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Using CONTAM to design ventilation strategy of negative pressure isolation ward considering different height of door gaps

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Abstract

Infectious disease departments in hospitals require pressure gradient to create unidirectional airflow to prevent the spread of contaminants, typically by creating active air infiltration through the difference between supply and exhaust air volumes. The door gap is the channel of air flow between rooms, so its height has an important influence on the pressure difference and infiltration air volume of the room. There is still a lack of research on setting reasonable ventilation strategies according to the different heights of door gaps at different positions in the building. In this study, model of a set of isolation wards was established and analyzed using the multi-zone simulation software CONTAM, and the ventilation strategies with different heights of door gaps were applied to the actual infection diseases department. The results show that in a building with ventilation system divided by functional area, the difference in the height of the door gaps requires different active infiltration air volumes. Pressure fluctuations in the medical and patient corridors are greater than in other rooms. The significance of this study is to understand the active infiltration of air to guide the design and operation of ventilation systems in infectious disease hospitals or building remodeled to isolate close contacts of COVID-19 patients. It is also instructive for the design of pressure gradients in clean workshops, biological laboratories, and other similar buildings.

1. Introduction

COVID-19 outbreak in 2019 caused rapid mass infection and has had a severe impact on the world. Especially the rapid spread of Delta and Omicron variants makes the COVID-19 pandemic more difficult to control [1]. The International Society for Influenza and Other Respiratory Viral Diseases (isirv) and WHO stated in a joint virtual meeting from 19th-21st October 2021 that there have been nearly 2.5 billion confirmed cases of COVID-19 to date, which is a gross undercount actual numbers and the death toll exceeds 5 million [2]. Infectious disease hospitals face more challenges than other places to treat patients infected with Covid-19. As the causative virus of COVID-19, the SARS-CoV-2 is mainly spread between people by respiratory droplets (>5-10 μm in diameter) and contact [3-5], but also by airborne particles encapsulated in aerosols (<5 μm in diameter) [6]. Aerosol particles containing SARS-CoV-2 can be suspended in the air for hours and can be transported from the source to several meters away [6]. Positive results of RNA samples detected in the air of hospital wards admitting COVID-19 patients support airborne transmission of SARS-CoV-2 from person to person via aerosols [7]. The spread of SARS-CoV-2 in healthcare settings has been a major issue in many countries in the process of epidemic prevention [2], SARS-CoV-2 is highly contagious and has the potential to cause large nosocomial outbreaks in hospital settings. Patients with existing diseases presenting in hospitals, as well as health care workers, are in a situation where they are high potentially infected with the SARS-CoV-2 and are at high risk of illness and death related to COVID-19 [8]. Research has shown that as of 28 April 2020, a total of 12.5% of COVID-19 infections in the UK were acquired in hospital [9]. In addition to personal protection (i.e., masks, protective clothing, goggles, etc.) and decontamination (i.e., hand washing, surface cleaning and disinfection, etc.) measures to reduce cross-infection in the hospital [10-12], the negative pressure isolation ward (NPIW) is an effective method to reducing the airborne transmission of SARS-CoV-2 [13,14].

In an infectious disease hospital, rooms are classified into different levels according to the degree of contamination. Using the pressure difference between adjacent rooms is an effective way to make air flow in a directional flow to avoid the cross-infection caused by the outflow of viruses generated by an infectious source. A negative-pressure isolation
ward (NPWW), as a place to house infected patients, aims to minimize the threat of exposure to airborne infectious agents of healthcare workers in the isolation room and others outside the room [15]. Although each country’s ventilation guidelines have different regulations on the pressure difference between rooms of different pollution levels, they all aim to prevent the flow of pollutants from the contaminated zone to the clean zone by maintaining a certain pressure difference [16–18]. Although these guidelines give the value of the differential pressure necessary to maintain cleanliness, they do not specify the conditions required to achieve the pressure gradient. The current mean of maintaining room pressure difference is to control the difference in air supply and exhaust air volume. Increasing the air volume difference in a room can acquire differential pressure. Air supply volume can be calculated according to the number of air changes in different standards, but no standard exists for exhaust air volume. In actual projects, many designers use an empirical value or simply make the exhaust air volume greater than the supply air volume to achieve negative pressure. This condition may not be a problem in the design of a single room but can lead to chaotic pressure gradients in a complex building where pressure gradients and airflow directions are tightly controlled. Previous research has studied the behavior of patients in isolation rooms to emit virus-containing droplets, analyzed the impact of air supply and exhaust on virus transmission and suggested methods to minimize virus transmission [19,20]. Ren et al. [21] compared the efficiency of three ventilation strategies to remove particulate matter in an inpatient unit. Cheung et al. [22] used a field model approach to analyze a single-compartment fire scenario and concluded that a larger door gap shows a lower resistance to smoke propagation, and a higher door gap results in a lower pressure gradient on both sides; thus, air may be re-entrained back into the room. Notably, these studies were limited to a certain separate compartment rather than interconnected areas. Emmerich et al. [23] coupled multiregional airflow and building thermal modelling tools to simulate the effect of infiltration on heating and cooling loads in office buildings in the US. Ren et al. [24] used three different models to simulate the impact of air infiltration in Australian dwellings. In summary, room ventilation strategy and door gaps height play a very important role in preventing the spread of pollutants. However, relatively few studies have been conducted on pollutants control considering building integrity and ignoring the flow field inside each room, particularly when active infiltration is used to control the pressure gradient. Moreover, studies on the effect of changing door gaps on pressure gradients and appropriate ventilation strategies are lacking. The purpose of this study was to explore the effect of door gap height on active infiltration air volume when the pressure difference gradient meets the standard requirements in multiple connected rooms to provide a reference for similar buildings to use the correct ventilation strategy to control the pressure gradient. In this study, an infectious disease hospital in China was selected as the reference object, and the multizone indoor air quality and ventilation analysis computer program CONTAM was used to simulate the airflow direction and pressure difference. A single isolated room model was established to discuss the effect of door gap height on pressure difference and air infiltration and then applied to an entire infectious disease department of the building to analyze the effect in multiple rooms.

