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State-of-the-Art Methods for Studying Air Distributions in Commercial Airliner Cabins

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Abstract

Air distributions in commercial airliner cabins are crucial for creating a thermally comfortable and healthy cabin environment. This paper reviewed the methods used in predicting, designing, and analyzing air distributions in the cabins. Two popular methods are experimental measurements and numerical simulations. The experimental measurements have usually been seen as more reliable although they are more expensive and time consuming. Most of the numerical simulations use Computational Fluid Dynamics (CFD) that can provide effectively detailed information. Numerous applications using the two methods can be found in the literature for studying air distributions in aircraft cabin, including investigations on more reliable and accurate models. Our review shows that studies using both experimental measurements and computer simulations are becoming popular. Our review also found that it is necessary to use a full-scale test rig to obtain reliable and high quality experimental data, and that the hybrid CFD models are rather promising for simulating air distributions in airliner cabins.

Keywords: Aircraft Cabin; Airflow; CFD; Experiment; Numerical Simulations

1. Introduction

Nowdays, more people, including those with impaired health or who are otherwise potentially sensitive to cabin environmental conditions, are traveling by air than ever before. Global traffic is estimated to be over one billion passengers annually [1]. The flying public demands a comfortable and a safe cabin environment because they may encounter a combination of environmental factors including low humidity, low air pressure, and sometimes, exposure to air contaminants such as ozone, carbon monoxide, various organic compounds [2]. It has been reported that international air travel could have the potential risks associated with airborne disease transmission [3, 4] and about 2.5% overseas travelers requested medical attentions for all sorts of health related problems during the flights [5]. Olsen et al. [6] have reported that 22 passengers among the 120 passengers on a flight from Hong Kong to Beijing were infected with the Severe Acute Respiratory Syndrome (SARS) in 2003. Therefore, it is essential to examine the cabin environment to ensure that it is safe, healthy, and comfortable for the flying public.

Air distributions in commercial airliner cabins are used to regulate air temperature and air velocity to create a thermally comfortable environment and to provide adequate ventilation for reducing gaseous and particulate concentrations of contaminant for maintaining a safe environment. The facts above leave an element of doubt whether the air distribution in airliner cabins is acceptable; in other words, the air distribution in airliner cabins may have the problem of providing comfortable and safe cabin environment. Furthermore, the air distribution in airliner cabin may be of unsteady state, low speed, high turbulence without knowing pulse frequency. Therefore, it is essential to study how the air is distributed in the air cabins and to characterize how the airflow transports pollutants.

Our literature review indicates that improvements have been made in the cabin air distribution systems. Nevertheless, such information tends to be sparse in the public literature. One possible reason is that aircraft manufacturers' are unwilling to share publicly the proprietary details of their designs. Since the comfort and safety of aircraft cabins are a matter of public interest and discussion, the related research by non-aircraft manufacturers has substantially increased during the last decade. The objective of this study is to provide an open database from carefully designed experiments for all concerned researchers working on cabin environment issues. To identify the state-of-the-art methods formed the basis of the investigation reported in this paper.

Our literature review also found that two main methods are available for the study and design of air distribution in an aircraft cabin: experimental measurements and numerical simulations. Experimental studies are usually thought to be more reliable but they are often very expensive and time consuming, so measurements are mainly used to provide data for validating numerical simulations [7, 8]. Moreover, as some characteristics of the airflow in aircraft cabin is unknown, it is hard to identify a proper instrument or measuring method to study it. A validated numerical tool can then be used to analyze many scenarios for achieving the best design at a low cost. As most numerical models apply to a particular fluid feature, a model suitable for studying air distribution in aircraft cabin has not been found. This paper will discuss the two methods used in recent studies of air distributions in aircraft cabins.

2. Experimental measurements of cabin air distribution

Table 1 shows a summary of the experimental studies on air distributions in airliner cabins published in the past two decades. The literature shows that the experimental equipment used to measure the air distributions can be divided into three types according to their measuring principles. Hotwire anemometers and hot-sphere anemometers are based on heat transfer principles; particle tracking velocimetry (PTV), particle streak velocimetry (PSV), particle image velocimetry (PIV), on optical principles; and ultrasonic anemometry (UA), on acoustics principles. This section will discuss these velocimetries in turn.

2.1 Hotwire and hot-sphere anemometers

Hotwire and hot-sphere anemometers are based on Newton's law for cooling. A higher air velocity can cool down a heated sensor so the air velocity can be determined from the sensor temperature. Figure 1 shows the hotwire and hot-sphere anemometers, respectively. As its name implies, a hotwire anemometer measures the velocity with a heated wire which is sensitive to the velocity direction. Thus, some hotwire anemometers can also measure airflow directions. However, a hot-sphere anemometer measures the omni-directional velocity magnitude, not the direction. Normally, the measuring range is 0.2 ~ 20 m/s for a hotwire anemometer and 0.05 ~ 5 m/s for a hot-sphere anemometer; the related accuracies are ±1% ~ ±3% and ±1% ~ ±5%, respectively. These two types of anemometers are point sensors.

