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Novel air distribution systems for commercial aircraft cabins

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Abstract

Air distribution systems in commercial aircraft cabins are important for providing a healthy and comfortable environment for passengers and crew. The mixing air distribution systems used in existing aircraft cabins create a uniform air temperature distribution and dilute contaminants in the cabins. The mixing air distribution systems could spread infectious airborne diseases. To improve the air distribution system design for aircraft cabins, this investigation proposed an under-floor displacement air distribution system and a personalized air distribution system. This study first validated a Computational Fluid Dynamics (CFD) program with the experimental data of airflow, air temperature, and tracer-gas concentration from an environmental chamber. Then the validated CFD program was used to calculate the distributions of the air velocity, air temperature, and CO_2 concentration in a section of Boeing 767 aircraft cabin with the mixing, under-floor displacement, and personalized air distribution systems, respectively. By comparing the air and contaminant distributions in the cabin, this study concluded that the personalized air distribution system provided the best air quality without draft risk.

Keywords: Aircraft cabin; Air distribution; CFD; Mixing air distribution system; Under-floor displacement air distribution system; Personalized air distribution system

1. Introduction

At a typical cruise altitude of 11,000 m (37,000 ft), the extreme ambient environment for commercial airplanes is not survivable for human beings without any protection. At that altitude, the air temperature is about -55°C (-67°F); the atmospheric pressure is only around one-fifth of that at sea level; and the moisture content is near zero [1]. An environmental control system is used to protect passengers and crew members in an aircraft from such an extreme ambient environment. The air distribution system is an important component of the environmental control system since it is used to distribute conditioned air properly to the cabin, providing a healthy and comfortable cabin environment. Since an aircraft cabin has a higher occupant density, more complex geometry and a lower outside air supply rate per person as compared to buildings, it is very challenging to design a comfortable and healthy cabin environment for commercial airplanes.

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Currently, mixing air distribution systems are used to distribute air in an aircraft cabin as shown in Fig. 1. Conditioned air is supplied at the ceiling level with a high velocity and then mixes with the air in the cabin. The air temperature in the cabin is rather uniform and contaminants in the cabin are diluted. However, the mixing air distribution system could easily spread infectious airborne diseases, such as influenza and SARS, from one infected passenger to other passengers [2]. It is therefore necessary to improve the air distribution systems.

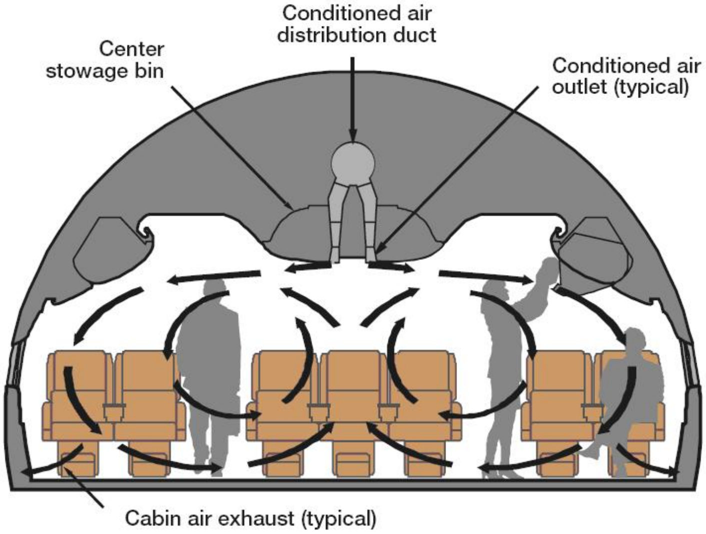


Fig. 1. Mixing air distribution system used for a wide-body commercial aircraft cabin [3].

On the other hand, displacement air distribution systems have been used for buildings with considerable success [4, 5]. This air distribution system can create better air quality in an indoor space than the mixing air distribution system. In an under-floor displacement air distribution system, clean and cool air is supplied to an indoor space from the floor. The heat sources in the space, such as human bodies, will generate thermal plumes that bring contaminated air to the upper zone. Then the contaminated air is exhausted from the ceiling level. Bauman [5] found that an under-floor displacement air distribution system can provide a much better air quality than a mixing air distribution system but with air temperature stratification. The air temperature stratification could impose draft risk to passengers and crew if the displacement air distribution system is incorrectly used in the aircraft cabin.

Furthermore, a new system with personalized air supply has begun to emerge [6]. A personalized air distribution system supplies clean and cool air directly to the breathing area of a person. The system creates a preferred microenvironment with clean and cool air. The personalized air distribution system can provide a superb air quality, but the draft risk could be even higher than the displacement air distribution system [6]. Although both the displacement and personalized air distribution systems have been applied successfully in buildings, they have not been used for aircraft cabins. Since an aircraft has a very different geometry and thermo-fluid conditions as compared to a building, the objective of this study is to explore if the displacement and personalized air distribution systems could be used in aircraft cabins.

2. A brief review of studies on air distributions in an aircraft cabin

Two main approaches are available for the studies of air distributions in an aircraft cabin: experimental measurements and computer simulations. There were many studies of air distributions in aircraft cabins in the last ten years using these two approaches.

Mo et al. [7] used particle image velocimetry to measure air distributions in an aircraft cabin. In this study, all seat backs except those next to windows were lowered so that the laser beam could penetrate the space. This made the cabin studied much different from the practical situation, although velocimetry could accurately measure the air distributions. Dechow [8] and Waters et al. [9] studied cabin air quality by measuring VOC, particulate, and ozone concentration, etc. However, they did not study the air distributions in detail. Garner et al. [10] conducted airflow measurements in a Boeing 747 aircraft. They used two ultrasonic anemometers to measure three-dimensional air velocity distributions in an empty cabin without heat sources and under steady-state inlet flow conditions. They measured instantaneous flow with a good spatial resolution. Although the measurements were only for an empty cabin, the study generated interesting data for further analysis of airflow in a cabin. Recently, Sun and Zhang et al. [11,12] used volumetric particle streak velocimetry to study some factors that have an effect on air speed at passenger breathing level in a mock-up Boeing 767-300 airplane with manikins in it.

Most of the experimental studies were done in a mock-up of a section of an aircraft cabin or in an actual stationary aircraft that simulated airflow in an aircraft cabin in flight. This is because an in-flight experiment is extremely expensive when the measurements have to be conducted with a reasonable spatial resolution in order to obtain meaningful results. Since the flow field could be unsteady, it imposes an untenable challenge in the measurements of transient contaminant transport because the response time of measuring equipment could be longer than the time-scale of the unsteady flow.

