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Investigation of the effects of temperature for supplied air from a personal nozzle system on thermal comfort of air travelers

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A B S T R A C T

Air travel has become the most popular form of long distance travel owing to speed and convenience. In order to create a healthy and thermally comfortable environment in the aircraft's cabin, personalized nozzle ventilation is supplied to passengers. In such a system, the temperature of the supplied air is normally lower than the ambient temperature by 5 °C. In this study, an experimental investigation of thermal responses and skin temperature measurements was carried out in a mock-up of an aircraft cabin. The results indicate that local cooling is an effective way to improve the overall thermal comfort, especially for cooling the upper body. Based on paired *t*-test analyses, there were no significant temperature differences between the effects of isothermal and non-isothermal air supply on subjective responses and mean skin temperatures. The regression models of local thermal and overall thermal sensations were obtained and analyzed. Such models will be beneficial for the optimum design of future personalized nozzle ventilation systems.

1. Introduction

One of the important design criteria for the development of new types of aircrafts is the thermal comfort of passengers [1]. In commercial aircraft, most often, there is a high passenger occupancy/density with low pressure and humidity in the aircraft's cabin [2]. Almost 30% of the passengers complain that it is too warm in the cabin [3]. Researchers have pointed out that the local and global thermal perceptions were often significantly different [4]. In order to meet the health and thermal comfort needs of all passengers, aircraft was usually equipped with personal air supply nozzle systems to create a self-controlled thermal environment. Personal control of thermal and air quality conditions are extensively used in buildings. However, the environment of the aircraft's cabin is a special environment with the high passenger density. In addition, the airflows in an aircraft are typically turbulent, with the velocities varying in magnitude, fluctuation frequency, and in a quasi-periodic manner because of the turbulent structural instability [5]. Thus, it is necessary to analyze the effects of personal air supply nozzle systems in aircraft cabins.

In commercial airplanes, air is supplied by an adjustable air nozzle located directly above each passenger's seat. When passengers turn on the nozzles, the air distribution in the cabin is altered significantly [6,7], thus affecting the human thermal comfort and air quality. Niu et al. [8] reported a substantial increase in the proportion of clean air to inhaled air when it was supplied from a nozzle attached to the seat's armrest discharging air towards the passenger's face. Zhang and Chen [9], and Zitek et al. [10], reported improved air purity in the breathing zone of airplane passengers when personalized ventilation (PV) was supplied with an air nozzle at the back of the seat discharging air towards the passenger's face. Shi et al. [11] calculated the entrainment ratio at different locations along a gasper-induced jet using a computational fluid dynamics model. They found that over 90% of the air in the passenger's breathing zone was entrained from the surroundings when the nozzle was turned on. However, in the aircraft cabin, the indoor thermal environment is controlled by both the main air supply system and the personal air nozzle system. The main air supply

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Nomenclature

PV	personalized ventilation
HVAC	heating, ventilation, air conditioning
ECS	environment control system
PAO	personal airflow outlet
MTSV	mean thermal sensation vote
MAMSV	mean air movement sensation vote
PD	percent dissatisfied (%)
DPV	ductless personalized ventilation
T	Temperature (°C)
RH	relative humidity (%)
V	velocity (m/s)
T_u	turbulence intensity (m/s)
e	correlation coefficient

Greek symbol

α	significance level
β	required power level
ε	the corrected coefficient for nonsphericit

