RESPONSE OF CONTAMINANT DETECTION SENSORS AND SENSOR SYSTEMS IN A COMMERCIAL AIRCRAFT CABIN

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ABSTRACT

To reduce the potential risk of airborne infectious diseases during an outbreak or to detect a chemical/biological release by a terrorist, it is essential to place appropriate chemical/biological sensors in commercial airliner cabins. This investigation studied sensor responses along the length of a fully occupied twin-aisle cabin with 210 seats by using a validated Computational Fluid Dynamics (CFD) program. The results revealed that seating arrangements can make cross sectional airflow pattern considerably asymmetrical. The trends of longitudinal contaminant transport in the business and economy classes were similar. The presence of galleys greatly affected the longitudinal transport of contaminants in a particular cabin section. The effects due to galleys is significantly reduced using a multiport sampling system. Multiport sampling systems also reduce the number of contaminant identification sensors required in a cabin considerably.

KEYWORDS

Experimental measurements, computer simulation, CFD, validation, sensor placement

INTRODUCTION

In March 15, 2003 a passenger with SARS infected many fellow passengers in Air China Flight 112 from Hong Kong to Beijing. Five of them died later as a result (Olsen et al. 2003; Lakshmanan 2003). The growing threats of chemical and biological attacks by terrorists have made matters worse. Infectious disease viruses or biological agents usually have an incubation period of a few hours to a few days (USAMRIID 2005) that can create a pandemic. However, chemical agents can kill passengers immediately. Hence fast detection of infectious disease viruses and chemical/biological agents in a cabin is critical to saving lives. For fast detection, Zhang and Chen (2007a) suggested to place sensors inside aircraft cabins.

Zhang and Chen's study used a nine-row, twin-aisle economy class section of a fully occupied airliner cabin.

Since most of the biological/chemical sensors are heavy, bulky, and expensive, their study concluded that to place limited amount of sensors in the ceiling center of the cabin is the most effective. But the distribution of airborne contaminants, such as biological/chemical agents, could vary significantly for different thermal conditions (Lee et al. 2006). Because the seating arrangements in different sections of a cabin differ considerably, the thermal conditions could vary along the longitudinal direction. Moreover the presence of galleys in between sections in an aircraft cabin can also have considerable influence on the longitudinal transport of contaminants. Hence this study attempts to address the contaminant distributions along the longitudinal direction with sensors placed at the ceiling center. To study the distributions, it is essential to use an effective research method with reasonable accuracy.

RESEARCH METHOD

Experimental measurements or computer simulations are popular methods for such a study. On-site measurements are difficult to control the thermo-fluid conditions and are time consuming and expensive. Though laboratory experiment by using cabin mockup is easier to control and more affordable, to study contaminant transport along the whole length of a commercial airliner cabin is still too costly. On the other hand, computer simulations are a cheap and efficient alternative. Computational Fluid Dynamics (CFD) models have been used extensively to predict airflows and contaminant transport in air cabins (Aboosaidi et al. 1991; Singh et al 2002; Garner et al. 2003; Lin et al. 2005 a,b; Zhang and Chen 2007 a,b). Previous studies (Aboosaidi et al. 1991 and Garner et al. 2003) have shown that the commercial CFD program, FLUENT perform reasonably well and hence it is used for the present study. But the software needs to be validated with experimental results before it can be fruitfully used (Chen and Srebric 2002).

VALIDATION OF CFD PROGRAM

Zhang and Chen (2007a) carried out experimental measurements in a mockup of a twin-aisle aircraft cabin

with four rows to validate the CFD program. Their study used the Re-Normalization Group (RNG) k-ε model to calculate the turbulent flow in enclosed environment as proposed by Chen (1995). The mockup had 28 seats in four rows. Only 50% of the seats were occupied by heated manikins. Our validation used the same cabin mockup and turbulence model with similar settings. Figure 1(a) shows the schematic top view of the cabin configuration. The air velocities and temperatures were measured using ultrasonic anemometers. The airflow at the inlet was obtained using omni-directional hot-sphere anemometers and the flow directions were estimated by smoke visualization. A SF_6 source was introduced at the head level of the middle passenger seated in the third row to simulate an airborne contaminant source, such as infectious disease viruses or chemical/biological agents. A photo acoustic multi-gas monitor with a multi-point sampler was used to measure the SF_6 concentrations at different heights. The accuracy of the measurements was 0.005 m/s for velocity, 0.025^{o}C for air temperature, and 0.01 ppm for the SF_6 concentration, respectively.