Compared with the experimental study, numerical studies of air distributions in an aircraft cabin are less expensive. There have been many numerical studies in the past decade. Olander and Westlin [13] used a zonal model to calculate airflow and contaminant concentration in an aircraft cabin. The zonal model could give a rough estimate of air distribution since it calculated only macroscopic flow between zones. Most of the numerical studies used computational fluid dynamics (CFD). Aboosaidi et al. [14] were one of the first to apply CFD to study air distributions in commercial airplanes with interior furnishings, although they did not consider passengers and thermal effects. Mizuno and Warfield [15] also carried out a similar study on air distributions in a cabin without passengers and other heat sources. However, they measured and calculated the carbon dioxide concentration. To account for the passengers in the airplane, Singh et al. [16] used heated cylinders on the seats to approximate occupants. Recently, with more realistic cabin geometry and interior furnishing, Lin et al. [17, 18] studied airflow and airborne pathogen transport in a section of a Boeing 767-300 cabin. They used both large eddy simulation and the Reynolds-averaged Navier-Stokes (RANS) models. Because of long computing time and high computing capacity needed for large eddy simulation, the large eddy simulation was only used for a simplified empty cabin. The results of large eddy simulation were then used to improve the RANS simulation.

The above review shows that experimental measurements, which are often considered reliable, can be very difficult and expensive for studying air distributions. Most of the experimental studies did not consider realistic thermo-fluid conditions or geometry. The spatial resolution of air and contaminant distributions is generally low. Although a zonal model uses little computing time, it does not produce accurate results. CFD seems like a good alternative. Among the two most popular CFD methods, large eddy simulation is too computationally demanding, so RANS modeling seems most appropriate for studying air distribution in an aircraft cabin. To the best of our knowledge, there have not been any CFD studies that compared different air distributions in an aircraft cabin.

3. Validation of a CFD program

This study selected a CFD program, FLUENT [19], with a RANS model to compare air distributions with different air supply systems. The RANS model is the renormalization group (RNG) k-ε model [20]. Like any other RANS model, the RNG k-ε model uses a lot of approximations. It is therefore necessary to validate the CFD program with the model [21]. Although the CFD program has been validated elsewhere, it is important that the software be validated together with the user [21].

The validation needs detailed and accurate experimental data of airflow and contaminant distributions in an aircraft cabin with well defined boundary conditions. Unfortunately, most of the experimental data for aircraft cabins available from the literature did not provide detailed information. As an alternative, this investigation used the data of the distributions of airflow, air temperature, and contaminant concentrations from a small office as shown in Fig. 2 [22] to validate the CFD program. This office configuration has similar flow characteristics to those found in an aircraft cabin. For example, the turbulent flow is mixed convection where both inertial and buoyant forces are important.

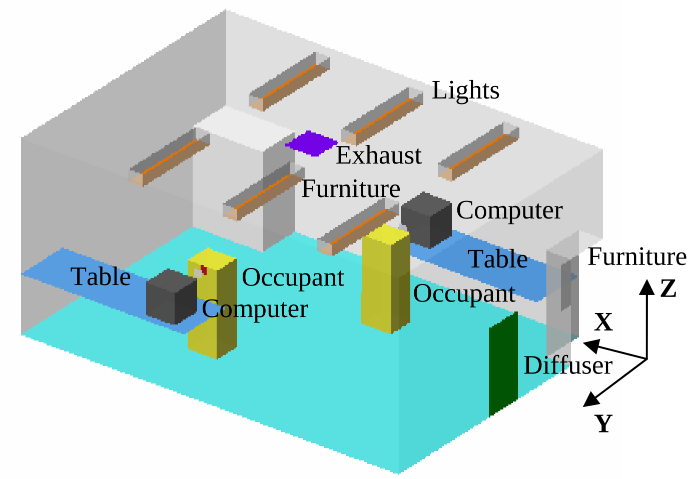


Fig. 2. The office configuration used for CFD program validation

Fig. 3 compares the airflow pattern in the mid-plane along the Y-direction. The airflow pattern computed by CFD is similar to that visualized in the experiment. The CFD can correctly reproduce the recirculation in the low part of the room. The magnitude of the air velocity also reflects a good comparison between the CFD results and smoke visualization.

Although we have the data at nine different locations in the room, the quantitative comparison for air velocity, air temperature, and contaminant concentration simulated by a tracer-gas (SF_6) was only presented at the center of the office as shown in Fig. 4. The results in other locations are very similar to those shown in Fig. 4. The air velocities were measured by omni-directional anemometers. It is difficult to measure an air velocity lower than 0.1 m/s because the convection from the anemometer probe would generate a false velocity of the same magnitude. The uncertainty for the measured air velocities was 10% of the readings. The error for air temperature measurements was 0.4 K, and the error for SF_6 concentration was 10% [23]. The agreement between the CFD results and the experimental data is very good for the air temperature, reasonably good for the air velocity, but rather poor for the SF_6 concentration in some locations. It is not very clear why we would have a larger discrepancy for SF_6 concentration. Nevertheless, the profile tendency can be roughly calculated by CFD.

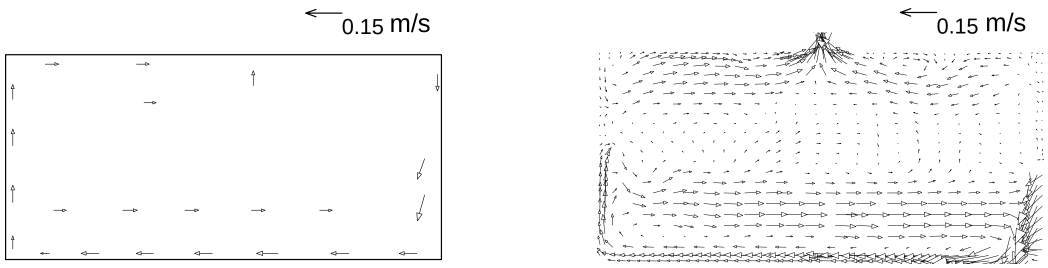


Fig. 3. The airflow pattern observed by smoke visualization (left figure) and computed by CFD (right figure) in the mid-plane along the Y-direction.

