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Transient transport model of particles resulting from high momentum respiratory activities: Inter-personal exposure

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**Abstract**

In this work, a transient mathematical multi-region zonal transport model of particle behavior resulting from high momentum respiratory activities (HMRA) is developed focusing on the transient inter-personal exposure (IPE) in indoor spaces ventilated by displacement ventilation (DV) systems. The developed model was validated by experimentation and by published empirical data.

Three stages are identified with respect to time for the variation of the IPE: a first stage dominated by the propagation and decay of the exhaled jet, a particles' redistribution stage, and a particles' removal stage. The inhaled dose is affected by the DV flow rate, cough velocity, particle diameter and distance between the occupants. The DV system with a flow rate of 100 L/s reduced significantly the inhaled dose during particle redistribution and removal stages decreasing the total inhaled dose by 83% compared to a flow rate of 50 L/s. IPE is higher when particle diameter is increased from 1 to 20 μm due to the opposition of particle removal by the upward DV.

A comparison between steady and transient modeling of the IPE showed that steady modeling captures the physics affecting particle spread due to HMRA but it over-predicts the inhaled dose. It is found that for a DV flow rate of 100 L/s and a cough velocity of 22 m/s during 1 s, and 1 μm particles, the minimum required distance between the occupants for a threshold inhaled dose of 10⁻⁵ kg is nearly 0.5 m by transient modeling while it is 2.15 m by steady state modeling.

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1. Introduction

With the increased time spent by people in indoor environments and the outbreaks of the Severe Acute Respiratory Syndrome (SARS) [1] a lot of concerns have been raised on people health in indoor environments, particularly on the control and possible prevention of airborne disease transmission [2]. Humans generate particles by the different respiratory activities (talking, breathing, sneezing, and coughing) [3] and through emissions from the skin, hair, and clothes etc. [4]. It is well established that one of the main contributors to cross-contamination between occupants in indoor environments are high momentum respiratory activities as sneezing or coughing [5–7] which will be studied in the current work. In fact, the intense upper respiratory activities generate a higher number of particles than the normal breathing [8]. Furthermore, pathogens delivered by strong expiratory jets could be transmitted for large distances up to 3 m in the horizontal direction for high outlet velocities [9,10] increasing the inter-personal exposure (IPE) between occupants.

The transient behavior of sneezing and coughing complicates modeling the spread of particles resulting from these activities. For simplification, some researches modeled coughing as steady state using computational fluids dynamics (CFD) [10] or simplified modeling [11] to understand the physics affecting disease transmission resulting from coughing. However, steady-state simulations might not reflect the complete physics affecting particle distribution resulting from transient respiratory activities (TRA). For instance, Rim and Novoselac [12] studied particle distribution caused by short term and continuous particle generation for different ventilation configurations. They found that for ventilation governed by buoyant flows, disease transmission resulting from a short-term source release differs from continuous source emission. Furthermore, the exposure is higher under continuous generation than under particle release for a limited period of time. Hence, contaminant exposure due to short-term indoor emissions differs from exposure estimated using steady-state source. From their observations, Rim and Novoselac [12] concluded that caution...
should be taken when making conclusions and recommendations about the risk of infection from short term sources emissions using steady-state simulations. Since high momentum respiratory activities (HMRA) as coughing and sneezing are transient, assessing the actual IPE from these activities requires transient modeling. Steady state simulations over-predict the IPE which might lead to over-designed ventilation flow rates to maintain acceptable indoor air quality (IAQ) [12].

Transient modeling not only allows assessing accurately the risk of infection but also can reveal the effect on IPE of transient parameters (e.g. period of injection, time) that cannot be captured by steady state modeling. For instance, Xiaoping et al. [13] observed that particle concentration variation with time can be divided into two main stages: a first stage dominated by the exhaled jet propagation, and a second stage affected by the ventilation configuration. The observation of transient particle concentration variation cannot be deducted from steady-state simulation. Furthermore, many efforts have been made to reveal the effect of ventilation types, relative orientation between the occupants, sneezing and coughing velocities, in addition to droplet size distribution on the transient spread of exhaled droplets in variable types of indoor environments using CFD and experimental simulations. Mui et al. [14] investigated by numerical simulations variable velocities and orientations of sneezing under mixed ventilation (MV) and displacement ventilation (DV) schemes. They concluded that the spread of droplets in the room was faster under MV than under DV. Gao and Niu [15] conducted a numerical study in a room occupied by two persons sitting opposite to each other. They concluded that the propagation of the high momentum sneezed jet in the horizontal direction is one of the main causes of cross-contamination between the occupants [15]. Licina et al. [16] investigated experimentally the effect of the distance of cough source from an exposed occupant, airflow velocity and direction on the IPE. They observed that increasing the separating distance between the exposed person and the location of the cough source decreases the peak exposure with an increased exposure delay time after the cough. They also reported that assisting flow from below (which is the case of DV) decreased the personal exposure with the increase of supplied air velocity. Chen and Zhao [8] studied particle distribution resulting from the different respiratory activities (breathing, coughing, and sneezing) for a wide particle sizes range extending from 0.1 to 200 μm. They showed that the exhalation velocity and the droplet size with initial diameter from 10 μm to 100 μm largely affected the particle distribution [8].

