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Transport phenomena of human exhaled droplets due to respiratory action in ventilated indoor environments

Key Messages

1. The transport dynamics of expiratory droplets was modelled and verified against experimental data.
2. Droplet size distributions in air were measured. Small droplets (initial size ≤45 μm) were largely airborne. Large droplets (initial size ≥87.5 μm) settled quickly.
3. The transport characteristics of expiratory droplets were highly influenced by ventilation airflow patterns. The location of the exhaust vent can play a significant role in controlling the dispersion pattern of expiratory droplets.
4. Deviations from the perfectly mixed condition were found. Further development of risk assessment models taking imperfect mixing conditions into account are needed.

Introduction

The mechanisms of airborne transmission in indoor environments remain poorly understood. In some current nosocomial infection control guidelines, 'droplet' and 'airborne' are identified as the two major transmission modes of airborne diseases. According to the classification, pathogen carriers of those termed 'droplet' mode are >5 μm and potential exposure is limited to within 3 feet from the source. In contrast, pathogen carriers of the 'airborne' mode have droplet nuclei of <5 μm. However, some droplets of >5 μm in size have much shorter evaporation times than their settling times. This largely ignored fact makes the 5-μm cut-off for the classification of droplet and droplet nuclei questionable. Experimental evidence shows that human expiration produces polydispersed droplets, the majority being smaller than 100 μm and having short evaporation times.

The role of the ventilation system in the indoor transport of airborne pathogen carriers is another important issue. The dilution effect of the ventilation systems has been widely studied. However, inherently the assumption that there is perfect mixing assumption is hardly tenable in an indoor environment, due to little being known about different ventilation airflow patterns. One major difficulty in such research is the detection of expiratory droplets in air. Many such droplets change considerably in size due to evaporation before reaching the sensing elements of many sampling-based aerosol detection instruments. This results in measuring the dried residues, rather than the actual droplets in air. Apart from problems related to measuring the polydispersed size and evaporative features of expiratory droplets, there are challenges in terms of numerical modelling. Many studies have therefore turned to model gas phase contaminants as surrogates or to monodispersed dry particles.

The aim of this project was to quantitatively characterise the transport dynamics of airborne droplets in various ventilation systems. Its specific objectives were:

1. To study the effects of different air flow patterns created by various ventilation systems on the motion of expiratory droplets and their removal mechanisms.
2. To evaluate the effectiveness of floor-based ventilation systems and unidirectional ventilation systems in preventing the transmission of airborne occupant-exhaled aerosols compared to the traditional ceiling-based ventilation system.
3. To investigate the thermal conditions created by different ventilation systems and their impact on droplet aerosol transmission and thermal comfort.
4. To study the effects of parameters such as supply air conditions, heat loading, and aerosol injection conditions on aerosol transmission within ventilated spaces.

Methods

This study was conducted from March 2005 to August 2006. The project was divided into two major phases. The first focused on a simple clean room geometry. A multiphase numerical model was developed and tested against experimental measurements of droplet dispersion in a clean room chamber. To address objectives

