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2D-PIV measurement of isothermal air jets from a multi-slot diffuser in aircraft cabin environment

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ABSTRACT

Mixing air ventilation systems are currently used in commercial aircraft environmental control systems (ECS), which are essential for creating a healthy, thermally comfortable and energy-efficient cabin environment. Based on previous studies, the cabin mixing air distribution is mainly driven by the supply air jets. Therefore, understanding the air jet behaviors within the cabin is necessary for evaluating and improving the cabin environmental quality. In this investigation, we performed a detailed and large-scale 2D particle image velocimetry (PIV) measurement to characterize the isothermal jets in the downstream area of one linear slot of a multi-slot diffuser in a ventilated aircraft cabin mockup. The measurements were taken at different inlet Reynolds numbers (Re) ranging from 1480 to 6940 based on the inlet velocities and the slot height. The PIV results clearly revealed the transitional jet structures in the entrainment process downstream of the slot. The free jets discharging from the slot quickly developed into quasi wall jets due to the Coanda effect. The mean velocity profiles, flow patterns, centerline velocity decay and mean vorticity profiles were then analyzed and compared among different inlet Re. Moreover, the cabin jet characteristics were further compared to results from previous studies. The experimental data and analysis in this research can provide references for designing better side ventilation configurations in single-aisle aircraft cabins.

1. Introduction

Currently, over one billion passengers travel by air annually [1]. The increasing flying public leads to increasing complaints about uncomfortable cabin environments and potential risks associated with airborne disease transmission during commercial air travel [1–3]. Commercial airliners typically cruise at an altitude of over 10000 m, where the ambient air temperature is approximately −55 °C and the air pressure is only 30 kPa. An environmental control system (ECS) supplies conditioned air to the aircraft cabin to protect the passengers and crew from the extreme ambient environment. At the ECS terminal, an air distribution system regulates the air velocity and air temperature and provides fresh air to dilute gaseous and particulate contaminants. Therefore, a high-performance air distribution system is crucial for maintaining a safe and thermally comfortable cabin environment and minimizing the risks of infectious airborne disease transmission.

A mixing air distribution system is currently used for the ventilation of commercial airliner cabins globally; these systems supply adequate air from the inlets at the ceiling or luggage compartment level and exhaust the mixed and contaminated air at the deck level. Previous studies have proven that the cabin airflow is mainly driven by the supplied air jets and is partially influenced by the thermal plumes generated from the passengers [4–7]. The initial jet velocity should be high enough to mix the cabin air well and to maintain the fully rotary airflow pattern. However, the air jets are also responsible for the thermal comfort level in the micro-environment around the passengers. The high-momentum air jets used in the mixing air distribution system may create draft complaints from passengers. The stagnant regions inside the airflow loops formed by the air jets also lead to poor local ventilation effectiveness [4–7]. Moreover, the conditioned air supplied by jets is used to remove the cabin heat load, which consumes large amounts of energy in the process of bleeding and handling ambient fresh air [8]. For this reason, the supplied air should be used

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efficiently to reduce the ECS energy consumption. For these reasons, air jets greatly influence the overall performance of cabin air distribution systems, thus deserving a careful examination. To improve the cabin environment quality, quantifying the cabin air jets is an essential prerequisite.

In this study, we conducted experimental measurements to obtain the cabin jet flow information. Liu et al. [9] concluded that experimental measurement and numerical simulation are the two approaches to studying cabin airflow fields. Experimental measurement can provide the most reliable airflow information for not only further data analysis but also setting simulation boundary conditions and numerical model validation. Then, a validated numerical model can predict the overall airflow quantities under different boundary conditions at a relatively low cost.

The measuring techniques used for studying indoor airflow fields can be divided into point-wise velocimetry and global-wise velocimetry [10]. The point-wise measuring techniques mainly include hot-wire anemometry (HWA), hot-film anemometry (HFA), hot-sphere anemometry (HSA), ultrasonic anemometry (UA) and laser Doppler velocimetry (LDV). Guo et al. [11] used a single-wire HWA to collect the data of a personal airflow outlet jet in a simplified aircraft cabin at a sampling frequency of 100 kHz. Different turbulence scales were calculated and wavelet analysis was applied to distinguish the dominated time scales. Suresh et al. [12] also employed an HWA to systematically investigate the free plane jet development in a transitional regime. Yao et al. [13] used a cross-wire HWA to measure the isothermal impinging air jets issuing from a round pipe in a closed cabin. They performed both power spectrum analysis and empirical model decomposition to gain deeper insight into the turbulence characteristics of jet impingement on a flat plate. The above research indicated that the high sampling frequency of an HWA is very useful for obtaining air jet turbulence information [11–13]. The HFA and HSA are omnidirectional methods with much lower sampling frequencies than HWA. Therefore, they are mainly used for measuring mean velocities rather than detailed turbulence information [14–16]. The accuracy of thermal anemometry is very sensitive to the flow direction. Therefore, thermal anemometers are better used under known or regular jet flow patterns [11–16]. In addition, the inaccuracy of thermal anemometry is high in low-velocity flow fields [10]. UA can provide accurate three-dimensional airflow information at the probe within indoor air velocity ranges. Thus, UAs have been used to obtain the averaged indoor velocity fields by point measurements [6,17]. These studies provided benchmark flow data to validate numerical simulations. Nevertheless, the large probe size limits the spatial resolution of UAs, which is insufficient for studying air jets. LDV is a non-intrusive velocimetry based on Doppler shift principles. LDV can obtain precise and dynamic airflow information at a single point using tracer particles. Körner et al. [18] used a 2D LDV to measure the large-scale flow structures in an isothermal ventilated room. Their major finding was a coherent oscillation of the large-scale flow structures by analyzing the temporal velocity signal. In general, point-wise anemometry is not suitable for a deeper understanding of the transitional and complex air jet phenomena in aircraft cabin.

