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Thermal comfort criteria for personal air supply in aircraft cabins in winter

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ABSTRACT

Personal air supply systems (PASSs) have shown great potential in buildings, but to date, the usefulness of PASSs in aircraft cabins in winter has not been examined. In this study, 40 subjects participated in experiments in a model aircraft cabin constructed at Chongqing University. The subjects were exposed to air from a personal air supply at flow rates of 0, 0.5, 1.0, and 1.5 L/s under eight different conditions: 28, 26, 24, and 22 °C while wearing winter clothing (≈1.23 clo); 24, 22, and 20 °C while wearing winter clothing with a jacket (≈1.55 clo); and 26 °C while wearing summer clothing (≈0.65 clo). The results indicate that the subjects were more thermally sensitive to the environment in the aircraft cabin than that in buildings. Because a higher draft rate (DR) at the face occurred under some conditions, a new DR model based on convective heat transfer at the face was constructed. The perceived air quality (PAQ) had a strong relationship with the airflow rate of the air supply and the standard effective temperature, implying that the PAQ is affected by the heat balance of the body. Thus, recommended adjusted thermal environment criteria for a personal air supply while wearing winter clothing that account for the thermal sensation, drafts, and PAQ are presented.

1. Introduction

As the living standard for many people increases and more people currently travel by air, there is an increasing demand for comfort while in flight [1]. For decades, the aviation industry and various research institutions have conducted studies with the objective of improving cabin comfort in order to meet this demand [2–6]. A typical aircraft cabin has two air distribution systems; however, it is not practical for the main air distribution system to satisfy all passengers owing to individual preferences [7] and poor thermoregulation on some flights [8]. To address this problem, personal air supply systems (PASSs) have been proposed.

Personalized ventilation systems have shown great potential in buildings [9,10] and are currently available on most aircraft. The outlet of a PASS is a nozzle installed under the luggage bin to provide clean conditioned air directly to passengers [11]. Although studies by Li et al. [12] and You et al. [13] have shown that a PASS may not improve the air quality in the cabin as a whole, this system can still directly improve the microenvironment of an individual and relieve psychological discomfort [14,15].

Several scholars have recently conducted studies on PASSs in aircraft cabins. For example, Zitek et al. [16] introduced a novel PASS that reduces airborne health problems and provides local compensation for the deficit in humidity. Fang et al. [17], Dai et al. [18], and Guo et al. [19] analyzed the characteristics of the jet flow from an actual cabin nozzle in a model cabin. Fang et al. [20] and Cui et al. [21] investigated the behavioral responses of passengers in an aircraft cabin and found that a PASS was used by a majority of the passengers. Shi et al. [22] used computational fluid dynamics (CFD) and mathematical models to evaluate the impact of the jet on the air quality in a passenger's breathing zone. Du et al. [23] investigated the appropriate airflow rate for an actual aircraft nozzle on the basis of thermal comfort experiments conducted in summer. It is well-known that the optimal thermal environment for an

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Abbreviations

DR	draft rate, %
PAQ	Perceived air quality
PASS	Personal air supply system
PMV	Predicted mean vote
PMV_{adj}	Adjusted PMV at a high air velocity based on the SET model
PPD	Predicted percentage of dissatisfaction
PR	Percentage of risk of unacceptable air quality
$PD_{(TSV=1)}$	Percentage of dissatisfaction, where TSV = 1 indicates dissatisfaction
$PD_{(T\&A)}$	Percentage of dissatisfaction that combines the thermal sensation and perceived air quality
PTS	Predicted thermal sensation based on the definition of the SET
SET	Standard effective temperature, °C
TSV	Thermal sensation vote

Symbols

G	Airflow rate, l/s
I_{cl}	Clothing insulation, clo
$I_{cl,static}$	Static clothing insulation (equal to the value of I_{cl} when $V_a = 0$), clo
R^2	Coefficient of determination
RH	Relative humidity, %
T_a	Air temperature, °C
T_g	Globe temperature, °C
Tu	Turbulence intensity, %
V	Air velocity, m/s
V_{face}	Air velocity in the region of the face, m/s
Ki	Constants, where i = 0,1,2,3,4

individual depends on the season [24] and that it is affected by the thermal history [25]. However, the criteria for the thermal environment in aircraft cabins provided by the personal air supply in winter under heating conditions have not been systematically studied and are not specified in current international standards [26,27] or Chinese standards [28,29].

