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Impact of Moving Objects on Contaminant Concentration Distributions in an Inpatient Ward with Displacement Ventilation

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ABSTRACT
Moving objects can disturb stratified flow and contaminant concentration gradient in an inpatient ward with displacement ventilation. This investigation used Computational Fluid Dynamics (CFD) to study the effect of moving objects, such as a walking visitor, a walking caretaker, the changing of the sheet on a patient's bed, and the swinging of the entrance door for up to four seconds, on the contaminant concentration distributions in a single inpatient ward. The CFD was validated by using the measured distributions of air velocity, air temperature, and contaminant concentration from the mockup of an inpatient ward. The contaminant was assumed to be breathed out by the patient lying on the bed. The results show that moving objects can cause a 10 to 90 second swing in the contaminant concentration distribution. The averaged concentration change in the breathing levels in the ward was generally less than 25%, so the risk level should remain the same. The closer the location of the moving object to the contaminant source, the larger was the change in the contaminant concentration. The displacement ventilation with 4 ach in an inpatient ward with a moving object can still produce the same air quality level as overhead mixing ventilation with 6 ach.

KEYWORDS: contaminant transport, displacement ventilation, overhead ventilation, inpatient ward, moving body, CFD

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INTRODUCTION

Air movement in indoor environments is strongly linked to the transmission and spread of airborne infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox, and SARS (Li et al., 2007). The lack of knowledge and insufficient data on ventilation requirements in hospitals, schools, and offices make it difficult to understand the spread of airborne infectious diseases (Li et al., 2007; Beggs et al. 2008). A study by Yin et al. (2009) showed that ventilation systems played a very important role in the transmission of exhaled particles from a patient to a caretaker in the same ward. They showed that displacement ventilation can provide a much better indoor air quality than overhead mixing ventilation. The ventilation effectiveness of a displacement ventilation system with a reduced ventilation rate of 4 ach can be the same as that of an overhead mixing ventilation system with a ventilation rate of 6 ach. However, there were concerns about whether a moving object such as a walking visitor, a walking caretaker, changing a sheet on the patient's bed, or swinging the entrance door in such an inpatient ward could destroy the stratified flow created by the displacement ventilation, thus decreasing the ventilation effectiveness (Brohus et al., 2006; Bjørn and Nielsen, 2002; Bjørn et al., 1997). Mazumdar (2009) found that a moving passenger in an aircraft cabin could carry a contaminant in the wake to positions far from the contaminant source. Thus, it is essential to assess the impact of moving objects on contaminant transmission in inpatient wards with displacement ventilation.

RESEARCH METHODS

An investigation of the impact of moving objects on airborne contaminant transmission inside an inpatient ward can be done experimentally or through computer simulations. Acquiring experimental data with meaningful temporal and spatial resolution is difficult and time consuming (Poussou, 2008; Thatcher et al., 2004). Computer simulations using Computational Fluid Dynamics (CFD) are an efficient alternative and can provide high resolution data. This is because CFD simulations can handle directly or indirectly the movement of an object in an inpatient ward. The indirect methods model the movement approximately, such as using a distributed momentum source (Zhai et al., 2002) or a turbulent kinetic energy source (Brohus et al., 2006). These indirect methods need little computing time, but they generate some uncertainties and the results may not be accurate due to the bold assumptions used. In contrast, the direct methods use moving and dynamic grids to simulate the movement. The accuracy is greatly improved, but unfortunately, the methods are computationally demanding.

To reduce the computing demand, a CFD model with combined dynamic and static mesh scheme can be used (Mazumdar and Chen; 2007). The CFD model uses dynamic meshes for regions where the movement takes place and static meshes for the rest of the computational geometry. This CFD model was validated with experimental data for airflow in an airliner cabin to be reliable. Hence, the method was selected for the present study.

The CFD model used a second-order upwind scheme and the SIMPLE algorithm. The Re-Normalization Group (RNG) k-ε model was used to model the turbulent flow inside an inpatient ward. Compared to other turbulence models, the RNG k-ε model was one of the best in terms of accuracy, computing efficiency, and robustness for modeling indoor environments (Zhang et al., 2007). This study used a commercial CFD program, FLUENT (Fluent, 2003). The CFD model was used to calculate the distributions of air velocity, air temperature, gaseous contaminant concentration, air pressure, and turbulence parameters. The contaminant concentration was normalized using:

$$\text{Normalized C} = \frac{C_p - C_s}{C_e - C_s} \tag{1}$$

where C_p is the contaminant concentration at the point of interest. C_s and C_e are the steady state contaminant concentrations at the supply inlet and at the exhaust outlet, respectively.

VALIDATION OF THE CFD METHOD

In order to verify that the CFD model can also be used in an inpatient ward with displacement ventilation, this investigation first used the measured data of air velocity, air temperature, and contaminant concentration as simulated by a tracer gas (Yin et al., 2009) from a mockup of an inpatient ward as shown in Figure 1 for the validation. Figure 1 shows that the ward was furnished with one bed, a TV set, and a piece of medical equipment. This ward had one patient lying on the bed and one caretaker standing on the right side of the patient. The air was supplied at 4 ach from the diffuser located near the floor on the opposite wall from the patient. The exhausts were located at the ceiling level on the wall near the patient's head and on the wall adjacent to the bathroom. The corresponding ventilation rate was 78 CFM (37 l/s). The thermo-fluid boundary conditions used for the CFD mockup are shown in Table 1, which were close to the measured data. The heat released from patient, caretaker, equipment and TV was 106 W, 110 W, 36 W and 24 W respectively. The air velocity and air temperature were measured using omni-directional anemometers at 56 locations along different heights in Poles 1-8, as shown in Fig. 1 (b). The accuracy of the measurements was 4 fpm (0.02 m/s) for velocity and 0.45^{o}F (0.25^{o}C) for air temperature. Yin et al. (2009) used continuous sources of an SF_6 tracer gas and particles (1 μm and 3 μm in size) to investigate the airborne contaminant dispersion inside the inpatient ward. The corresponding contaminant concentration profiles in the ward looked the same for the tracer gas and particles. Hence, the contaminant was simulated for simplicity by using the tracer gas in this investigation. The SF_6 concentrations were measured at 30 locations along different heights in Poles TG 1-5 (refer to Fig. 1(b)). The measurement accuracy of SF_6 concentration was 0.001 ppm. Experiments were conducted at three different times, and the repeatability was good.

Figures 2 and 3 compare the profiles of air velocity and air temperature at Poles 1-8 (refer to Fig. 1(b)), respectively. The height, velocity, and temperature were non-dimensionalized with respect to the height of the inpatient ward (H), diffuser face velocity (u_s), inlet (T_s) and main exhaust (T_e) temperatures. The repeatability of the experimental data is evident from the plots. The computed air velocity and temperature profiles were in good agreement with the measured data. The temperature stratification is clear in the results.

Figure 4 further compares the measured and computed profiles of the normalized SF_6 concentrations at Poles TG 1-5 (refer to Fig. 1(b)). The computed concentration at Poles 4 and 5 was higher than at the other poles. Our past experience found that it is very difficult to obtain a good agreement on contaminant concentrations calculated and measured, but discrepancies are acceptable for such a study. Again, the displacement ventilation shows very clear contaminant stratification.

Though the CFD validation for the inpatient ward was performed for a steady-state case, it could be used for cases with moving objects. For example, our group previously validated the CFD model in an airliner cabin under steady-state conditions (Zhang et al. 2009). The model performed similarly for water flow in a small-scale experimental model airliner cabin with transient conditions (Mazumdar, 2009). Thus, the CFD program FLUENT with the RNG k-ε model was used to further study the effect of moving objects on transient contaminant distributions in the inpatient ward.

CASE SETUP

To study the impact of moving objects on contaminant transmission and ventilation system performance in an inpatient ward, four different scenarios of moving objects were used, as shown in Fig. 5:

Case 1: A visitor moving along the foot of the patient bed from left to right. The visitor moved at a speed of 200 fpm (1 m/s) for 3 s and then stopped. The thermal boundary conditions used for the moving visitor were the same as those for the caretaker (refer to Table 1).

Case 2: A caretaker moving backwards and forwards along the bedside. The caretaker started his/her movement near the center of the bed at a speed of 200 fpm (1 m/s) towards the head of the patient for one second, then moved in the opposite direction for two seconds, finally coming to his/her initial position by moving for another second.

Case 3: Changing a sheet by moving it up at 200 fpm (1 m/s) for 0.75 seconds and then back down to the original position at the same speed over the patient.

Case 4: Swinging the entrance door by opening it inwards and then immediately closing it. The duration of the opening and closing processes was two seconds each at constant speed.