Mizuno and Warfield [9] conducted a comprehensive experimental study of the effect of cabin airflow on contaminant dispersion. They used hotwire anemometers to measure the velocity distributions without flow directions. Zhang et al. [10] used hot-sphere anemometers to obtain the boundary conditions from the diffusers in a full-scale, twin-aisle section of an aircraft cabin mockup. As the size of the diffuser was small and the inlet air velocity was relatively high, it was very difficult to obtain accurate flow information. Since the hot-sphere anemometers did not measure the flow direction, they estimated the flow direction by using smoke visualization, which could not provide highly accurate results. Recently, we applied the hot-sphere anemometers to measure the velocity magnitude on the diffusers of a MD-82 aircraft and found that the velocities varied greatly along the diffusers (Figure 2).

2.2 Optical anemometry

Optical anemometry is most popular for measuring air distributions in airliner cabins [11]. It generally consists of a laser system, one or more digital cameras, and a computer to control the system and store the data. Figure 3 [12] shows the setup of the system in a cabin. This technique seeds air with tracer particles, and then obtains the motion of these particles through the laser sheet by a digital camera. The flow measurement is two dimensional with one camera [13], and the measurements can be three dimensional with more than one camera. PSV, PTV, and PIV are often applied to the measurements of air distributions in aircraft cabins.

2.2.1 Particle streak velocimetry

The PSV system uses several adjoining laser light sheets of different wavelengths with a homogeneous power density distribution. This method can identify if a flow is two-dimensional or three-dimensional [14]. Singh et al. [15] used both smoke visualization and PSV to study the airflow pattern inside an aircraft cabin, with heated cylinders that were used to approximate the heat released by passengers. They found that the PSV was not sufficiently accurate for a precise understanding of the flow field. By employing the helium bubbles technique with Volumetric Particle Streak Velocimetry (VPSV), Sun et al. [16] and Zhang et al. [17] measured the airflow in a cabin mockup with manikins. They found that obstructions significantly affected the velocity field at the passenger breathing level. The large volume of airspace and the obstruction from the manikins also prevented them from acquiring detailed airflow data. The insufficient spatial resolution and the lack of velocity data near the boundaries prevented them from gaining a deeper understanding of the flow dynamics.

2.2.2 Particle tracking velocimetry

PTV is a well-known technique for the determination of velocity vectors within an observation volume [18]. Tracking the movement of the individual tracer particles in the air yields better results for low-speed flows. Müller et al. [19] used helium-filled bubbles as seeding particles for a PTV to investigate the isothermal flow in a full-scale Airbus A330-A340 cabin mockup with seats. Their study focused on the overhead region above the passenger seats in an effort to optimize the air outlet geometry. This effort opened the door to quantitative measurements of large-volume, low-speed flows, which were difficult to measure by other flow measurement techniques. Wang et al. [20] and Yan et al. [21] used an extended VPTV system to measure the airflow in a cabin with heated manikins, but only the upper part of the cabin was measured because it was difficult to light in the lower part of the cabin due to the light being obstructed by the seats and manikins. Compared with a PIV, the VPTV has a larger imaging window because of the sparsely seeded flow, has better positional accuracy, and is more applicable for large volume measurements. There is also three-dimensional PTV consisting of three or four digital cameras.

2.2.3 Particle image velocimetry

PIV systems are the most popular and versatile optical anemometry for measuring velocity and related properties in fluids. As PIV determines velocity through the movement of a group of particles seeded into the flow, it can be regarded as a high particle concentration mode of PSV. PIV can provide high spatial resolution of the velocity data and can measure instantaneous flow fields [22]. During the measurements, it is necessary to clear the optical paths needed for the PIV system. Thus, the geometry that can be measured is often restricted. For example, Mo et al. [8] performed airflow measurements in a cabin and lowered all the seat backs except those next to the windows so that the laser beam could penetrate the space. This made the cabin being studied much different from reality, although velocimetry could accurately measure the air distributions. Bosbach et al. [23], Günther et al. [24] and Lin et al. [25] also used a PIV system to measure the airflow in an empty cabin mockup, which was quite different from the practical in-flight situation. Zhang et al. [17] and Kühn et al. [26] applied a PIV system to measure the airflow patterns in a cabin in occupied situations, but the PIV measurement could only reach the upper part of the cabin as the seats and manikins significantly blocked the light for showing the airflow paths. Their measurements encountered the same problem as Mo et al. did. However, the study did demonstrate that the configuration of the air supply inlets and rising thermal plumes from the passengers had a large impact on the flow field inside an aircraft cabin.