Displacement ventilation is known to provide good IAQ in the occupied zone [17–19]. It was reported to have a high efficiency in the reduction of disease transmission when particles were generated by low momentum respiratory activities (normal breathing) as the upward convective plumes of the infected person carried nearly 100% of the exhaled particles to be exhausted at the ceiling level [18,20]. On the other hand, it was shown that higher momentum respiratory activities degraded the effectiveness of DV system in providing good IAQ in the occupied zone because they lead to a horizontal spread and accumulation of infected particles at the breathing level [11,21,22]. The performance of DV system in terms of removal of particles resulting from TRA was investigated by experimentation and CFD simulations. Gao et al. [23] studied the lock-up
phenomenon of human exhaled droplets in a room ventilated by DV and conducted CFD simulations to determine the IPE resulting from TRA [15]. Seepana and Lai [6] observed experimentally and by CFD that concentration peaks at the breathing height in DV were relatively high compared to MV due mainly to high sneezing velocity and thermal stratification. However, experimental and CFD techniques have high cost and computational time. Therefore, simplified modeling is an essential design tool for capturing the principal physics involved at low computational time [24]. Habchi et al. [18] developed a simplified zonal model to assess the risk of cross-contamination between occupants resulting from normal breathing activities in office buildings ventilated by DV. They extended their model to account for HMRA by coupling between two particles’ transport models [11]. Nevertheless, their developed models were steady hence they were not able to assess the variation with time of the IPE resulting from TRA as sneezing and coughing.

In this work, a transient zonal model is developed to compute particle distribution resulting from TRA in indoor environment conditioned by DV systems. The model is validated with experimental and literature data. This is followed by a parametric study conducted to assess the effect of variable factors on the cross-infection between occupants (DV flow rate, coughing velocity, particle diameter, and distance between the occupants). Recommendations for reduced IPE in spaces ventilated by DV system are established based on understanding transient particle behavior resulting from short-term release respiratory activities as coughing and sneezing.

2. Methodology

2.1. Mathematical model development

The simulation of transient horizontal particle spread resulting from HMRA requires coupling two transient sub-models extending the work done by Habchi et al. [11]. A transient transport model of exhaled particles computes the percentage of generated particles penetrating the infected thermal plume and tracks the exhaled jet propagation with time and distance. This model is coupled with another transient transport model for particle exchange between the different affected layers and regions. The developed transient multi-region zonal model will be validated by experimental and literature data.

Occupants are represented by heated cylinders [11,18,25,26] as shown in Fig. 1. The domain is discretized into horizontal layers with several lumped regions within each layer to capture the vertical motion of the air surrounding the thermal plumes and the effect of buoyant flows, [11,18,25]. Vertically three main zones are identified [11,18]:

- Zone I characterized by upward flow in the air surrounding the thermal plumes extends from the floor to the stratification height where the surrounding air and DV flow rates are equal [26,27];
- Zone II is bounded by the stratification and critical height where rising plumes expand [18,28]; and
- Zone III is a recirculation zone where surrounding air and thermal plumes merge together [18,28].

Establishing the flow field in the ventilated space is essential for computing the particle distribution within the room. In Zones I and II below the recirculation zone, lateral flow is negligible compared to vertical air motion [11,19,25]. The stratification and critical heights are affected by the DV flow rate and the strength of convective buoyant plumes. The thermal plume upward mass flow rate, $M_{pl}$ induced by the heat source for known room vertical temperature gradient $dT_{v}/dz$ is determined using Mundt correlation [27] as follows:

$$M_{pl} = 2.38 \times 10^{-3} \rho Q_{H}^{3/4} \left(\frac{dT_{\infty}}{dz}\right)^{-5/8} \text{m}_n \quad (1a)$$

$$\text{m}_n = 0.004 + 0.039 z_n + 0.38 z_n^2 - 0.062 z_n^3 \quad (1b)$$

$$z_n = 2.86(z - z_v) \left(\frac{dT_{\infty}}{dz}\right)^{3/8} Q_{H}^{-1/4} \quad (1c)$$

where $\rho$ is the air density, $Q_H$ is the heat source strength, $T_{\infty}$ is the room temperature, $z$ is the plume height from the floor, $z_v$ is the virtual point source height [18], and $z_n$ and $m_n$ are non-dimensional parameters defined by Mundt [27].

A mass balance applied for each layer $i$ gives the expression of the mass flow rate of the surrounding air $M_{a,i}$ at the interface between layers $i$ and $i + 1$:

$$M_{a,i} = M_s - \sum_{j=1}^{n} M_{w,ij} + \sum_{k=1}^{m} M_{pl,k} \quad (1d)$$

where $M_s$ is the mass supply flow rate, $M_w$ the wall plumes given by Jaluria formulation [11,29], $n$ is the number of vertical walls within a layer $i$, and $m$ is the number of convective thermal plumes. The stratification height is the level at which $M_{a,i} = 0$. The upward velocity strength $v_{up,i}$ in Zone I at layer $i$ is given by:

$$v_{up,i} = \frac{M_{a,i}}{A_{ij}} \quad (1e)$$

where $A_{ij}$ is the cross-sectional area of the air surrounding the plumes.

The critical height position from the virtual point source is given by:

$$z_c = 0.74 Q_{H}^{0.25} \left(\frac{dT_{\infty}}{dz}\right)^{-3/8} \quad (1f)$$

Particle distribution within zones I and II is computed in the horizontal level by dividing each layer into five principal regions [11]: infected plume region, exposed plume region, microclimate 1, microclimate 2, and macroclimate. A detailed description about the space discretization can be found in our previous work [11].

Microclimate 2 is of particular interest in predicting cross-contamination between occupants since it constitutes a cylindrical region tangent to the occupants and limited by their convective upward plumes until their expansion [11]. The exhaled jet is highly unidirectional propagating and decaying with time from the infected to the exposed occupant. In order to capture the transient propagation of the exhaled jet and to assess accurately the IPE, microclimate 2 was discretized into a number $N$ of tangent cylindrical sub-microclimates zones as shown in Fig. 1.

