A study on effective ventilation strategy to remove pollutant in an isolation room of a hospital

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ABSTRACT
This paper investigates the pollutant distribution patterns in a 'negative pressure' isolation room by means of objective measurement and CFD modelling. The isolation room has two air supply diffusers and two extract grilles mounted in the ceiling. Numerous strategies were simulated and the most effective method is described in this paper. This strategy has the supply diffusers replaced by the supply grilles and relocated closer to the wall behind the bed. In addition, the two ceiling extract grilles are relocated to the wall behind the bed at 0.3 m above the floor level. The results show that the low-level extraction technique adopted is very effective in removing pollutant at the human breathing zone as compared to extraction at ceiling level in the original design. It was found that the supply air grilles delivered air to the occupant with minimal air entrainment.

INDEX TERMS
Airflow; Pollutant; Isolation room; Modelling; Ventilation

INTRODUCTION
Over the last decade there has been an increasing awareness on indoor air quality and its interrelationship with the proper design of the air-conditioning and mechanical ventilation (ACMV) system. This is especially crucial in hospitals where airborne transmission of contaminated air is the second most prevalent cause of contracting a disease for patients, healthcare workers and visitors. The ACMV system in hospital assumes a more important role than just the provision of thermal comfort. In many cases, proper air-conditioning is a factor in patient therapy; in some instances, it is the major treatment. Systems serving highly contaminated areas, such as infectious isolation room and autopsy room, should maintain a negative air pressure with respect to adjoining room or corridor. The design of 'negative pressure' isolation room involves a series of complex decisions. The provision of interior finishing, and locations of supply diffuser and exhaust grille are vital. Various research works have studied the airflow patterns and pollutant distribution patterns in the healthcare facilities. Chow *et al.* (2000) investigated the ventilation system of a hospital operating theatre and found that the optimum supply air-distribution systems provide the desired effects within the surgical field rather than in the entire room. Researchers like Memarzadeh and Jiang (2000) compared the use of ultraviolet germicidal irradiation with increased ventilation flow rate to

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minimize the risk from airborne organisms in hospital isolation rooms. Gathon (1994) discussed the use of smoke-trail method to visualize the performance of the isolation system. Galson and Guisbond (1995) recommended design strategies for 'negative pressure' isolation rooms in hospitals. This specialized topic is still a subject of much research worldwide.

In this study, measurements were conducted in an isolation room with two supply diffusers and two extract grilles mounted on the ceiling. This layout is referred to as Strategy 1 in this paper. Results from the field measurement were used to validate the computational fluid dynamics (CFD) simulated results. This is to ensure that the prediction of the airflow and pollutant concentration in the subsequent case for other strategy is accurate and reliable. Numerous strategies were simulated and the most effective strategy is presented in this paper.

THE FIELD STUDY AND CFD SIMULATION

The Field Study

Air velocity and contaminant measurements were performed in an isolation room, 3.35 m (*L*) × 4.8 m (*W*) × 2.5 m (H), as shown in Figure 1. The air is delivered to the room via the two 0.6 m × 0.6 m square diffusers located at the ceiling and the contaminated air is extracted from the room via two 0.6 m × 0.6 m square diffusers mounted on the ceiling. The room is illuminated by six sets of three18 W lamps in each 0.6 m × 0.6 m square light fitting.

