A NEW UNDER-AISLE DISPLACEMENT AIR DISTRIBUTION SYSTEM FOR WIDE-BODY AIRCRAFT CABINS

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ABSTRACT

Air quality in aircraft cabins has long been criticized. Current widely-used air distribution systems on airplanes dilute inside generated pollutants by promoting air mixing and thus impose risks of infectious airborne disease transmission. In addition, low moisture content in cabin is believed to be responsible for headache, tiredness and lots of other unknown symptoms. To restrict air mixing while improving air humidity level, this investigation uses a validated computational fluid dynamics (CFD) program to design a new under-aisle displacement air distribution system for wide-body aircraft cabins. The new system supplies fully conditioned outside air at moderate momentum through a narrow channel passage along both side cabin walls to middle height of the cabin just beneath the stowage bins, while simultaneously humid air is supplied through both perforated under aisles. By comparing with the current mixing air distribution system in terms of distribution of CO_2 concentration, relative humidity, velocity and temperature, the new system is found being capable of lessening the inhaled CO_2 concentration by 30% and can improve the relative humidity from currently 12% to 22% without causing draught risks and moisture condensation on cabin walls.

INTRODUCTION

Commercial airplanes cruise at a typical altitude of 11,000 m where the outside temperature is about -55 ℃ (-67 °F), the atmospheric pressure is only about one-fifth of that at the sea level and the relative humidity is near zero. Under such an extreme ambient environment, human beings cannot survive without being protected by an environmental control system (ECS). As a part of the ECS, air distribution system plays roles including distributing air appropriately, cleaning up contaminated air, and minimizing cross disease infection, towards to creating a comfortable, healthy and safe cabin environment for passengers and crews. However, the current widely-used mixing air distribution system promotes air mixing by supplying high momentum air at the ceiling level and exhausting contaminated air at the deck level. The extensive air mixing is intended to dilute cabin inside generated pollutants and thus may impose risks of infectious airborne disease transmission. The outbreaks of airborne communicable diseases, such as the severe acute respiratory syndrome (SARS) in 2003 (Olsen et al., 2003) and later on possible multi-drug resistant tuberculosis transmission threats (Parmet, 2007), confirm such risks are not hypothetical but may come to reality. In addition, numerous long complaints about cabin air quality and thermal comfort should also be laid with significant attentions (NRC, 2002).

Since the mixing air distribution system mixes the cabin air very well, temperature inside is very uniform, hence it should not be the major reason leading to thermal discomfort. The mostly criticized in aircraft cabin is air dryness, which is believed to be responsible for headache, tiredness, eye, nasal and other unknown syndrome symptoms (Spengler and Wilson, 2003). During flight, the relative humidity of cabin air ranges averagely from 15 to 20%, as similar to typical wintertime indoor level (Hunt et al., 1995). Low humidity in cabins is attributed to the frequent renewal (20-30 ACH, air change per hour) of cabin air with the outside air that is substantially dry during cruise. Such large air change rate is upon the demand of maintaining thermal comfort and also the mission of diluting inside generated pollutants, though current cabin air quality is still being criticized. The other major reason without humidifying cabin air is to avoid moisture condensation on cabin walls because of relatively low temperature of aircraft shell at cruising. Low humidity is also thought to be helpful for inhibiting fungal and bacterial growth. Therefore, until a new air distribution system has been proposed that can lower the air change rate but without sacrificing thermal comfort and air quality, and at the same time a method has been found to prevent moisture condensation, the air quality and dryness problem in commercial cabins may not be well resolved.