As the CFD simulations used a combination of dynamic and static meshes, only 2.1 %, 1.5%, 1.1%, and 1.0% of the meshes inside the inpatient ward were dynamic for Cases 1, 2, 3, and 4, respectively. The maximum mesh size in the ward was 2 in (0.05 m). The total number of meshes used for the ward was approximately 1.2 million. User defined functions were implemented in FLUENT to describe and track the object's movements. Each case was computed using eight processors (1.8 GHz AMD 64) and 4GB of memory. The smallest time step used during the computations was 0.01 s. The residual for mass (sum of the absolute residuals in each cell/the total mass inflow) and the residual for energy (sum of the absolute residuals in each cell/the total heat gains) was less than 0.1% and 1%, respectively, for the computations. The normalized residual for the contaminant transport equation was below 1.0×10^{-5}. The initial conditions inside the ward were steady state with a continuous passive release of the tracer gas from the mouth of the patient. This implies that the tracer-gas was with zero velocity. Gupta et al. (2009, 2010) found that the momentum of exhalation was important for coughing but not significant for breathing and talking. Thus, the passive release could be acceptable. Each case was computed for two minutes of real time in order to obtain the transient contaminant distributions due to the body movement. The actual computing time took about two weeks for each case.

RESULTS

Contaminant Distributions in the Inpatient Ward with a Moving Object

Figure 6 shows the normalized distributions of the contaminant concentration across the plane of a visitor moving track in Case 1 at t = 0, 1, 2, 3, 60, and 120 s, respectively. The contaminant distribution at t=0 s was this for the steady state with a continuous contaminant release from the mouth of the patient. The contaminant concentration was low in the lower part of the ward, which is typical for displacement ventilation. The moving visitor could bring the contaminant in the wake. The contaminant concentration distribution at t=120 s was not the same as at t=0 s since the initial and final conditions were different due to the visitor relocating. For this cross-section, the contaminant concentration did not change much between t=60 s and t=120 s.

Figure 7 shows the normalized distributions of the contaminant concentration in the ward with the forward and backward motion of the caretaker. Very similar to in Case 1, the wake of the caretaker induced the contaminant generated from the patient bed during his/her movement. Once the caretaker stopped, the contaminant concentration returned to steady state level in approximately 90 s.

Figure 8 depicts the contaminant concentration distributions through a plane of the sheet movement above the patient in Case 3. When the sheet was moved up, it also induced the contaminant in the wake. Once the sheet was moved down over the patient, the contaminant induced was pushed out through both sides. The contaminant concentration returned to the initial level of the steady state in approximately 50 s.

Figure 9 illustrates the contaminant concentration distributions in the inpatient ward with the swinging movement of the entrance door in Case 4. The concentration distributions were at the height of breathing level of a standing person. The concentration distributions changed with the processes of the door opening and closing. But as soon as the door was closed, the concentration quickly returned to that of the steady state within 10 to 15 s. Compared to in the other cases, the movement of the swinging door made the least impact on the contaminant distributions in the ward as the door was far away from the contaminant source.

Table 2 summarizes the time needed to eliminate the effect of various object movements in the ward with displacement ventilation on the contaminant concentration distributions. Due to the relocation of the visitor, the thermo-fluid boundary conditions were different between the initial state and the final state. For the rest of the cases, the time needed to return to the original state was between 10 to 90 s. Such a short change was unlikely to cause a major change in the exposure risk of the visitor or caretaker to the contaminant concentration.

Contaminant Concentration at Breathing Levels in the Inpatient Ward

A quantitative comparison of the effect of various movement cases on contaminant transmission is presented in Figs. 10 to 13. Case 1 was also computed with an overhead air supply diffuser that supplied air at 6 ach. This is a conventional mixing ventilation system currently used in many wards. To compare the ventilation performance of the displacement ventilation cases with 4 ach, this paper shows the averaged contaminant concentrations at the breathing level of sitting and standing positions, i.e. at the breathing levels of a sitting person (3.7 ft or 1.1 m above the floor) and a standing person (5.3 ft or 1.6 m above the floor)

Figure 10 shows the variation of averaged concentration at the breathing level for all the cases. A normalized concentration was used for comparison. When the normalized concentration is 1.0, it is perfect mixing for an overhead ventilation system at 6 ach. If the normalized concentration for the displacement ventilation cases at 4 ach is the same as that for the overhead ventilation case at 6 ach, the air quality becomes the same with the same strength of the contaminant source. With the overhead ventilation, the movement of the visitor did not cause a notable swing on the averaged contaminant concentration at the two breathing levels. This is because the air velocity was generally high and the contaminant concentration was uniform. Thus, the wake of the moving visitor did not make an impact on the contaminant concentration distribution in the ward. However, the displacement ventilation system was more sensitive to the moving objects. The variation of the averaged contaminant concentration was within 25% for all the cases studied. At the breathing level in a sitting position, the averaged contaminant concentration with displacement ventilation was very low. However, at the breathing level in a standing position, the displacement ventilation system with the moving objects could lead to a higher or a lower contaminant concentration in the ward. Since the changes only lasted for less than 90 s, a slight increase or decrease in the contaminant concentration level would not be likely to have a notable impact on the risk level of the visitor or caretaker. This conclusion can be further confirmed by using the accumulated contaminant inhaled by the visitor or caretaker during this transitional period for the four cases.

In order to further evaluate the risk level, Fig. 11 depicts the breathed contaminant concentration at the sitting and standing levels of the caretaker and the visitor for the movement cases. The study was mainly for standing visitors and the caretaker, but the results for the sitting level were also provided for reference. Again, the variation of the contaminant concentration breathed by the visitor and caretaker due to their body movements was the least for the overhead ventilation case with 6 ach. The concentration near the breathing level of the visitor and the caretaker was generally lower with the displacement ventilation system. In Case 2 with displacement ventilation, the caretaker moved and his/her wake carried the contaminant, which caused a very significant change in the concentration. A similar phenomenon happened near the moving visitor in Case 1 but was not as significant as in Case 1, due to the visitor not being as close to the contaminant source as the caretaker. At most times, the displacement ventilation system provided a better air quality than the mixing ventilation system. The very large swing in the concentration level was generally short (about 30 s) and the averaged value did not change much, so it was less likely to cause a higher risk for the visitor or caretaker in the displacement system compared to in the mixing system.

Further quantitative analysis was performed at the pole positions TG 1-5 (refer to Fig. 1(b)). Except for TG4, all the other positions were around the contaminant source. Figure 12 illustrates the normalized contaminant concentration at the breathing levels at those positions. The contaminant concentration at the breathing level of a sitting position in the ward with the displacement ventilation at 4 ach was much lower than that with the perfect mixing ventilation system at 6 ach (normalized C = 1). However, at the breathing level of a standing person, the displacement ventilation system led to a poorer air quality than that of the perfect mixing ventilation. The main reason was that the locations were closed to the contaminant source. This was also confirmed by the experimental data for steady state cases (Yin et al. 2009). For TG4, it was located in a dead zone so the concentration was especially high. If the exhaust location were moved to a wall next to TG4 location, the concentration could become lower. Moreover, the contaminant concentration was unstable, especially at pole TG-5 in Case 1 where visitor movement was simulated. A spike in contaminant concentration was observed for Case 3 with the changing of the patient's sheet. This happened as the entrapped contaminant below the sheet in Case 3 was pushed out through the sides as the sheet came down. The contaminant pushed out was convected upwards due to the effect of the ventilation system, which caused an abrupt increase in the contaminant concentration. As observed before, the movement of the door did not make much impact on the contaminant concentration at those pole locations.

It might be subjective to emphasize the concentration levels at Poles TG1-5 since they were mainly around the contaminant source. Figure 13 shows the fraction of the space where the normalized contaminant concentrations at the breathing levels in the ward with displacement ventilation at 4 ach were less than 1 or those with perfect mixing ventilation at 6 ach. The figure shows that in most areas of the ward, the air quality was better than in the perfect mixing condition, although the perfect mixing condition had a much higher ventilation rate.

DISCUSSION

It should be noted that the study presented in this paper was conducted with limited conditions. For example, this investigation did not study different postures of the patient and caretaker; did not vary the speed of walking speed or the speed of changing sheet; did not simulate the actual exhalation with a variable momentum; did not simulate other exhaling activities, such as talking, sneezing, and coughing. Thus, the subject deserves further studies.

One should not extend the conclusions obtained from this study for other conditions that were not studied. For example, Qian et al. (2006) studied a two-patient award with different postures and found that the contaminant could be locked in the breathing zone of a lying person. Since this study was only with one lying person, the phenomenon was not found in this investigation.

