Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Performance evaluation of different air distribution systems in an aircraft cabin mockup

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ARTICLE INFO

Article history:
Received 3 March 2017
Received in revised form 5 August 2017
Accepted 10 August 2017
Available online xxxx

Keywords:
Aircraft cabin
Displacement ventilation
Mixing ventilation

ABSTRACT

The purpose of this study was to evaluate the performance of different ventilation systems in an aircraft cabin mockup. The related experimental research was conducted to obtain the local mean age of air, temperature and velocity distribution under different air distribution systems by using trace gas, thermocouples, and an ultrasonic anemometer measurement system. The results showed that in a comprehensive comparison of mixing ventilation and displacement ventilation, displacement ventilation has high ventilation efficiency. The velocity nonuniformity indices (VNUI), temperature nonuniformity indices (TNUI), and heat removal efficiency (HRE) of different ventilation systems in the cabin were compared and analyzed. A cabin airflow evaluation system is proposed. Compared to the mixing air supply, the displacement ventilation has high heat removal efficiency, but it aggravates nonuniformity. Using a plurality of air inlets can improve the uniformity of air temperature and velocity distribution. Side wall air supply is necessary to improve the ventilation performance of single-aisle cabin.

1. Introduction

There are more and more passengers choosing air travel, the cabin environment has high passenger density, the thermal comfort and safety of aircraft cabin environments have become an important problem [1,12]. The air distribution system commonly used in aircraft cabins consists of the air supply at the top and exhaust air at the bottom of the cabin, with mixing air within the cabin [2]. The contaminants transmitted during air travel are an important health issue [3]. Such as after one flight carrying a symptomatic person and 119 other persons, laboratory-confirmed SARS developed in 22 persons [34]. The cabin environment has high thermal load. The high temperatures found may induce inertia and concentration problems, which may lead to a lowering of intellectual capacity [4].

Currently, the mixing ventilation is widely used in aircraft cabins. The fresh air is supplied from the top (ceiling and side wall) of the cabin, and air is exhausted from the bottom outlets [5]. The representative models of the mixing ventilation include the ceiling air supply, the sidewall air supply and the ceiling and side wall air supply. The mixing ventilation system will form a significant vortex flow in the cabin, resulting in local air retention. Fresh air from the ceiling or the side wall enters into the cabin with a certain momentum. The air jet and the passenger-dissipated heat plume mix with each other to form large-scale circulation. Kuhn et al. [6,7] analyzed the interaction between air jets and thermal plumes under two different air inlet configurations and the flow rates at the different air inlet positions. The mixing ventilation system is not conducive to the exclusion of pollutants, and the dissemination of mutual interference between passengers seriously affects the cabin air quality.

For further improvement of the air quality of the cabin, extensive research put forward improvement methods such as displacement ventilation and personalized ventilation. The displacement ventilation system can remove contaminants more efficiently than conventional passenger aircraft cabin airflows [33]. Douglas et al. [8] performed mixing ventilation (MV) and underfloor air distribution (UFAD) under the same air supply rate. The UFAD system showed more promising results regarding the efficiency in the dispersion and removal of expiratory particles in the cabin. The ventilation rate of the aircraft cabin was dependent on the CO_2 levels [9,10]. Zhang et al. [11] proposed new displacement ventilation, supplying air from both under the aisles and below the stowage bins. The system can lessen the inhaled CO_2 concentration by 30% more than the mixing ventilation. As less energy is consumed with displacement ventilation (DV) systems in comparison to mixing ventilation (MV), the implementation of displacement ventilation systems has a potential to improve the energy efficiency of airplanes [17]. While a displacement ventilation system

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http://dx.doi.org/10.1016/j.ast.2017.08.009
1270-9638/

has a high ventilation efficiency and energy utilization efficiency but obviously leads to temperature stratification, its applicability in the cabin needs to strictly limit the temperature distribution [18]. The temperature distribution of displacement ventilation has the character of stratification. By the aircraft design standard ASHRAE Standard 161-2007 [16], the vertical temperature gradient in a room should be less than 2.8 °C. A combined floor and side wall based displacement ventilation system can weaken the vertical temperature gradient as well as ensure high heat removal efficiencies [14,15]. Tobias also studied the combined floor and side wall based displacement ventilation system [17] and obtained the similar result. The combined floor and side wall is equivalent to combination of displacement ventilation and mixing ventilation. The results obtained by Winzen show no severe losses of comfort must be expected with displacement ventilation compared to mixing ventilation [18].

Personalized ventilation (PV) could effectively avoid the passenger-inhaled polluted air by conveying fresh air to the breathing zone of the cabin environment [19]. The localized exhaust orifices placed near the source where passengers are can also improve the indoor air quality in the cabin [20]. Although the personalized ventilation supplied fresh air to passengers, the cabin air is still in need of central ventilation [21]. The personalized ventilation systems could also create temperature stratification [25].