Fortunately, concepts of new air distribution systems for aircraft cabins have been emerged, such as under-floor displacement air distribution system and personalized air distribution system. A typical under-floor displacement system supplies conditioned air from the low level at a low velocity and small temperature difference and extracts air at the ceiling level. The personalized air distribution system supplies conditioned air directly to the breathing region of occupants. Zhang and Chen (2007) proposed an under-floor air distribution system with perforated aisle air supply, and a personalized air system by supplying air from a seatback-embedded diffuser in front of a passenger in wide-body aircraft cabins, where both systems were found being capable of providing much better air quality than the current mixing air system. Schmidt et al. (2008) also applies computational fluid dynamics (CFD) to study an under-floor air distribution system for a single aisle aircraft cabin and pointed out draught risks may have for inside passengers. Again with CFD as the tool, Gao and Niu (2008a) investigated a personalized air system by supplying air through a flexible nozzle just beneath the nose and mouth of a passenger and claimed 60% of the pollutants can be shielded up from inhalation. Later, they (Gao and Niu, 2008b) further explored humidifying the supply air to relative humidity of 40-50%, but results show only the facial region may have higher moisture content whereas the whole cabin is still maintained in very low level of humidity. It should be noted that a personalized air distribution system usually requires a mixing or displacement air distribution system as a background system and moreover survey shows not all passengers use such system even though some of current airplanes are equipped with personal overhead gaspers.

This investigation therefore proposes a new under-aisle air distribution system by supplying air both from under-aisles and the two cabin sides above the seated passengers to improve air distribution efficiency and also enhance moisture content level. Performance of the new system in terms of cabin air quality, humidity distribution, risk of moisture condensation and thermal comfort are thoroughly evaluated.

VALIDATION OF A CFD PROGRAM FOR CABIN AIR DISTRIBUTION

As most researchers who investigated air distribution system for aircraft cabins used CFD as the tool, due to its efficiency, flexibility and relatively low cost, this study also adopted CFD to evaluate the proposed new system. One shall note that the mostly used RANS (by solving the Reynolds-averaged Navier-Stokes equations) CFD modeling employs significant amount of assumptions, so it is crucial to validate the CFD program and also the users to ensure reliable results have been obtained (Chen and Srebric, 2002).

Due to lack of quality data for displacement ventilation in aircraft cabins, this validation process used the air flow, temperature, and contaminant concentration data obtained from a small office served by displacement ventilation as an alternative. As shown in Figure 1, two occupants mimicked by box-shaped manikins were seated sedentarily in front of two desk computers in the office. In one corner of the office there was a file cabinet, and on the ceiling six fluorescent lightings were mounted for providing illumination. Conditioned cool air was supplied through a quarter-circular, perforated diffuser against another corner of the room, and a square ceiling exhaust extracted the room air to the outside. A contaminant source, simulated by a tracer gas pollutant, sulphur hexafluoride (SF_6), was introduced to the head level of one occupant to quantify the displacement ventilation in maintaining indoor air quality. More on the measurement details of this office can be refereed to the literature (Zhang et al., 2009).

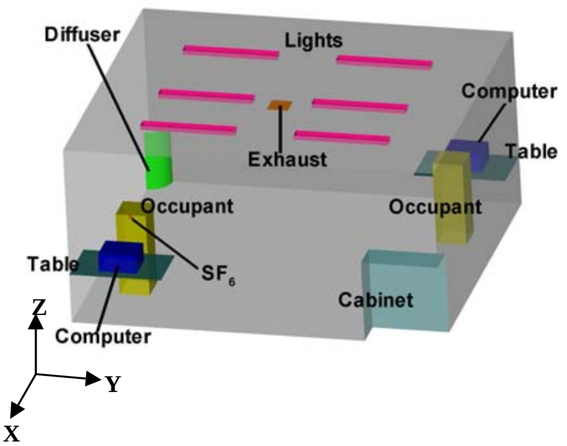


Figure 1 The office environment with displacement ventilation used for CFD validation

The validation used the Re-Normalization Group (RNG) *k*-*ε* turbulence model in solving the inside turbulent flow. The radiative heat transfer was estimated with an empirical formula so that thermal boundary conditions could be specified correctly. Due to the limited space available for this paper, the quantitative comparison for air velocity, air temperature and contaminant concentration was only presented at the center of the office on a vertical pole as shown in Figure 2. The agreement between the CFD results and the experimental data is more or less good for velocity, excellent for temperature, and reasonably fair for concentration. Note the accuracy of the anemometers for velocity measurement was 0.02 m/s with 1% error, for air temperature was 0.2℃ with 1% error, and the resolution of the tracer-gas measurement was 0.01 ppm and the accuracy was 1% of the measured values. The quantitative comparison of velocity, temperature and concentration profiles on other positions is similar though results are not listed in this paper for brevity. This validation therefore concludes the CFD program together with the users is capable of providing reasonable results for cabin air systems.