CONCLUSIONS

This study investigated the effects of moving objects on contaminant concentration levels in a single inpatient ward with displacement ventilation. The investigation was conducted by assuming a constant contaminant generated from the mouth of a patient lying on the bed and by using a validated CFD program. The study assumed a 4-ach ventilation rate for the displacement ventilation. To compare with a conventional design, this investigation also used a case of overhead mixing ventilation with 6-ach ventilation rate.

This study considered four different moving objects in the ward for up to four seconds of movements: (1) a visitor walking near the foot of the bed, a caretaker walking alongside the bed, changing of the sheet on the patient's bed, and swinging of the door. This study found that

1. Moving objects can carry a contaminant in their wake. The movement can cause a swing in the contaminant concentration at the breathing level of sitting and standing positions for 10 to 90 seconds.

2. The variation of the averaged contaminant concentration due to the moving objects was within 25% for all the cases studied. The closer the location of the moving object to the contaminant source, the larger was the change in the contaminant concentration. The variation at the breathing level was lower in the sitting position than in the standing position. Since the variation only lasted for less than 90 s and the averaged contaminant concentration did not change much, the variation would not likely change the risk level in the ward.

3. At most times, the displacement ventilation system with 4 ach ventilation rate provided a better air quality than the mixing ventilation system with 6 ach. The walking visitor and caretaker could experience a large swing in the concentration level due to the body movement in the ward. However, the swing was generally short (about 30 s) and the averaged contaminant concentration did not change much so it was not likely to change the risk level for the visitor or the caretaker.

4. The contaminant concentration in the ward with displacement ventilation was not uniform. The closer to the contaminant source, the higher the contaminant concentration. Hence at locations close to the contaminant source, the risk of transmission is higher with the displacement ventilation system compared to the mixing ventilation system.

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Table 1. Boundary conditions for the inpatient ward

Supply airflow rate	4 ACH	Floor temperature	22°C
Supply air temperature	19.5°C	Surface temperature of the caretaker	29.1°C
Ceiling surface temperature	22.5°C	Surface temperature of the patient	31.3°C
Surface temperature of the sidewalls	22.5°C	Surface temperature of the equipment	25°C
Surface temperature of the TV	24.8°C	Surface temperature of the visitor (Case 1)	29.1°C

Table 2. Time taken to eliminate the impact of various object movements in the inpatient ward in contaminant concentration

Case	Time (s)
1	Not applicable
2	90-100
3	50-60
4	10-15

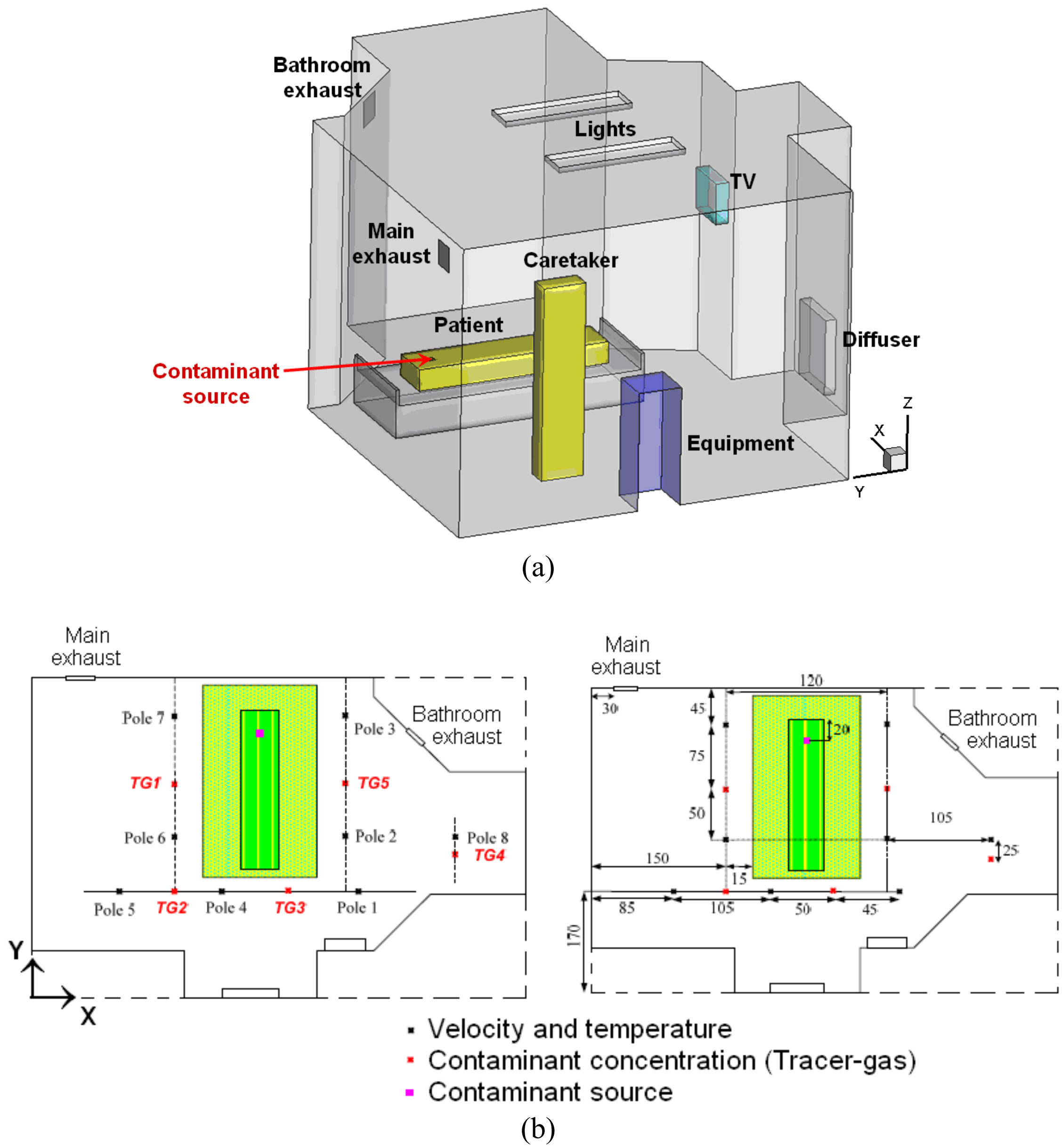


Fig. 1. (a) Schematic of the inpatient ward used for CFD validation; and (b) measurement locations (unit: cm) for the air velocity and temperature (Poles 1–8) and the contaminant concentration (TGs 1–5)