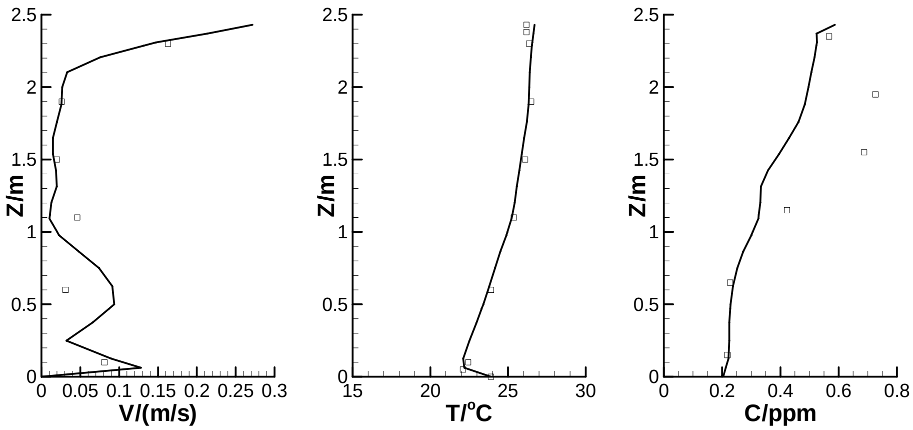


Fig. 4. The comparison of the profiles of air velocity, air temperature and SF_6 concentration between the CFD results (lines) and experimental data (symbols) at the center of the office.

The comparison of the CFD results with experimental data concludes that the CFD program with the RNG k-ε model is a good tool that can reasonably well predict airflow, air temperature, and contaminant transport in an enclosure with mixed convection. Although there are discrepancies between the computed results and measured data, the CFD model can be used as a tool to analyze air distribution in an aircraft cabin.

4. Case setup and numerical procedure

With the validated CFD program and the qualified users, the airflow, air temperature, and CO_2 concentration distributions in a section of a Boeing 767-300 cabin, as shown in Fig. 5 and Fig. 6, were studied. The section contained four rows, and each row had seven seats that were fully occupied. The maximum width of cabin (in the X direction) was 4.72m, the maximum height (in the Z direction) was 2.10 m. The aisle width was 0.48 m. Four strips of heat sources were used to simulate lighting at the ceiling. According to Topp et al. [24], a box-shaped manikin is sufficient for the study of global airflow in the space. Therefore, box-shaped manikins were used to represent the 28 passengers in the cabin. The total surface area of a manikin was about 1.8 m^2. The small square on the head level of each manikin was the location where a CO_2 source was released to simulate contaminant sources generated when passengers exhaled. Each passenger was assumed to produce 0.005 l/s of CO_2 through respiration.

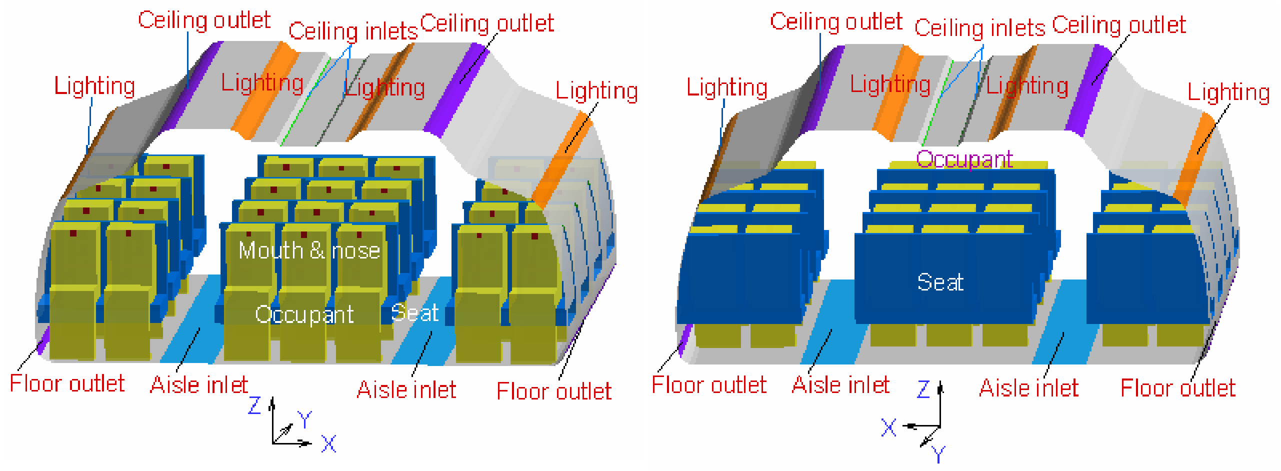


Fig. 5. Schematic of the mixing and under-floor displacement air distribution systems in a section of Boeing 767-300 cabin: left figure is for front view and right figure is for back view.

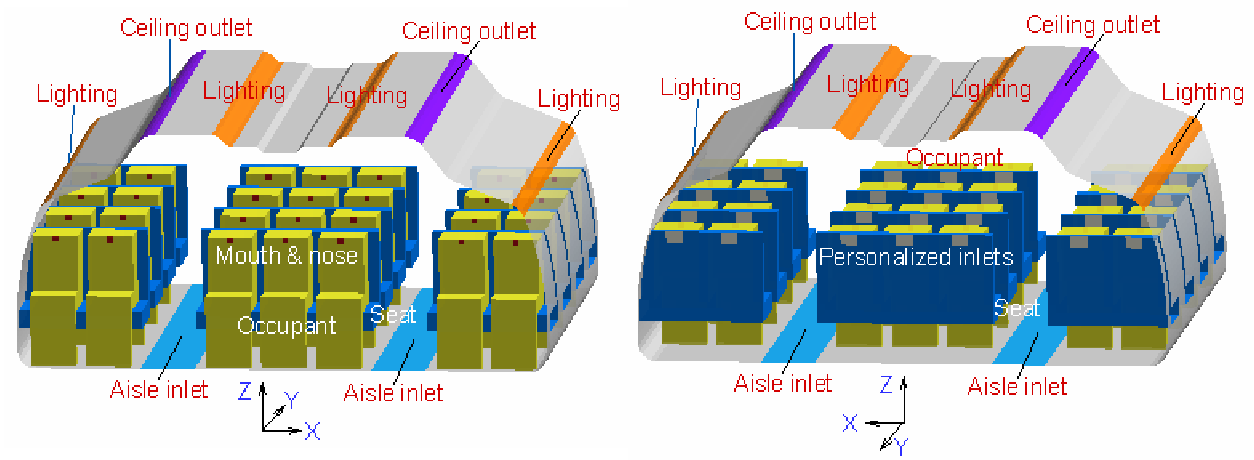


Fig. 6. Schematic of the personalized air distribution system in a section of Boeing 767-300 cabin: left figure is for front view and right figure is for back view.