Poussou et al. [27] conducted laboratory measurements on a one-tenth scale, water-based empty cabin model to generate high quality experimental data for investigating the effects of a moving human body on flow and contaminant transport inside an aircraft cabin. As the walls of the cabin were transparent, the PIV could measure the air distribution in the whole cross section. The movement of the body inside the water tank was similar to a passenger walking in an airliner cabin and transporting contaminants in his/her wake. Movement can significantly influence contaminant distribution and personal exposure in an enclosed space [18-30]. But the small-scale results could not be directly used since the change in the physical scale and working fluid complicated the interpretation of the equivalent effects in the full-scale model [31].

Our search of the literature found that PIV is very popular for air distribution studies. If the light obstruction can be solved such as using transparent materials done by Poussou et al. [27, 32], PIV is a good choice for studying air distributions in an airliner cabin.

Nevertheless, an optical anemometry is often heavy, bulky, and complex to use. In addition, most of the laboratory measurements of airflow have been performed on empty cabin mockups without consideration of the effects of occupancy. Measurement of airflow is important, but these studies were not an accurate representation of the in-flight conditions, as the airflow pattern in an occupied cabin can be significantly different from that of an unoccupied one. Even though some of these studies measured the airflow patterns in a cabin in occupied situations, the measurements could only reach the upper part of the cabin due to the technology limitation. For example, Figure 4 shows the measured velocity vectors with the VPTV system by Wang et al. [33] and with the PIV system by Bosbach et al. [34].

2.3 Ultrasonic anemometry

Due to the difficulties in using optical anemometries, ultrasonic anemometers have received considerable attention although they cannot measure detailed boundary conditions. A UA normally has three pairs of sensors. For each pair, one sensor generates the ultrasonic wave and the other one receives. When the air flows through the space between the two sensors, the air velocity in the direction of the sensors can be accurately determined by the travelling time of the ultrasonic wave. The UA is very sensitive to the velocity fluctuations. It can provide three-dimensional air velocity at positions that cannot be reached by a laser sheet and it can also give accurate turbulence intensity.

Garner et al. [7] used three-dimensional ultrasonic anemometry to measure the airflow in an empty Boeing747 aircraft cabin. Figure 5 shows the setup of the three-dimensional ultrasonic anemometry. The measuring range of UA of this type is 0 ~ 10 m/s and its accuracy is only 2% or less. Their measured results show that the velocity field was time varying and unsteady, with a periodic unsteadiness on the order of 3-4 minutes. Zhang et al. [10] conducted extensive three-dimensional experimental measurements of airflow and contaminant transport in a half-occupied 4-row twin-aisle cabin mockup. The measured airflow inside the occupied cabin was relatively stable, contrary to that observed by Garner et al. [7] and Baker et al. [35] in an unoccupied cabin. The studies of the velocity fluctuations by Zhang et al. [17] with different occupancy rates inside a mockup airliner cabin also confirmed this fact. They concluded that the experimental measurements were not free from errors. The smallest sensor used in the previous studies was with a span of 25 mm. The bulky sensor could not be used for measuring the air velocity from a diffuser in a cabin.

In summary, hotwire and hot-sphere anemometers are not very suitable for measuring the flow field as they normally cannot measure the velocity direction and are of low measuring frequency. Nevertheless, the anemometers can be used to obtain velocity magnitude at the diffusers. Optical anemometry that does not influence the flow field and can have a measuring frequency of 5-15Hz. Unfortunately, the measurements could only be conducted in the upper part of the cabin where the light is not blocked. The UA has a good measuring frequency of 20 Hz that is important for obtaining turbulent information of the airflow. The large size of the probe makes it hard be used for small spaces where the velocity changes rapidly.

Besides, our literature review found that making measurements in a full scale cabin were difficult. The experimental studies often lacked sufficient spatial and temporal resolutions to gain an understanding of the complex flow. Some of them considered the cabin to be isothermal or did not consider the thermal effects of the passengers. It is hard to accurately measure the flow conditions near air supply diffusers in a cabin. In addition, a full-scale air cabin mockup could easily cost a million dollars or more and may or may not represent real cabin conditions if the simulator contains only a few rows of seats [10]. Furthermore, in-flight airflow studies using full-scale laboratory mockups are expensive and time consuming. Varying cabin conditions such as different occupancy distributions, passenger capacities, and movements of crew and passengers [36, 37] would make laboratory measurements more complicated. Hence, cheaper and more efficient computer simulations seem more preferable for airflow studies in airliner cabins.

