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Displacement ventilation zonal model for particle distribution resulting from high momentum respiratory activities

Carine Habchi, Kamel Ghali, Nesreen Ghaddar*

Mechanical Engineering Department, American University of Beirut, P.O. Box 11-0236, Beirut 1107-2020, Lebanon

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A B S T R A C T

Indoor air quality (IAQ) is one of the major concerns of public health organizations. Displacement ventilation systems (DV) are frequently installed in indoor environments for their practicality and energy efficiency. High momentum respiratory activities (HMRA) (coughing, and sneezing) present a high risk of cross contamination between occupants due to greater penetration length of the exhalation jet carrying larger number of particles challenging the performance of DV systems.

The aim of this work is to develop a mathematical multi-zone transport model of passive and active particle behavior in spaces ventilated by DV system in order to study cross-contamination between occupants. The developed model incorporates the different physics affecting particle spread in the horizontal and vertical directions. The model was validated by experimentation using particles of 5 μm size and tracer gas jets. Comparison with measured particle concentration revealed that the current simplified model is capable of capturing the physics of the particle transport and predicting particle concentration in the room and breathing zones at low computational cost.

The model results showed that as the velocity of the exhaled jet increases, the proportion of particles penetrating the rising thermal plumes increases leading to a higher possibility of cross-contamination. The standalone DV system is not able of preventing accumulation at the breathing level of particles exhaled by high momentum jets. In addition the reduced distance between occupants significantly augments the risk of cross-infection. The gravitational effect can play a positive role in reducing disease transmission for nuclei diameter above 50 μm.

1. Introduction

Indoor air quality (IAQ) is one of the major concerns of public health organizations [1–3] given that people nowadays spend the majority of their time inside residential and office buildings [4–6]. Therefore, the breathable air quality in indoor spaces should be maintained high to avoid the spread of respiratory diseases. People constitute one of the main sources of particles carrying contaminants in indoor environments by exhalation resulting from the different respiratory activities (breathing, coughing, and sneezing) [7]. Respiratory patterns can be categorized into low momentum (breathing) [8,9] and high momentum respiratory activities (HMRA) (coughing, and sneezing) [10,11]. Despite their limited period, HMRA present a high risk of cross contamination between occupants [12] due to higher penetration length of the exhalation jet and larger number of particles it carries [13,14].

Displacement ventilation (DV) systems are frequently installed in indoor environments because they are classified as practical and energy efficient systems [15]. DV systems turn the air distribution upside down by supplying fresh air near the floor level at a low momentum with velocities lower than 0.2 m/s and temperature higher than 18 °C to avoid thermal draft to occupants in the lower zone [7]. The air motion in a space conditioned by DV system is essentially triggered by buoyancy forces resulting in upward convective thermal plumes that transport the contaminant away from the occupant's zone to be exhausted from the ceiling level [16]. Generally, heat sources have been associated with the contamination sources [7–17]. DV was shown to be very efficient in reducing cross-contamination in indoor environment for particles resulting from normal breathing since the thermal plumes rising from the infected occupants transport upward the majority of the exhaled particles due to their small horizontal momentum [7,18].

* Corresponding author. Tel.: +961 1 350000x253; fax: +961 1 363283.
E-mail address: farah@aub.edu.lb (N. Ghaddar).

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Nomenclature

A	area (m^2)
C	particle concentration (kg/m^3)
CFD	computational fluid dynamics
D	cylinder diameter (m)
D_p	particle Brownian diffusion (m^2/s)
D_t	turbulent diffusion coefficient (m^2/s)
DV	Displacement ventilation
g	gravitational constant (m/s^2)
Gr	Grashof number
HMRA	high momentum respiratory activities
IAQ	indoor air quality
L	cylinder length (m)
M	mass flow rate (kg/s)
Pr	Prandtl number
r	microclimate radius (m)
R	radius of the plume at a certain level (m)
R_e	Reynold number
Q_g	generated flux (m^3/s)
Q_p	penetrating flux (m^3/s)
T	temperature (K)
T_0	average skin temperature (K)
T_∞	average air temperature around the heated cylinder (K)
u	vertical velocity component within the boundary layer (m/s)
v	horizontal velocity component within the boundary layer (m/s)
v_d	deposition velocity (m/s)
v_s	absolute component of the particle settling velocity (m/s)
V_g	velocity of generation (m/s)
V_p	velocity of penetration (m/s)

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/K)
ρ	air density (kg/m^3)
λ	proportion of particles penetrating the thermal boundary layer
ν	kinematic viscosity of air (m^2/s)
ξ	transformation coordinate
η	transformation coordinate
θ	non-dimensional temperature
ψ	stream function

Subscripts

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

HMRA might reduce the effectiveness of DV system in particle removal since they would spread particles horizontally at the breathing level [13,19]. This raises the need to understand the physics affecting horizontal spread of contaminants resulting from HMRA. The development of a simplified model of particle transport and distribution in DV spaces would be important to assess the risk of cross-contamination between occupants and arrive at proper recommendations for the space layout and distance between occupants.

Indoor contaminant dispersion in spaces ventilated by DV systems was studied in literature by experimentation, computational fluid dynamics (CFD), and simplified modeling [7,10,13,18,20]. Simplified modeling of particle distribution in spaces ventilated by DV systems was shown to be very helpful in the design of this ventilation technique [7] since the main physics were captured through thermal plume modeling from heat sources integrated with upward convection which also accounted for the effect of the main design parameters on particle distribution within the space (supply flow rate and temperature and load distribution) [7]. Furthermore, simplified models constitute an easy design tool reducing significantly the computational time needed to solve similar problems by CFD and experimentation [21].

Different zonal models were developed in literature. In general, when contaminated sources are simultaneously acted as heated sources, DV systems divide the space in two major zones: a lower clean zone and higher contaminated zone [22,23]. Xu et al. [24] developed a simple zonal model for predicting contaminant distribution in spaces ventilated by DV system dividing the space into two zones separated by the stratification height, which is the level at which the rate of air entrained by the thermal plumes equals the supply flow rate. Yamanaka et al. [25] enhanced the model of Xu et al. [24] by introducing an interface layer to take into account the vertical diffusive transfer of the contaminant. The thickness of the interface layer was modeled by a balance between diffusion and convection [25,26]. Bolster and Linden [27] used a two layer model to investigate the steady particle transport for different locations of the contaminants' source (within and outside the thermal plume) in a space ventilated by DV. They found that the efficiency of DV system in particle removal is largely degraded for external source. Bolster and Linden [28] extended their model to study transient particle behavior for different contaminant release scenarios underlining the gravitational effect on particle spread. Kanaan et al. [20] improved the accuracy of simplified models by developing a multi-layer model to study the effect of the thermal stratification height on contaminant transport in DV systems combined with chilled ceiling. Habchi et al. [7] developed a multi-plume multi-layer transport model of active particles in offices ventilated by DV system. However, previously published models considered exhaled particles for normal breathing in which the majority of particles would be transported upward within the infected plume. Due to low momentum of exhaled jet during breathing, the vertical upward motion dominated particles distribution and horizontal interaction was limited to the entrainment process between the plumes and the surrounding [7]. Nevertheless, in order to model particle distribution resulting from other respiratory activities as coughing and sneezing gradients of concentration in the horizontal direction are significant and cannot be neglected. In fact, these respiration activities are characterized by generation jets of high