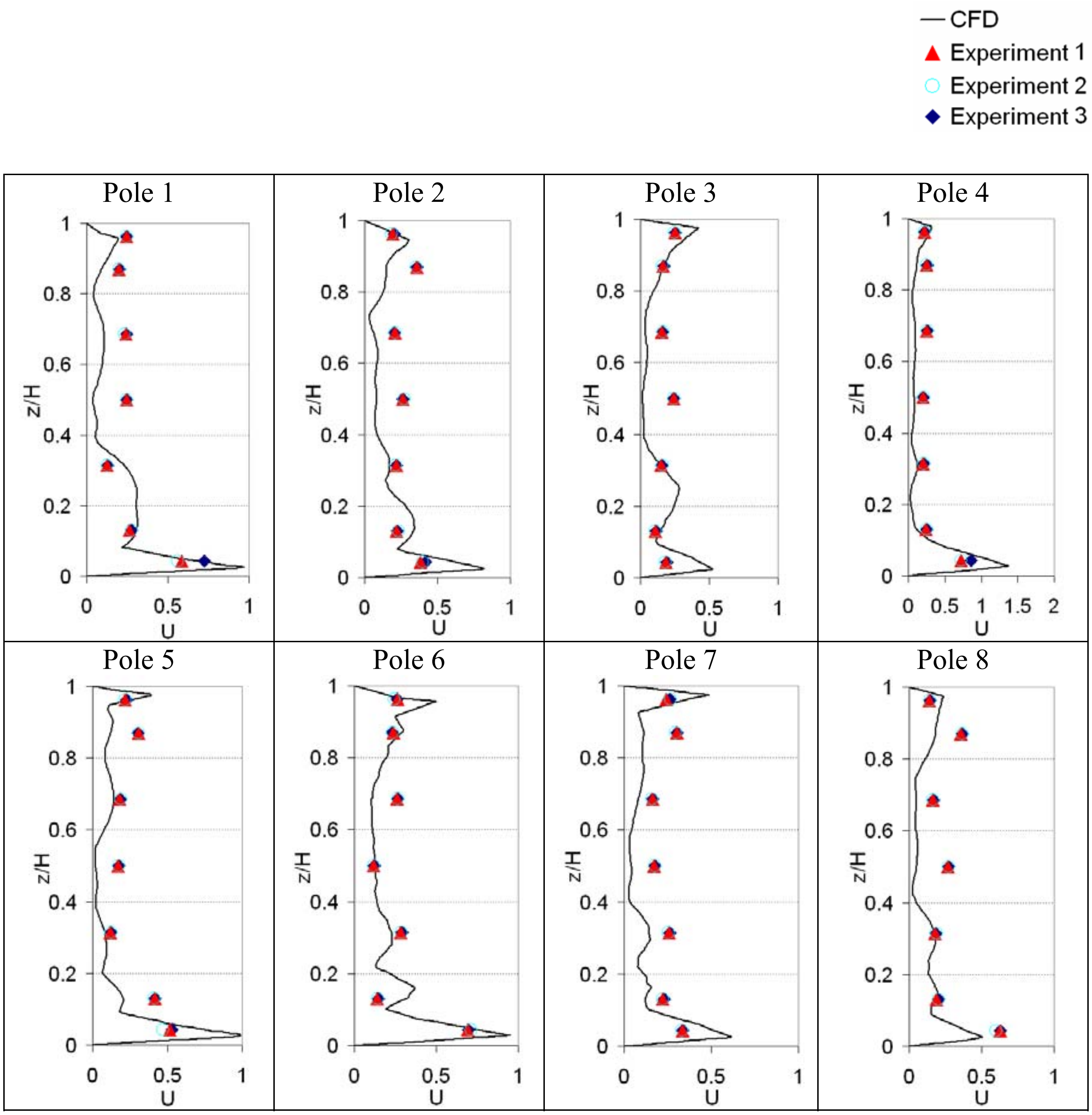


Fig. 2. The measured and computed air velocity profiles at Poles 1–8 in the ward, $U=u/u_s$, supply air velocity u_s=28 fpm (0.14 m/s), z = height above the floor, ward height H= 9 ft (2.7 m).

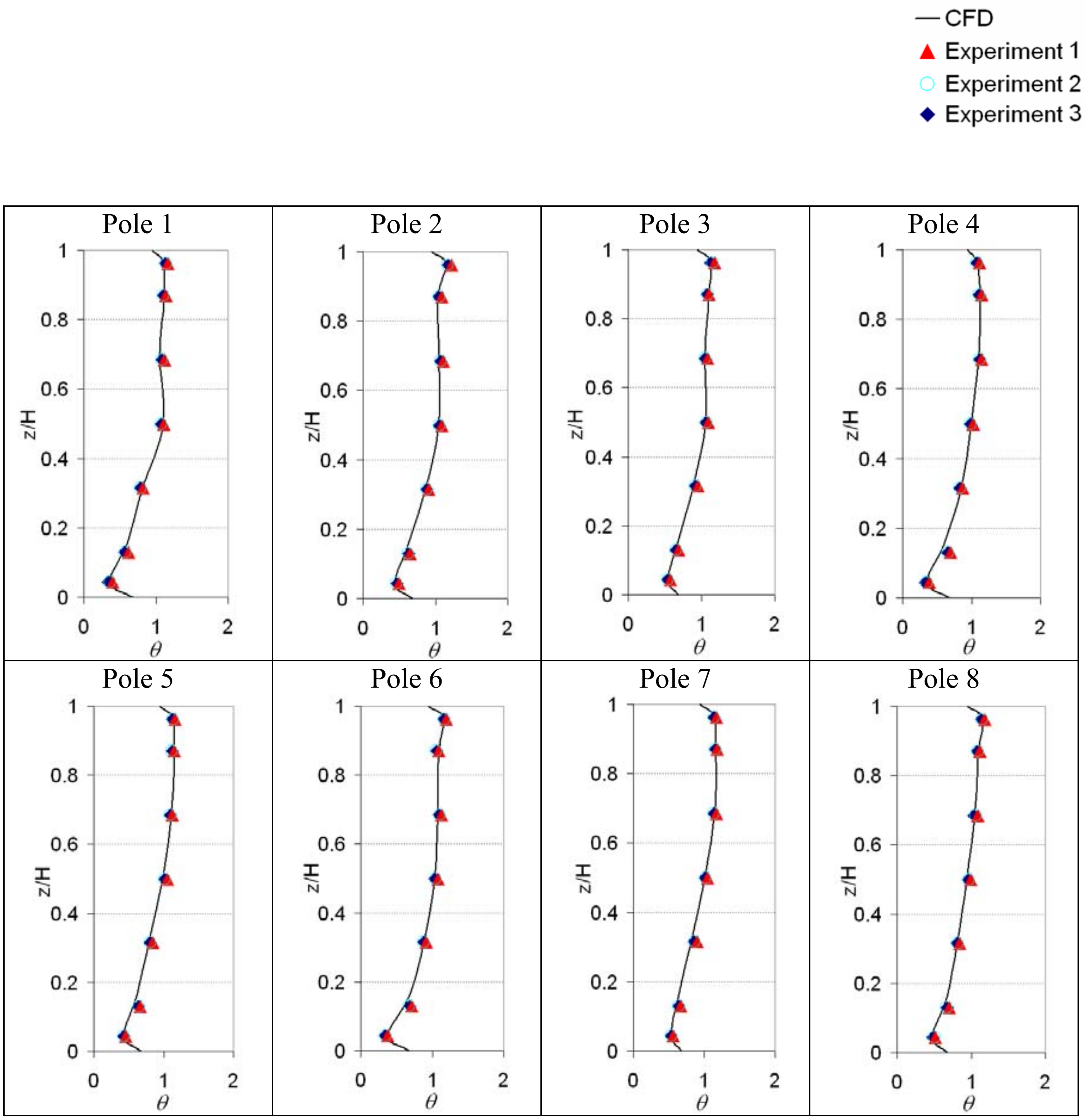


Fig. 3. The measured and computed air temperature profiles at Poles 1–8 in the ward, θ =(T-T_s)/(T_e-T_s), supply air temperature T_s=67.1^{o}F (19.5^{o}C), exhaust air temperature T_e=73.8^{o}F (23.2^{o}C), z = height above the floor, ward height H= 9 ft (2.7 m).