2.1.1. Characterization of exhaled jets

The characterization of exhaled jets is very important for accurate prediction of the resulting particle distribution. There have been extensive reviews [7,30] on the size distribution of human exhaled droplets. Nicas et al. [30] found a correlation between the equilibrium diameter of the completely evaporated particle ($deq$) and the initial diameter ($d_i$) where $deq = 0.44 d_i$ and this correlation was adopted in several studies [31–33]. Chen...
and Zhao [8] found that when the normalized evaporation time was lower than 0.051, the evaporation time can be neglected in the modeling. The coughing process has been simulated in several works with variable cough velocities. Gupta et al. [34] and Kwon et al. [35] conducted experiments on a number of human subjects to determine initial velocities of a cough and characterize the coughing process. Zhu et al. [10] showed that the peak cough velocity varied from 6 to 22 m/s. Chao et al. [36] reported that the average expiration air velocity was 11.7 m/s for coughing which is close to the average value of 11.2 m/s found by Gupta et al. [34]. Accordingly, the cough velocity was varied in the range of [6 m/s; 22 m/s] in this study. Furthermore, Gupta et al. [34] found that the average mouth opening for males during a cough is equal to 4 cm² which was used in several cough studies [37,38]. Therefore, this value was adopted in the current work corresponding to an equivalent mouth diameter of nearly 2.25 cm.

2.1.2. Transient propagation of the exhaled jet

In order to model particle spread resulting from coughing or sneezing, the transient propagation of the exhaled jet should be accurately modeled.

A top-hat profile was used for the generation velocity [10,15]:

\[
V_{\text{gen}}(t) = \begin{cases} 
V_g & \text{if } t \leq t_{rl} \\
0 & \text{if } t > t_{rl}
\end{cases}
\]

(2a)

where \( V_{\text{gen}}(t) \) is the generation velocity function of time, \( V_g \) is the generation velocity during the cough and \( t_{rl} \) is the cough release time. Chen et al. [39] modeled transient propagation of high momentum jets and validated their model for different ventilations configurations. Chen formulation [39] is used in the current study and is summarized below.

The horizontal jet peak \( V_{\text{max}} \) decreases with the horizontal co-ordinate \( y \) from the source and is a function of the injection velocity \( V_{\text{inj}} \) and the hydraulic diameter of the mouth \( d_{\text{inj}} \). \( V_{\text{max}} \) is given by the following expression [39]:

\[
V_{\text{max}}(y) = \begin{cases} 
V_{\text{inj}} & \text{if } y < 6.8d_{\text{inj}} \\
\frac{6.8d_{\text{inj}}V_{\text{inj}}}{y} & \text{if } y \geq 6.8d_{\text{inj}}
\end{cases}
\]

(2b)

The propagation jet is stopped by an obstruction (e.g. wall, exposed occupant) or damped when the jet peak becomes lower.
than a reference velocity of 0.25 m/s [39]. Thus, the maximal propagation distance \( y_{\text{max}} \) is given by:

\[
y_{\text{max}} = \min \left( y_{\text{ob}}, \frac{6.8 d_{\text{inj}} V_{\text{inj}}}{V_r} \right) \quad (2c)
\]

where \( V_r \) is the reference velocity and \( y_{\text{ob}} \) is the obstruction distance.

The time needed by the jet to reach a position \( y \) is given by Ref. [39]:

\[
t_{\text{tr}}(y) = \int_{0}^{y} \frac{1}{V_{\text{max}}(y)} \, dy = \frac{6.8 d_{\text{inj}}}{V_{\text{inj}}} + \frac{y^2 - (6.8 d_{\text{inj}})^2}{13.6 V_{\text{inj}} d_{\text{inj}}} \quad (2d)
\]

The decay of the velocity with time after the jet had reached a certain distance \( y \) along the unidirectional propagation line [39] (for \( y \) between 0 and \( y_{\text{max}} \)) is given by:

\[
V(y, t) = V_{\text{max}}(y) e^{-t/\tau} \quad (2e)
\]

where \( \tau \) is the time constant given by the following expression [39]:

\[
\tau = \int_{0}^{y_{\text{max}}} \frac{1}{V_{\text{max}}(y)} \, dy = \frac{6.8 d_{\text{inj}}}{V_{\text{inj}}} + \frac{y_{\text{max}}^2 - (6.8 d_{\text{inj}})^2}{13.6 V_{\text{inj}} d_{\text{inj}}} \quad (2f)
\]

The unidirectional horizontal jet decay \( \chi(y, t) \) along the propagation line (illustrated in Fig. 2) can be computed from:

\[
\chi(y, t) = \frac{V(y, t)}{V_{\text{inj}}} = \frac{V(y, t)}{V_p} = \frac{V(y, t)}{\lambda V_g} \quad (2g)
\]

where \( V_{\text{inj}} \) is the penetrating velocity computed from the exhaled particles model [11]. In fact, the upward plume of the infected person obstructs the propagation of the generated jet, thus the exhaled flow does not penetrate completely to the surrounding [11]. The penetrating portion \( \lambda \) can be determined by solving for the Navier–Stokes equations within the thermal boundary to compute the penetrating velocity \( V_g \) [11].

The propagation of the exhaled jet with time and distance affects the upward DV flow within each zone such that mass balances are conserved. The variation with time of the horizontal flow entering a sub-microclimate 2 number \( j \) \( \lambda_1 \chi(y_{j-1}, t) M_g \) is different from the horizontal exiting flow \( \lambda_2 \chi(y_j, t) M_g \) due to the time delay and flow decay resulting from the jet propagation. The difference between the horizontal entering and exiting flows is compensated by the vertical air motion within the surrounding air. Convective flows through a sub-microclimate 2 number \( j \) within the generation layer are illustrated in Fig. 2.