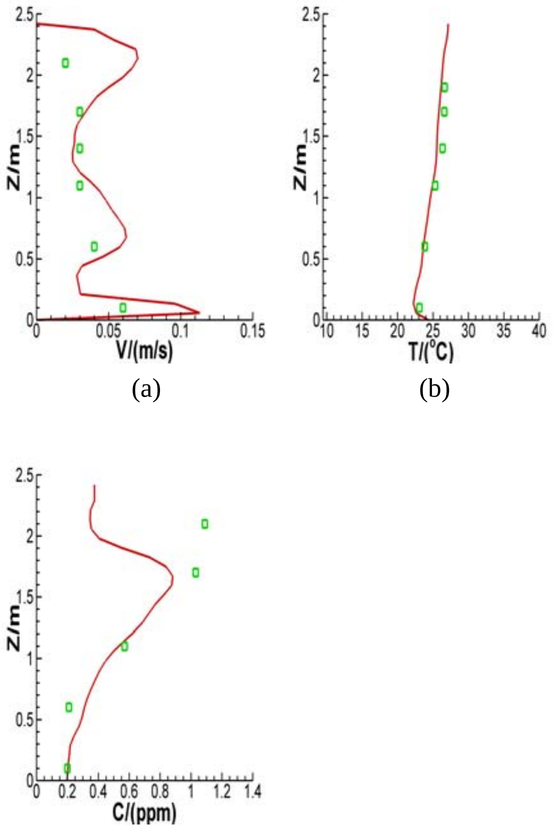
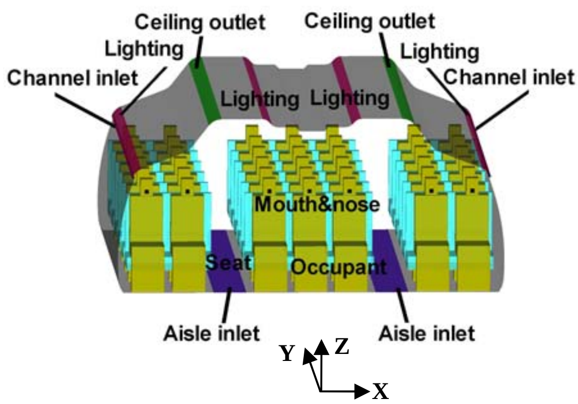


Figure 2 Comparison between the CFD results (lines) and experimental data (symbols) at the center of the office for air velocity, air temperature and SF_6 concentration along height

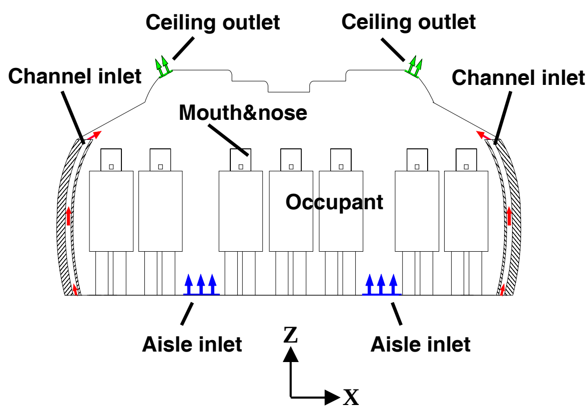
A NEW CABIN AIR DISTRIBUTION SYSTEM

With the validated CFD program, a new air distribution system in a section of a double-aisle aircraft cabin during cruise flight, shown in Figure 3(a), was studied. The cabin contains six rows of seats with all seats well occupied. Four strips of heat sources were used to simulate lighting at the ceiling. The box-shape manikins were employed to represent the seated passengers in cabin. The small squares on each manikin represent where carbon dioxide (CO_2) and moisture was released to simulate human exhalation effects.