Figure 1(b) shows the airflow pattern along the longitudinal direction along the mid-section of the cabin. The CFD model can capture the airflow pattern. Figure 2 further compares the experimental and computed profiles of air temperature and SF_6 concentration at two different positions indicated in Figure 1(a). In general, the CFD predictions match well with the experimental data except the SF_6 concentrations close to the SF_6 source. The airflow near the release region was not steady that caused difficulties in both the measurements and simulations of SF_6 concentration. Hence the commercial CFD program can predict the airflow, air temperature and SF_6 concentration profiles to a reasonable accuracy. Thus it is used as the tool in this investigation to further predict airflow, air temperature, and contaminant transport in a full length, twin-aisle aircraft cabin.

CASE SETUP

Figure 3 show the full length cabin used to study contaminant transport. The total seat number was 210 (18 in first class, 42 business class and 150 economy class). The seat pitches were 1.52 m, 0.97 m and 0.86 m for the first, business and economy class, respectively. The cabin was fully occupied and the heat from electronic devices, drinks, meals, etc., was neglected. The temperature boundary conditions for the walls were obtained from the on-site measurements. Zhang and Chen (2007a) found that contaminant from the window seats was most difficult to detect for a sensor installed in the cabin ceiling center. If a sensor could detect the contaminant from a window seat, it can easily detect contaminants released from other seats. Therefore, this study used eight sources from the window passengers in different sections. Two of those were from the first class (F1, F2), three from the business class (B1-B3) and three

from the economy class (E1-E3). The air flow rate in the cabin was 10 L/s per passenger (Zhang and Chen 2007c). The box-shaped manikins were used to represent passengers since Topp et al. (2002) found that they were sufficient for the study of global airflow in a space.

In addition to the above thermo-fluid boundary conditions, the CFD modeling used the second-order upwind scheme and SIMPLE algorithm with a segregated steady state solver. However, the unsteady state segregated solver was used to compute the contaminant concentration distribution with fixed airflow pattern. Our grid independence study performed on the four-row cabin concluded that a grid size no larger than 6 cm was appropriate (Chen and Chen 2007). This resulted in a total of 10.2 million tetrahedral cells for the full-length cabin. The case was computed in an 8-node, 16-processor Linux cluster. Each node had two processors (1.8 GHz AMD 64) and 4GB of memory. The airflow computations took about two and half weeks. The unsteady contaminant transport computations were simulated for 120 s of real time for the eight different sources. The results obtained were for a moderate contaminant release rate of 1.0×10^{-6} m^3/s as proposed by Zhang and Chen (2007a). The results can be easily scaled up or down to address other release rates.

RESULTS AND DISCUSSIONS

Full cabin studies

Figure 4 shows the representative airflow patterns in the first, business and economy class of the cabin computed with the CFD program. The flow patterns along the cross section for business and economy class were close to symmetric because of the symmetrical thermo-fluid boundary conditions used. The pattern was asymmetric for the first class, due to the asymmetric seating arrangement. The flow pattern along the longitudinal section of the cabin is highly three-dimensional for the first class not only due to seating patterns but also because of the end wall effect. The longitudinal velocity pattern at the middle rows of the business and economy class were fairly repeatable for each row.

Unsteady contaminant transport along the longitudinal direction was also studied. Figure 5 shows the contaminant concentration distributions at the mid-section of the cabin after the contaminants were released from F1 and B2 for 120 s (see Fig. 3 for source locations). The results show that, if a sensor has a detection capability of 0.1 ppm, it should be placed every two rows in the first class and every three rows in the business class, respectively. However if a sensor has a detection capability of 0.001 ppm, one sensor for the first class and another for the business class will be sufficient to detect contaminant released in any seat.

Figure 6 shows the comparison between the eight different release scenarios. The scenarios with B2 and E2 releases, i.e. the releases near the central business and economy class, the contaminant transport was similar. This is due to the similar airflow patterns in the business and economy classes.

The contaminant released by F2, i.e. the last seat of the first class, can affect the passengers in both the first and business classes equally. This is expected as the first and business class is only separated by a thin wall at the center (refer to Fig. 3). Hence both the first and business class sensors will work equally well for such cases.

