Analysis of Dispersion and Prediction of Infection Possibility according to Airborne Viral Contaminants: Tracer gas simulation

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ABSTRACT

The aim of this study is to analyse the physical characteristics of airborne virus, consider the possibility of using coupled analysis model and tracer gas for analysing virus diffusion in building space and, based on reports of how the infection spread in a hospital where patients were discovered, analyse infection risk using tracer gas density and also diffusion patterns according to the location, shape, and volume of supply diffusers and exhaust grilles. This paper can provide standards and logical principles for evaluating various alternatives for making decisions on vertical or horizontal ward placement, air supply and exhaust installation and air volumes in medium or high story medical facilities.

KEYWORDS

Airborne virus, Ward ventilation, Hospital infection, Tracer gas, CFD Simulation

1. INTRODUCTION

Around 2003, SARS, a type of corona virus, began appearing in a number of areas, including Hong Kong and North America, which led to the publication of many studies dealing with the virus's paths of infection. Some of the studies that analyzed how the virus spreads employed the CFD method, which uses tracer gas to simulate virus diffusion but without carrying out an analysis of the physical characteristics of virus. And many researches using a network model of airborne microbe transmission proposed a specific model for the spread of airborne pathogens, but because the model assumed for its analysis that the total volume of floating microbes has a fixed numerical value and because of the disadvantages of a network model, the model was not able to analyze in detail the process of airborne pathogens spreading inside a building space. In previous studies, either a network model or a CFD model was used. Although the two have different characteristics, we can use them in a coupled analysis and so expand the analysis range to the level we want. The aim of this study was to analyze the physical characteristics of the airborne virus, consider the possibility of using an analysis model coupled with tracer gas for analyzing virus diffusion in a building space and, based on reports of how the infection spread in a hospital where SARS patients were discovered, analyze the infection risk using tracer gas density as well as diffusion patterns that were based on the location, shape, and volume of supply and exhaust air diffusers.

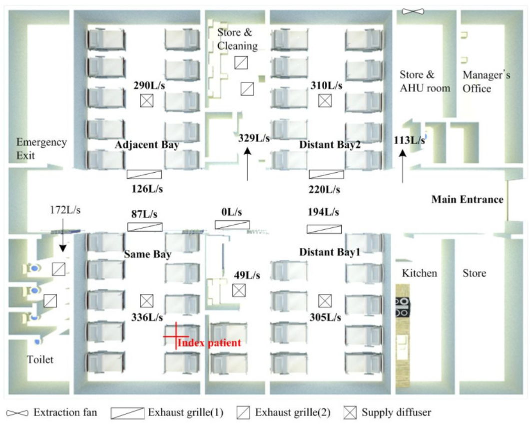


Figure 1 : SA & RA diffuser locations and airflow rate

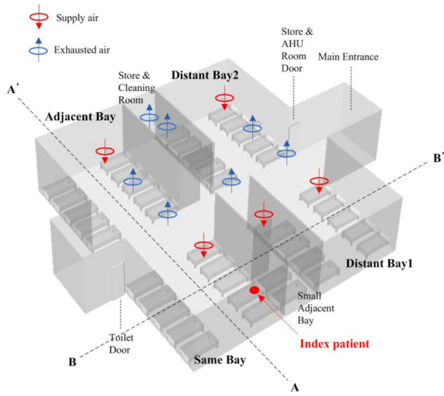


Figure 2 : CFD model of reference case

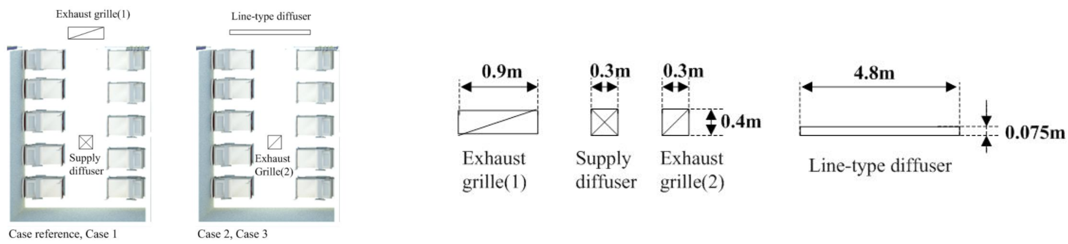
2. CASE ANALYSIS OF INFECTION RISK ACCORDING TO LOCATION OF SUPPLY AND EXHAUST AIR DIFFUSER