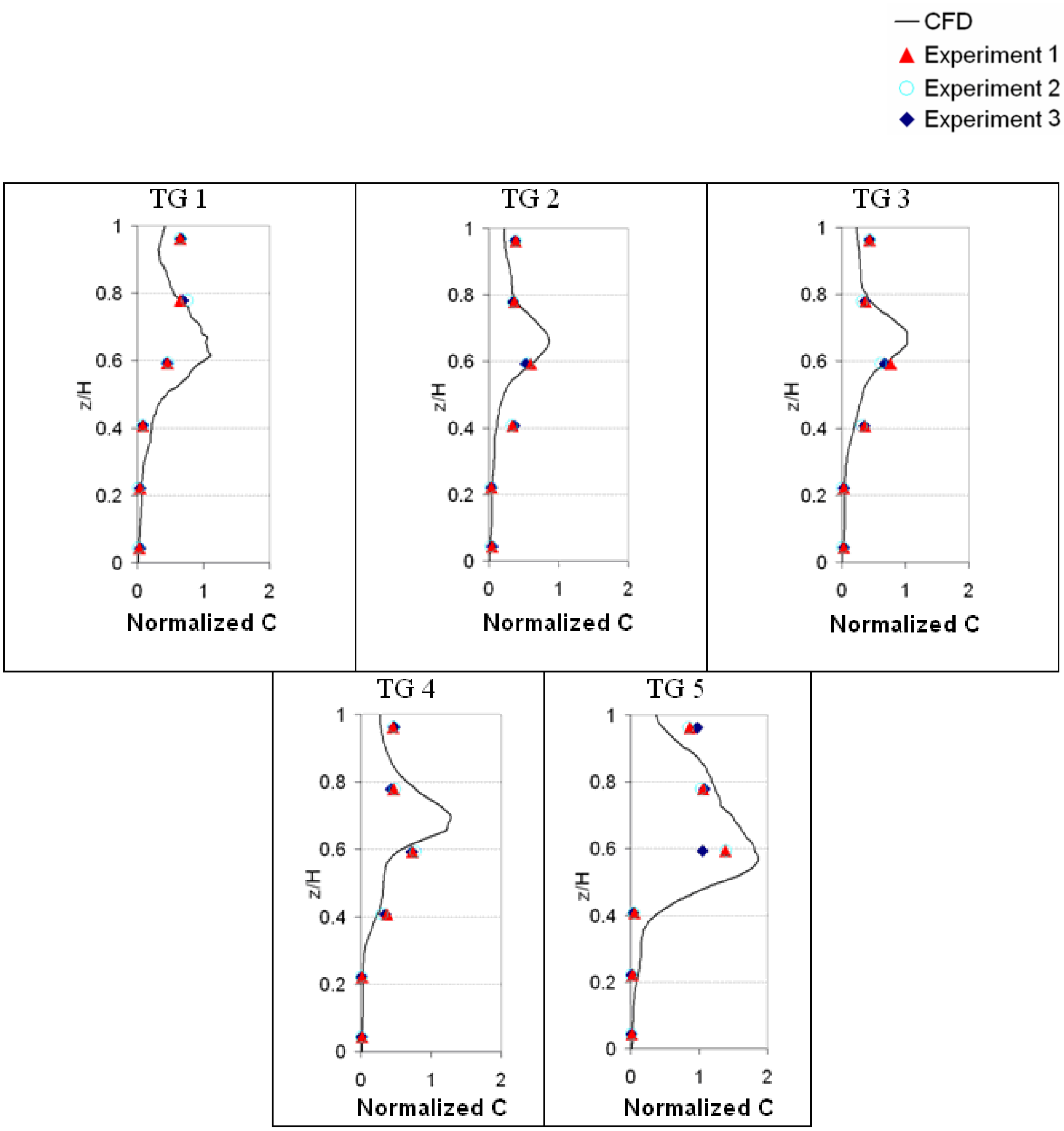


Fig. 4. The measured and computed contaminant concentration profiles at poles TG 1-5 in the ward, normalized $C=(C-C_s)/(C_e-C_s)$, C_s = supply concentration, C_e = exhaust concentration, z = height above the floor, H= 9 ft (2.7 m).

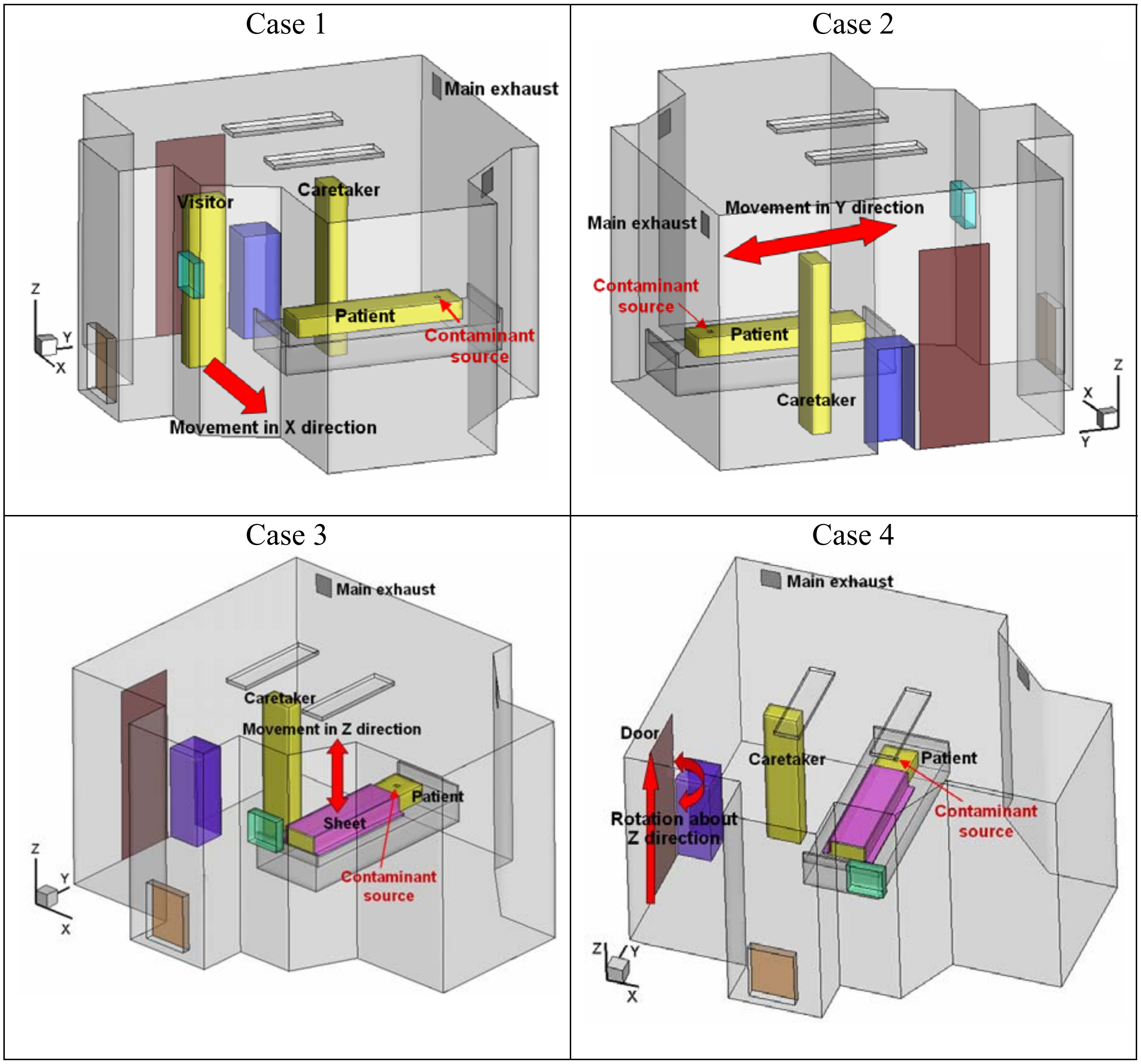


Fig. 5. Schematic representation of the four cases with moving objects inside the inpatient ward

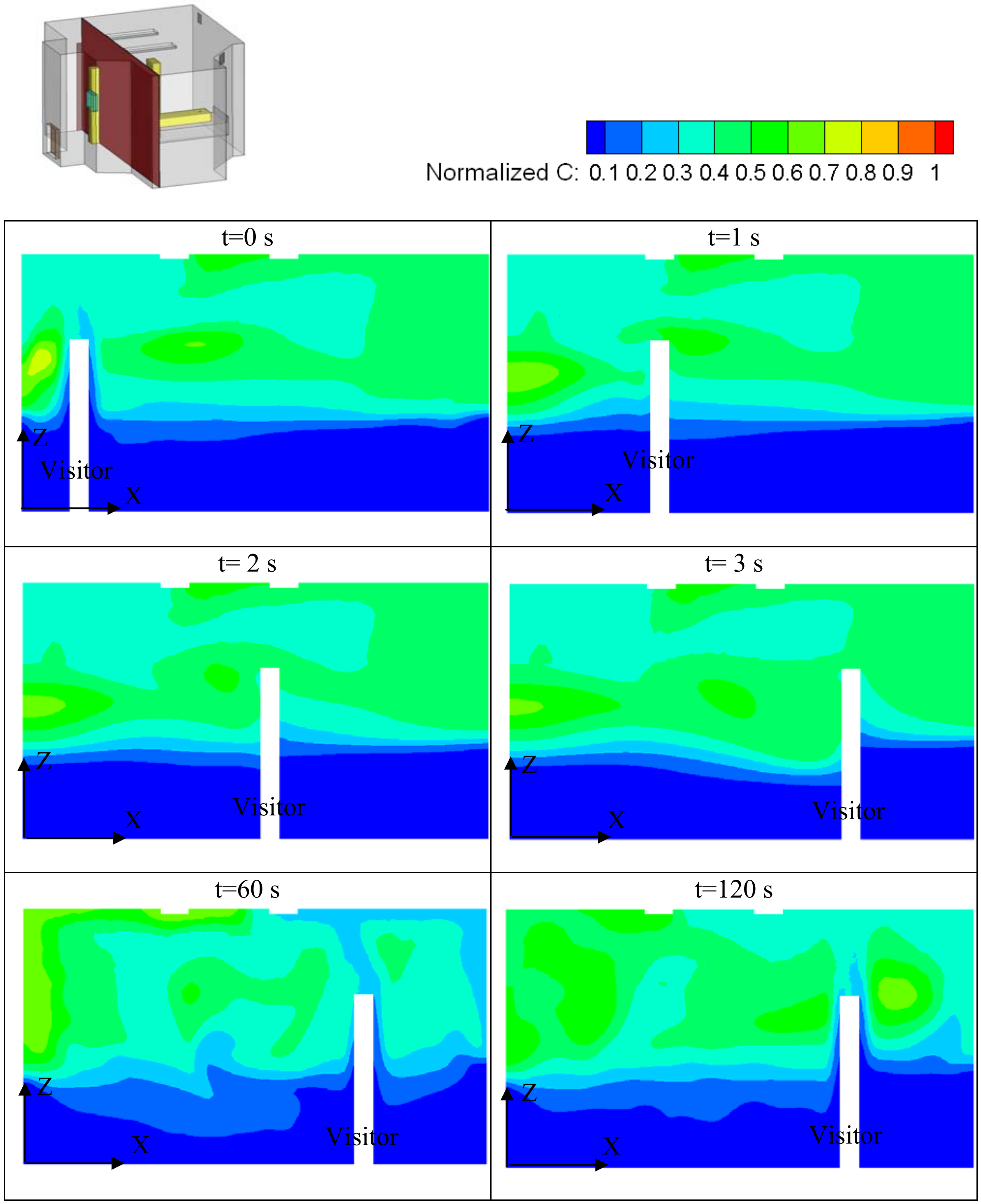


Fig. 6. Contaminant concentration distributions along the moving visitor track in Case 1 (at plane Y= 5.2ft or 1.57 m)