The new system supplies fully outside conditioned air at moderate momentum through a narrow channel passage along both side cabin walls to middle height of the inside cabin just beneath the stowage bins. Figure 3(b) shows the schematics of the system from the sectional view. The air channel is designed to run the length of the aircraft, which is actually a curved air passage formed by the cabin insulation wall and another thin, parallel wall with warm air runing upward after entering from the underdeck. Such design is in the consideration of supplying clean outside air directly to the inhalation region of passengers, as well as warming the cabin side walls to avoid possible moisture condensation on such walls, due to relatively low temperature on the cheek area of the airplane fuselage at cruising. Simultaneously, the other part of outside air mixed together with the recirculated air after humidifying is supplied through both perforated under-aisles (Figure 3(a) and (b)). Such under-aisle air supply is to ensure thermally comfortable cabin environment and also to elevate cabin humidity level. The new system does not change the total outside air supply rate and air recirculation ratio as compared with the current mixing air system.



(a)



(b)

Figure 3 A section of a wide-body aircraft cabin model, (a) the new under-aisle air distribution system, (b) schematics of air supply scheme (sectional view)

To show the extent of the new system in improving cabin air quality and humidity level, a mixing air distribution system was also studied and compared with the new system. As shown in Figure 4, the mixing air system supplies conditioned air from both linear slot inlets on the ceiling and extracts air at the deck level. Other settings are the same with the under-aisle system. Carbon dioxide (CO_2) was applied as an indicator for ventilation efficiency, so the performance of the proposed new system in terms of distributions of inhaling CO_2 concentration, air velocity, temperature, and relative humidity was compared with the current mixing system.

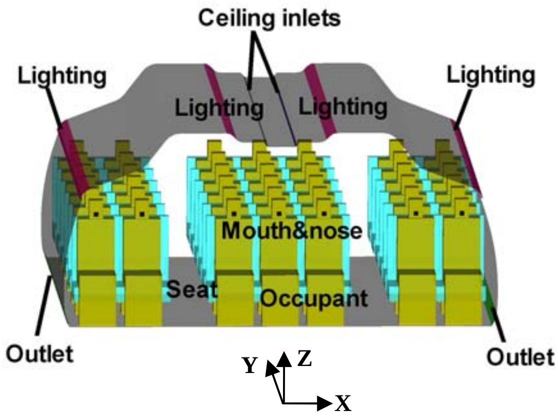


Figure 4 A current mixing air distribution system

Table 1 lists the design parameters for the two air systems. The design average air temperature for both systems in the cabin was controlled at 24℃. Each passenger was provided 10 l/s of conditioned air, in which 5 l/s was from the outside. In both cases a passenger was assumed to generate 0.005 l/s of CO_2 and 0.05 kg/s of moisture through respiration. Since in the new system, both channel inlets are only supplied with full outside conditioned air, the supply CO_2 concentration was assumed to be 350 ppm and there is no moisture. The aisle inlets supply the mixed outside air (3.572 l/s per person) with the recirculated air (5 l/s per person), so CO_2 concentration is around 933 ppm and also has been humidified into around 25% of relative humidity (at the saturation temperature of 22 ℃). The mixing system supplies the mixed air directly and therefore CO_2 concentration is around 850 ppm. The mixing system mixes the inside air very well, so air supply temperature should be lower than the under-aisle system to ensure thermal comfort. This investigtiation does not condsider heat dissipation from electronice devices and other heat sources. Moisture content in the mixing air supply is only from air recirculation generated by inside passengers, where the corresponding relative humidity is around 6%.