2. Methodology

2.1. Simulation tool and Multizone airflow model

CONTAM is an indoor air quality and ventilation analysis computer program. It can calculate airflow rates, pressure infiltration and exfiltration, room-to-room airflow rates and pressure differences in building systems driven by mechanical means [25] (Fig. 1). The reliability of CONTAM’s calculation results has been fully demonstrated in practical examples [26–29]. Computational fluid dynamics (CFD), another commonly used tool for fluid analysis, is a powerful and widely used technique for analysing the various physical phenomena of complex gas flows. The reliability and accuracy of CFD have been verified in the analysis of indoor environments prone to produce pollution, such as hospitals [19,24,30], kitchens [31,32] and laboratories [33,34]. Due to the large number of rooms in the building and the intricate forms, CFD requires a huge amount of computing resources and takes a long time to calculate. Compared with CFD technology, CONTAM has the characteristics of short calculation time, less resource occupation, and simple and clear description information. Therefore, CONTAM is the most suitable tool to analyze airflow, pressure, and pollutants between the various rooms for a building with multiple rooms.

Multizone airflow models have been widely used in analysis of pressure difference, airflow, and pollutant between different rooms [35,36]. The multizone airflow model in CONTAM is a macro model that ignores details of rooms when calculating the pressure and air volume, it is assumed that the air in the area is well-mixed and the parameters are uniform [25]. It uses the power exponential or quadratic relationship between the ventilation volume and the pressure difference between the airflow channels to simulate the ventilation in different types of airflow channels. In this study, the different height of the door gaps will cause different resistances for the air to pass through, resulting in different pressure drops, and finally the pressure on both sides of the door will be different. The air in each room of the building is connected through the door gaps when the door is closed, so a model of multizone airflow is required. The control of the pressure difference is realized by actively creating the difference between the air supply volume and the exhaust air volume. The layout and area of the room, etc., they have little influence on the control of pressure gradient, so it can be considered reasonable to assume that the air in rooms is well-mixed. Therefore, the using of multizone airflow model in CONTAM is feasible.

2.2. Building description

This study selected the infectious disease department of a hospital in China as the real reference object. It is designed according to the guidance of GB50849-2014 [37]. The infectious disease department is arranged according to the medical process of infectious diseases, and the functional division should be refined according to the needs of the treatment process. Zones are divided into contaminated zone, semi-contaminated zone, and clean zone according to the degree of pollution. The corridors are divided into medical corridor (MC) and patient corridor (PC) according to the type of personnel. The contaminated zone includes toilet room (TR), negative pressure isolation ward (NPWW) and buffer room (BR). They are also called ‘three zones and two corridors’.

The infectious disease department of this hospital contains eight sets of negative pressure isolated wards (15 m² per NPWW), each negative pressure isolated ward contains a separate toilet room (2 m² per TR). Negative pressure isolated wards are directly connected to the patient channel (1.30m²), at the same time, it is connected to the medical channel (45m²) through the buffer room (7m² per BR), the air between the rooms is connected through the door gaps. Fig. 2 is a sketch of the infectious disease department which detailed describes the distribution of rooms, personnel direction, and the position of infiltration element. The door height is 2.1m and the door width is 1.1m. The upper sides, left sides, and right sides of the door are well sealed, and only the lower side of the door gap is infiltrated [38]. Fig. 3 is a schematic diagram of the door gap. A seal bar that can adjust the position is installed at the lower part of the door. By adjusting the height of the seal bar from the ground, the size of the door gap can be controlled. Pressure difference between each room is 5Pa. The area outside of the medical and patient corridors is considered to be clean zone, and the base pressure in this zone is 0Pa.

