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Modelling and experimental study of performance of the protected occupied zone ventilation

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ABSTRACT

The main objective of this study is to develop theoretical models to predict the performance of a new type of air distribution method known as protected occupied zone ventilation (POV), and to validate the model by conducting experimental measurements. The goal is to find out experimentally the most effective and efficient way of airflow distribution to protect occupants from infection of epidemic respiratory disease. Experimental measurements were performed under three setup conditions, including exhaust at sidewall, exhaust above the protected occupied zone and with partitions in the middle of the room. Two models are developed in this study to predict the transient pollutant concentration in the protected zone and the polluted zone. The protection efficiency of POV is defined in this study as well, which varies from 8% to 50% depending on the exhaust location, supply air velocity and the usage of partitions. The calculated results by using the models agree with the measurement results with a slot Reynolds number of 667, 1000 and 1167. The POV can separate the protected zone from the polluted zone by up to 2800 ppm. The capacity of a POV system to separate the room into two zones with different concentration levels of contaminant indicates that the POV may protect people from infection of epidemic respiratory disease via a cross-contaminant inside a room.

1. Introduction

Nowadays global epidemic respiratory diseases break out more often than ever, e.g. Meschede smallpox (1970), measles (1985), tuberculosis (TB) (1990), SARS (2003), H1N1 (swine flu, 2009) and H7N9 (bird flu, 2013), which resulted in many disasters in different countries [1]. Flu viruses are spread mainly from person to person through coughing or sneezing by people with influenza in public spaces using various traditional ventilation methods, like natural ventilation, mixing ventilation (MV) and displacement ventilation (DV). The fact of the increasing public risk shows that conventional ventilation methods, like MV and DV, may not effectively protect people from the infection of respiratory disease in offices and public spaces.

As a matter of fact, MV has been used for more than 100 years, and the disadvantages of using MV systems are still challenging us today, as the supply of fresh air will be mixed up with polluted indoor air. As early as in 1899, Boyle demonstrated how MV mixed up indoor pollutants with the supply of airflow [2]. This is determined by the principle of the MV system, which aims to dilute the indoor contaminant level when keeping the indoor air at a certain level, which also mixes pollutants with the supply of fresh air. DV is designed to push pollutants away from the lower part of the room. DV has a high ventilation index, but it is also possible to have stratified exhalations in the occupied zone because of the vertical temperature gradient, which may increase cross-infection, and the system cannot be recommended [3]. Through DV, moreover, the supplied airflow reaching the breathing zone may also transport pollutants from the floor covering or from other pollution sources, which decreases the quality of the inhaled air [4]. In addition, the location of the return openings plays an important role in the distribution of the exhaled contaminant (tracer gas) in the room, which results in the fact that DV may not suitable for heating conditions. When the distributed return openings are located up high, the vertical DV produces a personal exposure index greater than one (1.5–2.0) [5]. CDC even recommends an increase in the supply of airflow rate up to 12 ACH to reduce the risk of exposure to infectious aerosols, which may be achieved using a downward airflow method [6]. By using a DWF, however, the exposure increases when the distance between the manikins (persons) is <0.5 m. The exposure can be as high as 2–13 times the fully mixed value at a distance of 0.35 m between the source and target manikins [7]. In recent decades, personalised ventilation has become popular and has been intensively studied. A carefully designed and properly

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Nomenclature

Latin symbols

C	concentration
d	the transmission factor
h	air jet slot height (m)
K	jet model coefficient
M_0	the initial momentum flux of jet
m	mass (kg)
n	air change rate
N	the total sampling number
Q	supply airflow rate ($m^3 s^{-1}$)
Re	Reynolds number
s_v	standard deviation of the air velocity
Tu	turbulence intensity
t	time (s)
$u_m(x)$	local maximum air velocity at a distance x from the jet slot (m/s)
U_0	average slot air velocity (m/s)
$\bar{v}$	mean air velocity
V	the volume of the room
x	coordinates along the wall surface horizontally
y	coordinates normal to the wall
$y_{1/2}$	the value of y at which the velocity u is half its centre-line value

