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PIV experimental research on gasper jets interacting with the main ventilation in an aircraft cabin

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ABSTRACT

Gaspers are one of the most widely used nozzles for personalized ventilation systems in transport vehicles. To investigate the interactions between gasper jets and the main ventilation (MV) over a large velocity range, particle image velocimetry (PIV) measurements were made at two scales with four different times between pulses, and the results were spliced. The obtained high-resolution data are not only useful for validating numerical models but also can reflect the interactions between the gasper jets and the MV. In a cabin environment, the decay of gasper jets was accelerated by the influence of the MV and deaccelerated to a lesser degree under cooling conditions by the temperature differences created by heated manikins. The jets from the diffusors of the MV deflected the gasper jets to a similar degree under both isothermal and cooling conditions, and the empirical equations for jet deflection were summarized. The investigation of fresh air transport showed that only 6% of the air delivered to the breathing zone of passengers was the fresh air issued from the gasper, and the rest was the entrained ambient air. Additionally, the influence of the gasper jet on the MV and an adjacent passenger was evaluated at larger scales. The gaspers with medium and high flow rates created a draft sensation, with draft risk values of 35.9% and 47.9% for the gasper user. The use of gasper with medium and high flow rates also caused a 9.6% and 30.4% velocity decrease around the adjacent passenger sitting downstream of MV.

Practical implications: This study introduced the cross time between pulses splicing method to solve the problem of PIV measurement of the flow field over a large velocity span, which not only provided high-quality data for validating the CFD model but also revealed airflow characteristics of gasper jets in a realistic cabin environment.

1. Introduction

In commercial airliners, conditioned air used to dilute contaminants and sustain thermal comfort in the cabin has been supplied by both lateral/ceiling diffusers and personal air supply nozzles [1,2], which provide main ventilation (MV) and personalized ventilation (PV), respectively. Most previous studies focused on the large-scale air distribution created by the diffusers because it influences the overall cabin environment [3]. However, the MV system in an aircraft cabin may not meet each passenger's thermal comfort and air quality needs [4]. As a supplement, PV creates a relatively isolated microenvironment for individuals by using a high-speed jet directed toward the breathing region [5,6], and gaspers are one of the most widely used personalized outlets in transport vehicles.

Many researchers have evaluated gasper performance from the perspectives of both thermal comfort [7–11] and air quality [12–14]. These subjective and objective studies indicated that gaspers in the cabin environment did not perform as expected and need to be further modified and improved; therefore, detailed investigations of the airflow characteristics of gasper jets are needed to supply fundamental data. Numerical simulations, mainly involving computational fluid dynamics (CFD), and experimental measurements are the two main methods of investigating gasper jets. Although numerical methods are more flexible and easier to implement, their results are unreliable until validated by experimental data [15]. The experimental approaches used to quantify the air distribution of gasper jets can be classified as point-based and global methods [16]. Typical point-based techniques include hot-wire or hot-sphere anemometry (HWA or HSA) and ultrasonic anemometry (UA), and the most popular global technique is particle image velocimetry (PIV).

Using point-wise techniques, Guo et al. (2014) [17], Dai et al. (2015) [18], and Tang et al. (2017) [19,20] utilized a high frequency

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HWA to obtain the air distribution of a gasper jet near the nozzle region (core region of the jet) at different flow rates, and the self-similarities and turbulent features were then analyzed. Although this research provided substantial boundary conditions for gasper jet CFD simulations, the measured region was too small to investigate the influence of gaspers on human thermal comfort. Moreover, these experiments were all conducted in an ideal rectangular cabin under isothermal conditions, and the summarized results were not suitable for a realistic aircraft cabin. Du et al. (2016) [21] measured the air velocity of a gasper jet in several radial directions using 8 HSAs at a resolution of 10 mm. The results were useful for analyzing thermal comfort at these distances but unsuitable for revealing the airflow characteristics of the gasper due to the insufficient resolution in the axial directions and the lack of directional velocity information for the HSAs. Li et al. (2015) [12] used seven UA probes to investigate the air distribution in a real aircraft cabin with gaspers on, and the effects of the gasper jets on thermal comfort and contaminant transport in the cabin were analyzed. However, the spatial resolution of the experimental data was restricted by the bulky UA probes.

To overcome the weaknesses of point-wise techniques, PIV is considered the most promising way to achieve a balance between the required coverage area and the spatial resolution of the data. However, most previous PIV measurements focused on global airflow or the air distribution controlled by the MV [22–24], and few PIV studies have focused on the air distribution from personalized outlets. In a recent study [25], the airflow distribution of a gasper jet above a simplified human simulator was measured by a PIV system. The PIV experimental data were considered ideal for validating the CFD models [11], and although the measured area was small and experimental conditions were limited, many different CFD models were evaluated with the data [13,14]. However, under this type of scenario, i.e., with a large velocity range and gradient, it was difficult to accurately capture both low- and high-speed air distributions using traditional PIV methods. For example, You et al. (2016) [25] only focused on the area where the jet was fully developed and falsely measured the velocity in the area near the outlet as even smaller than that in the downstream area, which did not conform with the jet decay characteristics. However, both the high-velocity (dominated by gasper jets) and low-velocity (controlled by MV) airflow fields are of the same importance in this scenario, in which both the performance and influence of gaspers in the cabin environment are investigated to improve CFD models and guide gasper design.

