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A simplified methodology for the prediction of mean air velocity and particle concentration in isolation rooms with downward ventilation systems

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ABSTRACT

Calculating the velocity and particle concentration indoor is critical for isolation rooms design. Computational fluid dynamics (CFD) is regarded as a powerful tool aiding in the indoor environment design for isolation rooms by enabling us to predict the velocity and particle concentration distribution in detail. However, CFD method is time-consuming and relatively expensive, especially for actual engineering application. So this study proposes a simplified methodology to predict the mean air velocity and particle concentration in the occupied zone of isolation rooms with downward ventilation systems. The methodology is based on a similarity theory analysis, by which the key similarity criteria are deduced. The correlating equation to calculate the mean air velocity and particle concentration in the occupied zone in isolation rooms is established by multiple linear regression (MLR) which is based on the numerical test results obtained by CFD. The equation correlates the mean air velocity and particle concentration with air supply volume rate, indoor particle generating rate, and other parameters. The calculated results agree with those from measurement and CFD simulations for the studied cases, generating a relative error less than 25%. It could offer the engineers a simpler path to calculate the mean air velocity and particle concentration.

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1. Introduction

Isolation rooms are widely used in clean production workshops, hospital operating rooms and clean wards. For these places, the indoor air flow and particle distribution should be designed carefully to maintain a clean indoor environment. Previous studies suggest that engineering simulations using computational fluid dynamics (CFD) are a valid method for investigating air flow behavior, temperature distribution and particle dispersion in different types of isolation rooms [1–4].

However, CFD is sometimes time-consuming and relatively expensive, which limits its application in actual engineering applications. Although the cost of CFD is acceptable when studying a limited number of cases for academic research nowadays, a more simplified method is always welcomed for those engineers or designers who are not CFD experts. Besides, in most cases the engineers or designers only concern the mean velocity and particle concentration in the key indoor areas, for example, the occupied zone in isolation rooms. For this purpose, the detailed air flow and particle distribution given by CFD seems unnecessary in terms of deciding the primary schemes for actual application. Furthermore, the indoor environment controlling or decision-making requests the real-time monitoring of air velocity and particle concentration indoor. The CFD calculation does not meet the request as it is hard to response the input parameters (e.g., air flow rate variation, source generating rate variation, and so on) in a short time or real time. A simple methodology that can real time response to the input parameters is necessary for this purpose.

This study therefore presents a simple way to predict the mean air velocity and particle concentration in the occupied zone (Occupied zone is defined as the central part of the room in this study, i.e. up to a height of 2 m and 0.5 m away from each wall [5].) in isolation rooms with downward ventilation systems, as downward ventilation system is regarded to be effective for controlling indoor particles and that current guidelines recommend use of downward ventilation systems for different kinds of isolation rooms [6–8]. The simple methodology is based on a similarity theory analysis, by which the key similarity criteria are deduced. The correlating equation to calculate the mean air velocity and particle concentration is established by multiple linear regressions (MLR), which is based on the numerical test results obtained by CFD method. The equation correlates the mean air velocity and particle concentration with air supply volume rate, indoor particle generating rate and other

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Nomenclature

A	Ceiling area, m^2
A_i	Air inlet area, m^2
b	Length of isolation room, m
C	Mean particle concentration in occupied zone, m^{-3}
c_p	Specific heat of air, J/kg K
g	Acceleration of gravity, m/s^2
G_s	Emission rate of particle, s^{-1}
h	Height of isolation room, m
Q	Volume of air supply, m^3/s
Q_T	Heat gain in occupied zone, J/s
T_i	Temperature of air supply, K
T_w	Temperature of walls, K
u	Mean air velocity in occupied zone, m/s
u_i	Speed of air supply, m/s
w	Length of air outlet, m
z	Height of air outlet, m
ν	Kinetic viscosity of air, m^2/s
ρ	Density of air, kg/m^3
$\Pi_1 - \Pi_{12}$	Dimensionless numbers/similarity criteria

parameters. It can be used to aid the engineers or designers to calculate the mean air velocity and particle concentration in a quick and simple way and achieve results with similar precision of CFD method, so as to avoid the complicated computation by CFD software.

2. Methodology

The methodology consists of three key parts: similarity analysis; numerical test and equation regression.