2.1 Analysis summary

The Prince of Wales Hospital in Hong Kong was selected for our infection risk case analysis because the first patient in Hong Kong infected with SARS was hospitalized there, and the process of how the infection spread to nearby patients is well documented. This paper will analyze the infection path based on the hospital's reports and then compare that with the infection risk predicted by tracer gas density. Figure 1 shows the ward layout at the time the SARS index patient was hospitalized, the ventilation locations and volumes, and the location of the index patient within the ward, and figure 2 shows a reference case for CFD analysis based on figure 1. Our analysis will show the tracer gas distribution in the ward and AA' and BB' sections. To examine the effect of ventilation shape, location, and air volume, four cases were created as shown in figure 3, and the resulting ventilation air volume conditions are as shown in table 1.

Table 1 Case study models' physical specifications (supply air and return/exhaust air)

(Liter/min)	Same bay		Adjacent bay		Small adjacent bay		Distant bay1		Distant bay2		Toilet		Store & cleaning		Store & AHU room	
	SA	EA	SA	EA	SA	EA	SA	EA	SA	EA	SA	EA	SA	EA	SA	EA
Reference	336	87	290	126	49	0	305	194	310	220	0	170	0	329	0	113
Case 1	336	336	290	290	49	49	305	305	310	310	0	0	0	0	0	0
Case 2	336	87	290	126	49	0	305	194	310	220	0	170	0	329	0	113
Case 3	336	336	290	290	49	49	305	305	310	310	0	0	0	0	0	0



(a) The inlet and outlet locations (b) The inlet and outlet size

Figure 3: Basic case layout for air conditioning system infrastructure

Table 2 Numerical Conditions

Modeling	Standard k-ε turbulence model
Human breathing	Uin = 0.89m/s, Tin = 32℃, Area = 3.293E-4㎡, Airflow rate = 0.003 ㎥/s Turbulence intensity = 0.1, Characteristic length = 0.01m
Supply boundary	Physical specifications: See Table 1, U_{in} = 2.5m/s, Tin = 22℃ Turbulence intensity = 0.1, Characteristic length = 0.02m
Exhaust boundary	Physical specifications: See Table 1 U_{out} = (mass flow conservation), k_{out}, ε_{out}, T_{out} = free slip
Wall treatment	Low-log / symmetric: free slip
Bedside	Adiabatic wall boundary condition
Grid cells	200,000

The reference case reflects the existing ventilation shape, location, and air volume. The air supply diffuser is 0.4m×0.4m in size, and the exhaust grille is rectangle 0.4m×0.9m in size. The air volume of the air supply is about 20% more than the air volume of the exhaust. Case 1 was created to explore the effect of the ventilation air volume, and while its inlet and outlet shapes and locations were the same as in the reference case, the air supply volume was set to be the same as the exhaust volume. Case 2 and case 3 were designed to analyze the effect of the ventilation system according to its shape and location. While the air supply in the reference case was coming from the middle of the partitioned ward and the exhaust was located at the boundary with other wards, with cases 2 and 3 the exhaust was located in the middle of the room and, instead of the existing air supply opening, a line-type air supply diffuser 0.075m×4.8m in size was located at the boundary with the other wards. The air supply and exhaust volumes in case 2 were set to be the same as those of the reference case, while those in case 2 were the same as those in case 1. Thus the four cases each have different air supply and exhaust characteristics, and accordingly, their general current movement directions will be different as well. Table 2 displays the general boundary and calculation conditions regarding air supply, exhaust, and breathing for the analysis of virus diffusion. To analyze virus diffusion for each case, the CFD model releases tracer gas from the index patient's location. Because the virus spreads through the oral or nasal cavity of a patient during breathing, normal breathing was assumed, and the boundary conditions for trace gas were set to be the same as for normal breathing, as shown in table 2. To distinguish the gas from ventilation air, N_2O gas was used.