The release from B3, i.e. the last seat in the business class, will be the most difficult to detect with a centrally located ceiling sensor because of the presence of galleys at its side. The number of infected rows with C=0.001 ppm is only three (3) business-class rows for contaminant released from B3 compared to seven (7) rows for contaminants released by B2. This is because the contaminant released from B3 passenger distributes evenly in between the huge galley segment behind it and the business class ahead. Hence from a sensors perspective such seating arrangements should be avoided. The release near B3 also presents the case of worst possible scenario observed near the galleys. For all other cases the number of rows infected in a particular section up to a concentration level of 0.001 ppm for the moderate release rate is more than three (3). Thus galleys can reduce longitudinal contaminant transports in a given section by more than 50% if compared to releases near the middle of that section. It is important for designing a sensor system.

The longitudinal transport of contaminant, an approximate measure of which can be obtained from the number of rows infected and the pitch of seats, is the fastest in the first-class section. This is due to the highly three-dimensional airflow pattern observed in the first-class section. The contaminant transport is the slowest for the economy-class. Thus sensor studies done for the economy class would definitely work for the business and first classes.

Comparison of multiport with single point sampling systems

The above study has shown that the galleys can have considerable influence on longitudinal transport of contaminant in a particular section and thus more sensors would be needed. One way to reduce the number of the sensors is to use a multiple-point sampling sensor system. The multiple point sampling would simultaneously collect air from a number of locations and the averaged contaminant concentration at those locations can be detected by a sensor. Figure 7 compares the responses of single point and multipoint sampling systems for the contaminants released from B2 and B3. In this scenario, a single-point sampling system used a

single sensor at ceiling center of the middle business-class section. A multipoint sampling system extracted air from a total of seven locations along the ceiling center (one location for each row). Then a sensor was used to measure the contaminant concentration in the extracted air that is the mixture of the air from the seven locations. Figure 7 shows that a single-point sampling system works very effectively for contaminant released close to the location of the sensor (B2 release) while its performance deteriorated considerably if the release was far away from the sensor location, such as the B3 release. The responses from multipoint sampling system for the two releases were similar. Hence the effect of galleys etc. would be less felt if the multipoint sampling system was used.

Figure 8 shows a comparative evaluation of sensor requirements for a multipoint sampling system with a single-point sampling system. The comparison used the contaminant distribution obtained at 120 s from the start of release. The contaminant released from F1, B2 and E2 passengers were investigated. Releases from different sections are considered separately to avoid complexities. The results show that, if the sensor with a detection capability of 0.1 ppm, the economy-class section would require 11 sensors for the E2 release by using the single-point sampling system. The number is reduced to three by using the multiport sensing system. If the detection capability of sensors is 0.001 ppm, then only one sensor is sufficient for the whole cabin if multipoint sampling system is used. Hence the multipoint sampling system can significantly reduce the number of sensors.

CONCLUSIONS

This investigation studied sensor response for contaminant releases in a fully occupied, whole length, twin-aisle airliner cabin. The study led to the following conclusions:

1. CFD is an effective tool to predict airflows and contaminant transport in the cabin with reasonable accuracy.
2. Seating arrangements can make cross sectional flow patterns asymmetric.
3. Longitudinal contaminant transport is similar in the business-class and economy-class sections.
4. The galleys can significantly affect longitudinal transport of the contaminants in a particular cabin section.
5. A multiport sampling system can reduce substantially the number of sensors required and is less sensitive to the effects caused by the galleys.

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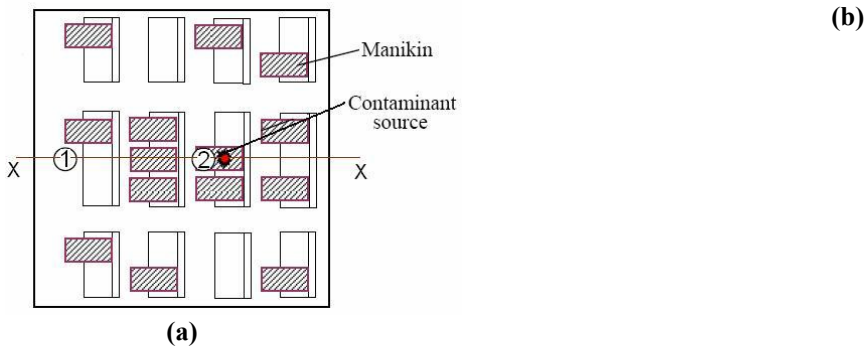
(b)