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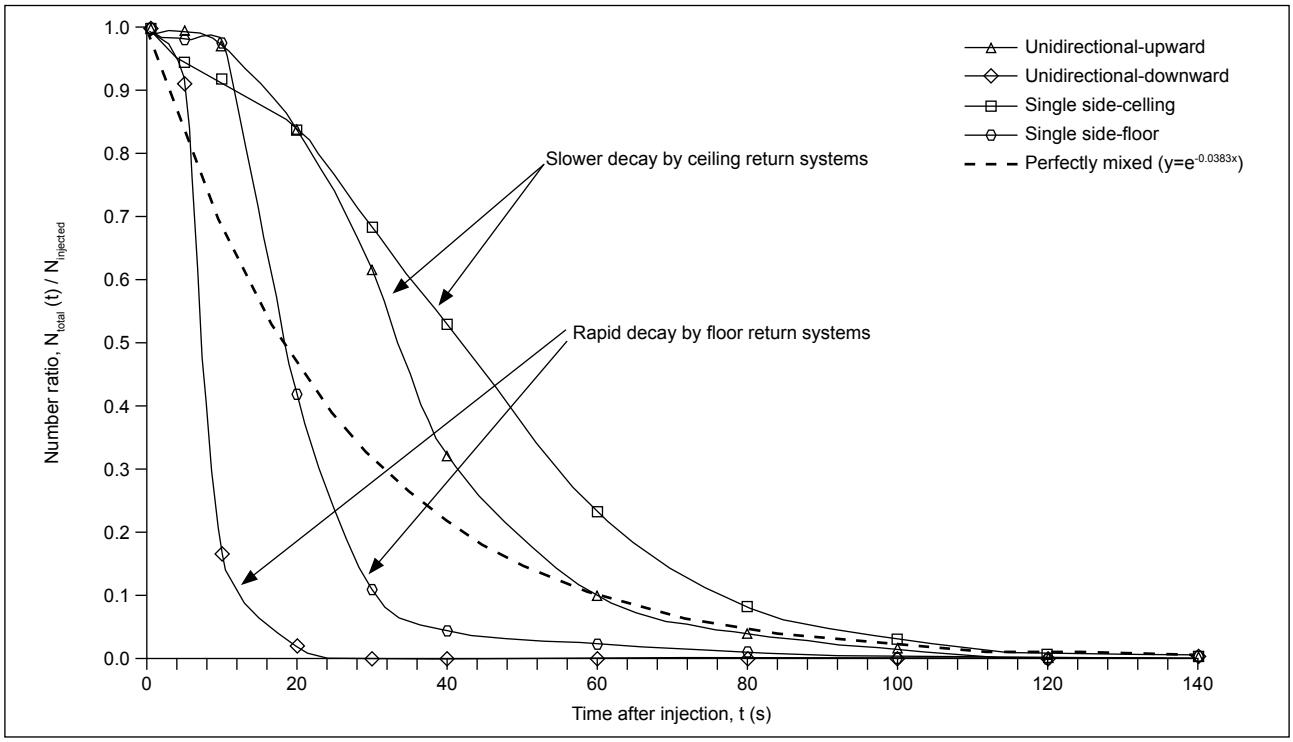

Fig 1. Number ratio decay profiles of different ventilation flow patterns

1 and 2, the model was then applied to different types of ventilation airflow patterns within the same room. The second phase focused on hospital ward geometry. Numerical simulations and measurements were conducted under both empty and occupied room conditions, using thermal manikins and other heat sources. Different droplet injection orientations were also studied (for objectives 3 and 4).

A Lagrangian-Eulerian numerical model was employed[1] to predict the motion of the expiratory droplets. This model considered the droplets and droplet nuclei as discrete individual particles and their motion was then described by force balance equations. Unlike the fully Eulerian-based (continuum phase) models, which were more commonly used previously, size change effect of each droplet due to evaporation as well as coagulation could also be modelled. The effects of turbulence from the carrier phase were modelled by adopting the stochastic approach.

Airflow and droplet dispersion measurements were performed in a class-100 clean room chamber with unidirectional downward airflow[1,2] and in a real hospital ward.[3] The simple clean room had internal dimensions of 4.8 × 4.8 × 2.6 m (W×L×H). The hospital ward had dimensions of 5.9 × 6.6 × 2.35 m (W×L×H) with a typical ceiling-based mixing type ventilation system. Flow patterns and turbulence parameters of the room air were captured by the particle image velocimetry (PIV) technique. For the measurement of droplet dispersion, a droplet generator was fabricated to produce droplets with non-volatile content. Polydispersed test droplets were injected to simulate human coughing. Source profile characterisation at the generator outlet and droplet dispersion measurements was performed using an optical interferometric Mie imaging (IMI) method, combined with an aerosol spectrometer. The experimental results were compared with the numerical results for verification of the model. The comparison showed that the multiphase numerical model was able to capture the size-specific dispersion characteristics of the expiratory droplets and droplet nuclei.