Computation of CO_2 and moisture dispersion in the cabin was handled as a passive tracer gas. Water vapor was thought of an ideal gas, so concentration of moisture content (density) can be easily converted into the partial pressure of water vapor. Hence relative humidity can be obtained once the saturated water vapor pressure with respect of air temperature is known.

Table 1
Design parameters for cabin air systems

Parameters	Under-aisle air system		Mixing air system
	Channel inlets	**Aisle inlets**	
Supply air flow rate per person (l/s)	1.428	8.572	10
Supply air velocity (m/s)	0.2083	0.09375	1.7224
Supply air temperature (℃)	24.0	22.0	19.5
Supply CO_2 concentration (ppm)	350	933	850
Supply water vapor content (kg/m^3)	0	0.004848 (RH: 25%)	0.001007 (RH: 6%)

This study used GAMBIT to build the geometry domain of the cases and generated the cells for CFD simulation. Both combined structured (hexahedral grids) and unstructured (tetrahedral grids) meshes were created in both cabins using the Tet/Hybrid scheme with Hex core. Then the RNG k-ε model was employed to model the turbulent flow just as we did in the validation process. The differential equations of continuity, momentum, energy, turbulent kinetic energy and its dissipation rate, CO_2 concentration and water vapor content, were finally solved with the finite volume method by dividing the domain into many spatial cells with the SIMPLE algorithm.

RESULTS

To quantitatively compare the new system with the current system, we have selected four vertical positions as shown in Figure 5 to analyze profiles of concerned parameters with height. These four positions were located just in front of the passengers at one side of the cabin due to relatively symmetric air characters found in the cabin.

Figure 6(a) presents CO2 concentration profiles at the four vertical positions. Since these vertical positions are across the manikin thighs and seats, so profile curves were broken into two pieces without data in between. The CO2 concentration in the inhaling regions (Z=1.1m) for the new system is around 930 ppm, which is much lower the mixing system that reaches around 1500 ppm. Such lower CO2 concentration (i.e., 30% improvement as compared with the current system) for the under-aisle system which is close to that at the under-aisle air supply, indicates cross air motion among passengers is very weak, so that the exhaled CO2 from one passenger is not transported to the inhalation region of other passengers.

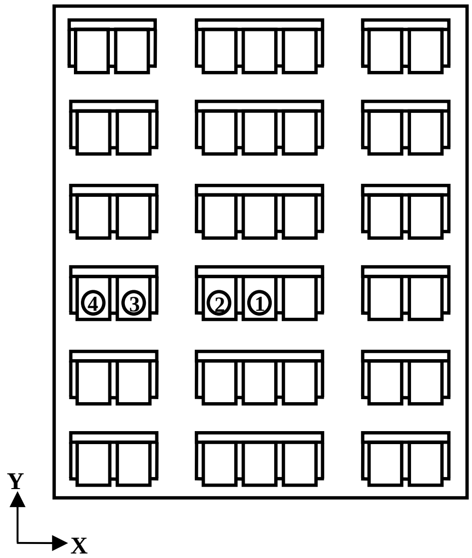
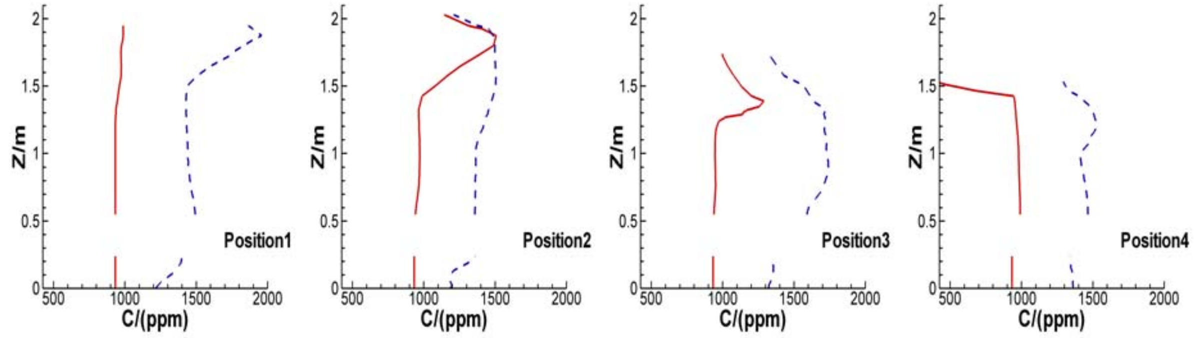