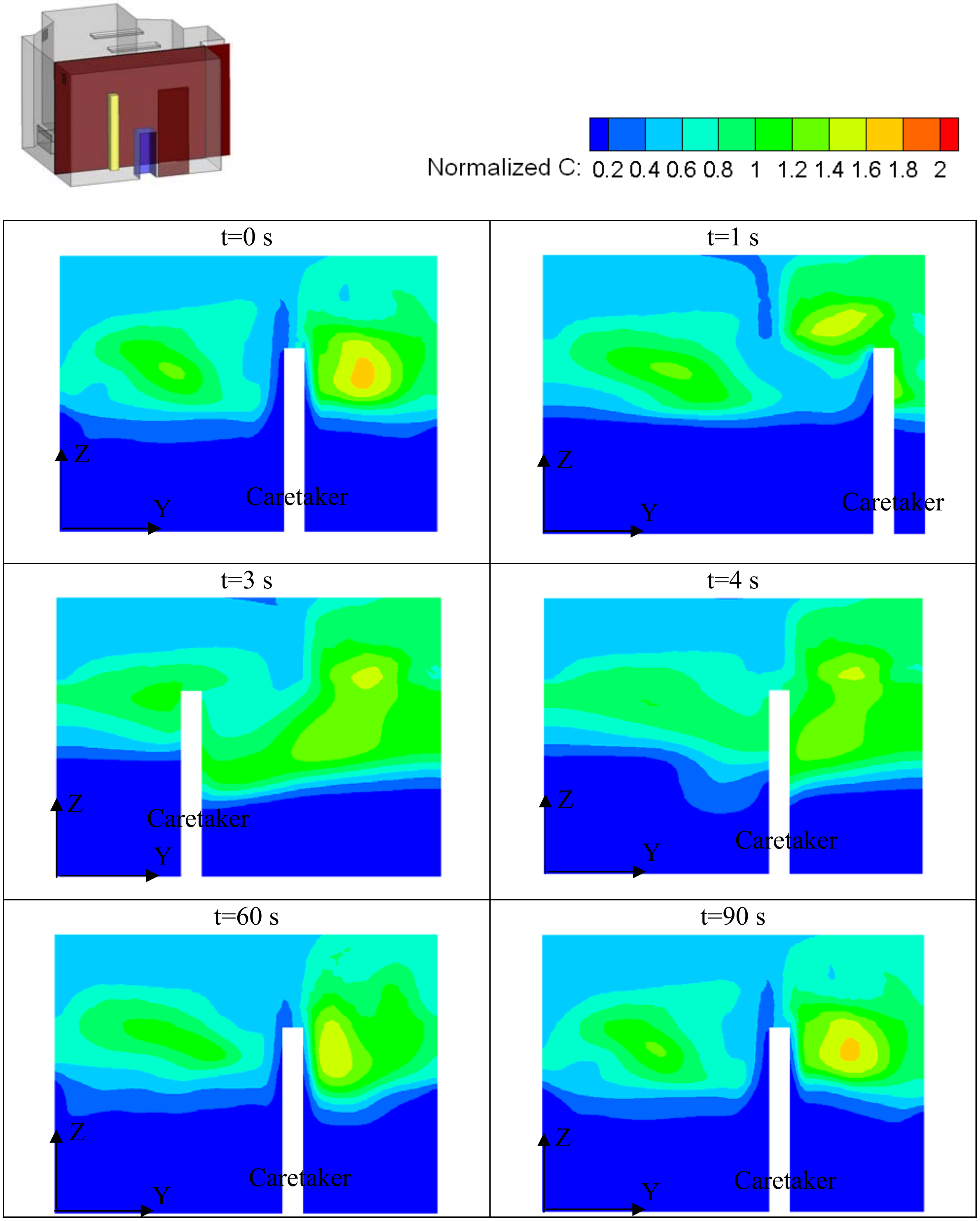


Fig. 7. Contaminant concentration distributions along the caretaker moving track in Case 2 (at plane X = 3.45 ft or 1.05 m)

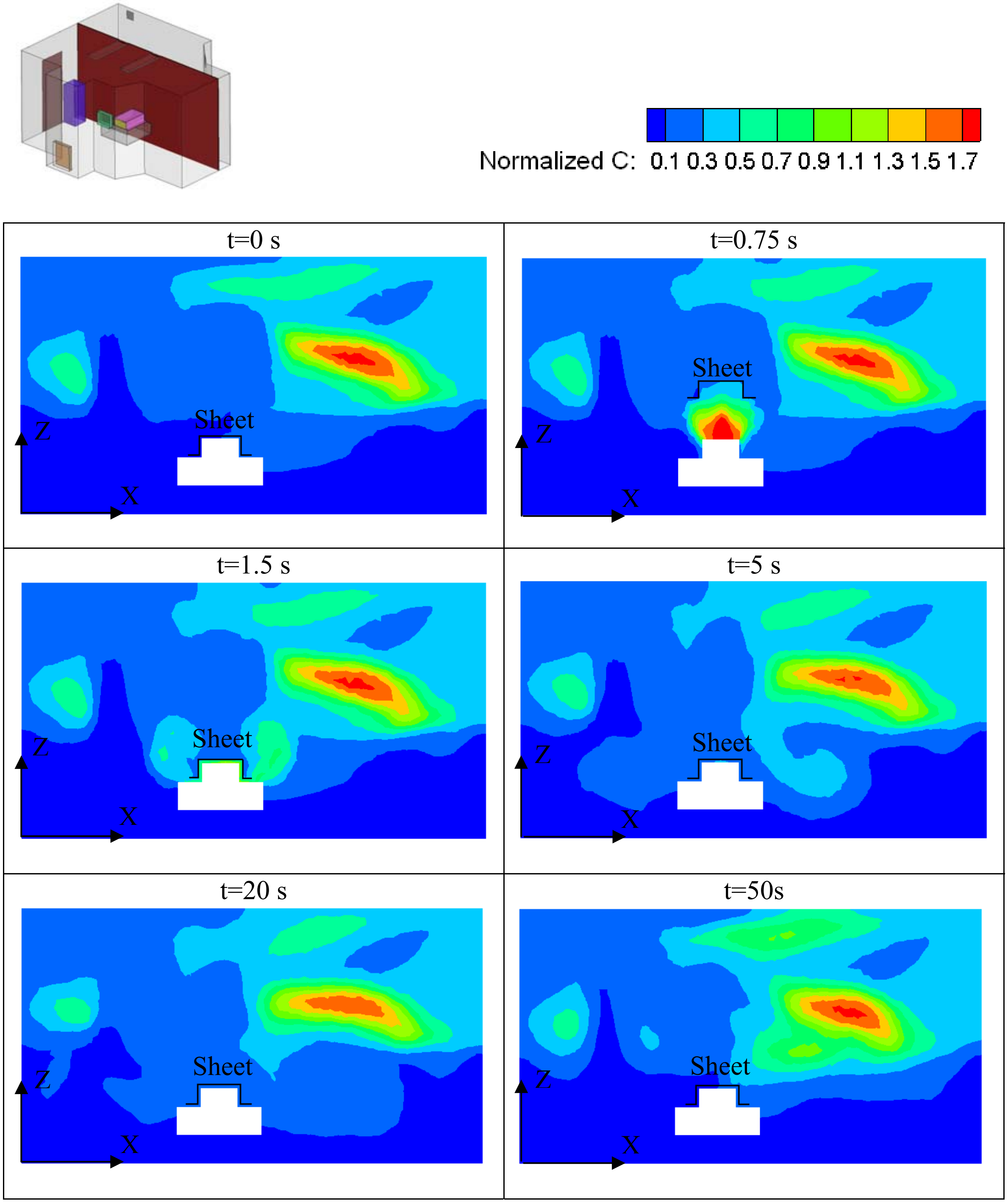


Fig. 8. Contaminant concentration distributions through the moving sheet above the patient in Case 3 (at plane Y = 9.02 ft or 2.75 m)