2.1. Similarity analysis

The indoor air parameters (such as velocity, temperature and particle concentration) may be influenced by many factors, including the ventilation rate, locations and dimensions of air supply opening and exhausts, heat and particle generating rate, and so on. For the same type isolation rooms, e.g., the isolation room with widely used downward ventilation system; the key factors influencing the air parameters may be few because the inlets and outlets of ventilation are fixed at certain locations. This makes it possible to correlate the air parameters with the factors in a general way with a dimensional analysis performed based on similarity theory [9].

As mentioned above, this study will only focus on isolation rooms with downward ventilation systems, where clean air is supplied from the ceiling and then exhausted from down-side walls (ceiling air supply and down-side return air flow pattern). For this case, the air supply opening is fixed in the center of ceiling and the exhausts are installed in the side walls (see Fig. 1).

Two assumptions are made for the following analysis. One is that the isolation rooms are located at the inner zones of the building, which means the walls of the isolation rooms can be treated as adiabatic. The other is that the heat and particle source are uniformly distributed in the isolation rooms, which agree with that of actual designing process of isolation rooms [10,11].

The dimensional similarity analysis comprises the following steps [12]: (1) a list containing all the related parameters is compiled, with their respective SI units (using unity for dimensionless quantities); (2) each dimensional quantity on the list is divided by its SI units, generating quantity per unit ratios (or groups); (3) considering N_{SI} the total number of independent SI units involved in the model, a number of N_{SI} quantity-unit groups are selected such that to have the simplest possible mathematical form and all SI units encountered to be represented in the N_{SI} groups; (4) each of the N_{SI} number of groups is assigned a value of 1, designated as “primary” groups; (5) the rest of the quantity-unit groups on the list are converted into an initial set of dimensionless numbers Π_i, by substituting the units using the N_{SI} primary groups; (6) the initial set of dimensionless numbers Π_i is further transformed by algebraic manipulation in order to obtain as many as possible dimensionless numbers to generate new dimensionless numbers with clear physical meaning.

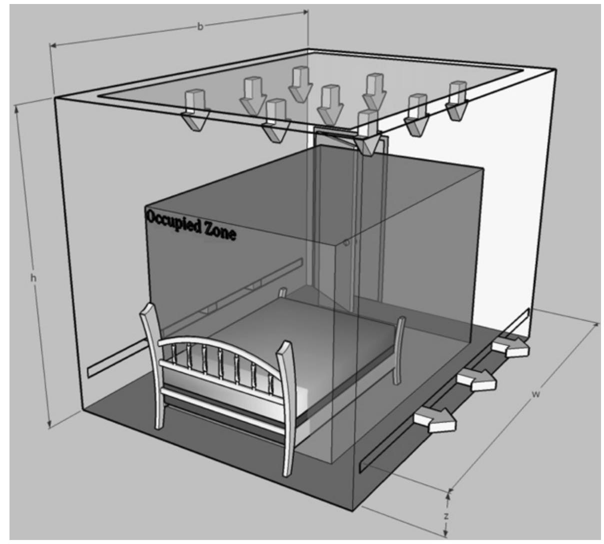

Fig. 1. Model and parameters of the isolation room.

Table 1 illustrates the selected key parameters and their SI units for the studied type of isolation rooms. Then 5 N_{SI} quantity-unit groups are selected. ρ, h, u_i, T_i and Q_T are designated as “primary” groups. The rest are converted into an initial set of dimensionless numbers Π_i. Two dimensionless numbers, $(1/C)\sqrt{\sum_{i=1}^{N}(C_i - C)^2/N}$ and $(1/u)\sqrt{\sum_{i=1}^{N}(u_i - u)^2/N}$, are added to reflect the characteristics of the air velocity and particle concentration distribution. They

Table 1
The key parameters for similarity analysis.

Parameter	Description	Unit
ρ	Density of air	kg/m^3
c_p	Specific heat of air	J/kg K
ν	Kinetic viscosity of air	m^2/s
g	Acceleration of gravity	m/s^2
Q_T	Heat gain in occupied zone[a]	J/s
T_w	Temperature of walls	K
Q	Volume rate of air supply	m^3/s
u_i	Speed of air supply	m/s
T_i	Temperature of air supply	K
A	Ceiling area	m^2
h	Height of isolation room	m
b	Length of isolation room	m
A_i	Air inlet area	m^2
z	Height of air outlet	m
w	Length of air outlet	m
G_s	Emission rate of particle	s^{-1}
u	Mean air velocity in occupied zone[a]	m/s
C	Mean particle concentration in occupied zone[a]	m^{-3}

[a] Here occupied zone is defined as the central part of the room in this study, i.e. up to a height of 2 m and 0.5 m away from each wall (see Fig. 1).

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