(a)
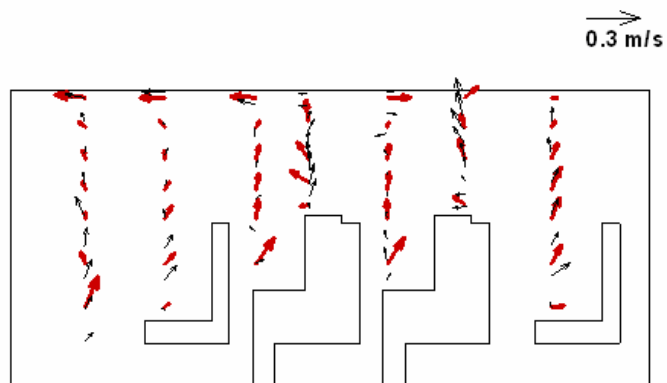
Fig. 1(a) Top view of the twin aisle cabin section used for the validation; (b) a comparison between the CFD (black arrows) and measured (red arrows) velocity profiles at section X-X
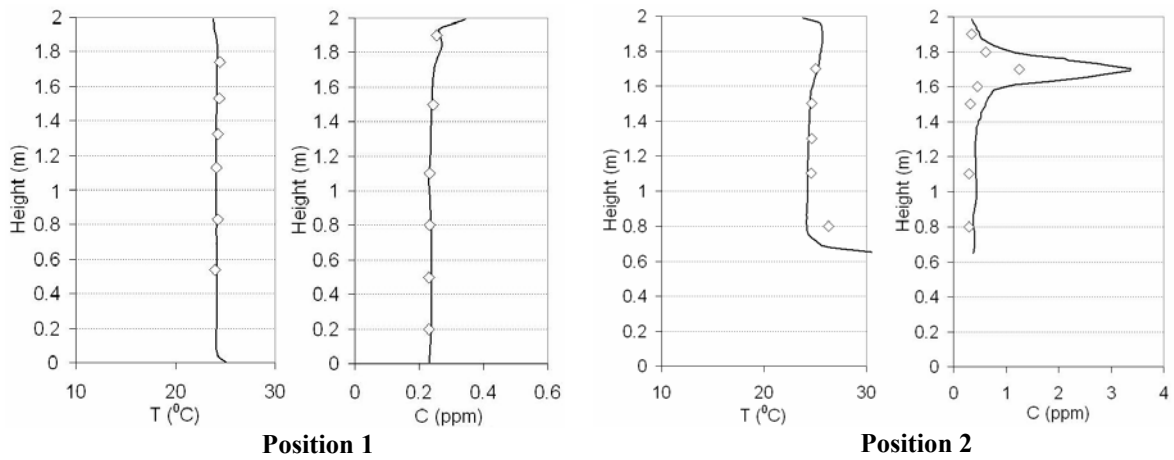
Position 1