This investigation compared three different air distribution methods in the cabin: mixing, under-floor displacement, and personalized air distribution. For the mixing air distribution system shown in Fig. 5, two ceiling inlets supplied conditioned air at a high velocity, and two floor outlets extracted air near the side walls at the floor level. The air supplied from the inlets was a mixture of outside air (5 l/s per person) and recirculated air (another 5 l/s per person). The under-floor displacement air distribution system shown in Fig. 5 supplied the same type of air mixture through perforated inlets located along the aisles. The air was extracted through the two ceiling outlets. The personalized air distribution system, as shown in Fig. 6, supplied 5 l/s per person of conditioned outside air through an inlet located on the seat-back in front of the passenger. The other 5 l/s per person of recirculated air was supplied from the two perforated inlets located along the aisles. In the same way as the under-floor displacement air distribution system, the air was extracted through the two ceiling outlets.

Table 1 summarizes the boundary conditions for the three air distribution schemes. The average air temperature for the cabin was controlled at 24^{o}C. The surface temperatures used for the mixing air distribution system were obtained from the measured data on a flight at cruising altitude by using an infrared camera; surface temperature information for the other two systems were estimated values. The criteria to estimate the surface temperatures in the displacement and personalized air distribution systems should make their cooling loads close to that in the mixing air distribution system since the design average air temperatures were the same in the three systems. All the seats were assumed to be adiabatic. The heat sources in the aircraft cabin were from the passengers and lights. The ratio of convective to radiative heat for the heat sources was estimated according to the recommendation from the ASHRAE Fundamentals Handbook [25]. The simulations did not consider the heat sources from electronic devices, and heat sources or sinks from drinks and meals. Thus, the supply air temperature in Table 1 could be higher than that used during actual airplane operation. For the personalized air distribution system, the personalized supply air velocity of 0.3 m/s was the minimum that could penetrate the thermal plume generated by human being so the air could reach the nose position [26].

Table 1 Boundary conditions for the three cabin air distribution systems

Item	Mixing air distribution	Under-floor displacement air distribution	Personalized air distribution	
			Personalized inlets	Aisle inlets
Supply airflow rate	10 l/s per person	10 l/s per person	5 l/s per person	5 l/s per person
Supply air velocity	3.04 m/s	0.073 m/s	0.35 m/s	0.037 m/s
Supply air temperature	19.5^{o}C	22.7^{o}C	19.5^{o}C	24.5^{o}C
Supply CO_2 concentration	850 ppm (air mixture)	850 ppm (air mixture)	350 ppm (outside air)	1350 ppm (recirculated air)
Ceiling temperature	22^{o}C	25.5 ^{o}C	24.5^{o}C	
Temperature of side wall above window	21.0^{o}C	21.0^{o}C	20.0^{o}C	
Window temperature	16.0^{o}C	16.5^{o}C	16.0^{o}C	
Temperature of side wall below window	22.0^{o}C	20.0^{o}C	21.0^{o}C	
Floor temperature	23.0^{o}C	22.0^{o}C	22.5^{o}C	
Temperature of lighting surfaces	24.7^{o}C	29.0^{o}C	31.0^{o}C	
Temperature of occupant surfaces	30.3^{o}C	30.3^{o}C	30.3^{o}C	

The numerical studies of air distributions in the aircraft cabin involved the solution of a set of governing partial differential RANS equations within appropriate boundary conditions. These governing equations include continuity, momentum, energy, CO_2 concentration, turbulent kinetic energy, and dissipation rate of turbulent kinetic energy. The partial differential equations were discretized into algebraic equations by using the finite volume method with a second-order upwind scheme. This study used GAMBIT (version 2.1.6) [19] to build the complex cabin geometry and to generate the cells for the CFD simulation. The cabin was divided into 24 sub-volumes for suitable grid generation. The hexahedral cells in the region around occupants were generated using the *Submap* scheme. Cells in other regions were primarily hexahedrons and secondarily wedges generated using the *Cooper* scheme. The grid size we used to generate the cells was around 5 cm. We used such a coarse mesh to save the computational effort due to the limited computing devices available. This was acceptable since we studied the global airflow instead of the detailed airflow around the manikins in the cabin. A high quality mesh was created in the domain with 92.54% of cells less than 0.2 in normalized EquiAngle Skew.

FLUENT solved the algebraic equations by integrating over all the cells. Because the equations are highly nonlinear, iterations were needed to achieve a converged solution. The iterations used the SIMPLE algorithm to couple pressure and velocity with a suitable solver. Two solvers were available in FLUENT, the segregated solver and the coupled solver. The segregated solver solves the algebraic equations sequentially. The coupled solver solves the equations simultaneously, thus requiring more computing memory. This investigation used the segregated steady-state solver.

A periodic boundary condition was used along the longitudinal direction to represent a cabin with infinite rows of seats. Buoyancy forces significantly influenced the cabin airflow, especially in the cases with the under-floor displacement and personalized air distribution systems. The Boussinesq assumption was used to approximate the buoyancy force. This study assumed that the contaminant CO_2 was passive and would not affect the airflow because of its low concentration. The CFD solution provided the airflow pattern and the distributions of pressure, air velocity, air temperature, CO_2 concentration, turbulent kinetic energy, and dissipation rate of turbulent kinetic energy.

With the case setup as described in the previous we did the computation in a personal computer with a Pentium 2.6 GHz processor and 1 Gb of memory. The continuity and momentum equations were thought to reach convergent when the ratio of the sum of the mass gain and loss on all boundary conditions to the overall mass gain in the cabin was less than 1.0e-6. In a similar method the convergent ratio limit for energy was 1.0e-3 and for the contaminant mass was 3.0e-3. Each case cost about 24 hours to complete.

5. Results

Figures 7, 8, and 9 show the flow pathlines colored by air velocity magnitude for the three air distribution systems. In the mixing air distribution system, the high velocity air from both ceiling inlets curved toward the cabin walls on both sides of the cabin. The air jet then flowed along the floor and mixed in the middle of the cabin. If one passenger in the cabin had an infectious disease, the virus could easily be spread to the entire cabin due to the strong mixing effect shown in the figure.

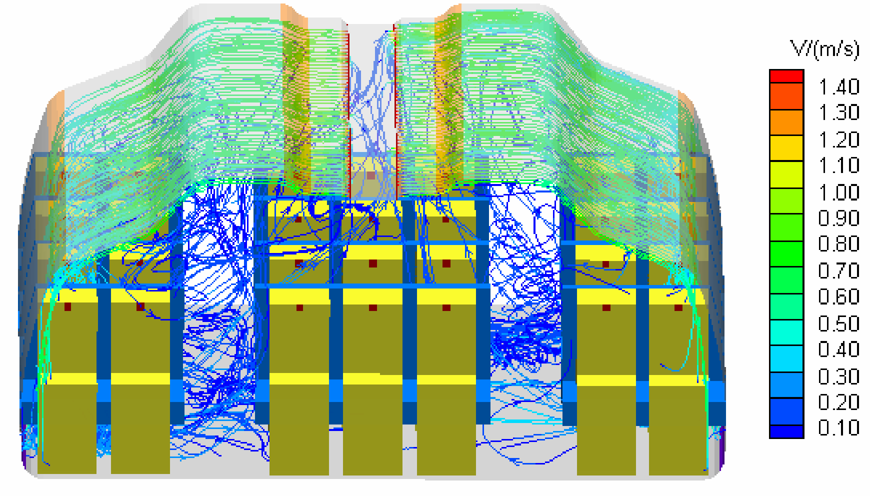


Fig. 7. Flow pathlines in the four-row cabin with the mixing air distribution.