2.1.3. Transient zonal model for particle distribution

The transient formulation of the jet propagation is used as boundary conditions for the transient multi-zonal model for spaces ventilated by DV system to predict particle spread resulting from HRMA. The model computes the temperature, velocity and concentration fields targeting mainly the transient IPE. The complete formulation for predicting the vertical temperature and velocity in different zones and coupling between the transport model of exhaled particles and multi-zonal model can be found in our previous work [11,18]. To predict particle distribution within the variable zones, the different physics affecting particle spread were included in the model

\[ [18,25,28,40], \text{For instance, convective DV flows and diffusion between and within the different regions were considered [11,18]. Furthermore, interactions between upward convective plumes and the surrounding air by lateral diffusion and air entrainment were incorporated in the proposed physical model [25,28]. Since the developed model involves particles of variable diameters, deposition on walls of variable orientation and gravitational effect were included.}]

The detailed steady state mass balances within the variable zones can be found in the work of Habchi et al. [11]. In the current model, the same physics are involved but transient formulation is incorporated. The contribution of this work is that it simulates the propagation of the exhaled jet between the occupants at the breathing level and assesses the transient IPE. In order to capture the transient particle spread microclimate 2 was sub-divided into 20 sub-microclimates zones to verify grid independent results. A sub-microclimate 2 region number \( j \) interacts with the adjacent regions and the infected or and exposed thermal plumes and the concentration in this zone is governed by the following equation.
Concentration at the breathing level of the exposed person \( C_{a,mic2,j,i} \) refers to entrainment, (surrounding air), its interaction area with plume molecular Brownian diffusion coefficient, \( M_a \) is the mass \( \rho \frac{\partial C_{a,mic2,j,i}(t)}{\partial t} = \left[ \max \left( M_{a,mic2,j,i-1} + \lambda \left( x(y_{j-1},t) - x(y_j,t) \right) M_g \right) \right] C_{a,mic2,j,i}(t) + \max \left( -M_{a,mic2,j,i} - \lambda \left( x(y_{j-1},t) - x(y_j,t) \right) M_g \right) C_{a,mic2,j,i}(t) - \max \left( M_{a,mic2,j,i} + \lambda \left( x(y_{j-1},t) - x(y_j,t) \right) M_g \right) C_{a,mic2,j,i}(t) + \max \left( -M_{a,mic2,j,i} - \lambda \left( x(y_{j-1},t) - x(y_j,t) \right) M_g \right) C_{a,mic2,j,i}(t) + \left[ \rho \gamma A_{a,mic2,j,i} C_{a,mic2,j,i+1}(t) - \rho \gamma A_{a,mic2,j,i-1} C_{a,mic2,j,i}(t) \right] + \left[ A_{a,mic2,j,i} D_p \rho \left( \frac{\partial C_{a,mic2,j,i}(t)}{\partial z} \right) \right] - \left[ \sum_{k=1}^{m} A_{int,mic2,j/pl(i,k)} (D_p + D_t) \rho \left( \frac{\partial C_{pl(i,k)}(t)}{\partial r} \right) \right] - \left[ \sum_{k=1}^{m} M_{int,mic2,j/pl(i,k)} C_{a,mic2,j,i}(t) \right] + D_p A_{int,mic2,j/mic2,j-1,i} \rho \left( C_{a,mic2,j-1,i}(t) - C_{a,mic2,j,i}(t) \right) \frac{r_{mic2,j} - r_{mic2,j-1}}{r_{mic2,j} - r_{mic2,j-1}} - D_p A_{int,mic2,j/mic2,j+1,i} \rho \left( C_{a,mic2,j+1,i}(t) - C_{a,mic2,j,i}(t) \right) \frac{r_{mic2,j+1} - r_{mic2,j}}{r_{mic2,j+1} - r_{mic2,j}} + \lambda \left( x(y_{j-1},t) \right) M_g C_g - \lambda \left( x(y_j,t) \right) M_g C_g \right]_{i=g}^{i=g}

\text{Normalized Concentration} = \frac{\text{Concentration at the breathing level of the exposed person}}{\text{Concentration at generation}} \quad (4a)

The maximal function is introduced to account for the variation in the surrounding airflow direction allowing the equation to be applicable within the different zones defined in the vertical direction [11,18]. For instance, the flow is upward below the stratification height while it is downward above the stratification height. The particle concentration is \( C \), \( v_s \) is the settling velocity, \( D_p \) is the molecular Brownian diffusion coefficient, \( D_t \) is the turbulent diffusion coefficient, \( M \) is the mass flow rate, \( t \) is the time, \( r_{mic2,j} \) is the radius of the sub-microclimate 2 number \( j \). The subscripts: \( i \) refers to the layer number, \( a \) refers to the air outside the thermal plumes (surrounding air), \( pl \) refers to the air inside the thermal plume, \( int \) refers to interaction, \( f \) to interaction and \( g \) refers to generation. \( A_{a,mic2,j,i} \) represents the cross sectional area of the sub-micoclimaten 2 number \( j \) at the interface between layers \( i \) and \( i + 1 \), and \( A_{int,mic2,j/pl(i,k)} \) its interaction area with plume \( k \) within the layer \( i \). These interaction areas are found mathematically as the intersection between two surfaces of defined geometry (the conical shape for the plumes and the circular shape for the sub-microclimates 2).

The terms of the right hand side of Equation (3) represent respectively: i) the vertical convection flux of particles in the sub-microclimate 2 number \( j \) resulting from the DV flow rate within the surrounding air affected by the propagation of the exhaled jet; ii) the gravitational flux; iii) the vertical diffusion flux; iv) the lateral particle diffusion fluxes presenting the interactions between the sub-microclimate 2 air region \( j \) and the plumes due to concentration gradients; v) the entrainment fluxes of the sub-microclimate 2 region \( j \) by the rising plumes; vi) the diffusive interactions of sub-microclimate 2 number \( j \) with the adjacent regions; vii) the horizontal convective flux which is only present within the generation layer due to the exhaled jet uni-directional propagation. The left hand side of Equation (3) is the transient storage term.