In this study, a large-scale 2D-PIV system was built to measure the jets from both gaspers and MV diffusors over a large velocity range. By analyzing the measured air distribution under different operation conditions and flow rates in an aircraft cabin mock-up, the characteristics of the gasper jets and their influence on the cabin environment were revealed, and their performance was discussed from the perspectives of air quality and thermal comfort.

2. Methods

2.1. Experimental platform and conditions

The experimental platform in this study is a 1:1 mock-up of the main body of a single-aisle aircraft (Boeing 737-200) with seven rows and 42 passenger seats occupied by 40 thermal manikins, as shown in Fig. 1(a). The cabin mock-up contained seven groups of multislot diffusers with 105–113 slots along each side at the stowage bin level. These multislot diffusers constituted the outlets of the MV. The detailed geometry of the cabin and manikins, thermal boundary conditions and air supply information for the MV can be found in our previous studies [26,27]. For the PV, a gasper from a functional retired MD-82 aircraft was mounted underneath the stowage bin of the fourth row. The air was supplied independently by an air compressor and went through a drying tube, a heat exchange brass tube (brass, 10 m), a mass flow controller (MCR Series, Alicat Scientific, AZ, USA) and an atomizer (detailed in Section 2.2). The cabin mock-up and all the components of the PV system were set up in a thermostatic chamber so that the air supply temperature of the gasper and MV was identical. Fig. 1(b) shows the structure of the gasper, which consists of a spherical knob for changing the jet angle, an adjustment knob that can move the middle cone in the axial direction and change the flow rate, and a plenum chamber that is the actual size of that in an MD-82 aircraft. To control the variables, the gasper was set vertically downward and "fully open", in which case the opening size (h) was 2 mm, and the constant diameter (D_0) was 12.6 mm. Then, five air flow rates (Q_0^1 = 0.79 L/s, Q_0^2 = 0.87 L/s, Q_0^3 = 1.06 L/s, Q_0^4 = 1.23 L/s and Q_0^5 = 1.41 L/s) for the gasper were selected as recommended by the Boeing company and ASHRAE (2007) [1].

To investigate the influence of thermal convection from the passengers on the gasper jets, experiments at all five flow rates were conducted under both isothermal (Cases 1) and cooling (Cases 2) conditions. Under isothermal conditions, the thermostatic chamber and the air supplied from the gasper and diffusors were set to 19 ± 0.5 °C. Under cooling conditions, the temperature of the supplied air was the same as that under isothermal conditions, but the thermal manikins were switched on at 75 W, which caused the average air temperature inside the cabin to reach approximately 22.7 °C. The detailed thermal boundary conditions under cooling conditions can be found in a previous study [24]. In addition, under isothermal conditions, gasper jets with no MV in the cabin were also investigated at five gasper flow rates (Cases 0). This scenario served as the control group used to characterize the influence of the MV. These measured jets with no MV under isothermal conditions in the aircraft cabin environment can also be used to study the influence of the complex cabin geometry on the jets by comparing the results with previous measurements in simplified cubic cabins. Table 1 and Fig. 2 show all 15 cases considered in this research with different operating conditions and flow rates.

2.2. PIV measurement setup

A high-power 2D-PIV system was used to measure the gasper jet air distribution inside the cabin mock-up. In contrast to other PIV systems, the employed system included two independent seeding systems to ensure a homogeneous tracer particle concentration between the gasper jet and the MV-controlled areas. As shown in Fig. 1(a), for gasper jets, the flow rate-controlled compressed air transported particles through the atomizer (PIVpart14, PIVTEC – GmbH, Göttingen, Germany) and directly into the cabin. Additionally, the other atomizer (PIVpart40, PIVTEC – GmbH, Göttingen, Germany) generated and added particles upstream of the MV supply air duct. These two systems seeded the same type of diethylhexyl sebacate (DEHS) droplets with a mean diameter of approximately 1.0 μm and the same particle density for both the gasper and MV, which ranged from 10 to 20 particles per interrogation window. To supply sufficient brightness for the tracer particles, a 350-mJ laser sheet with a thickness of 1 mm and a wavelength of 532 nm generated by a Beamtech double-cavity Nd:YAG laser device was used to freeze particle images recorded by a Dantec FlowSense EO 11 M CCD camera with a resolution of 4032 × 2688 pixels.

In this study, the scale of the gasper jets is in the millimeter range, whereas the passenger area controlled by the MV can be on the order of meters. To solve this multiscale issue, two regions of interest (ROI1 and ROI2) with different scales focused on gasper jets and the MV were selected, as shown in Fig. 3(b). The absolute locations were determined based on previous studies [24], and the origin of the coordinate system (X = 0 m, Y = 0 m) was selected as the middle of the cabin at floor level. The normalized relative coordinates of the gasper jets are detailed in Fig. 4(a). Moreover, to accurately quantify the air distribution of the gasper jets at a relatively small scale and over a large velocity gradient in ROI1, the length of the interrogation window, L_{int} (pixels), and the image magnification factor, M (pixel/m), should be small [28]. M was obtained during the calibration process by comparing the pixel distances (D_{pix}, pixel) in the camera view to the absolute (or object)