In the displacement air distribution system, the supply air was partly mixed with the surrounding air as shown in Fig. 8. The low velocity supply air from the aisle inlets flowed upward with the initial momentum and was then driven further upward to the outlets at the ceiling by the thermal plumes from the passengers. The airflow pattern shows some possible mixing especially in the center seating area although the global airflow was generally upwards.

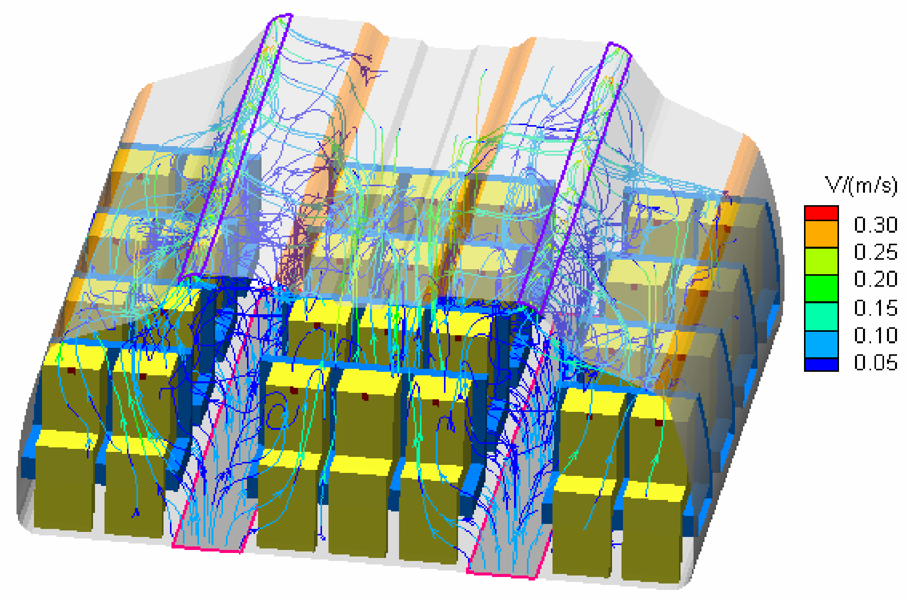
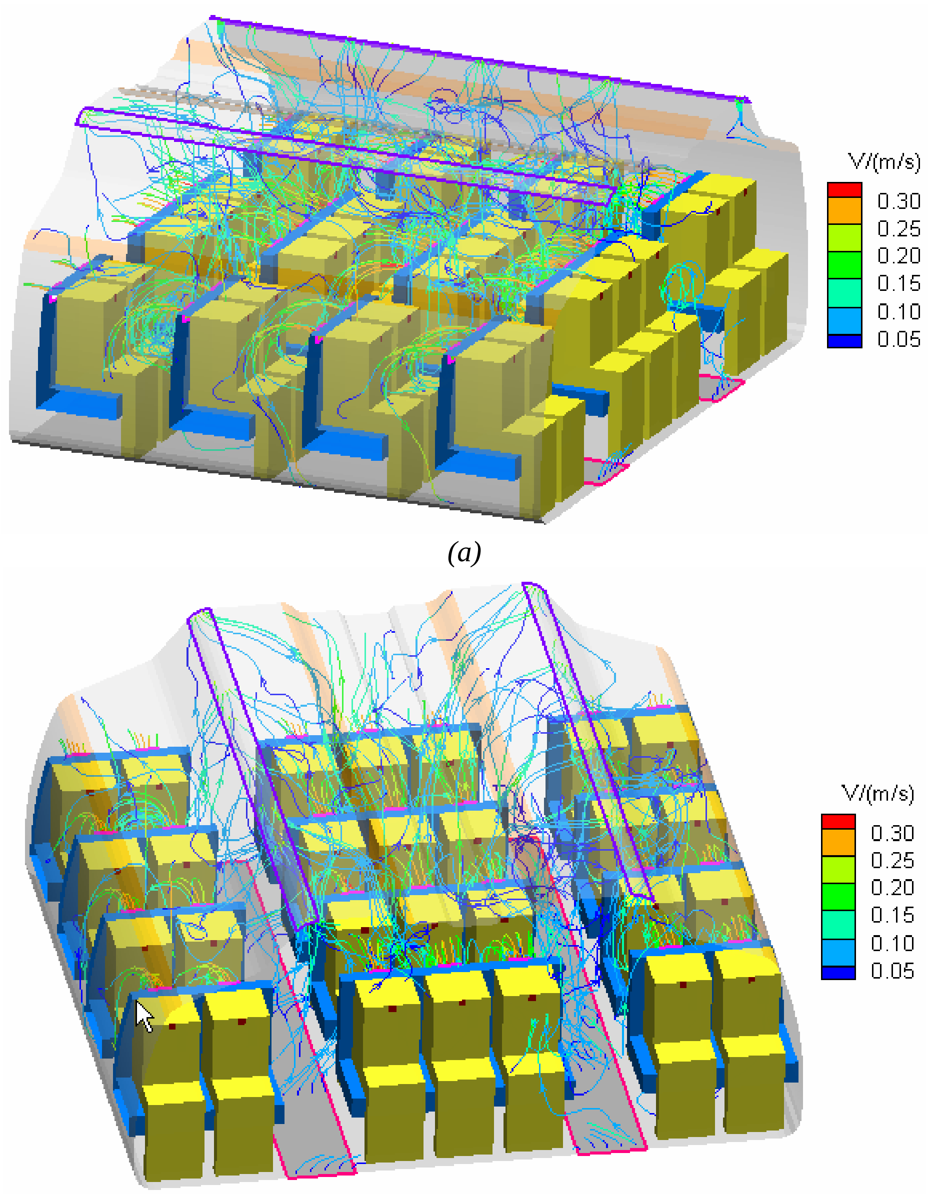


Fig. 8. Flow pathlines in the four-row cabin with the displacement air distribution.