In order to understand the effect of the different variables involved on the IPE, two parameters are defined and their variation in time is to be observed. The first parameter is the normalized concentration given by Equation (4a):

where the breathing level of the exposed person is simulated by the last sub-microclimate 2 which is adjacent to the exposed person at the nose level (centered at 1.05 m in height). The second parameter introduced is the infection index \( I \) in kg defined by the following equation [15]:

\[ I(t) = \int_0^t \frac{C_{in}}{C_g} M_{in} \, dt \quad (4b) \]

where \( C_{in} \) (kg/m³) is the inhaled concentration by the exposed person equal to the concentration within the last sub-microclimate 2 zone, \( M_{in} \) (kg/s) is the inhalation rate of the exposed person, \( C_g \)
(kg/m³) is the concentration of generation, \( t \) (s) the time. The infection index is used to assess the IPE. The inhaled dose (ID) during a certain period of time (\( T \)) can be determined according to the following equation:

\[
IDT = \frac{I(t_e,T)}{C_0} - \frac{I(t_b,T)}{C_1}
\]

where \( t_b,T \) and \( t_e,T \) are respectively the beginning and end time of the considered period.

### 2.2. Experimental methodology

In order to validate the ability of the current model in capturing the transient jet propagation and decay with distance, an experimental set-up was constructed in a controlled climatic chamber conditioned by a DV system (Fig. 3a). The experimental room is of inner dimensions 2.5 m × 2.75 m × 2.8 m with supply and return grills cross-sectional area of respectively 0.582 m (width) × 0.24 m (height) and 0.44 m (width) × 0.19 m (height). Two occupants were represented by thermal cylinders of 0.3 m in diameter and 1.2 m in height generating each 100 W. Due to the experimental constraint of highly insulated walls, the load was distributed between the lighting (100 W) and the heated cylinders such that the load per unit floor area is approximately 40 W/m². The DV supply conditions were a flow rate of 100 L/s and a temperature of 22 °C. A thermoanemometer (ABK precision 731A) with an accuracy of ±0.6 °C for temperature measurements and ±2% of full scale for velocity measurements was used.

In order to remove particles from the supplied air before introducing it to the chamber, high efficiency particulate filters (KS-NG-K1/2 HEPA filters) were adopted. Prior to each set of measurements, the light and the heated cylinders were turned on and the DV system was run for 3–4 h to reach steady-state conditions. Then mono-disperse heavy 5 μm particles of density of 912 kg/m³ were generated from a condensation aerosol generator (TSI Model 3475) (Fig. 3b) with a flow rate of 4 L/min at a velocity of 10 m/s during 4 s. The TSI generator used can generate mono-disperse particles with an aerosol geometric standard deviation smaller than 1.1. A chronometer watch of 0.01 s accuracy was used to control the generation time. The validation consisted of comparing measured and predicted particles concentrations at different distances (0.5, 1, and 1.5 m) from the generation (Fig. 3a).

Particle concentrations were measured using an optical particle sizer (TSI model 3330) (Fig. 3b) giving measurements with a relative error lower than 5%. A sampling time of 1 s was selected to track particle concentration variation with time. Results were recorded automatically by a computer for post-processing. The measured concentrations were normalized by the generation concentration for comparison with the predictions of the simplified model.

### 2.3. Parametric study

The developed mathematical model will be used to perform a parametric study to investigate cross-contamination between two occupants (75 W each) within a space of dimensions...
3.4 m x 3.4 m x 2.6 m ventilated by a DV system. The frequently encountered heat sources (occupants, lighting, external heat from walls) are considered. The lighting load was set to 100 W and wall heat fluxes to 200 W. The case study is selected to represent typical of ceiling load at 40 W/m² of floor area based on upper limit of load removal by DV system \[41,42\]. The generality of the obtained results is due to the fact that office spaces are usually configured in modular workstation units where each unit would have identical number of occupants as well as electrical load. One occupant generated particles transiently during 1 s simulating a cough released by an infected person while the second occupant was healthy simulating the exposed person. In order to assess the risk of HMRA, the effect of different variables such DV flow rate, coughing velocity, particle diameter, and distance between the occupants on cross-infection is studied. The DV supply flow rate is varied in the range of \([50\text{ L/s} - 200\text{ L/s}]\) and the supply temperature is fixed to 22 °C \[11\]. In fact, Habchi et al. \[18\] have shown that a flow rate of 100 L/s is required to insure both thermal comfort and IAQ for typical office spaces loaded by 40 W/m² ventilated by DV system considering normal respiratory activities. Then they extended their model to consider HMRA \[11\] but they considered continuous generation which might over-predict the IPE. In this study, a typical cough velocity in the interval of 6 m/s to 22 m/s and an exhalation area of 4 cm² \[34,43\] are used. Particle diameter is varied in the range of 1 μm—50 μm and the distance between the occupants is varied between 0.5 m and 3 m \[11\].

Interpersonal exposure was studied for different DV supply flow rates (50, 75, 100 L/s), cough velocities (6, 11, and 22 m/s), particles diameters (1, 20, 30, and 50 μm), and distances between the occupants (0.5, 1, 2, and 3 m). Each of these factors was varied while the other variables were fixed to capture the studied parameter effect on IPE.