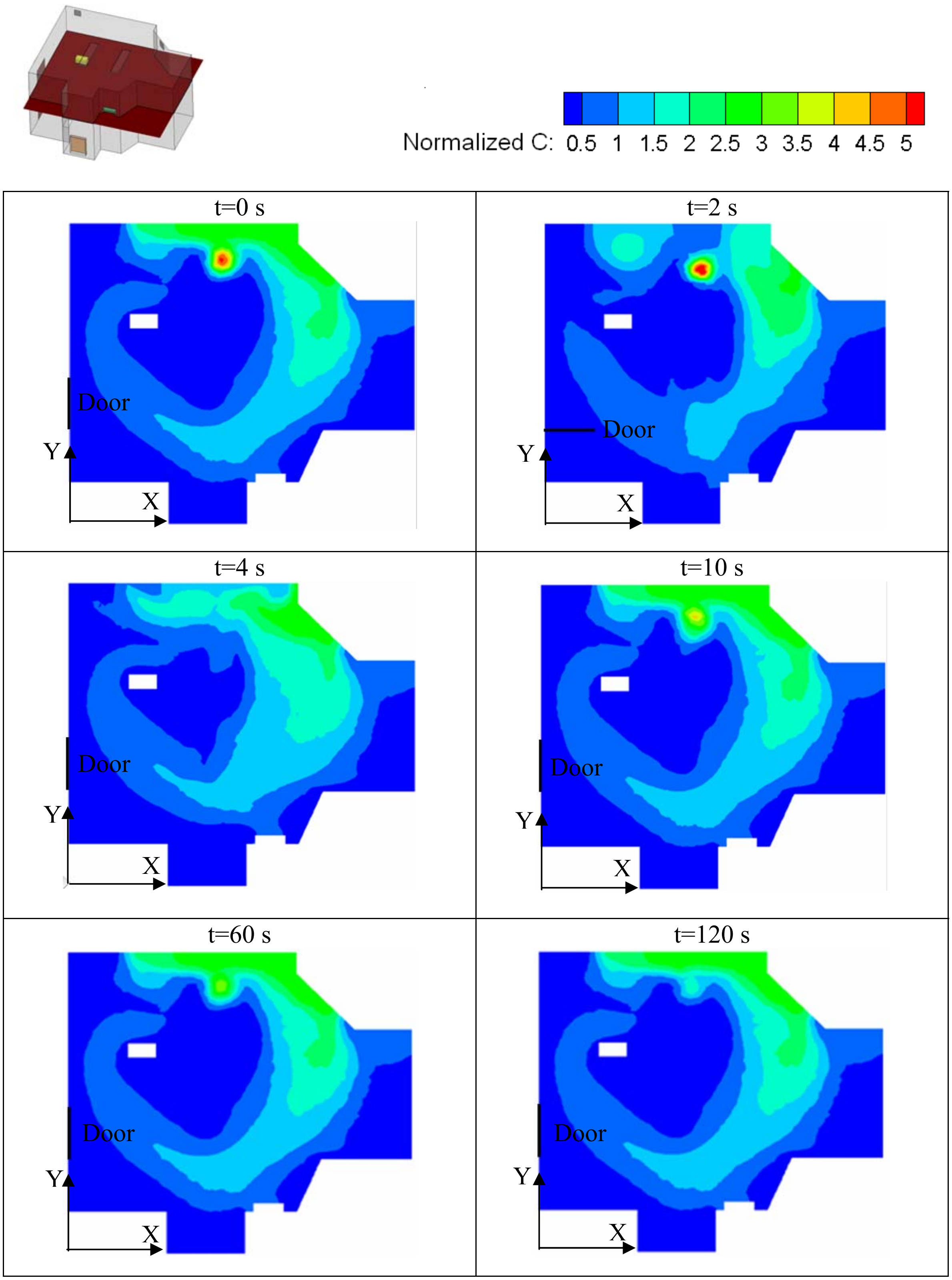


Fig. 9. Contaminant concentration distributions caused by the door swinging in Case 4 (at plane Z = 5.3 ft or 1.6 m)

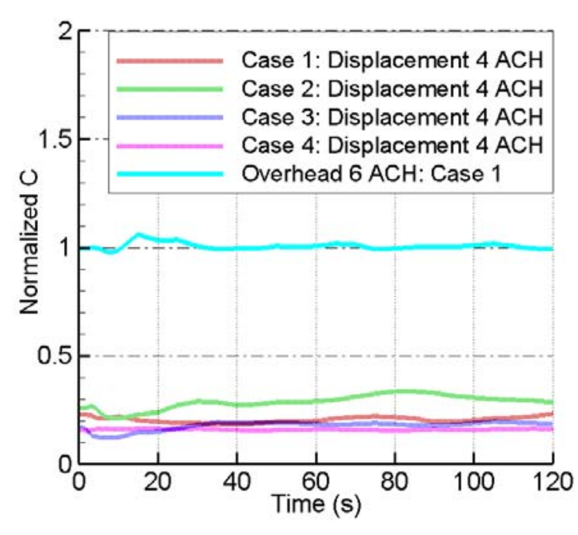
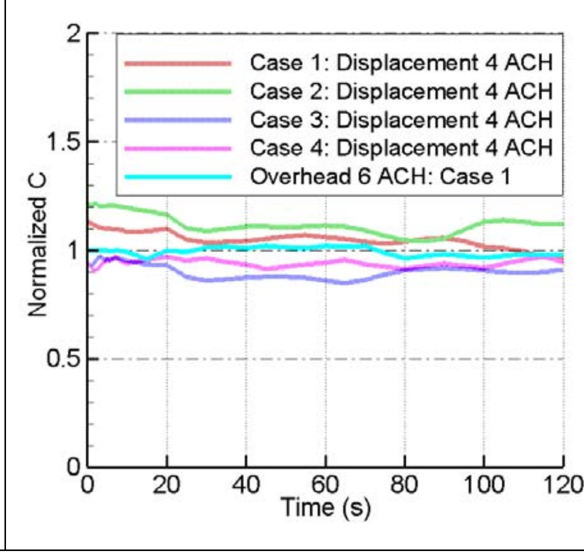
Z=3.7 ft (1.1 m)	Z=5.3 ft (1.6 m)
	

Fig. 10. The averaged contaminant concentration at the breathing levels of a sitting person (3.7 ft or 1.1 m above the floor) and a standing person (5.3 ft or 1.6 m above the floor) for the various movement cases