Results

The simple clean room geometry

The comparative efficiencies for removing expiratory droplets and droplet nuclei in the presence of the four ventilation systems are shown in Figure 1. The Unidirectional-downward system gave the best performance in terms of removing the droplets or droplet nuclei, followed by the Single side–floor system. The Unidirectional-upward system was ranked third and the Single side–ceiling system the worst. The four decay profiles were divided into two groups when compared with the 'perfectly mixed' condition. The two ventilation systems with floor exhaust vents had faster decay rates than the perfectly mixed curve, while the two ceiling exhaust systems had slower decay rates. By comparing the overall dispersion coefficients (Fig 2), two different lateral dispersion behaviours could be distinguished according to size. The small-size group (initial size ≤45 μm) had dispersion coefficients ranging from about 10 to 30 cm^2/s in the presence of purely turbulent dispersion in the Unidirectional systems. With the addition

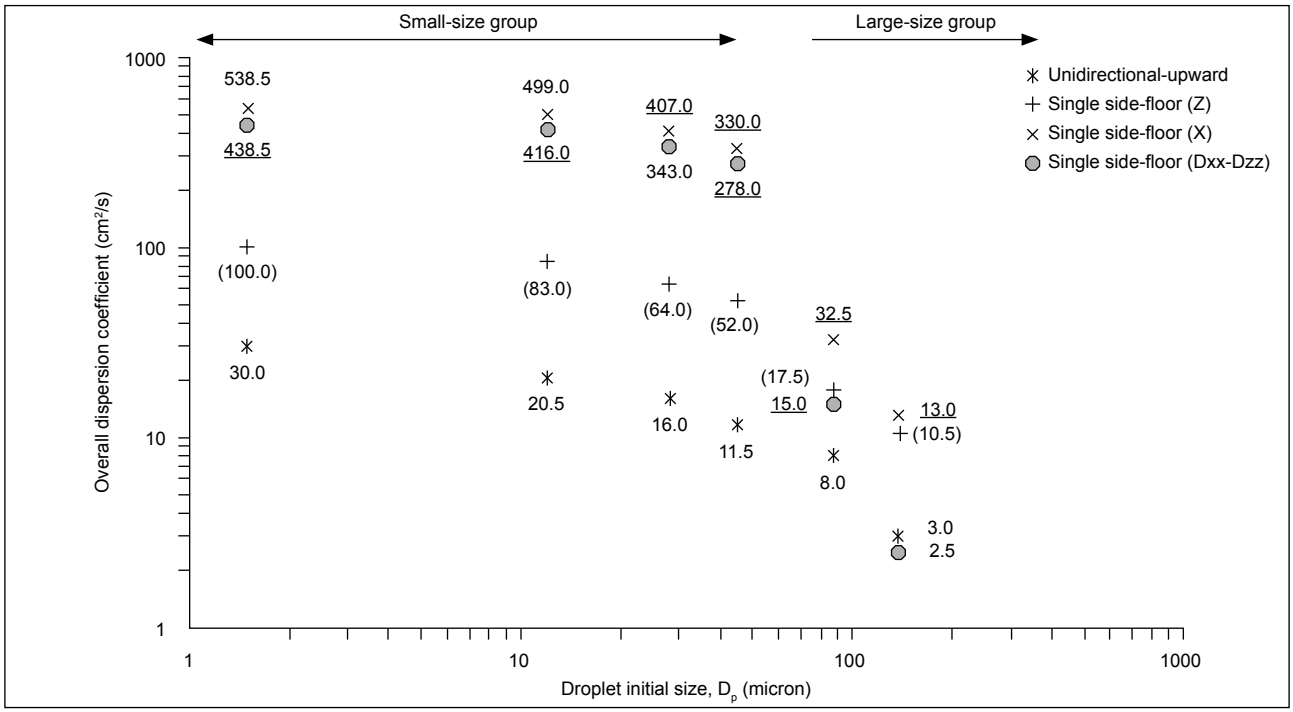

Fig 2. Overall dispersion in the two floor-supply flow patterns
The two ceiling supply systems had similar results