3. Results and discussions
3.1. Model validation with experiments

Fig. 4 represents the comparison between the model and experiments of the variation with time and distance of the particle concentration normalized by the generation concentration. Three cases were investigated at distances from generation of 0.5, 1 and 1.5 m while keeping occupants’ separating distance fixed at 1.5 m. After generation, the normalized concentration increases with time reaching a peak and then decays. As the distance from generation increases, the concentration peak decreases due to the exhalation jet decay and the time needed to reach this peak increases because of the time delay resulting from the jet propagation. Good agreement of the order of 10% with a maximum error of 16% was obtained between the model and experimental results validating the ability of the model in capturing the exhaled jet propagation and decay with time and distance.

3.2. Validation with literature data

The research study of Gao and Niu \[15\] was used to validate the ability of the model in predicting the variation of the IPE with time. In their work, two persons (contaminated and exposed occupants) in the seated position facing each other and separated by a distance of 1.2 m occupy a chamber of dimensions \(2.7\text{ m} \times 2.6\text{ m} \times 2.2\text{ m}\). The chamber is ventilated by the DV system with a supply flow rate of 0.024 m³/s and a temperature of 22 °C. One sneeze exhaled from the mouth of the infected occupant lasting for 1 s with a volume flow rate of 250 l/min is simulated \[15\]. The variation of the inhaled fraction by the exposed occupant is simulated during and after the sneeze. The case study of Gao and Niu \[15\] was simulated by our developed model.

Fig. 5 represents the comparison between Gao and Niu \[15\] and...
model results of the variation of the IPE with time. The results are in agreement with a relative error of the order of 10% with a maximum error of 15%. The obtained agreement validated the ability of the model in predicting the variation of the IPE with time by simulating it as the concentration within the last submicroclimate 2 which is at the breathing level of the exposed person.

3.3. Case study results

3.3.1. DV flow rate effect

Table 1 summarizes the effect of the DV flow rate on different parameters. As the DV flow rate increases, the stratification and critical heights are shifted upward resulting in an increase in Zones I and II heights and a decrease in Zone III height. It is clear that the increment of the DV supply rate strengthened the occupants’ thermal plume and the upward velocity in Zone I. This velocity decreases from a maximum value at the floor level to zero at the stratification height due to air entrainment by the convective rising plumes. The vertical air motion by buoyancy effects leads to temperature stratification within the space resulting in a temperature increase from the floor to the ceiling levels (see Table 1). As DV flow rate increases, room air temperature gradient decreases.

IPE was studied for different DV supply flow rates (50, 75, 100 L/s) for a cough velocity of 22 m/s, 1 μm particles in diameter, and 1 m separating distance between occupants. Fig. 6a illustrates the effect of the DV supply flow rate on the variation with time of the normalized concentration at the breathing level of the exposed person. Logarithmic scale was used for the figure’s axis for clarity of illustration. Three stages can be defined with respect to time for the different DV supply flow rates (Fig 6). The first stage is dominated by the propagation and decay of the exhaled jet (Fig. 6a) and is very fast lasting for few seconds (Table 2a). In the second stage, particles are redistributed by the ventilation system for several minutes. A final stage is the removal stage by deposition and upward transport by the DV system and has the largest period (Fig 6a). The observation of different exposure stages is in agreement with the findings of Xiaoping et al. [8]. Table 2a summarizes the periods of the three stages for each DV flow rate. The period of these three stages varied with the DV flow rate. The larger the flow rate is, the lower are the durations of the three stages (Fig. 6a and Table 2a).

Furthermore, the effect of the DV flow rate on the duration of a stage is highest for the third stage and lowest for the first stage (Table 2a).

For the different flow rates, a concentration peak (penetration peak) is observed during the first stage due to the jet propagation. The higher the DV flow rate is, the lower is the penetration peak because a larger number of particles is convected upward by the DV system (Fig. 6a). This observation is in agreement with the findings of Licina et al. [16]. A second inhaled concentration peak

| Model Parameters                        | DV supply flow rate (L/s) |
|-----------------------------------------|---------------------------|
|                                         | 50 L/s | 75 L/s | 100 L/s |
| Height of Zone I (m)                    | 1.25   | 1.35   | 1.55    |
| Height of Zone II (m)                   | 0.41   | 0.47   | 0.53    |
| Height of Zone III (m)                  | 0.94   | 0.78   | 0.50    |
| Strength of the occupant plume before expansion at the critical height (kg/s) | 0.044  | 0.053  | 0.067   |
| Maximum air velocity in Zone I (m/s)    | 0.00432| 0.00648| 0.00865 |
| Air temperature at the floor level (°C) | 23.49  | 23.38  | 23.27   |
| Air temperature at the ceiling level (°C)| 31.12  | 29.10  | 27.08   |

Fig. 5. Comparison of current model prediction of personal exposure in % as a function of time with values published by Gao and Niu [15].
(redistribution peak) at DV supply flow rate below 75 L/s appears during the second stage since the stratification height is close to the breathing level which results in accumulating particles in the breathing zone (Fig. 6a). As the DV flow rate increases from 50 to 75 L/s, the second peak is reduced and completely disappears for a flow rate of 100 L/s while the influence of the DV flow rate is less significant on the first peak which is dominated by the horizontal propagation of the exhaled jet (Fig. 6a).

The penetration peak (first stage peak) is two to three orders of magnitude larger than the redistribution peak (second stage peak). However, the duration of the first stage is much smaller than the second stage (Table 2a).

Fig. 6b represents the effect of the DV supply flow rate on the variation with time of the infection index. The rate of increase of the infection index is relatively high during the first stage and is reduced progressively with time to reach nearly zero at the end of the third stage. The profiles of variation with time of the normalized concentration and infection index are consistent with the work of Xiaoqing et al. [8]. Within the set of studied conditions, the higher the DV flow rate is, the lower is the rate of increase of the infection index during the different stages. The inhaled dose during each stage for the different flow rates was calculated and results were summarized in Table 2b.