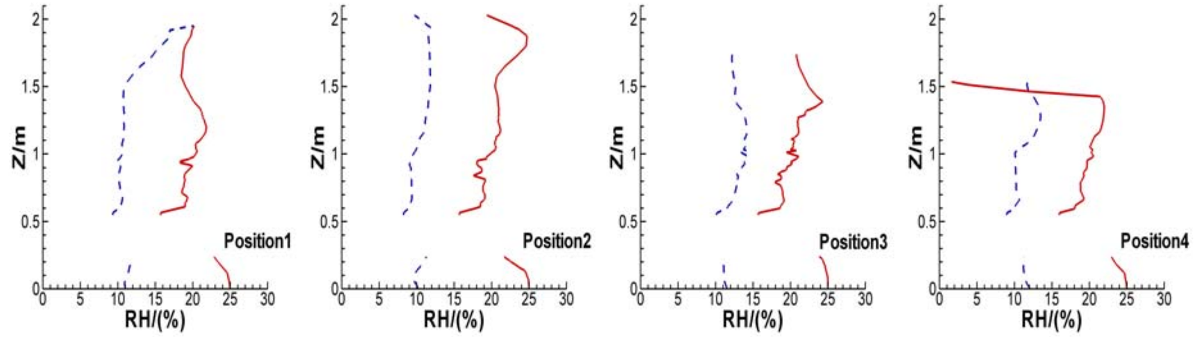
Figure 5 Four vertical pole positions where concerned parameters are analyzed along height

Figure 6(b) shows relative humidity on these four positions. The mixing system holds uniform relative humidity of around 12%, which is slightly lower than the typical sampling data in aircraft cabin. This is because this study only considers moisture generation from human respiration and neglects moisture evaporation human skins or drinks. After humidification, the humidity level in the new system is much elevated that arrives at 22% on average. There is no condensation on the aircraft shell, as showed in Figure 7 on a cross aircraft section. The higest relative humidity is at the cheek areas of the aircraft fuselage, but far from reaching saturation. The above humidity values are also a conservative estimate without considering other moisture sources. The elevated humidity should be effective to lessen the long complaints on air dryness and also helpful for reducing symptoms induced by low moisture level.

In order to evaluate passenger thermal comfort, velocity magnitude (Figure 6(c)) and temperature profiles (Figure 6(d)) are also plotted out. Velocity magnitude in the new system is kept in very low level less than 0.2 m/s, such weak air motion should not lead to draught risk, whereas in the mixing system there may be draught for the two passengers seated near the windows. Since these four vertical positions are very close to the passengers (in front of the passengers at 5 cm), temperature profiles between the two systems are similar with the dominant roles of metabolic heat release. The analysis of air velocity and temperature concludes there is no draught risk for the new under-aisle air distribution system.



(a)