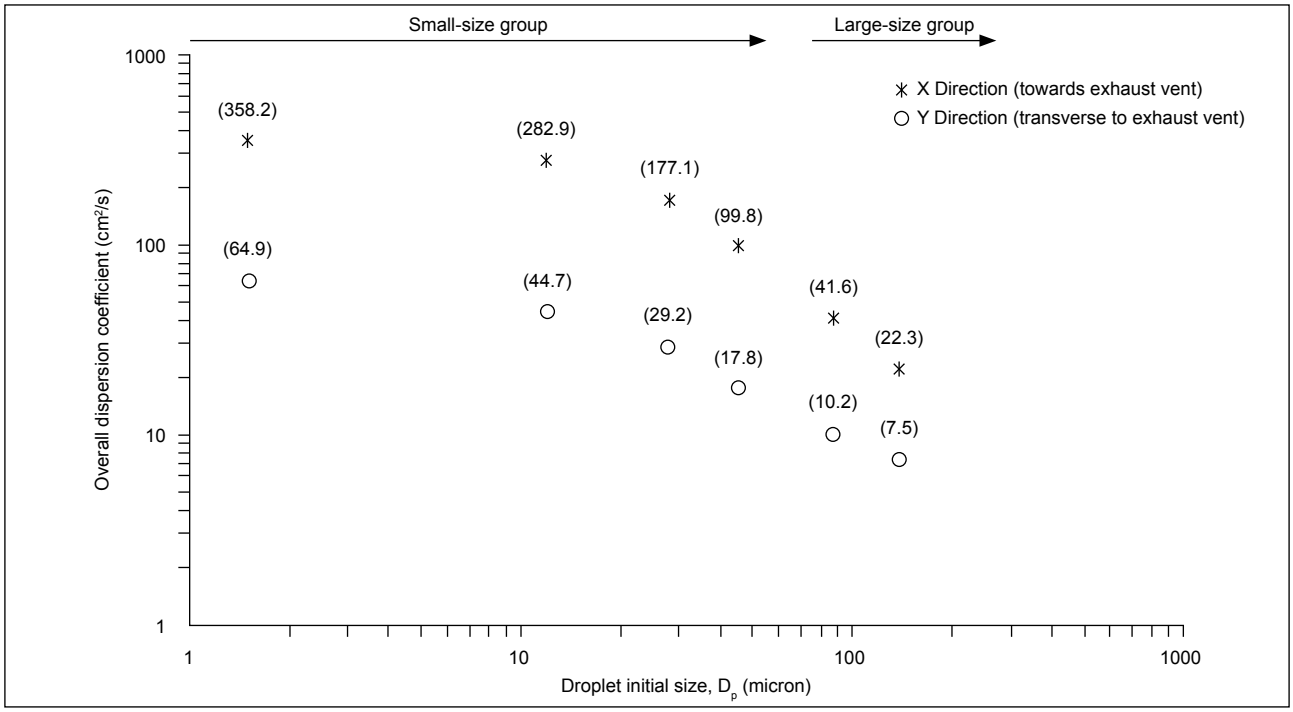

Fig 3. Overall dispersion coefficients of selected size bins in the hospital ward (empty room condition)

of bulk airflow transport in Single-side systems, the overall dispersion coefficients were increased to around 230 to 600 cm^2/s. In contrast, the overall dispersion coefficients of the large size group (initial size ≥87.5 μm) did not reveal such dramatic increases following the addition of bulk airflow transport. The heavy gravitational and inertial effects overwhelmed the dispersion mechanisms.

The hospital ward

Regarding hospital ward geometry, the increase in mean lateral dispersion distance was faster towards the exhaust vent than that in the converse direction. This is shown in Figure 3 in terms of overall dispersion coefficients. It suggests that the exhaust vent enhances bulk airflow in its direction as did the lateral dispersion of expiratory droplets,

and emphasises the significance of exhaust vent location in controlling the dispersion pattern of expiratory droplets.