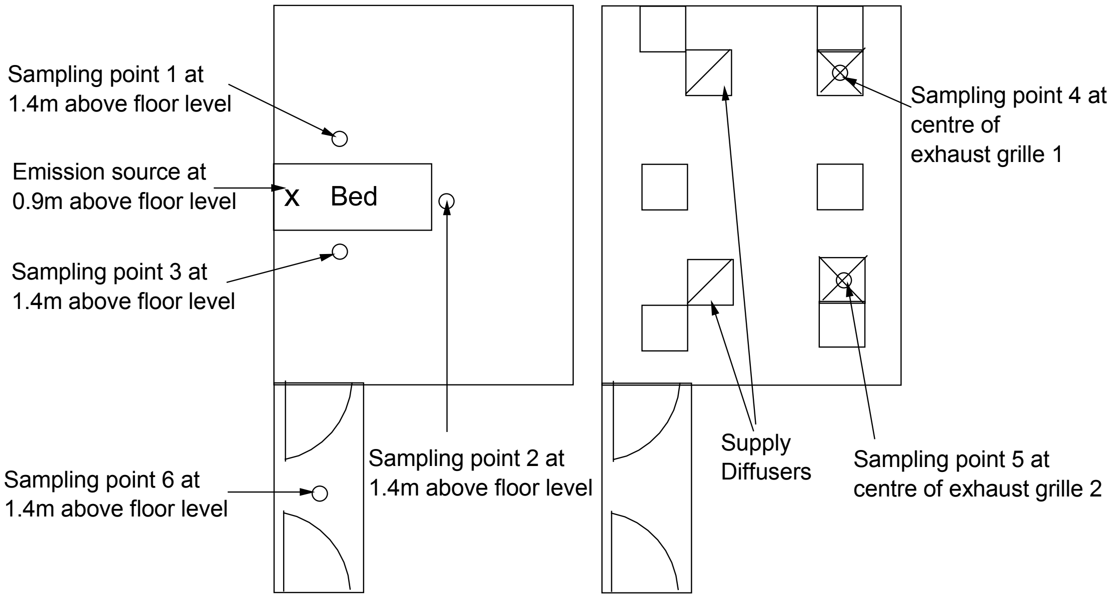

Figure 1 Sampling points in the isolation room (floor and ceiling levels).

In the airflow study, a vane anemometer is used to measure the discharge air velocity at the exit of a flow hood which encloses the air supply diffuser. The extract airflow rate is measured at the two extract grilles. The air velocity data is required for the supply diffuser and extract grille models in the numerical simulation. The floor area was divided into rectangular grids 0.8 m × 0.7 m to form a 6 × 5 matrix. Air velocity measurements were conducted at these 30 locations using four hot-wire anemometers fixed at different heights, 0.1, 0.6, 1.1 and 1.7 m, from the floor. In the contaminant study, SF_6 tracer gas was injected at a constant rate near the bed at about 0.9 m above floor level. The concentration of tracer gas is measured continuously using a gas analyser at six locations: three sampling points (SP1, SP2 and SP3) were located around the bed at 1.4 m from the floor level to monitor the exposure level of the healthcare staff at these locations; two sampling points (SP4 and SP5) at the two exhaust grilles; and one sampling point (SP6) at the corridor.

CFD Simulation

In the simulation process, the pre-processor generated the isolation room model with a pollutant source using unstructured grid meshes for Strategy 1. Different part of the model had different grid coarseness. The face of the diffuser, extract grilles, light fittings and door gap had mesh size of 40 mm. The entire space in the room had a volume mesh size of 100 mm. The finer meshes at the diffuser, extract grilles and door gap were to capture airflow details that were critical to this study. The boundary conditions specified for the model were based on data obtained from the field measurements. The heat generated from the human body and artificial lightings was modelled as 42 and 150 W/m^2, respectively. The temperature of all the other walls was defined as 24°C. The air was supplied to the room at 18°C with a total air exchange rate of 29.9 ACH. The source was simulated as a point emitting SF_6 at a rate of 0.3 l/min. In the modelling of the contaminant's migration patterns under steady-state condition, besides specifying the flow conditions across the boundaries, the species' conditions of the source term within the continuum and its boundaries must be defined. The mass flow rate of the species (SF_6) at the extract grille is 62.6×10^{-6} kg/s. After validation of the predicted results against the measured results, numerous strategies were simulated and the most effective method, Strategy 2 as shown in Figure 2, is presented in this paper. This strategy has the supply diffusers replaced by the supply grilles and relocated closer to the wall behind the bed. The ceiling extract grilles are relocated to the wall behind the bed at 0.3 m above the floor level.