Position 2

Fig. 2. A comparison between the CFD results (lines) and experimental data ($\Diamond$) for air temperature (T) and SF_6 concentration (C) at positions 1 and 2
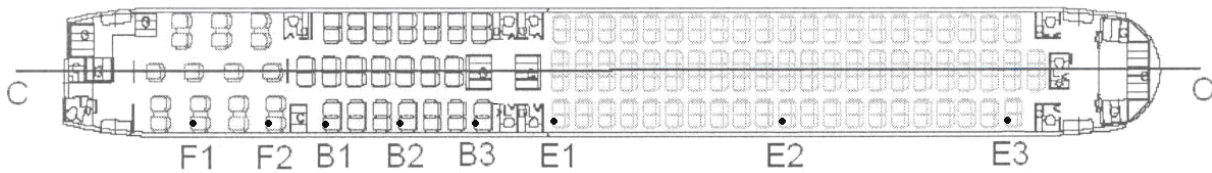
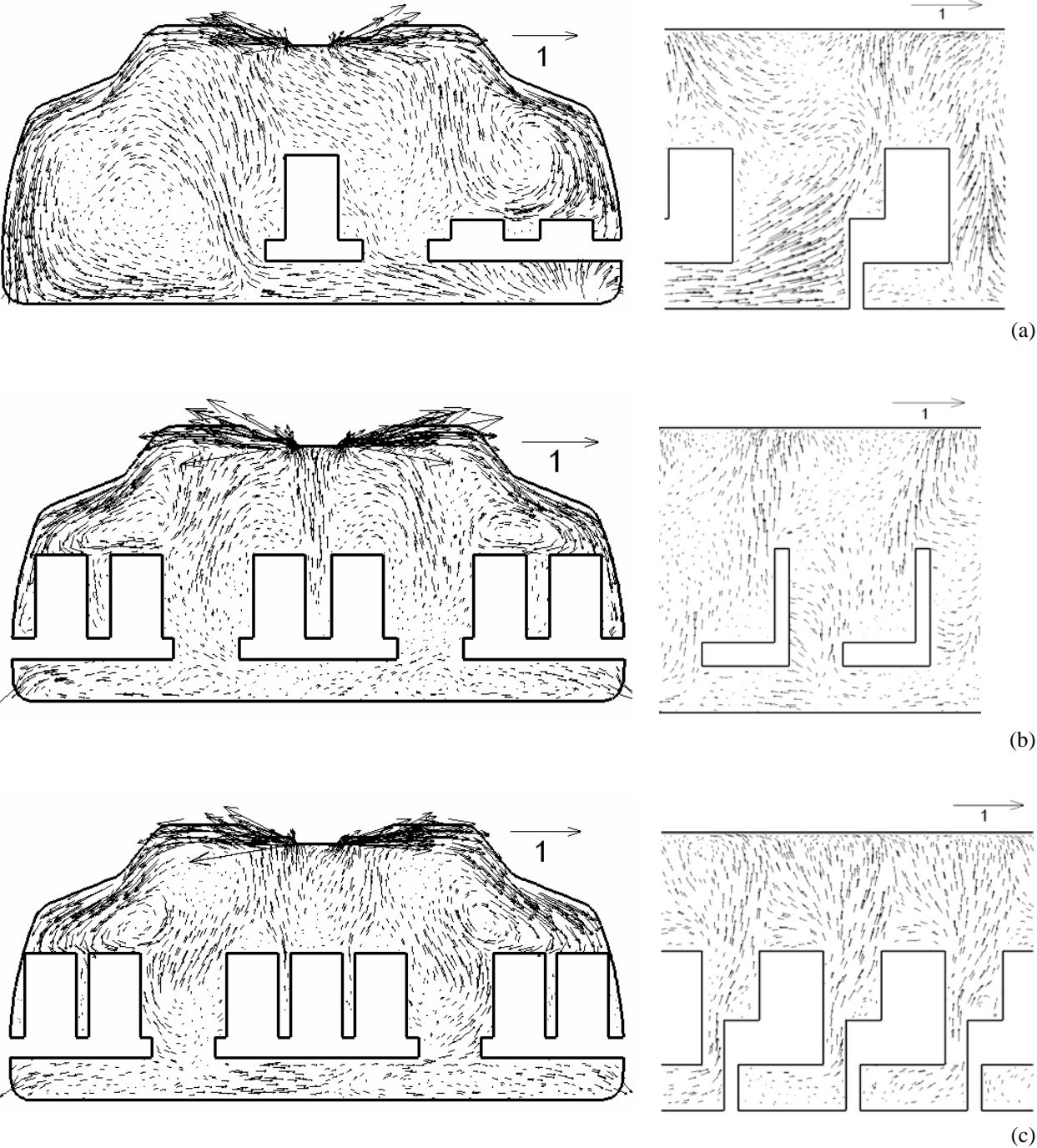**Fig. 3. Layout of a whole twin-aisle cabin used and the contaminant source locations**