3. Numerical simulations of cabin air distribution

Table 1 also shows a summary of the numerical studies in air distributions in airliner cabins published in the past two decades. Due to the increase in performance and affordability of high speed computers, numerical simulations have become a practical approach for studying airflow and contaminant distributions in airliner cabins. Compared to experimental studies, numerical studies of airflows in an aircraft cabin are less expensive and more efficient. The numerical simulations determine the airflow and contaminant transport in the spaces by solving a set of equations modeling the flow, energy, and contaminants. Almost all numerical models approximate and simplify the real airflow. Considerable efforts are still being made to seek more reliable and accurate models. There have been many numerical studies in the past decades. Depending on the extent of approximations, simplifications, and applications, the numerical models can be classified as zonal models and Computational Fluid Dynamics (CFD) models [38].

3.1 Zonal models

A zonal model can create a multi-dimensional flow network in a flow domain. By dividing an enclosed space into sub-zones, the zonal model solves the conservation equations of mass, energy, and contaminants and calculates the flow rate between sub-zones by simple correlations for flow and pressure [39] or for flow and temperature [40]. A zonal model requires prior knowledge of the flow pattern. The division of a domain has strong influence over the modeling result. Since an experienced user can obtain accurate results [41], the zonal model has a considerable number of applications. Olander and Westlin [42] used a zonal model to calculate airflow and contaminant concentration in an aircraft cabin. The box model is quite similar to the zonal model since it is assumed to be completely mixed in each box. The zonal or box model could give a rough estimate of the air distribution since it calculates only the macroscopic flow between zones. Ko et al. [43] used a sequential box model to estimate the concentration of tuberculosis in each box zone. Both the box and zonal models are, in principle, lumped methods. Their objective was to model the airflow as a simplified flow network; the governing equations are linear. However, the use of a zonal model is not as easy as one may think, especially if one has to handle special cells. By comparing zonal models with very coarse-grid CFD simulations, the zonal models do not show much superiority in reducing computing time. In many cases, the overhead time in preparing the data input for a zonal model may be longer than that for a CFD simulation.

3.2 CFD models

A CFD model numerically solves a set of partial differential equations for the conservation of mass, momentum (Navier-Stokes equations), energy, chemical-species concentrations, and turbulence quantities. The solution provides the field distributions of air pressure, air velocity, air temperature, the concentrations of water vapor (relative humidity) and contaminants, and turbulence parameters in an aircraft cabin. Despite there being some uncertainties in the models, requiring sufficient knowledge of fluid mechanics on the part of a user, and demanding a high capacity computer, CFD has become the most widely used tool for studying air distributions in airliner cabins due to the rapid increase in computer capacity and the development of user-friendly CFD program interfaces. Examples can be found in [9, 11, 15, 19, 21, 24, 25, 27, 35, 37, 44-52]. The CFD models used were Reynolds Averaged Navier-Stokes equation (RANS) models and Large Eddy Simulation (LES).

3.2.1 RANS models

Most of the CFD simulations used RANS models. A RANS model approximates Reynolds stresses through eddy viscosity or solves extra transport equations for Reynolds stresses. Depending on how many transport equations are used to solve the eddy viscosity, RANS eddy viscosity models are further categorized as zero-, one-, two-, three-, and four-equation models. The most well known and applied models for air distribution in a cabin are the two-equation standard k-ε [53] and RNG k-ε [54] models. Reynolds stress models need to solve six extra transport equations and the solution procedure may not stable, which makes them less popular [55].

Yan et al. [21] used the standard k-ε model to simulate the airflow field in a full-scale Boeing 767-300 mock-up with unheated manikins. Their results showed that the CFD results agreed with the experimental data in the sense that the two big vortices were captured by the simulation, but the plume above the middle passenger was not captured. Zítek et al [52], to design a personal ventilation system in a cabin, applied the standard k-ε model to simulate the airflow around a seated manikin. Their results presented the relative deviations of air velocity magnitude between the measurement data and the CFD results. The discrepancies between the simulated results and the experimental data were very significant.

