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A simplified mathematical model for predicting cross contamination in displacement ventilation air-conditioned spaces

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ABSTRACT

The aim of this work is to develop a mathematical multi-plume multi-layer transport model of active particle behavior in spaces ventilated by a displacement ventilation (DV) system in order to study cross-infection between occupants in typical internal offices. The developed model incorporates particle deposition on walls and the effect of gravitational settling on particles distribution. The model was validated using published data from the literature revealing that the current simplified model is able to capture the physics of the problem and predict particle concentration and transport at low computational cost.

The model results show that as the particle diameter increases, the gravitational settling increases, thereby lowering the stratification in particle concentration created by the DV system and thus increasing the particle concentration at the breathing level of the exposed person. For a flow rate of 60 L/s, this effect remains until reaching a particle diameter above 10 μm where deposition on the floor opposing the DV principle acts as a removal factor. For the critical inhalable range, as the diameter increases, gravitational settling accumulates particles in the occupied zone, thereby increasing the probability of cross-infection. To overcome the settling effect, higher ventilation air flow rates are recommended to provide good indoor air quality (IAQ).

1. Introduction

Exhaled droplets produced by the different human respiratory activities (breathing, coughing, and sneezing) constitute one of the main sources of infectious particles in indoor environments (Fanger et al., 1988). Human exhaled droplets are subject to fast evaporation before reaching their equilibrium diameter of droplets nuclei (Chen & Zhao, 2010; Morawska et al., 2009; Nicas et al., 2005). Droplets with equilibrium diameter smaller than 15 μm fall within the human inhalable range (Dockery & Pope III, 1994; Chen & Zhao, 2010; Nicas et al., 2005). In many cases, these emitted particles (droplets after evaporation) become airborne and can spread within the space before being escaped, deposited or inhaled by other healthy occupants (Lai & Cheng, 2007). The indoor particle dynamics depends largely on their diameter (size) and the air flow field associated with space air conditioning system. The heating, ventilation, and air conditioning (HVAC) system should be designed to effectively remove the contaminants as they are generated to minimize cross contamination between occupants.

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Nomenclature

$A_{a,i}$	cross sectional area outside the thermal plume at the interface between the layers i and $i+1$ (m^2)
$A_{int,i}$	interaction area between the plume and its surrounding within layer i (m^2)
$A_{p,i}$	cross sectional area at the interface between layers i and $i+1$ inside the thermal plume (m^2)
A_w	wall surface area (m^2)
C	particle concentration (kg/m^3)
C_∞	core concentration outside the concentration boundary layer (kg/m^3)
CFD	computational fluid dynamics
d_p	particle diameter (m)
D_p	particle Brownian diffusion (m^2/s)
D_t	turbulent diffusion coefficient (m^2/s)
DV	displacement ventilation
F_0	buoyancy force at the source (m^4/s^3)
H	height above the heat source (m)
HVAC	heating, ventilation, and air conditioning
I	integral number
IAQ	indoor air quality
J_d	deposition flux of particles towards a wall (kg/m^2 s)
k	index for the wall orientation
m_n	non-dimensional parameter defined by Eq. (1b)
M_a	mass flow rate within the surrounding air region (kg/s)
$M_{ent,I}$	mass flow rate of room air entrained by the plume in layer i (kg/s)
M_{pl}	mass flow rate within the plume (kg/s)
M_s	supply mass flow rate (kg/s)
M_w	mass flow rate within the wall plume (kg/s)
n	number of walls
N	number of layers
Q_H	heat source load (W)
q_a	upward flow within the thermal plume (m^3/s)
q_p	upward flow within the thermal plume (m^3/s)
q_w	wall plume flow rate (m^3/s)
r	radial coordinate from the centerline of the plume (m)
R	radius of the plume at a certain horizontal level (m)
$S_{p,i}$	particle concentration source term in layer i inside the plume (kg/m^3 s)
S_{ai}	contaminant generation in layer i outside the plume (kg/m^3 s)
Sc	Schmidt number
t	time (s)
T_∞	ambient temperature at the surrounding of the plume (K)
TP	thermal plumes
u^*	friction velocity (m/s)
v_{dc}	deposition velocity on the ceiling (m/s)
v_{df}	deposition velocity on the floor (m/s)
v_{dv}	deposition velocity on a vertical wall (m/s)
V_w	velocity profile for wall plumes (m/s)
V_∞	maximal velocity at the limit of the wall velocity boundary layer (m/s)
x	coordinate in the horizontal direction (m)
X	wall width (m)
z	height above the floor (m)
z_{mi}	mid-height of layer i (m)
z_n	non-dimensional parameter defined by Eq. (1c)
z_s	point source height (m)

Greek symbols

ρ	air density (kg/m^3)
ν	kinematic viscosity of air (m^2/s)
λ	ratio of density plume radius to the velocity one
β	index of the wall orientation
δ_w	wall boundary layer thickness (m)
ΔT	excess temperature which is the difference between the temperature inside the plume and its surrounding (K)
ΔT_o	excess temperature at the plume centerline (K)
ΔT_{wa}	difference in temperature between the wall and the surrounding air

Subscripts

a	air
c	ceiling
sur	surrounding
d	deposition
e	entrainment
f	floor
h	horizontal
i	layer number
j	wall number within a layer
k	occupant number
l_c	distance below the top of the cylinder (m)
max	maximum
n	number of walls within a layer
p	particle
pl	plume
s	settling
v	vertical
w	wall