Subscripts

a	air
$a\text{-}s$	supply air
g	global
sk	skin
sd	standard deviation
head	head
chest	chest
back	back
upper arm	upper arm
forearm	forearm
hand	hand
thigh	thigh
lower leg	lower leg

system can create a uniform thermal environment. Thus, the necessity of a personal air supply nozzle system constituted the focus of some prior investigations [12,13]. Cui et al. [12] found that 63% of passengers used the nozzles during the flights. Fang et al. [13] reported that over 50% of subjects adjusted the personal nozzles to improve the thermal comfort of their upper body. Upon cooling of the upper body, the variations in local and overall thermal sensation votes, and the mean skin temperature were the most significant [14]. Therefore, the effects of personal nozzles on thermal comfort were significant, although the main air supply system can create a uniform indoor thermal environment in the aircraft's cabin. It is thus necessary to install the personal air supply nozzle system. In addition, in order to learn the characteristics of the jet flow from aircraft nozzles, some experimental investigations were carried out in an aircraft cabin mock-up [6,15–17]. However, the temperature of the supplied air is always maintained by the environment control system (ECS) in the range from 19 °C to 21 °C, and is lower than the ambient temperature by almost 5 °C. Based on these analyses, the cooled air is used to remove heating load. The cabin's heating load is typically in the order of 20kW per 1kW of power during cooling [18,19]. In instances where a heating load of 30kW is removed, 300kW of power will be consumed for air bled from the engines, and 400kW of power for overcooling the ECS drag [20]. Thus, cooling of air is very costly. It is very important to optimize the temperature of the supplied air from the nozzle. However, among the existing standards [21–25], only ASHRAE 161-2013 [21] recommends the minimum airflow rate (equal to 0.94 L/s) for a personal airflow outlet (PAO). No prior comments have been found in existing standards, or in the literature, on the temperature of the supplied air for a PAO in relation to aircraft cabins. The temperature of the supplied air is always the same with that of the temperature of the main air supply, and it is lower than the ambient temperature by almost 5 °C [22–25]. However, the rationality for this setup still needs to be analyzed and justified.

Correspondingly, this study reports a series of experiments conducted to measure airflow and human skin temperature, and to collect subjective responses. The effects on thermal comfort of different nozzle air temperatures were then analyzed. The findings provide fundamental evidence for an optimal design for the personalized nozzle supply system in an aircraft's cabin.

2. Material and methods

2.1. Experimental system

The experimental studies took place in a mock-up of an aircraft cabin based on the cross-sectional size of the Airbus A320 aircraft. The dimensions of the experimental cabin were 4.9 m × 3.9 m × 2.35 m, as shown in Fig. 1. In order to avoid the effect of the outdoor thermal environment, the cabin was located in an air-conditioned room, which was also treated as the departure lounge. Eighteen seats from a retired Airbus 320 aircraft were arranged in three rows of six seats in the cabin (see Fig. 1(2)). The distance between neighboring rows was 0.81 m. The nozzles, which were used in the tests, were also from the retired Airbus 320, and they were installed beneath the luggage rack. The distance between the nozzle and the location of the seat's back rest, in front of the nozzle, was approximately 0.41 m.

The cabin's environment was sustained by an air-conditioning system comprising a main air supply system and a personal air supply system (the nozzle system), as shown in Fig. 1(2). The main air supply system complied with the requirements of ASHRAE 161 [21] to create a healthy thermal environment for passengers. In the main air ventilation system, the supplied air was a mixture of fresh and returned air, and was supplied to the cabin through the air distribution ducts using a pressurization fan. The air then flowed into the mixer through the return air inlets for circulation, as shown in Fig. 1(b). The main air supply system provided air to the cabin's environment at a temperature within the range of 16 °C–30 °C with an accuracy of ±0.5 °C. According to the requirements of the ASHRAE standard 161-2013 [21], local air velocity of seated passengers and crew should be kept lower than 0.36m/s. Based on the data, in this aircraft cabin, the velocity around the seated passengers was in range of 0.1m/s to 0.35m/s to meet the requirements of the standard [21]. The air supply from the personal nozzle offered flexible control to meet the comfort demands of individual passengers. In this system, the air supply is delivered through nozzles located above the seats through the separate ducts, and enters the cabin as a jet of airs. It was designed to follow the requirements of the ASHARE standard 161-2013 [21]. The air velocity at the central part of the nozzle outlet varied from 0m/s to 25m/s, and was