In the personalized air distribution system shown in Fig. 9, the air jets from personalized inlets are designed to have enough momentum to reach the breathing area of the passengers. From this point the air was driven upward to the outlets on the ceiling by the thermal plumes in a similar way as that in the displacement air distribution system. The air movement for the recirculated air from the aisle inlets was not very evident, since the supply air volume and air velocity were only a half of those for the displacement air distribution system. The airflow pattern shows that the outside air was directed to the passengers. Therefore, even if there was a passenger with infectious diseases, the other passengers should not be affected.



(a)

(b)

Fig. 9. Flow pathlines in the four-row cabin with the personalized air distribution: (a) side view; (b) front view.

In order to quantitatively compare the performance of the three air distribution schemes for the aircraft cabin, this study selected ten representative vertical locations in the cabin for the evaluation of air distribution systems. As shown in Fig. 10, the ten positions were only on one side of the cabin due to the rather symmetrical airflow observed in the cabin. Positions 1 through 5 were located between the passengers and the back of the seat directly in front of the passengers. Positions 6 through 10 were located behind positions 1 through 5 and in front of the torsos of the passengers.

Fig. 11 compares the air velocities in the cabin at the ten locations with the three air distribution schemes. The mixing air distribution system generally had the highest air velocity, especially near the ceiling level where air velocity from the diffuser was high. The velocities near the side wall (shown in Positions 1 and 6 in Fig. 11) were higher than those in other positions, because the jet from the ceiling curved along the side wall. The jet traveled further along the floor, which is reflected in the slightly high air velocity near the floor. However, the seats effectively blocked the flow and the jet lost its momentum. In Positions 5 and 10, the air was in the recirculated region and so the jet effect was diminished. Thus the air velocities for the mixing air distribution system were low and were comparable to that for the other two air distribution systems. The air velocities through the passengers' thighs and seats were zero as reflected by the broken lines located at Positions 6, 7, 9 and 10 in Fig. 11. It is also interesting to note that the air velocities above the passenger heads in Positions 6 through 10 were higher than those in Positions 1 through 5. This is due to the thermal plumes generated by the passengers.

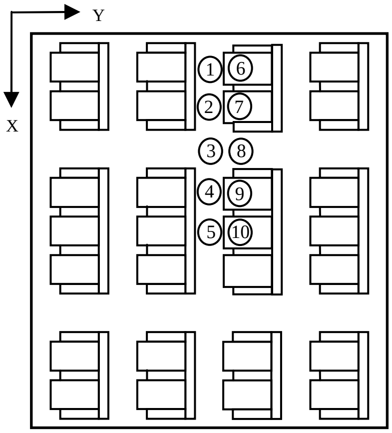


Fig. 10. The locations in the aircraft cabin where the results were compared (top view).

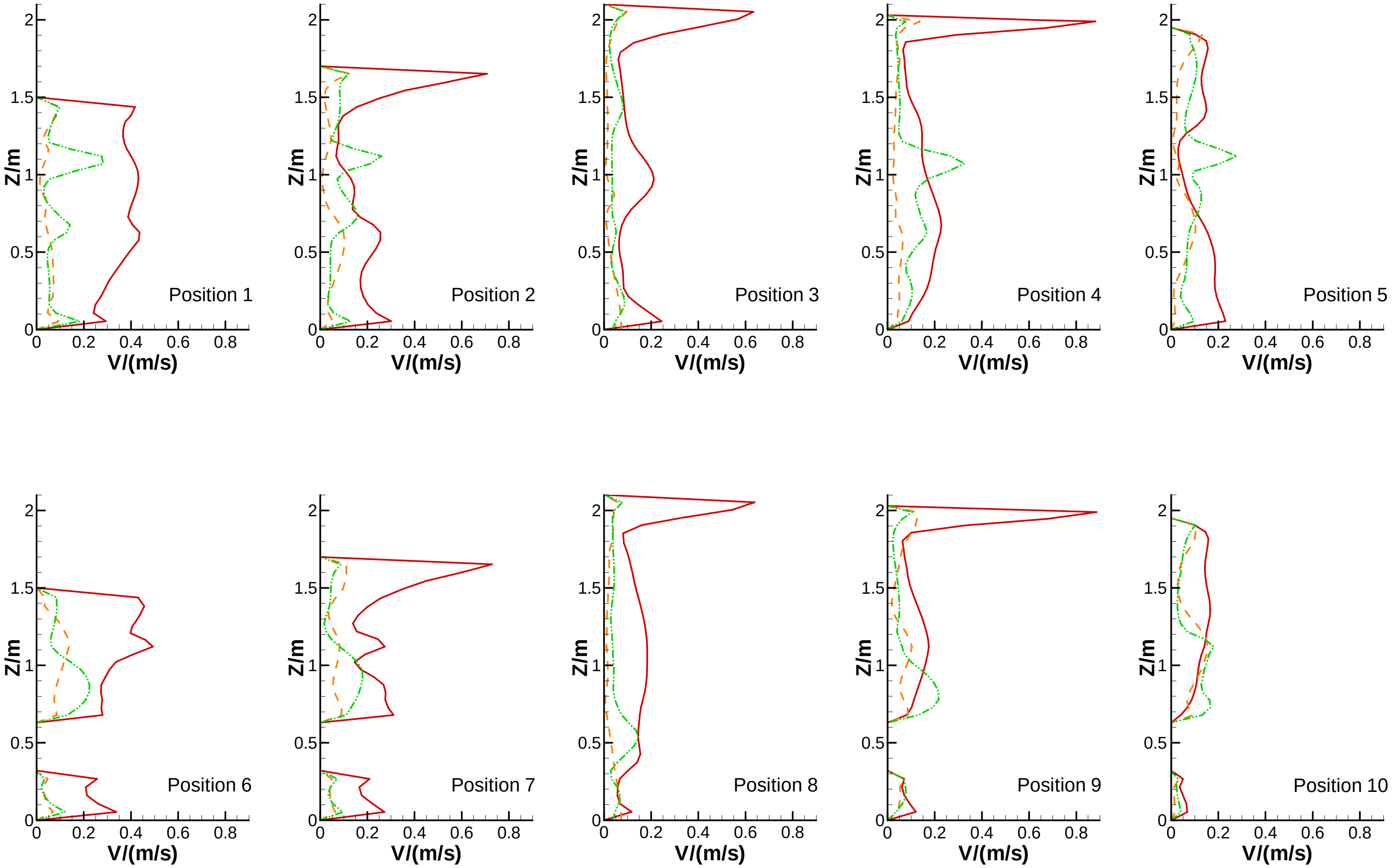


Fig. 11. Comparison of air velocity distributions in the cabin with different air distribution systems: mixing air distribution - solid lines, displacement air distribution - dashed lines, personalized air distribution - dash-dot-dot lines.