For the different flow rates, the first stage represented the highest inhaled dose. As the DV flow rate increases, the infection index is reduced for the three stages but the rate of reduction is highest for stage 3 and lowest for stage 1 due to the decay of the exhalation jet with time (Table 2b). Therefore, stage 1 presents the highest probability of cross-contamination between occupants. For a DV flow rate of 50 L/s, stages 2 and 3 represented a significant percentage of the total exposure. The DV system with a flow rate of 100 L/s reduced significantly the inhaled dose during stages 2 and 3 decreasing the total inhaled dose by 83% compared to a flow rate of 50 L/s. The DV flow rate of 100 L/s was adopted for the rest of the study.

### 3.3.2. Cough velocity effect

IPE was studied for different cough velocities (6, 11, and 22 m/s) for a DV flow rate of 100 L/s, 1 μm particles in diameter, and 1 m separating distance between occupants. Fig. 7a and b illustrate respectively the effect of the cough velocity on the variation with time of the normalized concentration at the breathing level of the exposed person and the infection index. As the cough velocity increases, the exhaled mass flow rate is incremented proportionally (for the same mouth opening) and the proportion of particles penetrating the thermal plumes of the infected occupant increases, therefore the IPE is increased (Fig. 7). Hence, the higher the cough velocity is, the faster and stronger is the attained concentration peak (Fig. 7a), and the higher is the infection index (Fig. 7b). The coughing velocity largely affected the exposure during the first

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**Table 2a**

| DV supply flow rate (L/s) | First stage time interval | Second stage time interval | Third stage time interval |
|---------------------------|--------------------------|---------------------------|--------------------------|
| 50 L/s                    | [0 s; 10 s]              | [10 s; 200 s]             | [200 s; 2600 s]          |
| 75 L/s                    | [0 s; 7.5 s]             | [7.5 s; 100 s]            | [100 s; 1000 s]          |
| 100 L/s                   | [0 s; 4 s]               | [4 s; 50 s]               | [50 s; 300 s]            |

**Table 2b**

| DV supply flow rate (L/s) | First stage inhaled dose (kg) | Second stage inhaled dose (kg) | Third stage inhaled dose (kg) |
|---------------------------|-------------------------------|-------------------------------|-------------------------------|
| 50 L/s                    | 15.79e-6                      | 8.78e-6                       | 4.42e-6                       |
| 75 L/s                    | 8.78e-6                       | 1.29e-6                       | 2.45e-6                       |
| 100 L/s                   | 3.98e-6                       | 1.98e-6                       | 0.05e-6                       |
3.3.3. Particle diameter effect

IPE was studied for different particles diameters of 1, 20, 30, and 50 μm for a DV flow rate of 100 L/s, a cough velocity of 22 m/s and 1 m separating distance between occupants. Fig. 8a and b illustrate respectively the effect of the particle diameter on the variation with time of the normalized concentration at the breathing level of the exposed person and the infection index. With the increase of particle diameter, the gravitational settling effect opposing the upward transport of particles within the microclimate zones is strengthened leading to particle accumulation within the occupied zone. On the
other hand, particle deposition by gravitation increases acting as a sink of particles. These two counter effects of increased particle diameter results in non-monotone variation of the concentration with particle diameter. This explains the fact that the IPE is higher when particle diameter is increased from 1 to 20 μm due to the opposition of particle removal by the upward DV. For larger particle diameters, the deposition by gravitation becomes dominant playing a major role in decreasing IPE (Fig. 8).

3.3.4. Separating distance effect

IPE was studied for different distances between the occupants at 0.5, 1, 2, and 3 m for a DV flow rate of 100 L/s, 1 μm particles in diameter, and cough velocity of 22 m/s. Fig. 9a and b illustrate respectively the effect of the distance between occupants on the variation with time of the normalized concentration at the breathing level of the exposed person and the infection index. As the distance between occupants increases, the microclimate zone 2

![Figure 9](image_url)

**Fig. 9.** Effect of the distance between occupants on the variation with time of: a) the normalized concentration at the breathing level of the exposed person; b) the infection index.

![Figure 10](image_url)

**Fig. 10.** Variation with distance between the occupants of the total inhaled dose.

![Figure 11](image_url)
relating the occupants is larger. Therefore, the IPE is reduced as the exhaled jet decay is higher reducing contaminant transmission to the exposed person with a larger time delay. These findings are consistent with the ones of Licina et al. [16]. The effect of the distance on the IPE is reduced in stages 2 and 3 compared with stage 1 due to the decay of the exhaled jet. Fig. 10 represents the variation of the total inhaled dose with distance between the occupants showing that as the separating distance is reduced the rate of increase of the total inhaled dose is incremented and becomes significantly high below 1 m. The IPE is largely reduced for a separating distance of 3 m which justify the common recommendation of keeping a large distance between occupants for reduced exposure.

