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Evaluation of different air distribution systems for sleeping spaces in transport vehicles

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ABSTRACT

Air distribution in the sleeping space of a transport vehicle is important for sleep quality, especially during a long journey. In order to design a thermally comfortable sleeping space with fresher air, this investigation used a verified computational fluid dynamics (CFD) method to obtain the distributions of air velocity, air temperature, and CO_2 concentration in the sleeping space with displacement, personalized, and mixing ventilation systems. This study used the facial-area speed ratio, mean age of air, and draft risk obtained by CFD to evaluate the air distribution effectiveness. The results showed that the performance of the personalized ventilation system was better than that of the displacement and mixing ventilation systems because it provided superior thermal comfort and higher air quality. The distributions of air velocity, air temperature, and contaminant concentration computed by CFD were validated with corresponding experimental data obtained in a full-scale test rig.

1. Introduction

Time spent sleeping accounts for one third of a person's lifetime. Sleep can help people overcome fatigue [1], enhance their immunity [2], and protect their memory [3]. People who sleep poorly may not function well in social, occupational, and educational settings [4–6]. Thus, sleep has an impact on quality of life and work efficiency. Although sleeping time on a journey may not be as long as in bedroom, good sleep in vehicles such as trains, coaches, ships, airplanes, and spacecraft is essential to overcoming fatigue and sometimes jet lag. Compared to a typical bedroom with dimensions of $4 \times 3 \times 3$ m^3, the sleeping space in a vehicle can be quite small ($2 \times 1 \times 1$ m^3). It is very challenging to create a suitable sleeping environment in such a small space, because of the need to organize the air distribution so that it removes heat and CO_2 effectively without causing a draft.

Numerous investigations have been conducted on the various factors that affect quality of sleep [7,8]. These factors include the mental and physical characteristics of a sleeping person as well as environmental factors, such as thermal conditions, air quality, acoustics, and lighting level, in the person's bedroom [9]. A number of studies have focused in particular on the effects of thermal conditions and air quality. Miyazawa [10] tracked the sleep of five high school students for 214 days and found that 23 ± 3 °C was the most suitable sleeping temperature. Furthermore, it has been found that air temperatures higher or lower than the comfortable one would decrease slow-wave sleep and rapid-eye-movement sleep, and increase the frequency and duration of wakefulness [11]. Exposure to humidity during sleep can increase wakefulness and decrease slow-wave sleep and rapid-eye-movement sleep [12]. Sekhar [13] suggested that a high level of CO_2 may shorten the duration of sleep. However, these studies all assumed a uniform sleeping environment and did not consider the impact of variations in environmental parameters on sleep quality.

Creating a suitable air distribution can make a sleeping environment more thermally comfortable and ensure good air quality. Task air conditioning and full-volume air conditioning have been widely studied in sleeping spaces because of their thermal performance and energy efficiency [9,14–17]. However, most of the studies have focused on air distributions in large bedrooms. Very few studies are available on the environment in close proximity to a sleeping person. For example, Pan et al. [17] evaluated a bed system

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in which air was supplied by means of two symmetrically placed plenums on both sides of the mattress. They found that the system could save energy compared with conventional air-conditioning system used in a room. Lan et al. [14] used a personalized ventilation system that was positioned next to the head of a sleeping person. Cardiac measurements showed that personalized ventilation was better for sleep than the well-mixed ventilation for a room. Although several investigations found air distribution to be very important for thermal comfort and air quality in trains [18], aircraft [19], and spacecraft [20], very few focused on the sleeping state. The literature review suggested that it is essential to study air distributions in the sleeping spaces of transport vehicles.

Therefore, our investigation focused the thermal environment and air quality in close proximity to a sleeping space. This paper reports the results of the study.

2. Research method

There are two primary methods of investigating air distributions in small sleeping spaces: experimental measurements [16,17] and numerical simulations [15,21,22], such as by the use of computational fluid dynamics (CFD). Liu et al. [23] pointed out that CFD is less expensive and more efficient for air distribution design than experimental measurements, but the modeling of turbulence can create some uncertainties. They recommended validating CFD with experimental data for the same flow characteristics before using it for design and analysis. Therefore, the present investigation has used the CFD method to evaluate the thermal environment and air quality in sleeping spaces while conducting experimental measurements of the flow characteristics for validation of the CFD results.