The RNG k-ε model was an improved standard k-ε model that has an additional term in the ε equation. To account for the passengers in the airplane, Singh et al. [15] used heated cylinders on the seats to approximate occupants and performed a steady-state simulation using the RNG k-ε model. They used a symmetric boundary condition in the middle of the plane to reduce the computational domain, which contradicted the smoke flow visualization results. Lin et al. [45, 47] studied airflow and airborne pathogen transport in a section of a twin-aisle aircraft cabin with the RNG k-ε model. The simulation substantially under-predicted the turbulence intensity, especially in and around the breathing zone. Zhang et al. [56] used the model to study the airflow and contaminant transmission in a twin aisle, economy-class section of an airliner cabin. Figure 6 shows the comparison of the airflow pattern measured and computed in a cross section. Poor agreement was found between the computed results and the experimental data. Due to the difficulties in measuring accurate flow boundary conditions from the air supply diffusers, it is impossible to identify the reason for the discrepancies. The RNG k-ε model was also used by Zhang and Chen [57] and Gao and Niu [58] to assess the performance of novel cabin ventilation systems, showing that personalized ventilation should be used for air cabins. Our review found that this model is the most popular for studying airflow in an aircraft cabin.

3.2.2 Large eddy simulation

The LES separates small-eddies from large-eddies in a flow with a filter. LES has only one or no empirical coefficient and can provide very detailed turbulent flow information, so it is superior to RANS models. Figure 7 shows an example of the airflow calculated by LES for a cabin. However, one has to solve the transient flow even if the flow is steady and the flow details are not needed. The LES accuracy depends on grid resolution. Therefore, LES always requires much more computing time (at least two orders of magnitude longer) than RANS modeling for a steady-state flow.

Lin et al. [46, 47] conducted a LES to obtain the turbulent flow in a generic cabin mockup. The turbulence level predicted was in fairly good agreement with the experimental data. Because of the long computing time and high computing capacity needed by LES, the LES results were used to improve the RANS simulations.

LES used excessively fine grids for the near boundary flow. One recent approach was to use a RANS model for the near boundary region and LES for the far-wall region. This hybrid approach is also called Detached Eddy Simulation (DES). DES can reduce the computing cost and maintain the accuracy of LES [59].

4. Discussion

Experimental measurements in a full scale cabin are difficult due to limitations in spatial and temporal resolutions. Accurate measurements of the air supply conditions from a complex diffuser in an airliner cabin are still challenging [10]. Most of the experimental measurements were conducted in a short-section of cabin mockups with only a few rows of seats or no seats [10, 60, 61], which can introduce end-effects. The cabin mockups were different from real aircraft cabins, and the influence of the differences on the airflow is still unknown. Therefore, it is necessary to use a full-scale test rig for obtaining reliable and high quality experimental data because CFD simulation models for a whole cabin are also different from those for a regional air distribution study.

In addition to the several popular CFD models discussed in the previous section, other CFD models have been used to study air distributions in airliner cabins. Dygert et al. [51] used a realizable k-ε model with enhanced wall treatment to study the flow field in a B767 coach-class. Bosbach et al. [23] used a low-Reynolds-number model and a two-layer k-ε model for their study on jet separation. Their results showed that the jet profile was best described by the low-Re model.

There are different kinds of meshes, such as structured meshes, unstructured meshes and hybrid meshes. The algorithms for generating structured meshes include algebraic grid generation, elliptic grid generation and grid marching methods. For unstructured mesh generation, the most popular algorithms are those based on Delaunay triangulation. Other methods, such as quadtree or octree approaches are also used [62]. There are many different commercial software can be used for these mesh generation algorithms. As the geometry of and furniture and passengers in aircraft cabin are complex, it is better to generate unstructured meshes. Hybrid meshes can be used to reduce the number of cells.

The combination of both experimental measurements and CFD simulations is becoming more popular [10, 27, 48, 52]. As in many other CFD applications, there is a need for highly resolved data to validate the simulations and to determine the most appropriate model for the given geometry and flow conditions. The combined use of the two methods has permitted achieving a reliable understanding of cabin flow fields in a time- and cost-effective manner and this use combines the advantages of the two methods.

5. Concluding remarks

This paper has reviewed the experimental measurements and numerical simulations of air distributions in aircraft cabins. Hotwire and hot-sphere anemometers, Particle Tracking Velocimetry (PTV), Particle Streak Velocimetry (PSV), Particle Image Velocimetry (PIV), and Ultrasonic Anemometry (UA) have been used to measure the airflow field. The hotwire and hot-sphere anemometers provide point-by-point data and have great uncertainties when the air velocity is low. Hotwire anemometers cannot easily be used to measure airflow direction, nor can they measure flow direction. The PTV, PSV, and PIV give mainly two-dimensional flow fields. When they were used in an airliner cabin with passengers and seats, the laser light sheet was blocked so it could not be used in the area. The UA can give three-dimensional, point-by-point airflow information. However, its sensor was too bulky for small areas, such as for measuring the airflow from an air diffuser.

The zonal model is simple but requires prior knowledge of the airflow. Thus, Computational Fluid Dynamics (CFD) has become most popular for studying air distributions in airliner cabins. The RNG k-ε model is more popular than the standard k-ε model and other Reynolds-Averaged Navier-Stokes equation (RANS) models. Large Eddy Simulation (LES) can provide more accurate and detailed flow information but requires a two-order magnitude of computing time. The hybrid LES/RANS model or Detached Eddy Simulation (DES) model are less computationally demanding and seem promising.

