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Experimental study of transient air distribution of a jet collision region in an aircraft cabin mock-up

Jiayu Li[a], Junjie Liu[a,*], Xiaodong Cao[a], Nan Jiang[b,c]

[a] Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
[b] School of Mechanical Engineering, Tianjin University, Tianjin 300072, China
[c] Tianjin Key Laboratory of Modern Engineering Mechanics, Tianjin 300072, China

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ABSTRACT

In commercial airliner, the mixing air distribution system in which air enters the cabin from the multi-slot diffusers underneath the luggage compartments and exhausted near the floor are most commonly used for air circulation, which result in two-jet collision regions with strong uncertainty and unsteady characteristics in cabin. In such unsteady regions, previous time-averaged data may miss much valuable information for studying thermal comfort, researching contaminant transport and verifying unsteady simulation modes. In this study, to experimentally explore more unsteady characteristics in cabin, we focused on this two-jet collision region in the middle of the aisle in the cabin, and a long time series of velocity fields was measured by particle image velocimetry (PIV) with a sampling frequency of 3 Hz under both isothermal and cooling conditions. Through the measured data, the fluctuation characteristics of four typical points were discussed and compared under two operating conditions. By observing the long time series of the measured transient flow field, three typical instantaneous airflow fields were identified under each of the two conditions. Then, POD analysis was utilized to mathematically reveal the coherent structure from the various instantaneous flow fields. These high-quality experimental data of instantaneous flow fields are also valuable for validating transient simulation models.

1. Introduction

In commercial airliners, mixing air distribution systems are commonly utilized for air circulation [1–3]. However, these systems are far from perfect, as indicated by passenger complaints about discomfort and frequent cross-infection incidents, especially in recent years [4–7]. To design a thermally comfortable cabin environment with good air quality and energy performance, it is necessary to further study the air distributions in aircraft cabins.

In the last two decades, by both experimental measurements and numerical simulations, many studies of the air distribution in cabins have been done [2], and most of them focused on the steady state because they are more convenient to work with and lead to easier conclusions. However, because the aircraft cabin environment always has many uncertain characteristics, such as frequent jet interactions, multiple heat sources, and a complex and irregular interior geometry [8], and the instantaneous characteristics of the air distribution in the cabin play an important role in thermal comfort and pollutant dispersion, time-averaged data alone may not reflect the real airflow features sufficiently. Moreover, many simulation researchers utilizing unsteady turbulence models, such as the Large Eddy Simulation (LES) model and transient RANS model [9–11], achieved better results even compared to time-averaged experimental data. Hence, to explore the air distributions in aircraft cabins in greater detail, the unsteady features in the cabin must be studied in deeper.

Although few researchers have studied the air distribution in the transient state, some valuable discoveries in unsteady phenomena have been made by studying other relevant issues in aircraft cabins. Garner et al. [12] used three-dimensional ultrasonic anemometers to obtain experimental data for validating computational fluid dynamic (CFD) results in an empty Boeing 747 cabin. They found that the air distribution in the cabin environment is definitely time-varying and unsteady, with an uncertainty period on the order of 3–4 min. Lin et al. [8] used a transient RANS model to study the unsteady flow field in a B767-300 cabin with symmetrical boundary conditions, and a swing motion across the symmetric plane was

* Correspondence to: Room 228, Building 14, Tianjin University, Tianjin 300072, China.
E-mail address: jjliu@tju.edu.cn (J. Liu).

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observed. However, due to limitations of computing resources, they were only able to complete a time period of approximately 15 s, which is thought to not be sufficient to study the period of fluctuations. A time series of consecutive instantaneous air velocities in a generic empty cabin was obtained by Lebbin [13] with a PIV system. Lin et al. [14] and Ebrahimi et al. [10] used these data to validate their transient CFD models, and an energy spectral analysis through a fast Fourier transform (FFT) was performed by Lin et al. [14]. However, the data that they selected to validate the CFD model and analyze the transient characteristics were only several points extracted from the PIV-measured flow field, which could not reflect the global information of the transient velocity field. Moreover, the measurement was performed in an overly simplified cabin mock-up under only isothermal conditions, while the air distribution in an isothermal empty cabin can be very different from a cabin fully loaded with passengers [15,16]. Wu and Ahmed [9] numerically studied the transient aircraft cabin flow in a B767-300 with unsteady boundary conditions. Many instantaneous flow characteristics were revealed, and the CFD model was validated by a time-averaged velocity field obtained by Wang et al. [17].

The common ways that are used to validate transient numerical models by comparison with time-averaged velocity fields or velocity-time curves from several points are far from sufficient because the simulated instantaneous flow structures have not been validated. To solve this, the proper orthogonal decomposition (POD) method is a way to extract the dominant flow structure from the various instantaneous air distributions, and it was first introduced for use in turbulence analysis by Ref. [18]. This method can be utilized to validate the transient CFD model by comparing the coherent flow structures calculated from the numerical results and the PIV data, especially for the large-eddy simulation (LES) model [19–21]. In previous studies, the "snapshot" method [22,23] was the most widely used POD method for analyzing the PIV data [24,25], but there have been no reports of using this method in a full-scale aircraft cabin environment.