2.2 Infection rate according to tracer gas density

As shown in figure 4, when current conditions are applied to the reference case, we can see that the N_2O gas, which represents breathing air, spreads to the entire ward once it is emitted from the index patient's location. In the reference case, the air supply comes from the center of the partitioned ward, and the air leaves at the boundary of the ward. Because the air supply volume is greater than the exhaust volume, there is a difference in leftover air volume (air supply – air exhaust) in the partitioned wards, which is turn creates a density difference between the wards. Because of this, when we examine the contour line that appears in figure 4, the air volume being supplied at the center of the same bay is greater than the exhaust volume and causes the virus tracer gas N_2O to go beyond the central air supply of the adjacent bay and push out to distant bays 1 and 2. When the densities of the partitioned wards are compared, the average density of index patient's bay was 0.0045419 ppm; of the adjacent bay, 0.0005861 ppm: of distant bay 1, 0.0002027 ppm; and of distant bay 2, 0.0001054 ppm. Excluding the first bay, each ward showed a density difference with respect to the tracer gas. This is because the inflow volume of tracer gas from the first bay is determined by the pressure and distance difference of leftover air volume in each ward. When these average N_2O densities of the wards are viewed together with the infection rate of SARS by location, we can see that as the average density increases so does the infection rate. In other words, the index patient's bay, which had an N_2O average density of 0.0045419 ppm, had the highest infection rate, 0.65; whereas the adjacent bay, where the average density was 0.0005861 ppm, had an infection rate of 0.52; and the distant bay, where the average density was 0.001540 ppm, had the lowest infection rate, 0.18. Figure 5 shows these results as a distribution map and a trend line. Looking at the trend line, we can see that the infection rate shows average density as an independent variable and is expressed as a logarithmic function, as in Equation (1). This logarithmic function explains the infection rate to be 86.6%. The implication is that, by using such a trend line, virus diffusion possibilities and the risk of infection for various hospital designs can, to a certain extent, be evaluated quantitatively. Figure 6 shows the average density of N_2O for the partitioned wards for each case.