The trend in studying air distributions in airliner cabins is to use both experimental measurements and CFD simulations. This effort can reduce the experimental costs and make the CFD simulation more reliable.

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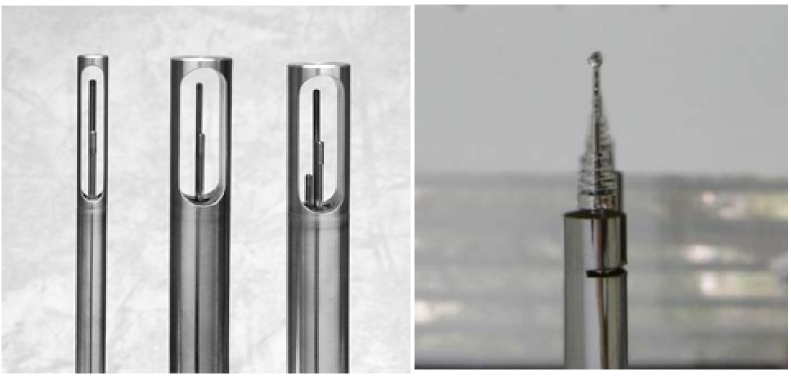


Fig. 1 Measuring probes of hotwire anemometers (left) and a hot-sphere anemometer (right).

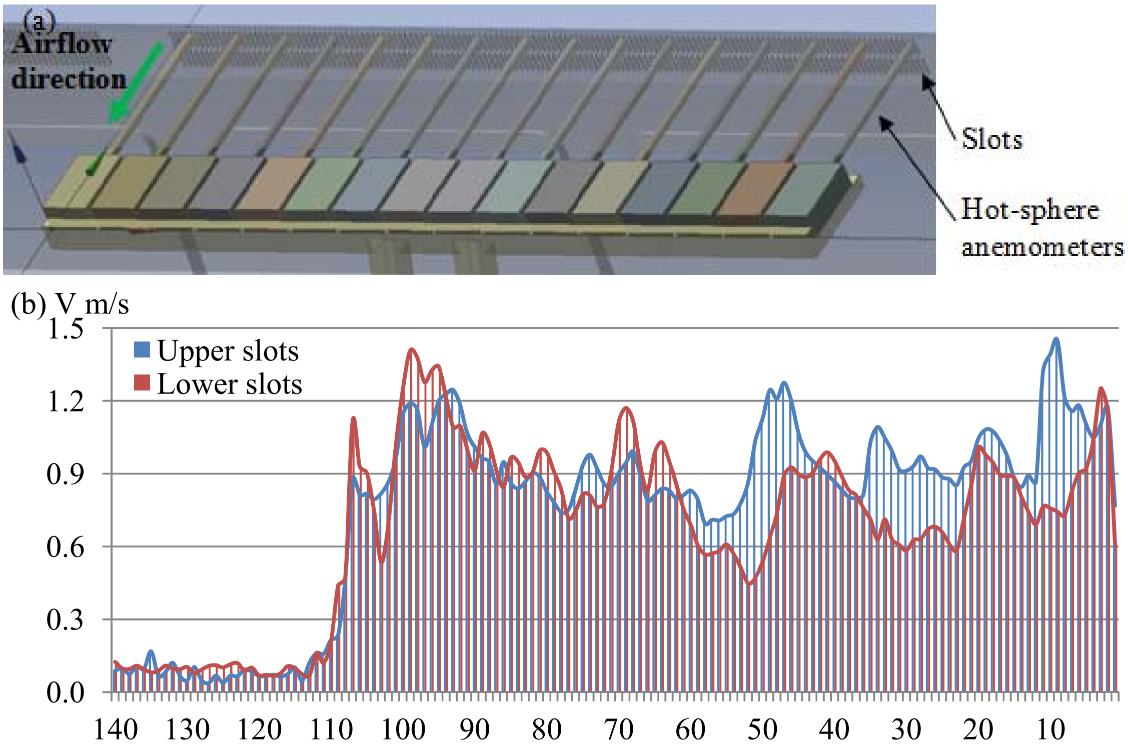


Fig. 2 (a) Setup of hot-sphere anemometers and (b) measured velocity magnitude on the diffusers in first class cabin of a MD-82 aircraft (X axis represents the number of slot)