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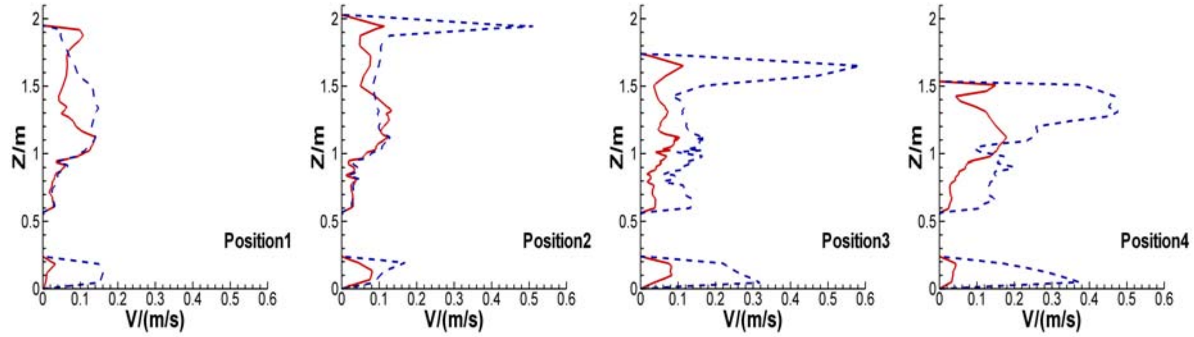
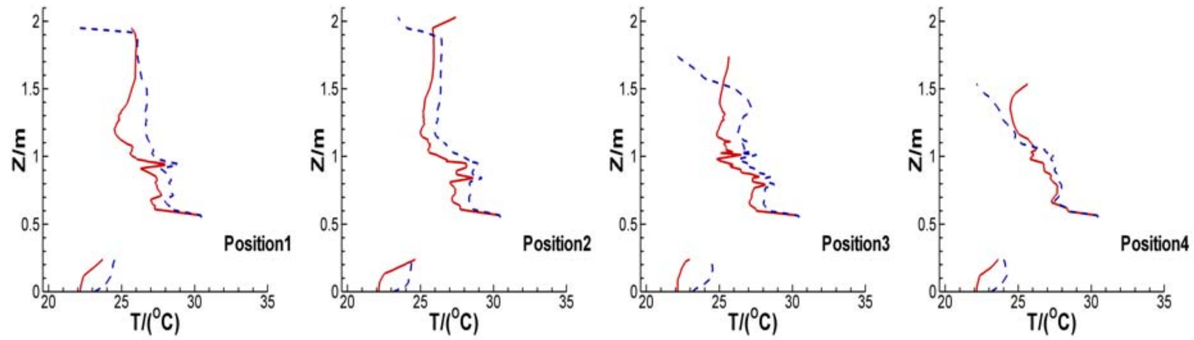


(c)



(d)

Figure 6 Comparison of CO_2 concentration (a), relative humidity (b), air velocity magnitude (c), and air temperature (d) in both cabin air systems at the four vertical positions: red solid lines for the new under-aisle displacement air distribution system, blue dashed lines for the mixing air system

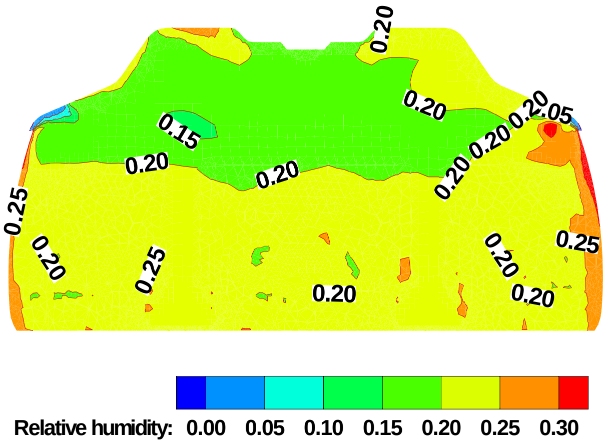


Figure 7 Distribution of relative humidity across a section in the Y direction

CONCLUSIONS

This study shows that the investigators are capable of using a commercial CFD software to compute the air distribution in enclosed environment correctly by compared with the experimental data obtained from a small office room. Then CFD was applied to investigate a new under-aisle air distribution system by simultaneously supplying air from both under aisles and channel inlets below the stowage bins. The new system was found being capable of lessening the inhaled CO_2 concentration by 30% as compared with the current mixing air system and can improve the relative humidity from 12% to 22% without causing condensation risks. There should be no draught risks on benefit of warm air supply from both under aisles and weak air motion created inside the cabin. Therefore, with comprehensively good performance based on this analysis, the new air system is recommended for possible use on future airplanes.

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