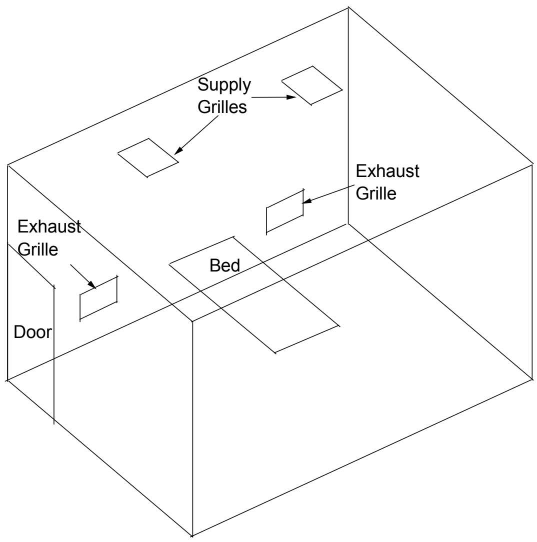

Figure 2 Isolation room with Strategy 2

The concentration profiles at the 1.4 m height level will be presented for each strategy. In addition, the pollutant removal efficiency (PRE) will be computed based on the time-average concentration of pollutants in the extract air divided by the time-average concentration of pollutants in the breathing zone. This is a direct indicator of the effectiveness of the ventilation system in removing the indoor pollutants. The index is a function of the locations of the pollutant sources and the pollutant emission momentum.

RESULTS AND DISCUSSION

Validation of Predicted Results against Experimental Results

The predicted air velocity is in reasonable correlation with the measured velocity. The percentage difference between the measured and predicted results ranged between –6.3 and 11.1. The predicted concentration is in good correlation with the measured concentration at all the locations. The percentage difference between the measured and simulated results ranged between –2.5 and –6.6. It is observed that the predicted concentration was consistently lower than the measured concentration. The model is reasonably accurate in predicting the concentration profile in the isolation room.

Airflow and Concentration Distribution Profiles based on Strategy 1

It is observed from the air velocity vector plot, not shown in this paper, that there is a high-speed jet of air from the supply diffuser. The airflow profile shows a large amount of air mixing in the room. The patient on the bed experiences about 0.15 m/s. This is within the threshold value of less than 0.25 m/s as recommended by the ASHRAE Standard 55 (1992). Figure 3 illustrates the concentration distribution pattern of a horizontal plane at 1.4 m from the floor level to represent the breathing level of the healthcare worker while treating the patient.

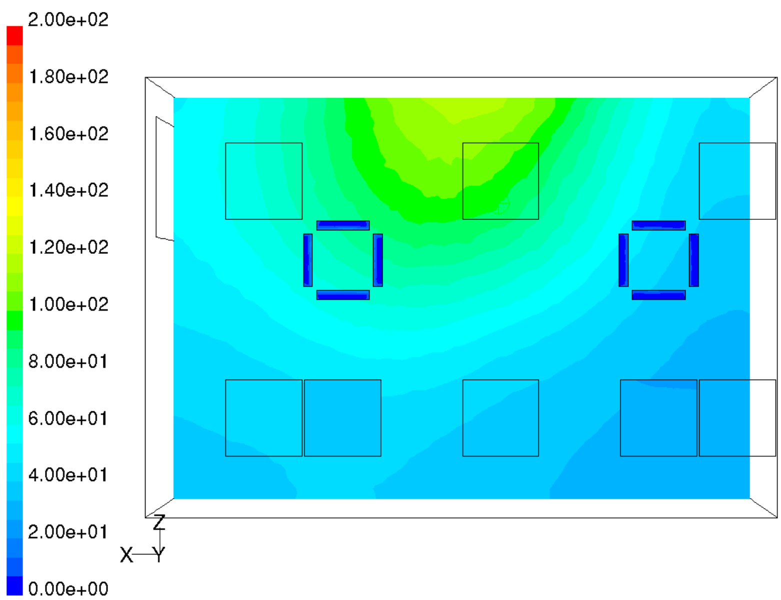

Figure 3 Concentration profile of SF_6 for Strategy 1.

It is obvious that the highest concentration is found near the patient. The pollutant's concentration is diluted as it moves away from the patient. The dispersion of pollutant is not symmetric and this is influenced by the airflow pattern in the room. A region with the lowest concentration of pollutant is found near the doorway. This substantiates on the matter that air not marked with tracer gas infiltrates to the room from the corridor via the door gap. Table 1 shows that the pollutant's exposure level of the healthcare worker ranged between 40 and 93.3 ppm. The highest concentration is found at SP2 while the lowest concentration is found at SP1. The absolute concentration of pollutant may not mean anything in this study but it is the relative concentration between one location to the other that is of importance. The healthcare worker giving treatment to the patient should be standing at location 1 with the lowest pollutant exposure level. Strategy 1 has low PRE values that ranged between 0.34 and 0.79. It shows that this strategy is very poor in removing pollutants from the room. An ideal PRE value should be at least 1 to indicate an effective pollutant removal system.