3.3.5. Comparison between steady and transient modeling

The physical effect of different parameters (DV flow rate, coughing velocity, particle diameter, and distance between the occupants) on particle behavior computed from the transient model is consistent with the conclusions made from the steady-model [11]. Therefore, steady modeling is helpful in understanding the physics affecting particle spread resulting from HMRA. In order to compare the ability of steady and transient modeling in predicting the IPE, the inhaled dose during the first stage (which is dominated by the jet propagation) was calculated for both models. The inhaled dose computed by transient modeling was calculated using the concentration profile obtained from the transient simulation. On the other hand, the inhaled dose obtained by steady modeling was computed using the steady-state concentration [11]. Fig. 11 illustrates the comparison of the inhaled dose predicted by transient and steady modeling for variable DV flow rate, cough velocity, and distance between the occupants. Steady modeling significantly over-predicts the IPE (Fig. 11). For instance, if the threshold inhaled dose is set to $10^{-5}$ kg, for a cough velocity of 22 m/s during 1 s, 1 μm particles in diameter, and a separating distance of 1 m transient modeling predicts a minimum required DV flow rate of 75 L/s while steady modeling predicts that even an oversized flow rate of 200 L/s is not enough (Fig. 11a). Furthermore, for a DV flow rate of 100 L/s, 1 μm particles in diameter, and a separating distance of 1 m transient modeling predicts that the whole coughing velocity range is acceptable while steady modeling lead to the conclusion that the maximum possible coughing velocity is 10.25 m/s (Fig. 11b). Finally, for a DV flow rate of 100 L/s and a cough velocity of 22 m/s during 1 s, and 1 μm particles in diameter, the minimum required distance between the occupants is nearly 0.5 m by transient modeling while it is 2.15 m by steady modeling (Fig. 11c). Therefore, steady modeling should not be used to predict the inhaled dose since it leads to largely over-predicted values.

4. Conclusion

A transient mathematical multi-zone transport model predicting particle behavior in spaces ventilated by DV system was developed in order to assess transient IPE. Experimental validation was performed showing that the developed model is capable of predicting the transient jet propagation and decay with distance and time, and can be used to assess the transient IPE. The variation of the IPE with time can be categorized into three stages: a first stage dominated by the propagation and decay of the exhaled jet, a particles’ redistribution stage, and a particles’ removal stage. Within the set of studied conditions, the larger is the flow rate, the lower are the durations of the three stages and the effect of the DV flow rate on particle behavior is the highest for the third stage and the lowest for the first stage due to the decay of the
exhaled jet with time. The inhaled dose during the first stage is the highest and is largely affected by the cough velocity, the particle diameter and the distance between the occupants. As the cough velocity increases, the IPE is increased since the quantity of the generated droplets and their momentum increases. As the separating distance is reduced, the rate of increase of the total inhaled dose is incrementated and becomes significantly high below 1 m. For particle diameters above 30 μm, the deposition by gravitation becomes dominant playing a major role in decreasing the IPE.

Steady modeling of the IPE due to HMRA is able of capturing the physics of particle distribution but should not be used to predict the inhaled dose since it leads to largely over-predicted values compared to transient simulations. For example, for a cough velocity of 22 m/s during 1 s, 1 μm particles in diameter, and a separating distance of 1 m transient modeling predicts a minimum required DV flow rate of 75 L/s while steady modeling predicts than even an oversized flow rate of 200 L/s is not enough for a threshold inhaled dose of 10−5 kg.

This study investigated the effect of several parameters (DV flow rate, coughing velocity, particle diameter, and distance between the occupants) on exhaled particle distribution and cross contamination between occupants. However, many other factors affect respiratory droplets spread and are worthy of future studies as the evaporation of exhaled droplets, enhanced particles’ spread by velocity fluctuation, injection profile during coughing, coughing duration, velocity decay along radial direction, and thermal plumes development below the head level within the occupied space...

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References

[1] G. Viegi, M. Simon, A. Scognamiglio, S. Baldacci, F. Pistelli, L. Carrozza, L. Annesi-Maesano, Indoor air pollution and airway disease state of the art, Int. J. Tuberc. Lung Dis. 8 (12) (2004) 1401–1415.
[2] J.D. Spengler, X. Sexton, Indoor air pollution: a public health perspective, Science 221 (4605) (1983) 9–17.
[3] L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, C.Y.H. Chao, C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.H. Lin, Q. Chen, A hybrid model for predicting stack particle distribution and deposition in indoor environments with a new drift penetration model, Atmospheric Environment 40 (2006) 863–876.
[4] S. Annesi-Maesano, Indoor air pollution and airway disease state of the art, Int. J. Tuberc. Lung Dis. 8 (12) (2004) 1401–1415.
[5] L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, C.Y.H. Chao, C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.H. Lin, Q. Chen, A hybrid model for predicting stack particle distribution and deposition in indoor environments with a new drift penetration model, Atmospheric Environment 40 (2006) 863–876.
[6] S. Annesi-Maesano, Indoor air pollution and airway disease state of the art, Int. J. Tuberc. Lung Dis. 8 (12) (2004) 1401–1415.
[7] L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, C.Y.H. Chao, C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.H. Lin, Q. Chen, A hybrid model for predicting stack particle distribution and deposition in indoor environments with a new drift penetration model, Atmospheric Environment 40 (2006) 863–876.
[8] S. Annesi-Maesano, Indoor air pollution and airway disease state of the art, Int. J. Tuberc. Lung Dis. 8 (12) (2004) 1401–1415.
[9] L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, C.Y.H. Chao, C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.H. Lin, Q. Chen, A hybrid model for predicting stack particle distribution and deposition in indoor environments with a new drift penetration model, Atmospheric Environment 40 (2006) 863–876.
[10] L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, C.Y.H. Chao, C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.H. Lin, Q. Chen, A hybrid model for predicting stack particle distribution and deposition in indoor environments with a new drift penetration model, Atmospheric Environment 40 (2006) 863–876.
[11] L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, C.Y.H. Chao, C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.H. Lin, Q. Chen, A hybrid model for predicting stack particle distribution and deposition in indoor environments with a new drift penetration model, Atmospheric Environment 40 (2006) 863–876.
[12] L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, C.Y.H. Chao, C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.H. Lin, Q. Chen, A hybrid model for predicting stack particle distribution and deposition in indoor environments with a new drift penetration model, Atmospheric Environment 40 (2006) 863–876.
[13] L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, C.Y.H. Chao, C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.H. Lin, Q. Chen, A hybrid model for predicting stack particle distribution and deposition in indoor environments with a new drift penetration model, Atmospheric Environment 40 (2006) 863–876.