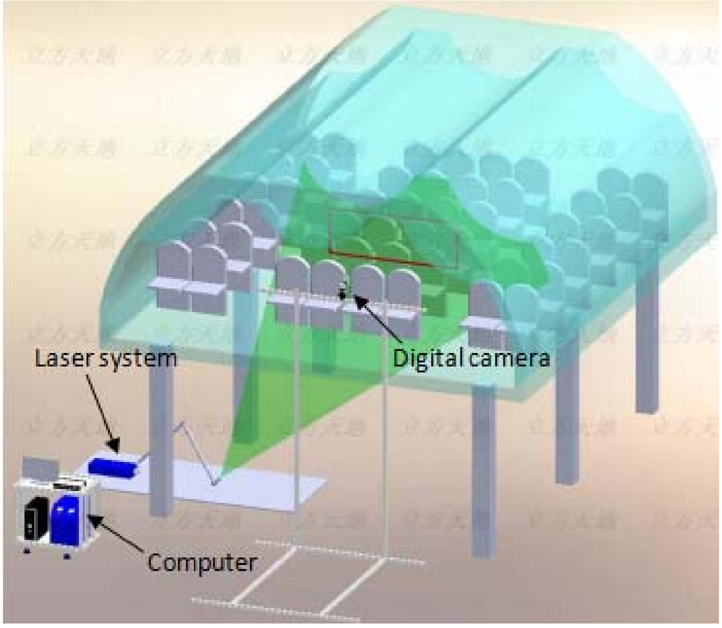
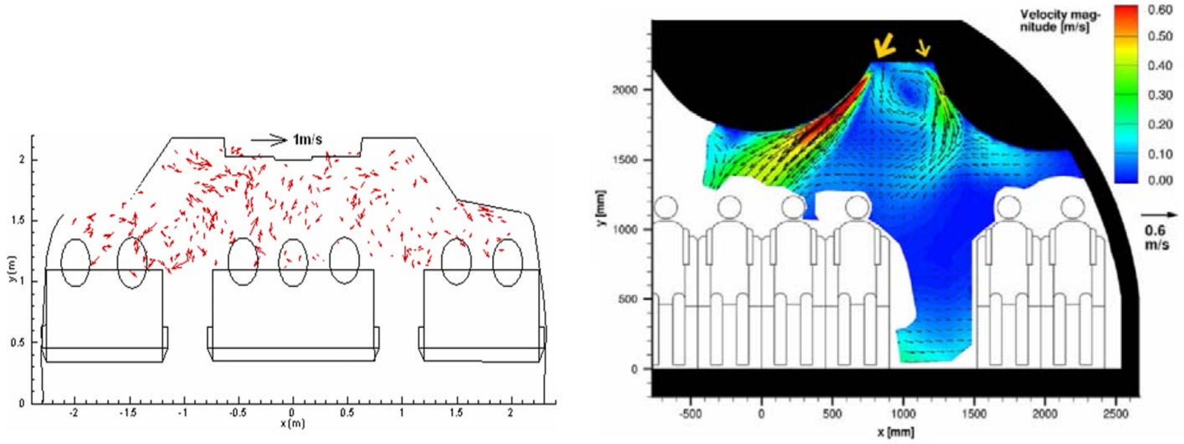


Fig.3 Setup of the optical anemometry in a cabin [16]



(a) With a VPTV by Wang et al. [37] *(b) With a PIV by Bosbach et al.[38]*

Fig.4 Measured velocity vectors by different optical velocimetries

Fig.5 Set up of the UA

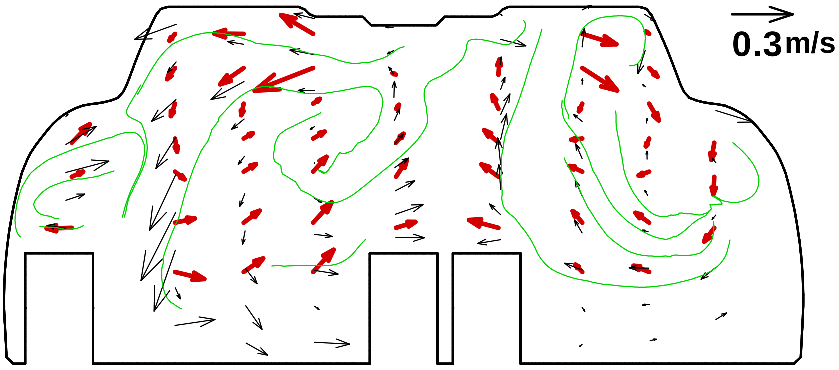


Fig.6 Comparison of the airflow pattern measured in the cross section of a cabin mockup by Zhang et al.[14] (measured by UA - bold vectors in red color; computed by CFD - light vectors in black color; and airflow paths computed - the green lines)

