 50        | 0.805                     | 0.163     | 2.097                                  |                                       |
| Limited ventilation living room fire |           |                           |           |                                        |
|                       | 10        | 0.092                     | 0.012     | 0.180                                  |                                       |
|                       |           |                           |           |                                        |
|                       | 50        | 0.134                     | 0.027     | 0.350                                  |                                       |
|                       | 60        | 0.550                     | 0.073     | 1.081                                  |                                       |
|                       | 50        | 0.805                     | 0.163     | 2.097                                  |                                       |
| Kitchen fire          |           |                           |           |                                        |
|                       | 10        | 0.092                     | 0.012     | 0.180                                  |                                       |
|                       |           |                           |           |                                        |
|                       | 50        | 0.134                     | 0.027     | 0.350                                  |                                       |
|                       | 60        | 0.550                     | 0.073     | 1.081                                  |                                       |
|                       | 50        | 0.805                     | 0.163     | 2.097                                  |                                       |

**Implication of inhaled fire smoke particles**

Clinical studies pointed out that short-term exposure to 1.2 to $1.45 \times 10^5$ ultrafine particles/cm$^3$ could induce a variety of changes in the cardiovascular parameters in healthy volunteers.$^{[48,49]}$ Based on the current measurement, total number concentration of $1.26 \times 10^7$, $4 \times 10^6$, and $1.58 \times 10^5$ particles/cm$^3$ were detected in the three residential fire scenes at the selected time. All of the dosages exceeded the recommendations by the clinical studies in number concentrations. These implied tremendous cardiovascular risk for firefighters. According to NIOSH, the exposure limit for inorganic arsenic and chromium compounds were recommended not to exceed 0.002 mg/m$^3$ and 0.5 mg/m$^3$ in normal working conditions. Arsenic mass concentration in the limited ventilation living room was measured at 0.0023 mg/m$^3$, exceeding recommendations from NIOSH. Chromium mass concentrations in the living room and kitchen were below the NIOSH standard. Close attention should be paid to arsenic particles, and firefighters are suggested to use respiratory protection especially in the smoldering room fire.

The numerical study shows substantial nasal dosages for firefighters during overhaul of the three residential fire scenes. For a duration of 10 min, firefighting activities at the breathing rate of 30 L/min, 0.061 µg, 6.78 µg, and 0.699 µg mass dosages in the nasal cavity of specific toxic particles are detected in the living room, smoldering living room, and kitchen fire; albeit, simulations used continuous inhalation model. At the same time, mass dosages, penetrating deep into lower respiratory tract were estimated at 4.65, 720.4, and 28.26 µg in the three fire scenes respectively, suggesting significant risk of increased lower respiratory disease and cardiovascular risks. For firefighters working for a longer duration (60 min) in fire events without SCBAs, they are usually in moderate cardiac load at the breathing rate of 50 L/min. Mass dosages in the nasal cavity are 0.061 µg, 6.89 mg, and 375.8 µg in the three fire scenes, significantly threatening the respiratory and cardiovascular health of the firefighters. In this circumstance, 0.163, 134, and 8.74 µg of smoke particles deposit onto the middle meatus for the three fire events, which could further travel deep into sinus and cause sinus dribbling or sinusitis,
shorten firefighters’ career life. The toxic particle mass dosages in the human airway suggest that firefighters should not remove SCBAs during either fire suppression or overhaul, especially in the smoldering fire events, such as in the limited ventilation living room fire.

Currently, there is no direct research connecting inhalation dosimetry and the respiratory consequences of firefighters. More clinical investigations are needed. These findings indicate that real time particle size distribution and concentration measurements, as well as deposition estimations, are crucial in determining the actual exposure risks. It should be noted that the current simulations used simplifications including using only instantaneous peak particle concentration and continuous inhalation, which may differ from dosages in real fire events. However, the chosen peak particle concentration during the start of fire overhaul was a reasonable first step to assess firefighter’s inhalation risk.

Conclusion

Simulation in a realistic firefighter nasal cavity replica with facial features and external environment was performed to estimate the realistic exposure of particles for firefighters in three residential fire scenarios. Inhalation risk assessment in terms of actual dosimetry (in mass, number, and surface area) of toxic particles was conducted by using the deposition equations developed in the firefighter nasal cavity, middle meatus, and penetrate regions. By using experimental measurements of particle concentration and size distribution in representative fire scenes, predictions of airway dosages in all dose metrics (mass, number, and surface area) for firefighter in fire scenarios were performed.

Firefighters usually remove their SCBAs during overhaul of residential fires. The simulation showed a strong monotonic increase of nasal dosages (of smoke particles) with breathing rate and fire activity duration across all residential fire scenarios. The high mass dosages modeled identified deposition in the middle meatus and penetration into lower airways, suggesting a risk of sinusitis, rhinitis, and lower respiratory and cardiovascular diseases. Particles with larger size were the dominant factors in mass and surface area dosages. The firefighters are recommended not to remove their SCBA during fire suppression and overhaul, especially in smoldering fires.

Further clinical investigations are needed to link inhalation dosimetry and respiratory diseases. In addition, a complete inhalation risk assessment requires recommendation based on surface area. The particle concentration in real time in fire overhaul is critical to be applied in recognizing the actual exposure risks. Nonspherical particles will be added in future studies. Moreover, firefighters’ inhalation risk assessment with self-contained breathing apparatus and cyclical breathing pattern should also be considered in the future.

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Real time smoke particle size distribution and concentration in three fire scenes were obtained from Underwriters Laboratories’ large-scale fire experimental measurements.

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ORCID

Yidan Shang  http://orcid.org/0000-0001-8705-1625
Lin Tian  http://orcid.org/0000-0002-7779-1926

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