When the droplets were injected vertically upward, the smaller ones (1.5 and 12 μm) remained at higher positions in the occupied condition compared to the empty room. This could be caused by the upward thermal plumes, induced by heat sources. Droplets of larger size exhibited vertical motion characteristics similar to those found in the empty room condition. This suggested that the influence of thermal plumes on the vertical motion of expiratory droplets decreased with increasing droplet size. The effect of thermal plumes on the lateral transport of expiratory droplets was not as significant as that on the vertical movement, as shown by lateral dispersion behaviour with the two injection conditions. In the lateral injection condition, the small size droplets stayed at a low level after injection, leading to higher chance of deposition. Droplets of larger size still exhibited gravity-dominated behaviour. Along the coughing direction, direct penetration of expiratory droplet into the breathing zone of the patient in the next bed was possible.

The extent of droplet exposure at patient breathing levels due to lateral injection orientation was higher than that under vertical injection orientation by three to four orders of magnitude. However, the exposure level at the breathing zone of workers was much lower than that in the breathing zone of patients and indicates direct penetration of expiratory droplets into the breathing zone of the patient in the next bed. Lateral dispersion of expiratory droplets was enhanced in the direction towards the exhaust vents. It can be observed by comparing the exposure levels between different bed arrangements in the vertical injection condition. The expiratory droplets (especially the smaller ones) generally stayed higher than the patients' breathing level. The upward thermal plumes could also enhance such effects. Simulations of a moving occupant showed that the air recirculation zone was likely to ensue behind the mover. Such air movement could enhance turbulence diffusivity, and enhance lateral dispersion of small expiratory droplets.

Discussion

The current project adopted a multiphase numerical model, which was able to capture the transport dynamics of polydispersed, evaporating expiratory droplets. A non sampling-based optical remote sensing method (the IMI method) was also adopted to measure the sizes of droplets and droplet nuclei in air. These methods therefore appear to be suitable tools for future research in droplet dispersion dynamics.

The transport characteristics of expiratory droplets are markedly affected by the ventilation airflow pattern. Small size droplets (initial size ≤45 μm) exhibited airborne transmission behaviour. Large size droplets (initial size ≤87.5 μm) did not stay in the air long enough for airborne transmission, due to the dominant influence of gravity. Ventilation systems with floor exhaust vents perform better in removing expiratory droplets. This implies that the settling of the expiratory droplet could enhance their removal through floor extraction vents. Bulk lateral airflow was found to be a much stronger lateral dispersion mechanism for expiratory droplets than turbulent dispersion. Unidirectional systems performed better in containing droplets or droplet nuclei from dispersing laterally, as opposed to the Single-side systems. The location of the exhaust vent can play a significant role in controlling the dispersion patterns of expiratory droplets. When expiration is directed laterally towards the next bed, the initial expiratory jet can penetrate directly into the breathing zone of the patient in that bed, causing very high levels of exposure. Different ventilation systems also revealed imperfect mixing distribution behaviour. Our results suggest that current infection control practices and policies should be reviewed. Issues of concern include: the 5-μm classification between 'airborne' and 'droplet' modes, the 3-feet recommended distance as a 'droplet' mode precaution, and risk assessment models incorporating imperfect mixing conditions.

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References

1. Chao CY, Wan MP. A study of the dispersion of expiratory aerosols in unidirectional downward and ceiling-return type airflows using a multiphase approach. Indoor Air 2006;16:296-312.
2. Wan MP, Chao CY. Transport characteristics of expiratory droplets and droplet nuclei in indoor environments with different ventilation airflow patterns. J Biomech Eng 2007;129:341-53.
3. Wan MP, Chao CY, Ng YD, Sze To GN, Yu WC. Dispersion of expiratory aerosols in a general hospital ward with ceiling mixing type mechanical ventilation system. Aerosol Sci Technol 2007;41:244-58.