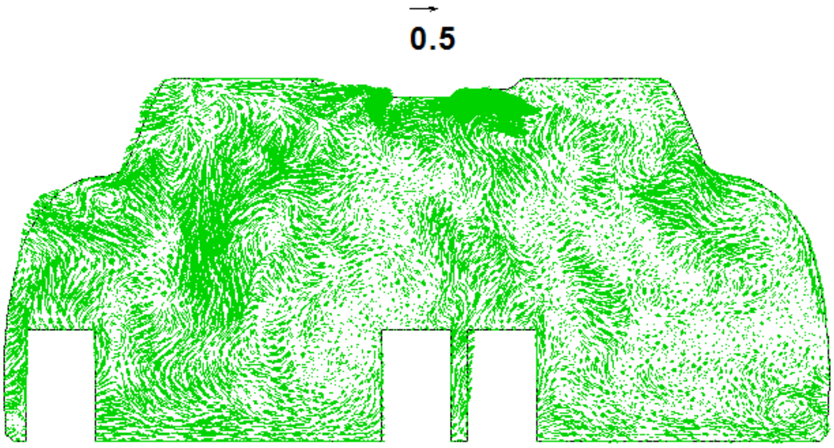


Fig.7 A flow field on a cross section of a cabin mockup obtained by using LES

Table 1 Summary of previous work on cabin distributions (velocity field (V), contaminant concentration (C), temperature (T); hotwire (HW), sonic/ultrasonic anemometry (SA/UA), particle tracking velocimetry (PTV), volumetric particle tracking velocimetry (VPSV), particle image velocimetry (PIV), thermocouple(TC), gas sensor (GS), volumetric particle tracking velocimetry (VPTV), Planar Laser-Induced Fluorescence (PLIF), Particle Streak Tracking (PST)).

Author(s)	***Year***	***Cabin***	***Manikins***	***Tech(s)***	***Data***	***CFD***
Aboosaidi et al.	1991	A cabin mockup	None	N/A	V	RANS
Olander and Westlin	1991	DC 9-21, DC 9-41 and MD-80's	Passengers	N/A	V, C	Zonal model
Mizuno and Warfield	1992	A cabin mockup	None	HW, GS	V, C	RANS
Müller et al.	1997	A340	N/A	PTV	V	RANS
Singh et al.	2002	B737 mockup	Heated cylinders	PSV	V, T	RANS
Mo et al.	2003	B737	A thermal manikin and heated cylinders	PIV	V	None
Garner et al.	2004	B747-100	None	UA	V	An augmented laminar Taylor-stabilized finite turbulent model
Wang et al.	2005	B767 mockup	Thermal manikins	VPTV	V	None
Sun et al.	2005	B767 mockup	Thermal manikins	VPSV	V	None
Lin et al.	2005	B767	Human-shape manikins	None	V, C	RANS/LES
Zhang et al.	2005	B767 mockup	Box manikins	None	V,T, C	RNG k-ε
Bosbach et al.	2006	A380	None	PIV	V	RANS
Lin et al.	2006	Half of a generic empty cabin mockup	None	PIV	V	LES
Günther et al.	2006	A380 mockup	None	PIV	V	RANS
Baker et al.	2006	B747	None	SA	V	RANS
Zhang and Chen	2007	B767 mockup	Box manikins	None	V, C, T	RNG k-ε
Kühn et al.	2008	A380 mockup	Thermal manikins	PIV, TC	V, T	None

Yan et al.	2008	B767 mockup	Box manikins	VPTV, GS	V, C	Standard k-ε
Zhang et al.	2008	B767 mockup	Box manikins	UA, GS	V, C, T	RNG k-ε
Mazumdar and Chen	2008	B767 mockup	Box manikins	UA, GS	V, C	RNG k-ε
Wang et al.	2008	B767 mockup	Thermal manikins	VPTV, GS	V, C	None
Sze et al.	2009	Cabin mockup	Heated cylinders	PIV	V, C	None
Wan et al.	2009	Cabin mockup	Heated cylinders	PIV	V, C	RNG k-ε
Yin et al.	2009	B767 mockup	Box manikins	None	V,T, C	RNG k-ε
Bianco et al.	2009	Executive aircraft cabin	None	None	V, T	RANS
Bosbach et al.	2009	A380 mockup	Thermal manikins	PIV	V	None
Rosenstiel et al.	2010	Full-scale cabin mock-up	Heated dummies	PSV	V	None
Poussou et al.	2010	Small-scale, water-filled model	Box manikins	PIV, PLIF	V, C	RNG k-ε
Dygert et al.	2010	B767	Thermal manikins	N/A	V,T, C	Realizable k-ε
Zítek et al.	2010	B767 mockup	Box manikins	PIV	V, T	Standard k-ε