The appropriate personal air supply airflow rate under heating conditions is related to the actual air quality and psychological perceptions such as the perceived air quality (PAQ), drafts, and thermal comfort [30]. Overheating causes discomfort due to warmth and increases the enthalpy of the inhaled air, which both negatively affect the PAQ [31–33] [34]. On the other hand, it is important for people to not feel overly cool in order to minimize draft complaints [35]. However, the current draft model introduced by Fanger [36] and incorporated into thermal comfort standards [37] is only suitable for uniform environments in buildings. Furthermore, passengers are believed to be more sensitive to the distributions of the air temperature and air velocity in aircraft cabins [38–40] because the posture of the human body is mostly stationary in a settled aircraft seat. Thus, how people respond to their personal air supply during heating in aircraft cabins is still an open question.

This study was conducted to inspect the thermal and psychological factors that affect the demands of PASSs in aircraft cabins. A quantitative analysis was conducted in an attempt to find the optimal thermal environment parameters that could be applied to PASSs used in winter in aircraft cabins.

Thus, a three-row model aircraft cabin equipped with environmental monitoring instruments was used for human experiments involving 40 subjects under different conditions, which are described in detail in the methods section. The thermal sensation, local drafts, and PAQ versus the nozzle airflow rate under different conditions are presented in the results section. A further analysis of the data with the conventional models used in buildings was also conducted. In the following discussion section, new models suitable for the thermal environment in an aircraft cabin are discussed. Thus, the optimized thermal comfort zone for a personal air supply while wearing winter clothing based on the experimental data and new models is presented.

2. Research method

This paper presents the results of three series of experiments in a three-row model aircraft cabin. The experiment involved 40 subjects, and the thermal environment criteria required to ensure comfort in an aircraft cabin when using a personal air supply nozzle were investigated.

2.1. Experimental platform

The experiments were performed in a three-row (18-seat) aircraft cabin whose cross section was based on an Airbus A320 aircraft, which is 3.9 m wide, 2.35 m high, and 4.9 m long. The cabin was situated in an air-conditioned room where a stable external thermal environment could be maintained.

The thermal environment in the aircraft cabin was modified by an air-conditioning unit, as shown in Fig. 1(a), which comprised both the main air distribution system and a personal air distribution system. In this study, the personal air supply nozzle was designed to supply mixed air consisting of 50% recirculated air and 50% fresh air (isothermal conditions). Fig. 1(b) shows a schematic of the front view of the nozzle, which is from a retired Airbus 320 aircraft. The nozzles were placed above the seats, as shown in Fig. 1, and the distance between adjacent rows was approximately 81.3 cm.

2.2. Instruments and measurement method

A portable environmental monitoring station (BSU102, LSI) and an indoor air-quality monitor (Telaire 7001, GE) were used to monitor the background thermal environment during the experiment and were placed at a height of 0.6 m in the middle of the cabin. The ranges and accuracies of the instruments are listed in Table 1. A digital mass flow meter (MF5712) with an accuracy of ±2.5% for measurements in the range of 0–3.33 L/s was used to measure the supplied airflow rate (G, L/s) of the nozzle.

The air velocity (V, m/s) and turbulence intensity (Tu, %) around each occupant were measured at heights of 0.1, 0.6, and 1.1 m using eight omnidirectional velocity sensors of an air distribution measuring system (AirDistSys 5000, Sensor Electronic, Poland), which have an accuracy of ±0.02 m/s in the range of 0.05–5.00 m/s. The data were collected at 8 Hz, i.e., eight samples per second.

2.3. Experimental conditions

Table 2 summarizes the environmental conditions for the three sets of experiments. Series I was conducted in summer with an ambient temperature in the cabin of 26 °C and was used a baseline