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Numerical evaluation of influence of door opening on interzonal air exchange

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A B S T R A C T

Ventilation plans for rooms with contaminated air must address pollutants because they affect the air quality of adjacent areas. A ventilation plan typically maintains a negative room pressure to remedy this problem. However, the transport of indoor air pollutants between rooms is affected by the movements of humans and doors. The purpose of this study was to evaluate the influence of door opening on the interzonal air exchange volume. We measured the interzonal air exchange volume by dispersing sulfur hexafluoride (SF_6) as a tracer gas, swinging or sliding a door between an air-contaminated room and a corridor in an office building, and measuring the direction and velocity of the airflow. The results were compared to those of a computational fluid dynamics (CFD) simulation. We modeled the influence of swinging and sliding of a door at various speeds and air temperature differences between rooms on the interzonal air exchange volume. The measured absolute interzonal air exchange volume was very similar to the value obtained from CFD simulation (0.428 m^3), and the measured and simulated values of flow rate variation over time were also quite similar. The interzonal air exchange volume through the doorway was decreased to 0.052 m^3 with a sliding door, compared to 0.317 m^3 for a swing door, for isothermal conditions. However, the interzonal air exchange volume through the doorway were not significantly different for a swing door versus sliding door when a temperature difference between areas was involved.

1. Introduction

Ventilation plans for rooms with contaminated air, such as chemistry laboratories, smoking rooms, bathrooms, hospitals, medical and health care facilities, must address pollutants because they affect the air quality of adjacent areas. A ventilation plan typically maintains a negative pressure difference between a room and adjacent areas to remedy this problem [1]. A negative pressure difference is obtained by supplying less air to the area than is exhausted from it. Various negative pressure differentials and ventilation rates, in the form of air changes per hour (ACH) in a room, have been recommended to prevent contaminated room air from leaking into adjacent areas. Systems serving highly contaminated areas, such as autopsy and airborne infectious isolation rooms, must maintain negative air pressures in these rooms relative to adjoining rooms or corridors [2,3]. In 1994, the US Centers for Disease Control and Prevention (CDC) recommended a negative pressure of 0.25 Pa and an exhaust flow of 1.8 m^3/min or 10% greater than supply to control the direction of airflow between a room and its adjacent areas, and one decade later, the CDC raised the desirable level of the negative pressure to 2.5 Pa for health care facilities [4,5]. However, despite planned ventilation, the transport of indoor air pollutants between rooms and floors is affected by temperature differentials and moving objects, such as human movement and door opening. Although there have been many studies on the performance of such rooms with negative air pressure, there have been relatively few studies conducted to assess how door opening motions and human passage through doors affect airflow [6–8]. Adams et al. [9] studied the effect of a pressure differential on containment effectiveness. They found that passage through a door reduced containment and concluded that containment effectiveness was improved when the pressure differential

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between rooms was increased.

Computational fluid dynamics (CFD) simulations have been used increasingly in design, optimization of ventilation systems, and the prediction of air movement in ventilated spaces [10–12]. A few investigations conducted using CFD simulation with dynamic mesh techniques have indicated that transient events such as object movements play important roles in indoor dynamic airflows and contaminant dispersion. For example, Matsumoto et al. [13], Shih et al. [14], and Tung et al. [15] used dynamic grid deformation approaches to generate the computational mesh around a moving body in an isolation room. Choi and Edwards [16,17] modeled the contaminant transport induced by a person walking from one room to another and from a room into a long hallway using large eddy simulations. They found that the human wake may transport material over a distance of 8 m when there is no ventilation system. Hang et al. [18] investigated how the walking motion of health care workers influences gaseous dispersion in a six-bed isolation room and reported that the ventilation design and air change rates in the room affected airborne transmission much more than human motion. Goldasteh [19] and Wang and Chow [20] found using CFD simulation that human motion can significantly influence particle re-suspension and particle dispersion in the isolation room. Mazumdar et al. [21] found using CFD simulation that a moving passenger in an aircraft cabin could carry a contaminant in his wake to positions far from the contaminant source. They also used CFD simulations to investigate the effects of moving persons and movements of objects, such as a walking visitor, a walking caretaker, the changing of the sheet on a patient's bed, and the swinging of an entrance door for up to four seconds, on the contaminant concentration distributions in a single inpatient [22].