This paper is part of a series of studies with the intent of quantitatively evaluating the performance of various cabin air distribution systems. In our previous studies, a high-power 2D-PIV system for obtaining the large-scale air distribution in a cabin was built [16], and a high-spatial-resolution global airflow field was measured and analyzed [26]. However, experimental studies of the transient global air distribution in the cabin environment are still lacking. In this research, a large-scale 2D-PIV system was utilized to obtain instantaneous flow fields for a long time series in a 7-row cabin mockup. The collision region of two lateral jets was selected as the research area because it had the greatest uncertainty and significantly influenced the flow pattern in the whole cabin. With the high-quality measured data, the velocity fluctuation characteristics of several typical points were analyzed, and the domain flow structures were revealed by POD analysis.

2. Methods

2.1. Aircraft cabin mock-up

The schematic of the experimental platform is shown in Fig. 1, depicting a full-scale aircraft cabin mockup inside a thermostatic chamber. The cabin mockup was designed as a replica of a 7-row section in the main body of a Boeing 737-200, which was occupied by 40 thermal manikins (42 seats). Each manikin was wrapped with nickel chromium wires of 2 mm in diameter, which were heated with 380 V of direct electrical current to ensure that the heat load of each manikin was 75 W. To facilitate the PIV measurements, transparent acrylic resin was used in the middle section of the cabin fuselage to allow optical access. The dimensions of the cabin

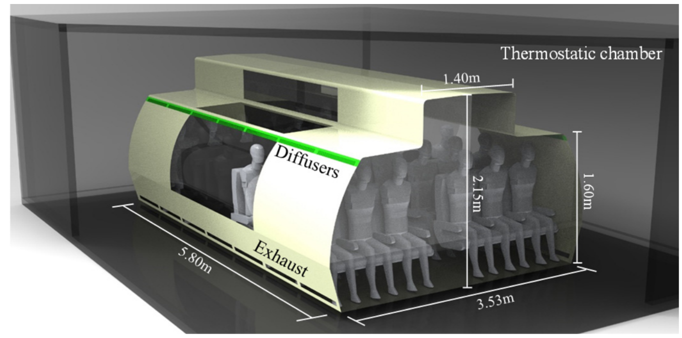

Fig. 1. Schematic of the aircraft cabin mock-up.

Table 1
Operating temperature conditions.

Operating temperature	Isothermal condition	Cooling condition
Thermostatic chamber temperature	19.0 °C	19.0 °C
Supply air temperature	19.0 °C	19.0 °C
Exhaust air temperature	19.0 °C	22.7 °C

at floor level were 5.80 m (Z) × 3.25 m (X), and at luggage carrier level, they were 5.80 m (Z) × 1.26 m (X). The heights were 2.15 m and 1.60 m from the floor to the ceiling and to the bottom of the luggage compartments, respectively. Detailed information on the cabin geometry and manikins can be found in the corresponding Chinese pattern (CN201310293870.8 and CN201310294658.3) and will not be repeated here.

Air was supplied from the lateral diffusers into the cabin with relatively symmetrical boundary conditions with a velocity of approximately 1.8 m/s and a total air volumetric flow of 1420 ± 60 m^3/h, corresponding to 9.4 L/(s·person) [27]. The detailed air supply boundary condition can be found in a previous study [26]. A series of experiments was conducted under both isothermal and cooling conditions, and Table 1 lists the operating temperatures for the two sets of conditions investigated in this research. Under isothermal conditions, the current to the manikins was switched off, and the supply air temperature was set to 19.0 °C (±0.5 °C), which was equal to the ambient air temperature of the thermostatic chamber. Under cooling conditions, the air supply temperature remained at 19.0 °C (±0.5 °C), and the averaged air temperature in the cabin was increased to 22.7 °C due to the heated manikins, and the detailed thermal boundary condition could be found in Ref. [26]. Between two operational conditions, there were at least 90 min to ensure the stable condition was reached.

2.2. PIV measurement setup

In this study, a large-scale 2D-PIV system was utilized to measure the airflows inside the cabin mockup, which consisted of Beamtech Nd:Yag lasers with a maximum energy 350 mJ/pulse output and a 4032 × 2688 pixel resolution Dantec FlowSense CCD camera. A light sheet with a thickness of 1–3 mm in the measurement region was formed by the laser beam passing through the cylindrical lens. An automatic transverse gauge was used to control the location of the light sheet. The CCD camera was equipped with an AF Nikkor 35-mm lens and installed on a guide rail to ensure that the position was perpendicular to the illuminated planes. The laser device and camera were controlled by a synchronizer with a time sequence to obtain the sequential pars of images.

One difficulty in realizing this PIV experiment over a long time series is to ensure the concentration of the tracer particles for such a long time. In this series of experiments, diethylhexylsebacate (DHES) droplets with a mean diameter of approximately