The cabin ventilation has a major effect on passenger thermal comfort. The cabin needs strict temperature control owing to the large temperature variation [22]. Therefore, the velocity, temperature and CO_2 concentration were used to evaluate the cabin environment under the mixing ventilation, displacement ventilation and personalized ventilation. Considering the combined factors, the personalized ventilation system has the best performance [23,24]. The combination of different types of ventilation such as DV and MV, PV and DV might show a better performance than using only one mode. The evaluation system for airflow performance is reviewed in the building environment research. Four primary tasks have been revealed, including contaminant removal, air exchange, heat removal and occupant protection. Within these tasks, the most important goal of using ventilation should be the protection of occupants from contaminants [26]. However, the evaluation system is not applied to quantitative evaluation of cabin environments. The cabin environment has high passenger density, high air exchange and thermal convection. Less air draft was perceived at the window seats and the middle rows, and higher air draft was perceived close to the aisle in an aircraft mock-up of a Dornier 728 [28]. Therefore, a highly effective air distribution system is very important for passengers in an aircraft cabin [13,27]. The uniformity is a very important index to guide cabin environment design. The ASHRAE Standard 161-2007 recommends the best air velocity between 0.1 m/s and 0.3 m/s. The upper limit recommended by the standard for vertical temperature difference is 2.8 °C, and for horizontal temperature difference is 4.4 °C [16]. Nonetheless, there is still a dearth of a complete standard to evaluate the effect of ventilation in the cabin. Further studies are still necessary. According Conceicao's [32] review, the airborne dispersion of contaminants was different, such as the CO_2 concentration and expiratory droplets. The different contaminants have different cross-infection risks. The fresh air is very important to passengers. Therefore, the mean age of air is the more reasonable index.

The displacement ventilation and mixing ventilation were studied and compared in this study. The purpose of this study was to evaluate the air distribution in the cabin. The experimental research was conducted to obtain the local mean age of air, temperature field and flow field of the cabin mockup under different air distribution systems by using trace gas, an ultrasonic anemometer and a thermocouple measurement system. By comparing the velocity nonuniformity indices (VNUI), temperature nonuniformity indices (TNUI), mean age of air and the heat removal efficiency (HRE) of different air distribution systems, a reasonable evaluation system of the cabin airflow was obtained.

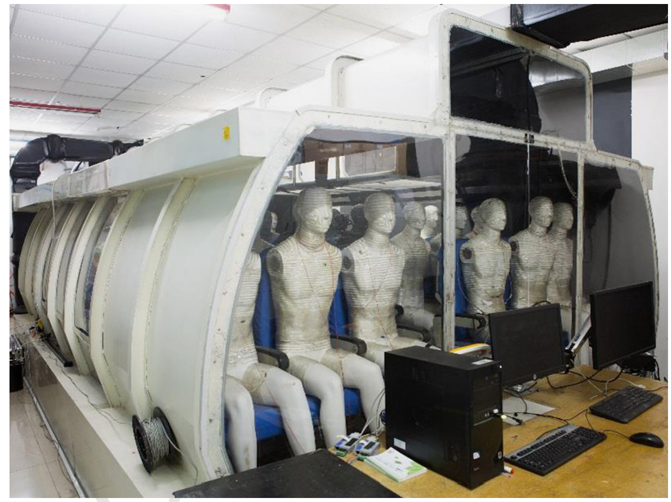

Fig. 1. The experimental facility cabin mockup.

2. Methods

2.1. Experimental facility

The research team set up a measurement system for obtaining accurate temperature and velocity in a seven-row cabin mockup built with the same dimensions as the Boeing 737-200 in full-scale, as shown in Fig. 1. The cabin mockup had seven rows with a single aisle. The seat pitch is 760 mm. Forty-two thermal manikins were placed in the seats and simulated the effect of the passenger positions on the airflow patterns.

The height of a sitting thermal manikin was 1.40 m, with the surface area of 1.339 m^2 and a volume of 0.055 m^3. Based on the real heat load of various parts of the passengers, the manikins were wrapped with different lengths of nickel–chromium wires on every part. Every thermal manikin heat load was controlled to 75 W. Under the cooling conditions, we turned on all the thermal manikins. The supply air temperature was controlled at 19 ± 0.5 °C. The supply airflow rate was set to 9.4 L/s/person. The cabin skins at cruise have relatively low temperatures, which are not reproduced in the experiment. The modern commercial aircraft are using the very low thermal conductivity of composite materials, which can insure the thermal environment reliability and safety [29]. Therefore, the temperature of the thermostatic chamber was controlled at 19 ± 1 °C. The internal wall temperatures can be found in a previous publication [30].

For the mixing ventilation system, the supply air was distributed from the side wall or ceiling of the cabin, and the supply air had a high momentum into the cabin. The high momentum airflow caused an efficient mixing of the fresh air and the thermal plumes and created a large-scale circulation. Finally, the recirculated air left the cabin through the bottom outlets.

Three forms of mixing ventilation are shown in Fig. 2: (a) sidewall supply and bottom return mixing ventilation: the air diffusers for the supply air are located below the luggage rack on the side walls. The diffusers detail size can be found in a previous publication [35], the supply air velocities is 2 m/s; (b) ceiling supply and bottom return mixing ventilation: this supply air from the ceiling of the cabin uses two perforated ceiling jets (the diameter is 20 mm) at an angle of 120°, the mean supply air velocities is 3.2 m/s; and (c) ceiling and sidewall supply and bottom return mixing ventilation: the supply air is provided while blowing the