$$y = 0.132 \ln(x) + 1.404 \tag{1}$$

Where, y: Infection possibility, x: tracer gas density

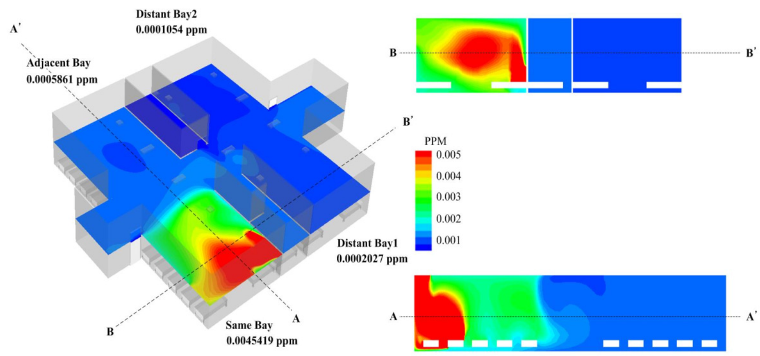


Figure 4: Simulation results of reference case

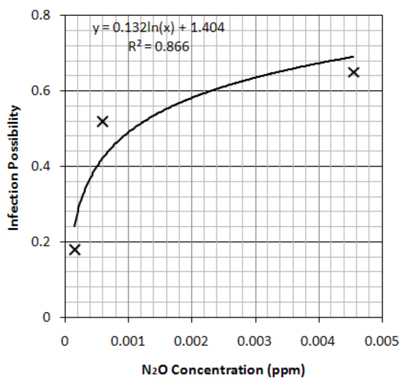


Figure 5: Infection possibility according to N_2O concentration

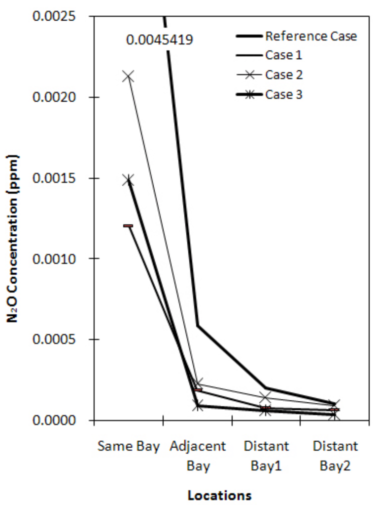
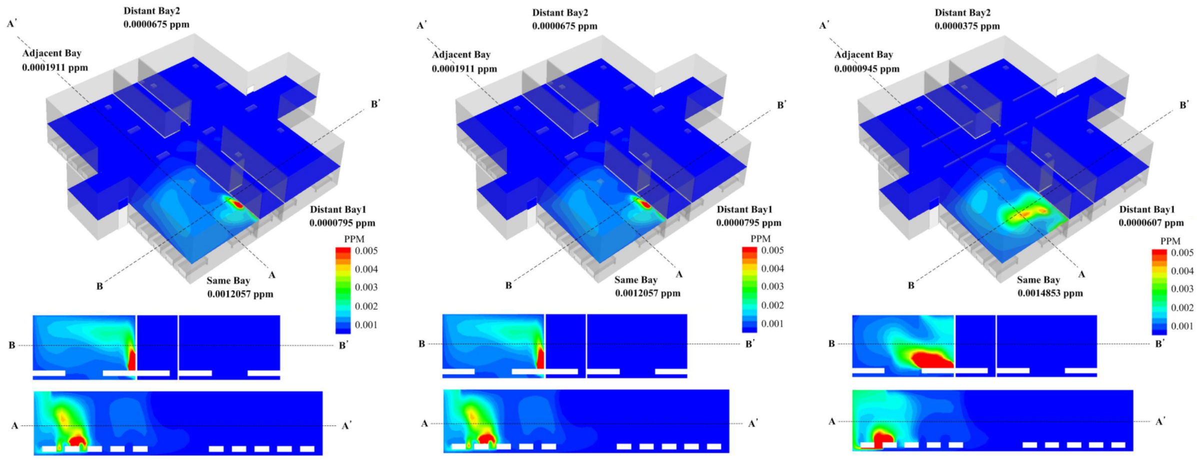


Figure 6: Tracer gas concentration profiles of each case



(a) Case 1 (b) Case 2 (c) Case 3

Figure 7: Simulation results of each case

2.3 Impact analysis on the difference between supply and exhaust airflow rate

Generally, partitioned wards have a higher volume of air supply than of air exhaust. This causes static pressure within the space, and the leftover volume of air exits through existing cracks, such as various openings, door or window crevices, and fissures. With the reference case, the air supply volume is similarly about 20% greater than the air exhaust volume. This causes the leftover volume of air to move to low-pressure areas within the ward space. In case 1, however, the air supply and exhaust volumes are set equally, so there is no leftover air. In other words, the same amount of air leaves the ward as is supplied to the ward. When N_2O is emitted from the index patient's location in case 1, N_2O spreads to the entire ward, as can be seen in figure 7(a). Although the air supply and exhaust in case 1 occur in the same locations as those in the reference case, the movement of current due to pressure differences between the partitioned wards occurs only weakly because there is no leftover volume of air. Looking at the contour line that indicates density in figure 7(a), we can see that the volume of air being supplied at the center of the index patient's bay is the same as the volume of air being exhausted, and only part of the N_2O is transmitted to the adjacent bay, distant bay 1, and distant bay 2. When the density levels of the partitioned wards are compared, the average density of the initial bay is shown to be 0.0012057 ppm; of the adjacent bay, 0.0001911 ppm; of distant bay 1, 0.0000795 ppm; and of distant bay 2, 0.0000675 ppm. When case 1 is compared to the reference case, we can see that in all the partitioned wards, the density of N_2O is reduced to less than 50%. This is mainly because there is no movement of air from the index patient's bay to other partitioned wards, and so N_2O is thus accumulated within the initial bay, and much of the polluted air in the same bay space is exhausted. Also, because there is no great pressure difference between the partitioned wards, there is less N_2O transmitted from the initial bay to the other wards than in the reference case.