Greek symbols

ρ	air density ($kg\,m^{-3}$)
η	the exhaust air ratio of Zone I to the overall exhaust air in the room
λ	the space ratio of the Zone I to the whole room
δ	the contaminant transfer co-efficiency
ε	ventilation effectiveness

Subscripts

a	air
ai	air mass with the supply airflow
ao	air mass with the exhaust airflow
c	concentration
ci	pollutant mass with the supply airflow
co	pollutant mass with the exhaust airflow
cs	pollutant source
e	exhaust
exp	exposure
i	inlet
IO	inhaled air
m	maximum airflow velocity
P	pollutant
PEC	personal exposure concentration
PV	pollution in personalised air
s	supply

Superscripts

m	mass
v	volume

Numbers

1	Zone I
2	Zone II

maintained PV system should provide clean air with no pollutants [8]. One study shows that up to 80% of inhaled air could consist of fresh personalised air with a supply flow rate of less than 3.0 l/s [9]. Personal Exposure Effectiveness (PEE), which uses different PV devices, varies from 0.3 to 0.5 [8]. However, personalised airflow still induces ambient air into the breathing zone, which may not have a protected boundary within the occupied zone. If the ambient air is polluted, the inhaled air may also get polluted during the inhalation process. The droplets that were released by the cough machine at a distance of 1 m from the manikin move in bulk and had high velocity when they reach the inhalation zone, which may increase the risk of cross-infection [10]. When PV is applied with displacement ventilation, the PV can also substantially improve the inhaled air quality when the pollution source is not located in the vicinity of the personalised flow, e.g. floor pollution [11]. Even PV can maximise the fresh air rate in the breathing zone, but it may not avoid mixing the polluted air with the supply fresh air.

In addition to MV, DV and traditional PV, an air curtain has been used by industry to protect air leakage from the doorway. Theoretical and experimental studies have been conducted to model the performance of different air curtains [12,13]. The dimensioning methods have been developed for designing air curtains. A breakthrough phenomenon was found, which can be classified into three different types. In cases where the discharge momentum flux of the jet is too weak, the jet is drawn aside by the pressure difference and does not reach the opposite edge of the doorway. In such a breakthrough situation, the air curtain is not capable of fulfilling its purpose and air flows through the doorway practically without any barrier [12]. The jet discharge angle also has a strong influence on the jet's ability to resist the breakthrough. Small discharge angles, leading to a high jet momentum flux, give more tolerance to the breakthrough. A theoretical approach was developed to determine the thermal loss through the doorway with an air curtain (Sirén 2003 b). It found that the thermal loss through a properly working air curtain is due to the turbulence generated entrainment-spill process, which is proportional to the thermal loss coefficient and the square root of the jet momentum flux. The tightness efficiency of an upward-blowing air curtain can be as high as 80%, which depends on the discharge angle, suction capacity of return and initial momentum [14]. Similar to an industrial air curtain, the protected occupied zone ventilation (POV) was subsequently proposed by using a low turbulence plane jet to separate an office environment into a few subzones [15]. The POV can be applied in a protected occupied zone (POZ), which is defined as an area of the occupied zone in a room consisting of the breathing zone and the personal working zone, where occupants spend most of their time in the office. The POZ has the dimensions of (length x width x height) 1.5 m × 1.5 m × 1.8 m, which is mainly protected by a plane jet or an air curtain [16]. The performance of POV remains unclear regarding the PE and breakthrough phenomenon.

Therefore, there is a substantial lack of understanding of the fundamental and critical principle of airflow distribution to create a safe, healthy and productive work environment. The insufficient understanding results in using less effective ventilation to protect people from infection from epidemic respiratory disease in open plan offices and public spaces. Furthermore, there are not enough results and achievements to show the principles of airflow distribution that will support personal ventilation methodology to keep office workers away from the infection of respiratory disease. In fact, most offices and public spaces need new airflow distribution solutions regarding the insufficient protection function of the conventional ventilation methods. Fundamental research into the efficient and effective airflow distribution for ventilation is urgently needed to meet the demands of keeping office workers away from the infection of respiratory disease.

The main objective of this study is to develop theoretical models to predict the performance of a new type of air distribution method, POV, for office rooms and to validate the model by conducting experimental measurements. The goal is to find out experimentally the most effective and efficient method of airflow distribution