Fig. 4. Representative airflow patterns along the cross sectional and longitudinal directions in the (a) first; (b) business and (c) economy classes
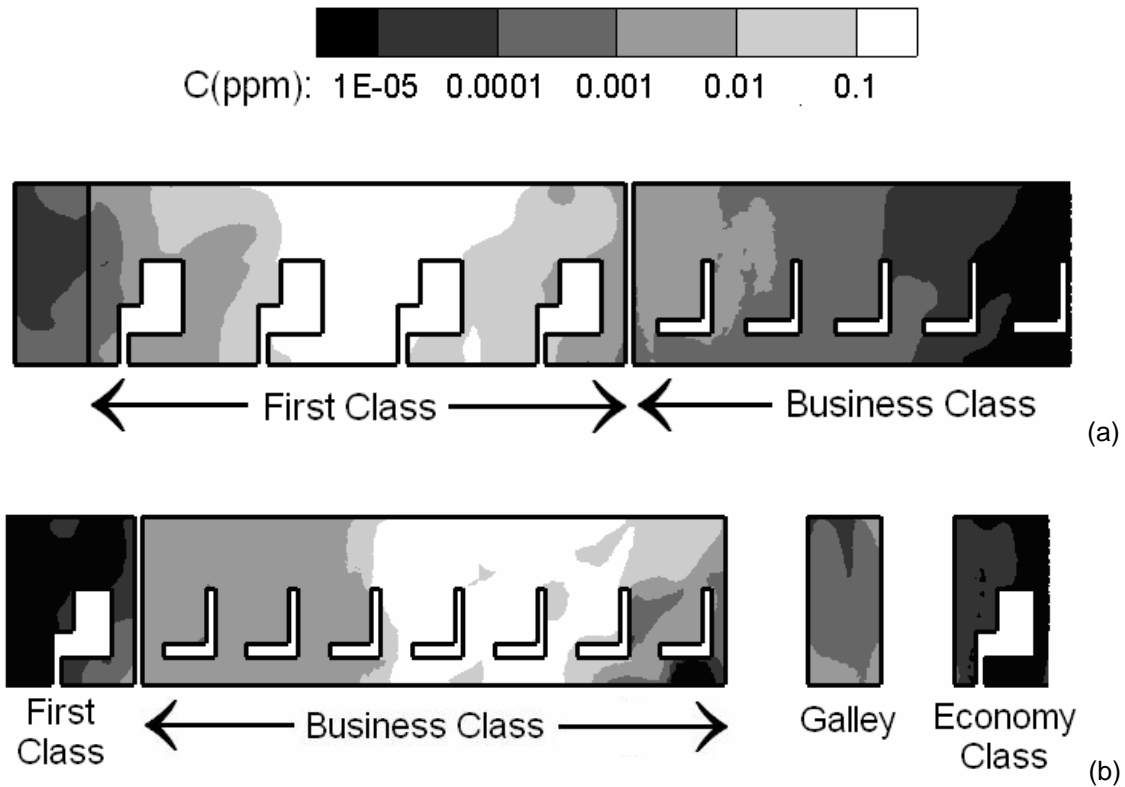
Fig. 5. Contaminant concentration distributions along the longitudinal direction (a) for the first class due to a source released from F1 for 120 s and (b) for the business class due to a source released from B2 for 120 s.
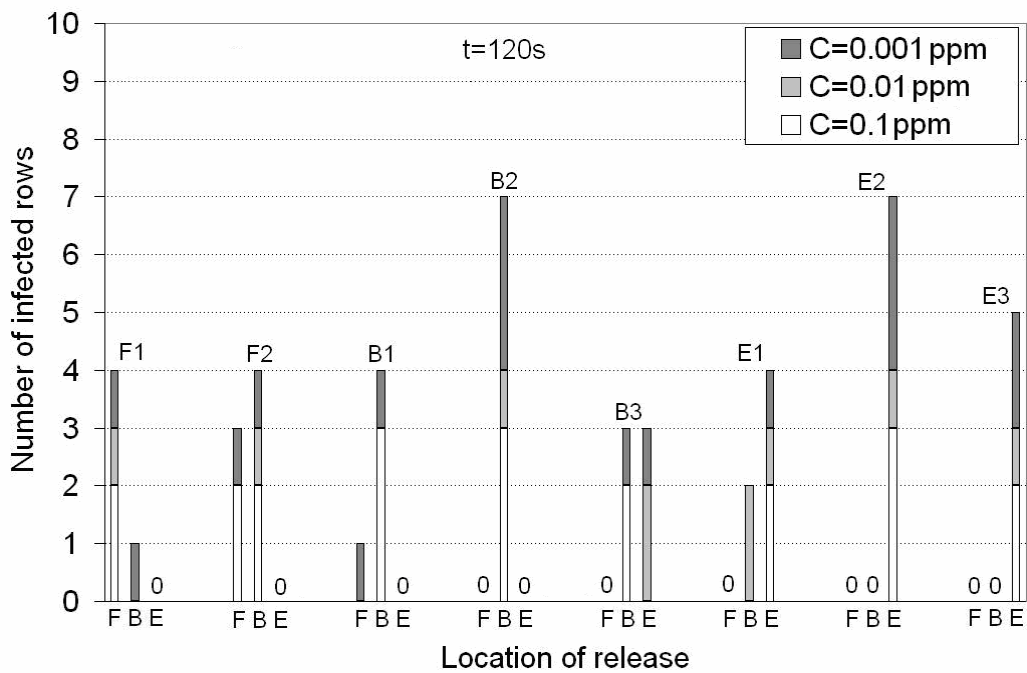

