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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.

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

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Nomenclature

A	area (m^2)
C	particle concentration (kg/m^3)
CFD	computational fluid dynamics
d_{inj}	hydraulic diameter of the mouth (m)
D_p	particle Brownian diffusion (m^2/s)
D_t	turbulent diffusion coefficient (m^2/s)
DV	Displacement ventilation
HMRA	high momentum respiratory activities
IAQ	indoor air quality
ID	inhaled dose (kg)
I	infection index (kg)
IPE	inter-personal exposure
M	mass flow rate (kg/s)
Q_H	heat source strength (W)
r	microclimate radius (m)
R	radius of the plume at a certain level (m)
t	time (s)
t_{rl}	cough release time (s)
t_{tr}	traveling time (s)
TRA	transient respiratory activities
T_∞	room temperature (°C)
v_s	absolute component of the particle settling velocity (m/s)
v_{up}	upward velocity strength in Zone I (m/s)
V_g	generation velocity (m/s)
V_p	penetration velocity (m/s)
V_{inj}	velocity of injection (m/s)
V_{max}	peak velocity of the horizontal jet (m/s)
V_r	reference velocity (m/s)
y	horizontal propagation coordinate of the exhaled jet from the mouth (m)
y_{ob}	obstruction distance (m)
z_c	critical height (m)

Greek symbols

ρ	air density (kg/m^3)
λ	proportion of particles penetrating the thermal boundary layer
χ	uni-directional horizontal jet decay
τ	time constant (s)

Subscripts

a	air outside the thermal plumes (surrounding air)
d	deposition
ent	entrainment
ex	exposed
g	generation
i	layer number
in	inhaled
inf	infected
int	interaction
j	sub-microclimate 2 number
m	number of rising plumes
max	maximum
mac	macroclimate
mic	microclimate
n	number of walls within a layer
pl	plume
s	settling
w	wall

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