The under-floor displacement air distribution system generally had the lowest air velocities, since the supply air velocity from aisle inlets was very low and the main driving force for this air distribution system came from the thermal plumes generated by the passengers. At the breathing level for a seated passenger, the personalized air distribution system created the highest air velocities in Positions 1, 2, 4, and 5 due to the jets from the personalized supply air inlets. The jet effect can still be felt in the regions in front of passengers with the personalized air distribution system. Fig. 12 shows the detailed airflow pattern in the region. Note that the air velocity at the head and chest of the passengers was lower than 0.25 m/s. It is therefore unlikely that the personalized air distribution system would cause a draft that could be felt by the passengers.

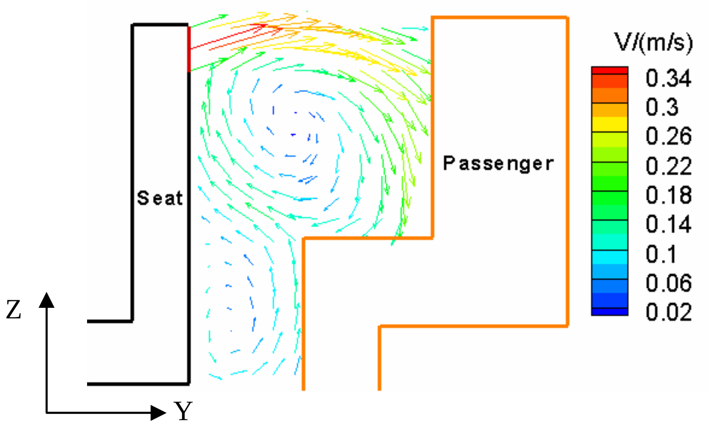


Fig. 12. Detailed airflow pattern on the Y-Z plane in the middle section of the cabin.

The air temperatures for the mixing air distribution system were more uniform than those for the other two air distribution systems as shown in Fig. 13. At the top level of Positions 1, 4, 6 and 9, air temperatures were high since this region was next to the lighting. The air temperatures near the floor and ceiling (except in the lighting region) were low, because of the low surface temperature of the airplane shell during a flight. The low temperatures at the head level of the passengers for the personalized air distribution system were caused by the low-temperature personalized supply air. At the low part of the cabin, the air temperature with the personalized air distribution system was a little bit higher than that with the displacement air distribution system because the warm recirculated air was supplied from aisle inlets.

There was a temperature stratification present in the displacement and personalized air distribution systems. The air temperature difference between the head and ankle level of a passenger was less than 3 K for all three air distribution systems, and so there should not be any risk of discomfort caused by the stratification. A low temperature region between the thigh and head of a passenger was created by the personalized air distribution system. The air temperature in the region was above 20°C. The cool jet air should be a welcoming breeze for the passengers and should not cause complaints due to draft.

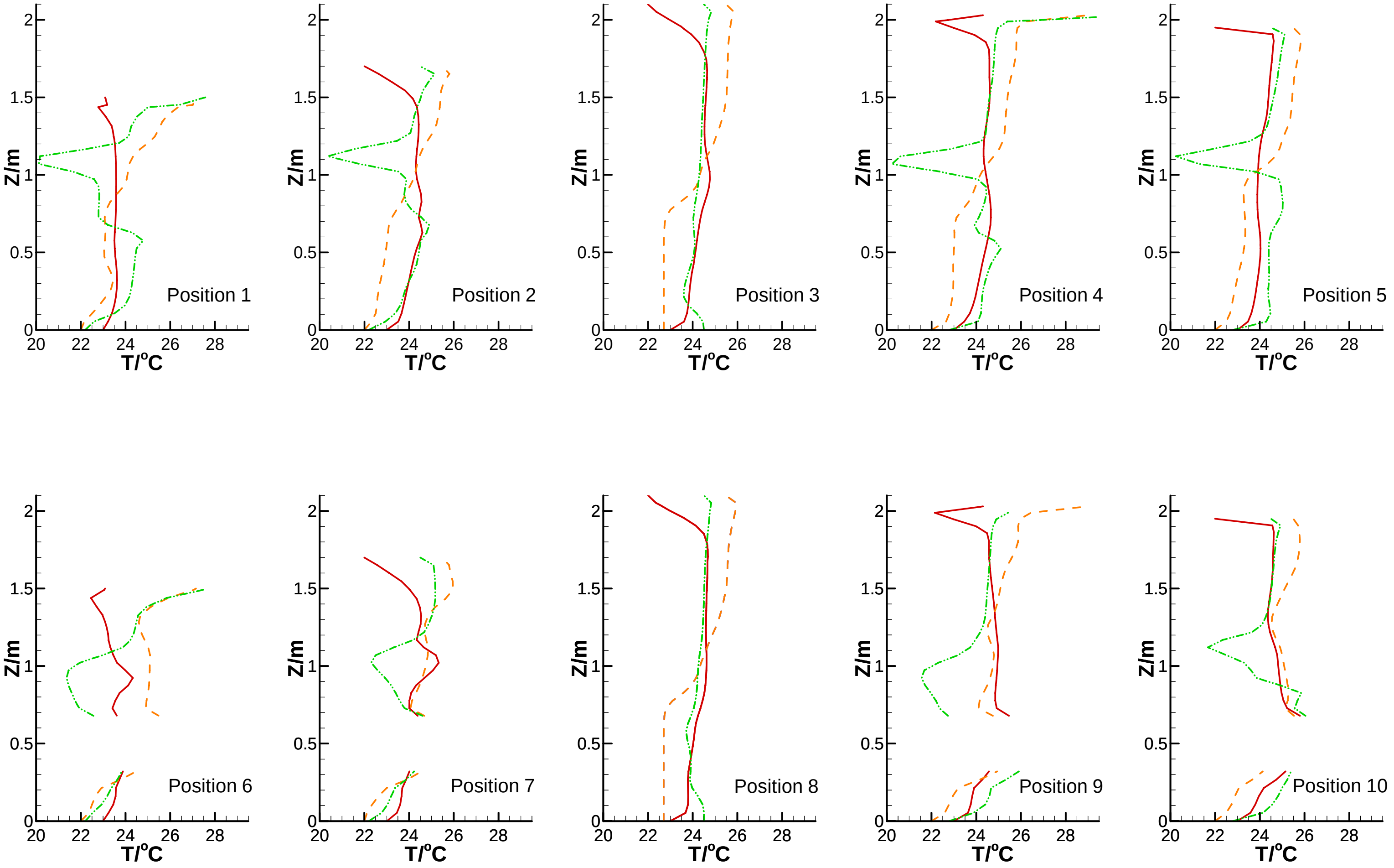


Fig. 13. Comparison of air temperature distributions in the cabin with different air distribution systems: mixing air distribution - solid lines, displacement air distribution - dashed lines, personalized air distribution - dash-dot-dot lines.