Fig. 6. Number of rows infected in 120s for a continuous release (F: First Class, B: Business Class, E: Economy Class)
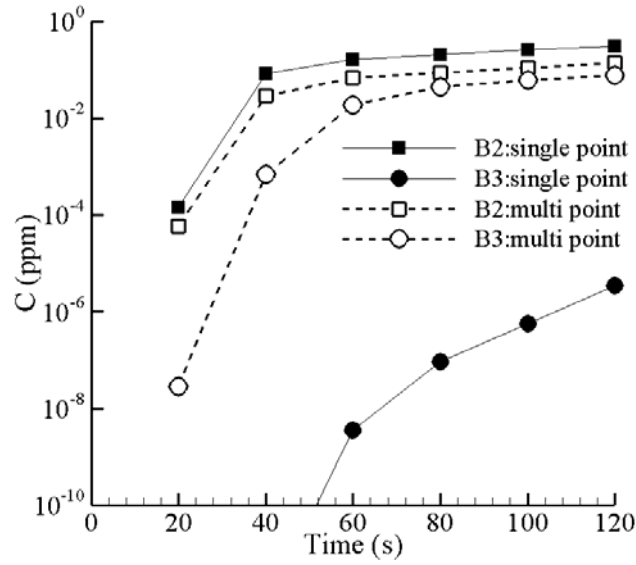
Fig. 7. Responses of the single and multipoint sampling systems in the business class for B2 and B3 releases
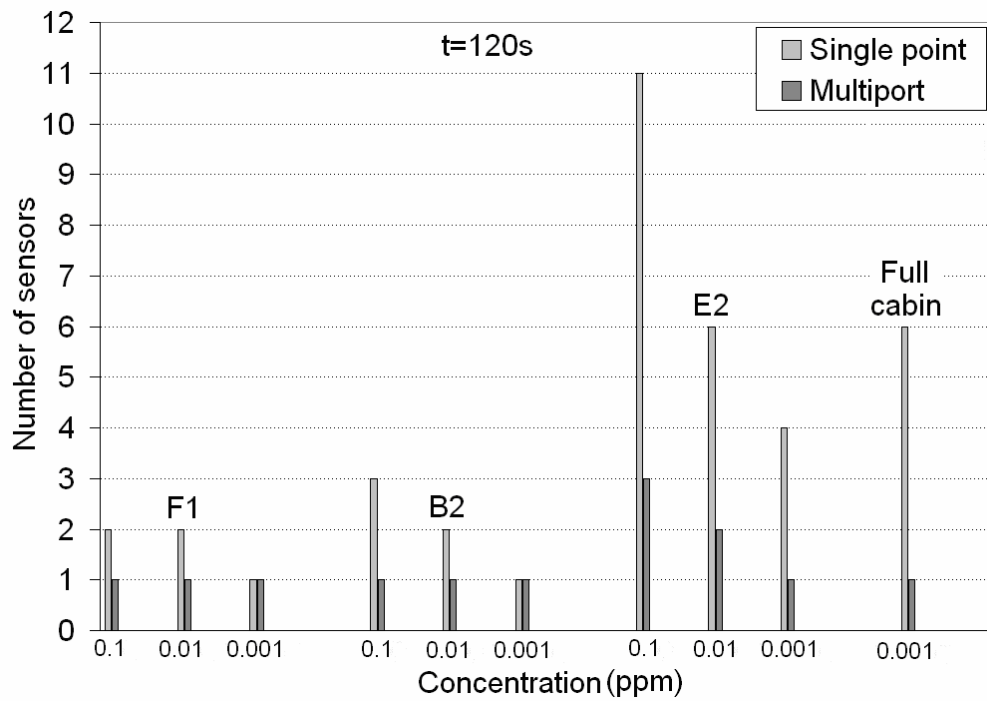

Fig. 8. Comparison of sensor requirements for the multi-port and single-port sampling systems based on the contaminant concentration profiles at 120s