Global-wise velocimetry seeds air with tracer particles and then tracks the motion of the particles using image recording devices in the measured region illuminated by light sources. Thus, global-wise velocimetry can obtain the velocity field and related statistical information in a global domain without disturbing the airflows. Particle image velocimetry (PIV) is one of the most widely used and sophisticated global-wise velocimetry methods for flow field studies [19]. Specifically, PIV has gradually become a powerful technique to measure indoor airflow fields over the last decade [20]. PIV uses an image correlation method to determine the velocity vectors with high seeding density, which provides a higher signal-to-noise ratio and a higher spatial resolution compared to other types of global-wise velocimetry. Therefore, PIV is an ideal measurement tool to investigate the dynamic jet behaviors, such as the spatial vortex structure and the turbulent transitional process. PIV has been successfully used to measure jet flows in the built environment. Van Hooff et al. [21,22] conducted detailed PIV measurements of isothermal plane wall jets at transitional slot Reynolds numbers (Re) in a reduced-scale water-filled model. They analyzed both the time-averaged quantities and instantaneous flow fields to provide new insights into the transitional plane wall jet behaviors. Liu et al. [23] used PIV to study multiple jet flow structures in a three-dimensional chamber with opposed jets. The measurement results showed good agreement with CFD simulations. Cao et al. [24,25] performed PIV measurements to study the wall jet structure discharged from an active chilled beam at a high turbulence level in a full-scale chamber. Their results proved that the jet quickly attached to the ceiling and became fully turbulent at a short distance downstream of the slot at relatively low Reynolds numbers. Nastase et al. [26] measured the jet flows from an innovative diffusion grille with two types of ailerons using PIV. They found that the flow from the grille with lobed ailerons ensured a better jet flow distribution in the occupied zone with a higher induction and mixing effect. Elvsén and Sandberg [27] used three types of whole-field measurement techniques to study a buoyant jet in a room with displacement ventilation. PIV was applied to measure the local entrainment flows into the buoyant jet near the diffuser. These studies demonstrate that PIV can provide detailed information about the complex jet flows in full-scale indoor environment [24–27]. Nevertheless, their measurement resolution was commonly restricted due to the large measuring area. Conducting high-resolution measurements in full-scale models remains difficult.

The air jets in an aircraft cabin differ from those in a room due to the low velocities, high turbulence level, irregular contours and extremely confined space. Some researchers used PIV to characterize cabin airflows in several small regions [28–30]. Lin et al. [28] used stereoscopic PIV to measure the air distributions in 5 small regions in an empty and generic cabin mockup. The measured instantaneous velocity signals correlated well with the large eddy simulations. Wan et al. [29] and Sze et al. [30] used PIV to characterize the airflow patterns in four small regions in an occupied aircraft cabin. They identified the basic cabin flow patterns but did not provide enough information on the jets.

Some researchers conducted large cover PIV measurements to study the global airflow fields in cabins [4,5,7and31]. Bosbach et al. [31] used PIV to measure the isothermal airflow field in a generic cabin mockup. Their results showed that the incoming jets stayed attached to the cabin contour and then formed a large-scale circulating stream in the whole cross section, clearly demonstrating the driven force by the side jets on the entire airflow loop. Kühn et al. [4] conducted large field PIV measurements of air distributions in a fully-occupied A380 cabin mockup. They found that the supplied air jets mainly attached to the cabin contour, while partially influenced by the negative buoyancy forces and rising thermal plumes. They adjusted the ventilation configurations by changing the flow rate distribution between the ceiling inlets and the lateral inlets. They was found that the air distributions were obviously influenced by the ventilation configurations. Nevertheless, they did not further analyze the jet behaviors due to the low spatial resolution. Cao et al. [5] performed large-scale PIV measurements in a single-aisle Boeing 737 cabin mockup with a much higher spatial resolution. They concluded that the jets from both