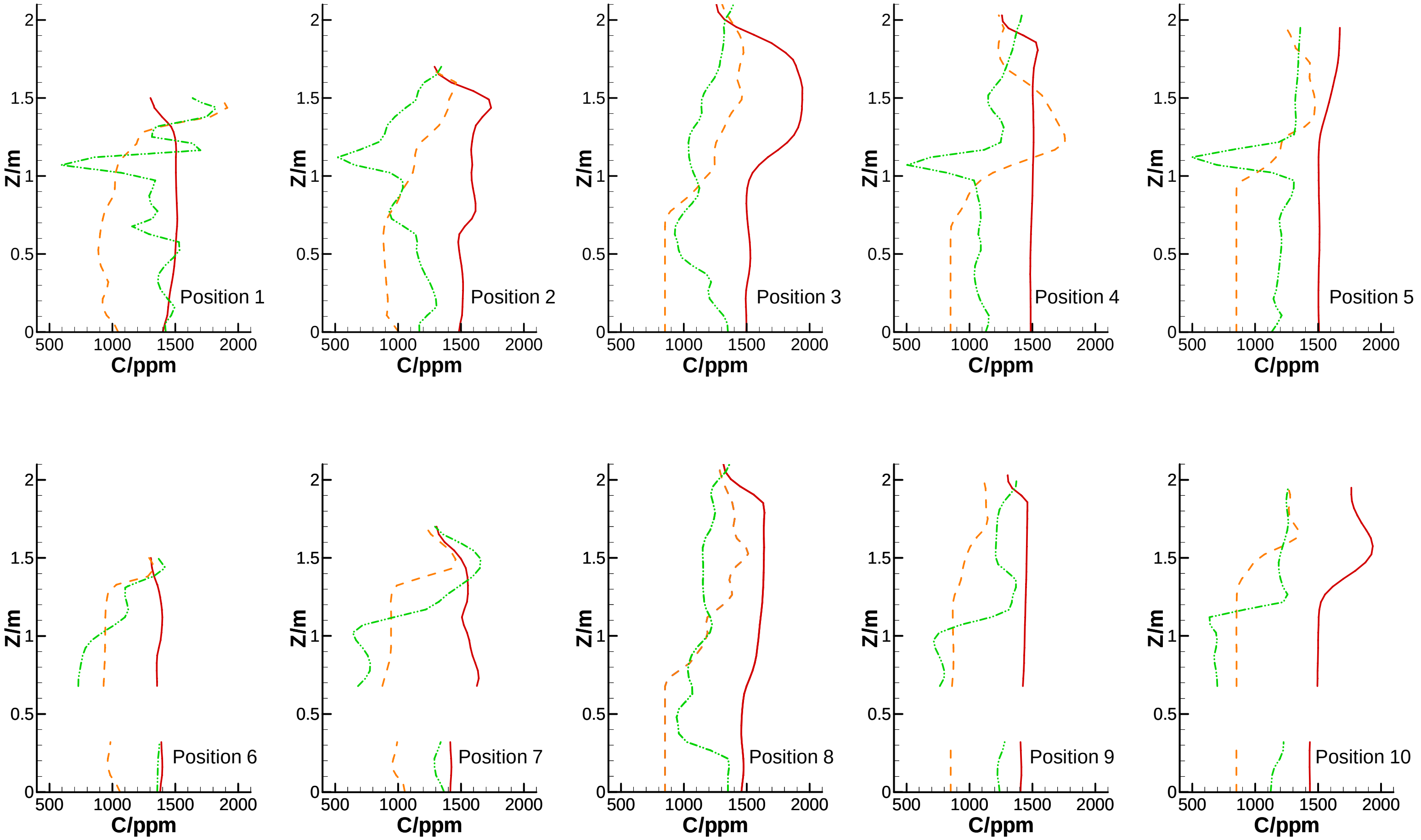


Fig. 14. Comparison of CO_2 distributions in the cabin with different air distribution systems: mixing air distribution - solid lines, displacement air distribution - dashed lines, personalized air distribution - dash-dot-dot lines.

Figure 14 shows the CO_2 concentration profiles in the cabin with the three air distribution systems. The CO_2 concentration profiles are very similar to those of the air temperature profiles. The CO_2 concentration with the mixing air distribution was rather uniform. This confirmed that the overhead ceiling supply of air did in fact create a mixed condition. The mixing could spread infectious diseases. However, the mixing was not perfect because the CO_2 concentration in some regions was higher than that in other regions. The CO_2 concentration stratified in both the displacement and personalized air distribution systems. The personalized air distribution system had a higher concentration of CO_2 at the low part of cabin than the displacement air distribution system, because the air supplied through the floor inlets was 100% recirculated air with a high CO_2 concentration. The personalized air distribution system had a much lower CO_2 level at the breathing zone, since outside, low CO_2 concentration air was directly supplied to the zone. Among the three air distribution schemes, Fig. 14 shows that the personalized air distribution system created a breathing zone with the lowest CO_2 concentration while the mixing system had the highest CO_2 concentration. The personalized air distribution system could be the most effective in eliminating the possible spread of infectious diseases in a cabin.

6. Conclusions

This investigation first validated a FLUENT CFD program that used the RNG k-ε model, with experimental data from an environmental chamber with displacement air distribution. Then FLUENT was used to simulate the distributions of airflow, air temperature and CO_2 concentration in a section of an aircraft cabin with mixing, under-floor displacement, and personalized air distribution systems. The results show that the mixing air distribution system generally had the highest air velocity, most uniform air temperature and highest CO_2 concentration. It can also easily spread infectious diseases from one passenger to the others due to the mixing airflow patterns. The air temperature and CO_2 concentration stratified in the cabins with the displacement and personalized air distribution systems. In the center seating area, there was a slight chance of mixing for the displacement air distribution system, so the risk of spreading infectious diseases existed in the cabin. The personalized air distribution system created the lowest CO_2 concentration in the breathing zone with a slightly lower air temperature than the other two systems but without much draft risk. The direct supply of outside air to the breathing zone in the personalized air distribution system could effectively eliminate the risk of spreading infectious diseases in the cabin. By considering combined factors of air velocity, air temperature, and CO_2 concentration as well as the airflow patterns, it was concluded that the personalized air distribution system created the best cabin environment and is therefore recommended for possible use in commercial airliner cabins.

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