Airflows across a doorway due to door opening have also been studied by means of scale models and analytical models. Julian et al. [23] studied the effects of door-opening motions using a variety of doors, with and without the passage of a human figure, on the movement of potentially contaminated air into and out of an isolation room, using a Reynolds-number-equivalent model in water. These experiments demonstrated that a hinged door design generates greater air exchange across an isolation room doorway than a sliding door design. Petri Kalliomäki et al. [24] studied the containment effectiveness of these two different door types both quantitatively and qualitatively for various scenarios involving hospital isolation rooms. They found that the exchange volume ranged between 1.2 and 2.4 m^3 with a hinged door.

The purpose of this study was to evaluate the influence of door opening and closing actions on the interzonal air exchange volume as a function of the total cycle time for door opening and the temperature difference between areas. To achieve this goal, a full-scale room model was set up with a single hinged swing door. Using this model, tracer gas measurements and smoke visualizations were carried out without forced ventilation or a pressure difference. In addition, by CFD simulation of two types of doors (a single hinged swing door and a sliding door), fundamental design data were acquired concerning the influence of door opening and closing actions on the interzonal air exchange volume as a function of the total cycle time for door opening and the temperature difference between areas.

2. Full-scale measurements

Measurements were obtained using a full-scale room model. A schematic of the measurement scheme and details of the CFD validation model are provided in Fig. 1 and Table 1. The model consisted of two identical rooms: an indoor room and a corridor, separated by a wall with a connecting door in the middle. The door was a single hinged swing door with dimensions of 0.8 m × 2.1 m (width × height). The indoor area had dimensions of 2.5 m × 2.5 m × 2.5 m (width × length × height), and the corridor area had dimensions of 2.5 m × 2.0 m × 2.5 m (width × length × height). This model was used to study the interzonal air exchange volume between areas. To minimize the risk of infiltration at the indoor area, the indoor area of the model was constructed of airtight vinyl, without any openings, in a small laboratory space, and the corridor area of the model was an open space. Using this model, the airflow was visualized, the direction and velocity of the airflow were measured, and the interzonal air exchange volume was measured. The measurement devices used are listed in Table 2. The interval for door opening and closing was set to 0–4 s (door opening) → 4–6 s (door opened) → 6–10 s (door closing) → 10–12 s (door closed), and the rotational speed of the swing door was $\pi/8$ rad/s.

2.1. Smoke visualizations

Airflow patterns were visualized by generating water-and glycol-based smoke with a smoke generator (Porta Smoke PS-2005, Dainichi Co., Ltd.). The smoke generator was placed in the indoor area, and an airflow pattern was visualized in the horizontal plane around the door in the corridor area during door opening and closing. The height of the Nd:YVO4 laser beam was 1.2 m from the floor. The density and the size distribution of the smoke were not measured. However, the particle size was several tens μm or more, according to the manufacturer's documentation, and was thus suitable for airflow pattern visualization. Inside the indoor area, the smoke was mixed with a desk fan. The distribution fan was shut down approximately 5 min before door operation and recording of the smoke flow through the doorway. Airflow visualization was recorded with a digital camera (Canon 5D Mark II, Canon EF 16–35 mm F2.8 lens, 1920 × 1080 pixels (full HD video), 25 fps) from the upper side of the door.

Recorded still images of a section 1.2 m from the floor are shown in Fig. 2. These images illustrate the variation in the airflow characteristics produced by door opening and closing actions, as evidenced by smoke visualization. The smoke was distributed in the vicinity of the door, and a large vortex was generated in the direction of the door rotation by the door actions. Immediately after the door was fully opened, the airflow movements began to settle down slowly, and the large vortex took over in the negative y direction, as shown in Fig. 2(a) and (b). The large vortex took over in the positive x direction when the door was closed, as shown in Fig. 2(c) and (d).

2.2. Direction and velocity of airflow

The direction and velocity of airflow were measured using a three-dimensional (3-D) ultrasonic anemometer to ascertain variations in the airflow around the door due to the door opening and closing actions. To acquire the measurements, the anemometer was set 0.1 m away from the edge of the door in the corridor area when the door was fully opened, at a height of z = 1200 mm (i.e., 1200 mm above the floor).

The measured variations in air velocity produced by the door opening and closing actions are shown in Fig. 3. The air velocity changed when the door opened and closed. The x direction indicates the horizontal component of the velocity, and the y direction indicates a direction perpendicular to the direction vector from the corridor to the indoor room. The negative air velocity in the x direction increased greatly immediately after the door was fully opened and immediately after the door closing action began. The maximum air velocity in the x direction was −0.450 m/s, measured 6.45 s after the door closing action began. The negative air velocity