This investigation first used airflow data from four cases with basic flow characteristics to verify the CFD model. The verification process primarily examined the turbulence model, wall functions, and numerical algorithm that had been used in the CFD method [24]. The verified CFD method was then used to obtain the distributions of air velocity, air temperature, and CO_2 concentration in a sleeping space with different ventilation systems under various thermal and flow conditions. On the basis of the simulated distributions, this study evaluated the thermal environment and air quality in the sleeping space in terms of the facial-area speed ratio under different velocity ranges; mean age of air; and draft risk. The evaluation process identified the best air distribution for the sleeping space. This investigation then set up an experimental rig to validate the resulting design in the sleeping space. The following sections describe the research method in detail.

2.1. CFD method

CFD consists of direct numerical simulation, large eddy simulation, and Reynolds-averaged Navier–Stokes (RANS) modelling. Liu et al. [23] recommended using RANS modelling because it provides good results with the least amount of computing time compared with large eddy simulation and direct numerical simulation. RANS modelling has incorporated a variety of turbulence models. Zhang et al. [25] compared a number of these models and found that the RNG k–ε model [26] is stable and provides good results. Zhang's study included mixed convection with a jet supplying cool air and a warm floor that is similar to the present investigation, the flow features were the same. Therefore, the present study used the RNG k-ε model. Since this turbulence model is for high-Reynolds-number flow, our study used the standard wall function [27] for the flow near a rigid surface. The SIMPLE algorithm [28] was used to couple the pressure and velocity calculations. The standard interpolation scheme was adopted for pressure, and the second-order upwind scheme was used for all the other variables [29]. The under-relaxation factors for the pressure, momentum, energy, and concentration equations were fixed at 0.3, 0.7, 1.0, and

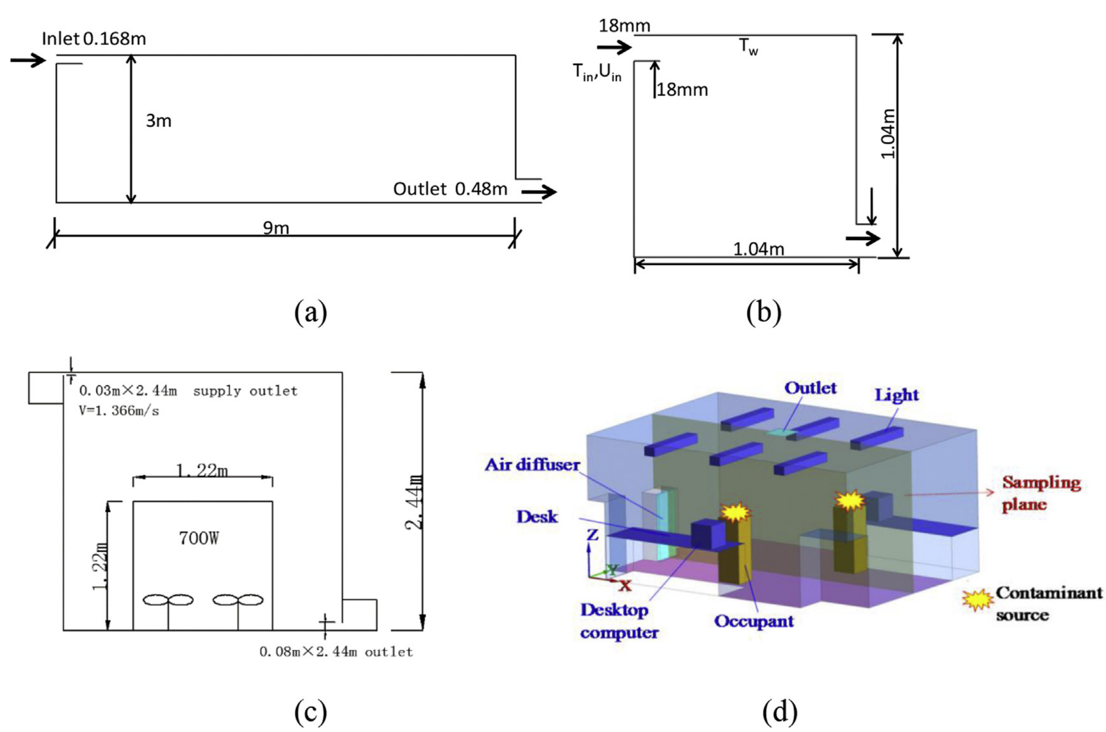

Fig. 1. Four cases with experimental data from the literature were used to verify the CFD program and the user's ability to use the program correctly: (a) 2D forced convection flow, (b) 2D mixed convection flow, (c) 3D mixed convection flow, and (d) 3D realistic flow.