2.4 Impact analysis according to air diffuser shape and location

The air supply and exhaust volumes in case 2 match those of the reference case, but the air is exhausted at the center of the ward and it is supplied at the boundary with other partitioned wards. The ventilation locations in case 3 are the same as those in case 2, but the air supply and exhaust volumes are set to be the same so there would be no leftover volume of air. With both cases, unlike the reference case, the air comes from a line-type air supply diffuser. When N_2O is emitted from the index patient's location in cases 2 and 3, the N_2O spreads throughout the ward, as can be seen in figure 7(b) and figure 7(c). With case 3, shown in figure 7(c), because the polluted air is exhausted at the center of the ward and new air comes in through the line-type air supply diffuser at the boundary, N_2O is isolated in the index patient's bay and cannot spread. Because of this, the average density of the initial bay is 0.0014853 ppm, which is higher than that of case 2, where the air supply is greater than the exhaust, but because the efficiency of isolating polluted air is high in case 3, the average density of the adjacent bay is 0.0000945 ppm, that of distant bay 1 is 0.0000607 ppm, and that of distant bay 2 is the lowest of all cases, at 0.0000375 ppm. In case 2, the N_2O being emitted exits at the center of the ward, and the gas that would otherwise spread out is pushed inward by the line-type air supply diffuser. As shown in figure 7(b), however, because the supply of air is greater and produces a leftover volume of air, the gas eventually diffuses to other partitioned wards. Because of this, the average density of the index patient's bay is 0.0021274 ppm, higher than that of case 1, where a rectangular-type air supply is used. The average density of the adjacent bay is 0.0002291 ppm; of distant bay 1, 0.0001422 ppm; and of distant bay 2, 0.0000934 ppm, which is a fairly high level. When the analysis results are considered all together, we can see that the current movement changes according to ventilation shape, location, and the volume of air supply and exhaust. In particular, an imbalance in air supply and exhaust produces a static pressure in parts of the room, and the leftover air in the room is transmitted to other spaces, thus spreading the index patient's exhaled breaths. It was also shown that when air is exhausted within the partitioned room and air is supplied from the boundary area of the room, the index patient's exhaled breaths do not spread to other spaces but are isolated and exhausted. Thus, in terms of the design of the air supply, we found that a line-type air supply diffuser, which increases wind velocity, was better for isolating exhaled breaths than a square-type air supply diffuser.

3. CONCLUSION

The studies of how the airborne pathogen that causes the SARS virus is spread were carried out mainly by researchers in the medical field. In the field of architecture, a variety of studies were done on the diffusion of air pollutants in buildings using gases such as CO_2, N_2O, or SF_6, but research on the diffusion of viruses in buildings was limited. There were some discussions on how the virus might diffuse in structures, but they were done without accurate information about the characteristics of the virus.

We can summarize our research as follows. With pathogens that can be airborne, documentary research found that, although the viruses have a density greater than that of water, they exist in various particle forms that can float in air. Furthermore, in contrast to bacteria and rickettsia, because their size is nano-scale, Brownian motion allows them to move like gas molecules through the air. In other words, although they are solids, they can be classified as gaseous substances because of the way they diffuse in the air, and, accordingly, it is reasonable to use tracer gases in analyzing the virus diffusion path or the infection risk. Using the case of a hospital where a patient infected with SARS was hospitalized and infection spread, we analyzed the infection risk according to the density of tracer gas, and the results showed that the higher the density of tracer gas, the higher the infection risk was. The infection rate indicated by the tracer gas density could be expressed as a logarithmic function. This function showed that the average density of tracer gas corresponded to an infection rate of 86.6%. We believe that using this trend line will make it possible to perform a quantitative evaluation of virus diffusion and infection risk for various future hospital designs.

We have seen that interior air movement changes according to ventilation shape, location, and air supply and exhaust volumes. In particular, an imbalance between the air supply and the exhaust can cause a static pressure within a room, which can cause interior air to be transmitted to other spaces; during that process, virus particles from an infected person's exhaled breath can spread. We also found that, with respect to ventilation location, if air is exhausted within a partitioned room and supplied from the boundary of that room, an infected person's exhaled breaths can be isolated in that room and vented out. Regarding the design of an air supply, we found that a line-type air supply, which increases wind velocity, is more effective in isolating exhaled breaths than a square-type air supply diffuser.

This paper can suggest standards and logical principles for evaluating various alternatives for making decisions on vertical or horizontal ward placement, air supply and exhaust installation, and air volumes in high-rise hospitals.

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