Table 1 Healthcare worker's pollutant exposure level and PRE value for Strategy 1

Sampling point	Conc. of pollutant (ppm)	Pollutant removal efficiency (PRE)
1	40	0.79
2	93.3	0.34
3	60	0.52

Airflow and Concentration Distribution Profiles based on Ventilation Strategy 2

The air leaving the ceiling supply grille is thrown down towards the floor rather than towards the wall in Strategy 1 with ceiling diffuser. The air moves towards the patient and extracted from the room via the extract grilles mounted on the wall. It is observed to have less mixing between the air coming into the room via the supply grille and the air in the space as compared to Strategy 1. The patient experienced reasonable air velocity of 0.1 m/s on the bed. Figure 4 shows a pollutant distribution profile very different from those experienced in Strategy 1.

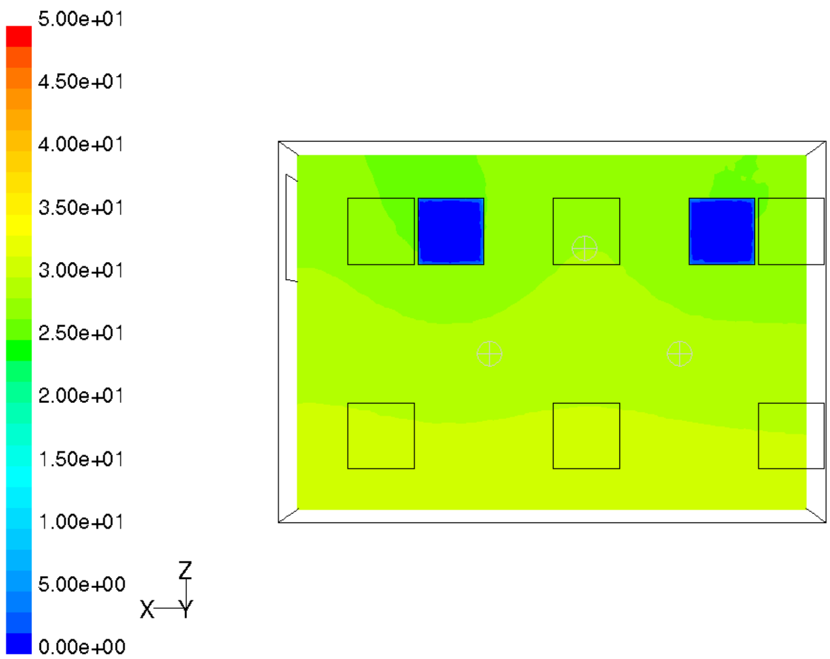

Figure 4 Concentration profile of SF_6 for Strategy 2.

This could be due to the type of supply device and new location of the supply device. The column of air from the supply grille would flow down towards the floor and extracted behind the patient's bed. Table 2 shows that the healthcare worker's exposure level, 28–29 ppm, is much lower as compared to the previous case. There is no significant difference in the exposure level when the healthcare worker is treating the patient at the three locations. The PRE values at all the locations have exceeded the value of 1.

Table 2 Healthcare worker's pollutant's exposure level and PRE value for Strategy 2

Sampling point	Conc. of pollutant (ppm)	Pollutant removal efficiency (PRE)
1	29	1.08
2	28	1.12
3	29	1.08

CONCLUSIONS

The CFD model used in this study to predict airflow and pollutant distribution patterns in the isolation room is well validated. The percentage difference between the predicted and measured air velocity ranged between –6.3 and 11.1. On the other hand, the percentage difference between the predicted and measured concentration of pollutant ranged between –2.5 and –6.6, respectively. The types of ventilation strategy have great influence on the airflow pattern and pollutant distribution in the room. Strategy 2 has better PRE values exceeding 1 and lowest exposure level at the three locations. The air velocity at the patient's bed is within the recommended threshold value of less than 0.25 m/s. A list of design strategies has been formulated to reduce the pollutant's exposure level of the healthcare worker from the patient.

1. Select the right type of diffuser to minimize inter-mixing between the supply air and the air in the room.
2. Air supply terminals and exhaust grilles should be arranged to allow clean supply air to flow from the healthcare worker to the patient with infectious disease.
3. Extract grille should be located at the low level and near the infectious source.

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