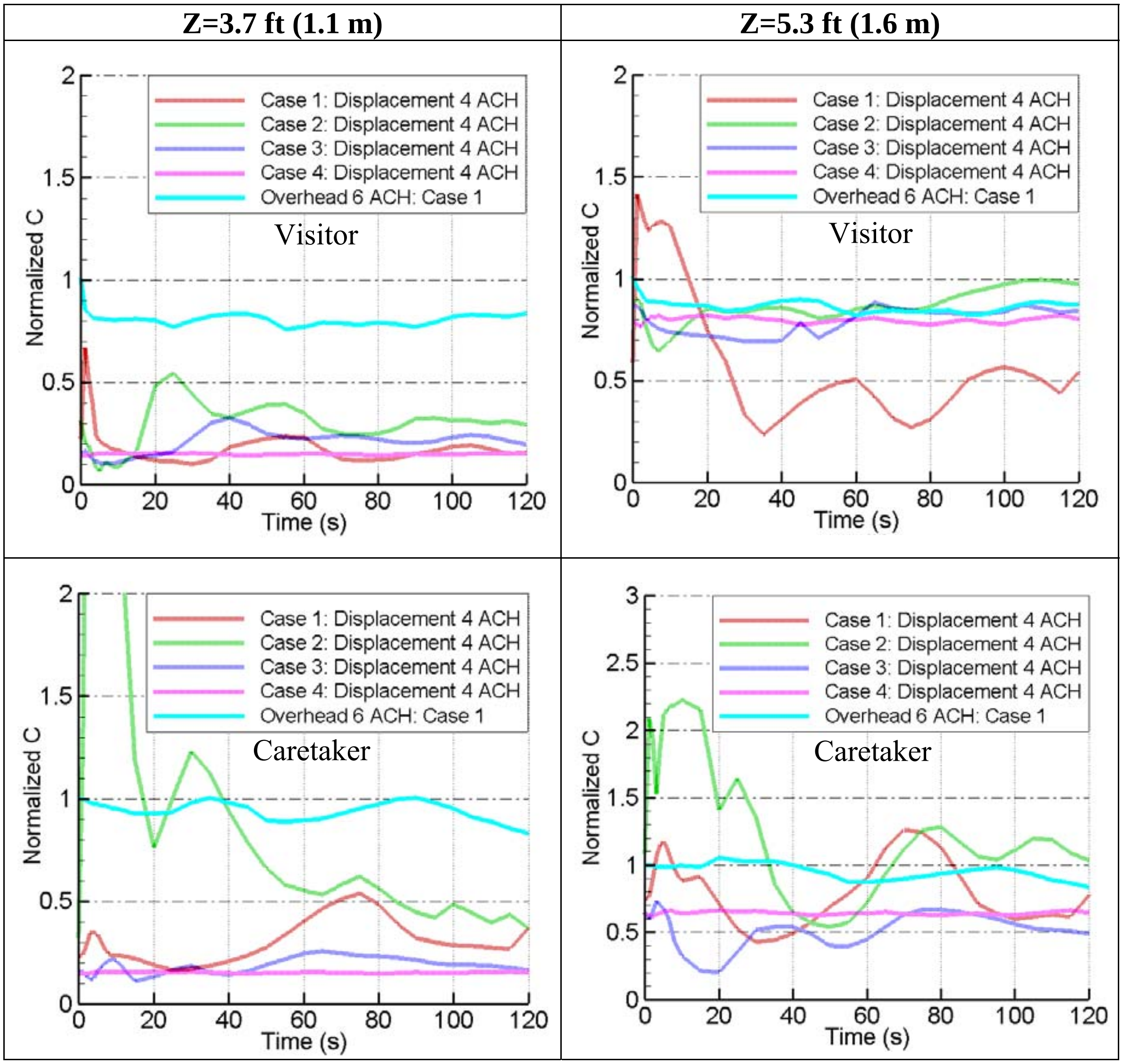


Fig. 11. The contaminant concentration breathed in by the visitor and the caretaker in the inpatient ward with moving objects

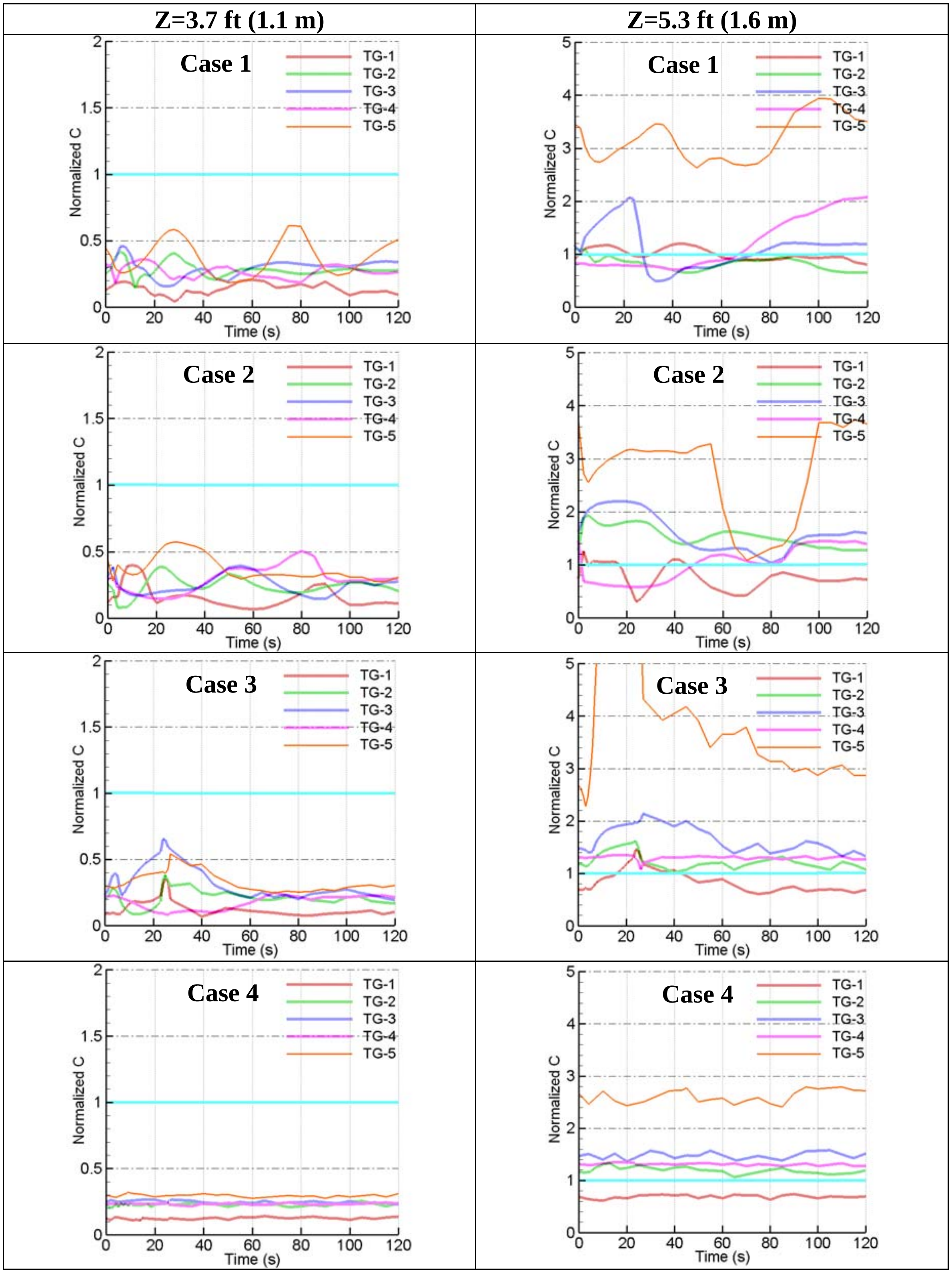


Fig. 12. Contaminant concentration at the breathing levels at TG 1-5 positions for the four cases with moving objects

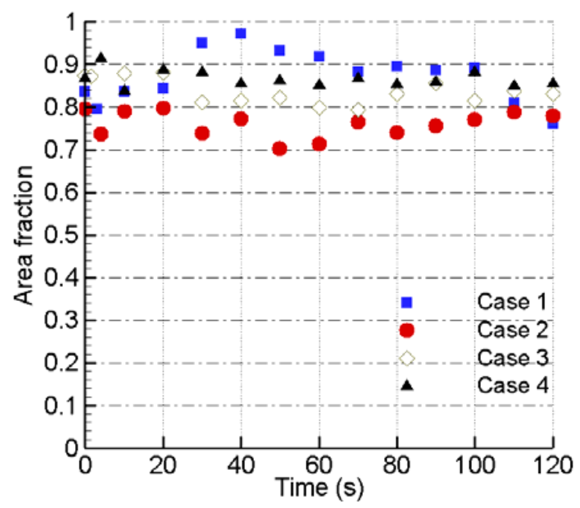
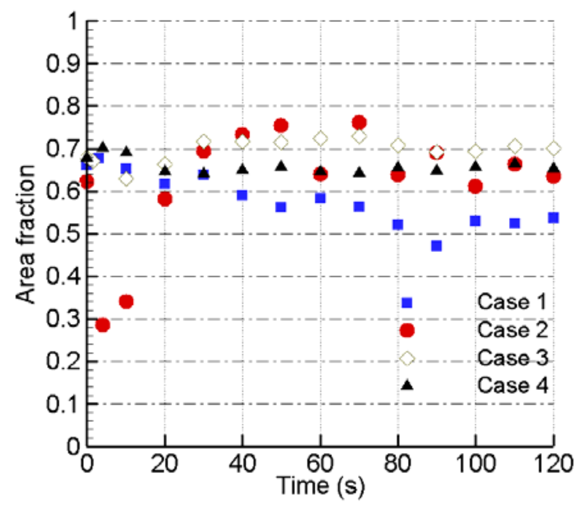
Z=3.7 ft (1.1 m)	Z=5.3 ft (1.6 m)
	

Fig. 13. Area fraction in the ward with the displacement ventilation at 4 ach where the contaminant concentration at breathing levels was less than that in perfect mixing ventilation at 6 ach