Distribution of supply-air outlets and exhaust-air outlets for each room in the infectious disease department is listed in Table 1. In order to avoid the leakage of pollutants, the ventilation system between the contaminated zone and the semi-contaminated zone is independent of each other.
2.3. Model establishment and verification

The NPIW is the most important room in the entire infectious disease department. The way to avoid cross-infection is to keep the air outside the NPIW to always flowing into the NPIW and to ensure that the contaminated air in the NPIW is only exhausted from the toilet room or through the exhaust fan. Door gaps, as the communication path of air in each room, play an important role in the air supply and exhaust volume required by the control of pressure gradient. Therefore, a set of isolation room containing complete functional areas was selected as the research object to study the ventilation strategy, and this isolation room was also connected to the medical corridor (MC) and patient corridor (PC). The
parameters of the model selected for the study is completely consistent with the actual isolation ward, including the height of the door gap, the width of the door, the room area and the air supply parameters. Fig. 3 shows the sketch of the single set of isolation room model and the model in CONTAM. The drawing also marks the designed pressure of each room and the arrangement of doors between rooms.

Elements in the model contain multiple rooms, simple air handling systems and air flow paths. In this static scene, all doors are closed by default, and air tightness is good except for the lower door gaps. The height of door gaps in the baseline model is 20 mm. The selected infectious disease hospital has reached the design pressure; therefore, the design pressure can be regarded as the actual pressure at this time. The actual parameters shown in Table 2 and the design pressure of the room were input into CONTAM. The air infiltration element we built in CONTAM and the accuracy of the model were verified by comparing the simulated pressure difference of the baseline model with the design value. Then, the effect of door gap height on the air volume required for pressure gradient control was studied by modifying the height of the door gaps between different rooms.

The orifice area data model in CONTAM was selected in the simulation. In this model, the value of discharge coefficient is 0.6, and the flow exponent is 0.65 (default of orifice area data model in CONTAM). Details of the baseline model in CONTAM are shown in Table 2.

The orifice area data model is one of the one-way flows using the power law model. This model allows users to input five parameters: cross-sectional area, flow exponent, discharge coefficient, hydraulic diameter and Reynolds number. Cross-sectional Area refers to the observable area of the opening. Flow exponent n is between 0.6 and 0.7 for typical infiltration openings. Discharge coefficient C is related to the dynamic effects and is typically close to 0.6 for a sharp-edged orifice and slightly higher for other openings in buildings. Hydraulic diameter is equal to 4 × Area/Perimeter. For square openings, this equals the square root of the area, and for long thin openings, it is two times the width. The transition from laminar flow to turbulent flow occurs over a broad range of Reynolds numbers with the flow being fully laminar at approximately below 100. Hydraulic diameter and Reynolds number have little impact on the calculations. Default values should be used except for special circumstances where they need to be modified [25]. The ventilation rates of supply air and exhaust air of a single room entered in CONTAM are shown in Table 3.

### Table 1
Distribution of ventilation system.

| Description | Supply inlet | Exhaust outlet | Air exchange rate (1/h) |
|-------------|--------------|----------------|-------------------------|
| NPIW        | Yes          | Yes            | ≥12                     |
| TR          | No           | Yes            | ≥12                     |
| BR          | Yes          | No             | ≥6                      |
| PC          | Yes          | Yes            | ≥6                      |
| MC          | Yes          | Yes            | ≥6                      |

### Table 2
Details of the baseline model in CONTAM.

| Input parameters          | Value |
|---------------------------|-------|
| Temperature (°C)          | 26    |
| Clean Zone Pressure (Pa)  | 0     |
| Model in CONTAM           | Orifice Area Data |
| Door Crack Size(m²)       | 1.1 × 0.02 |
| Area of Toilet (m²)       | 2     |
| Area of Isolation Ward (m²) | 15   |
| Area of Buffer Room (m²)  | 7     |

### Table 3
Ventilation rates of supply air and exhaust air.

| CASE | NPIW | TR | BR | PC | MC |
|------|------|----|----|----|----|
|      | m³/h |    |    |    |    |
| Case 1 | 540 | -  | 0  | 180| 180|
| Case 2 | 540 | -  | 0  | 180| 180|
| Case 3 | 540 | -  | 0  | 180| 180|
| Case 4 | 540 | -  | 0  | 180| 180|
| Case 5 | 540 | -  | 0  | 180| 180|
| Case 6 | 540 | -  | 75 | 180| 180|
| Case 7 | 540 | -  | 0  | 180| 180|
| Case 8 | 540 | -  | 0  | 180| 180|

| CASE | ventilation rates of exhaust air (m³/h) |
|------|----------------------------------------|
|      |                                        |
| Case 1 | 690 | 150 | 0  | 240| 180|
| Case 2 | 650 | 110 | 0  | 240| 180|
| Case 3 | 615 | 75  | 0  | 210| 180|
| Case 4 | 765 | 75  | 0  | 240| 180|
| Case 5 | 765 | 150 | 75 | 240| 180|
| Case 6 | 690 | 150 | 0  | 240| 255|
| Case 7 | 615 | 150 | 0  | 315| 255|
| Case 8 | 690 | 150 | 0  | 135| 105|

Fig. 3. Sketch of adjustable door gap.
The consistency verification of room pressure is shown in Fig. 4 and the verification of simulated pressure differentials and design pressure differentials is shown in Fig. 5.

The simulation results in the single set of isolation room were confirmed to be consistent with the design values. However, in an entire infectious disease sector, pressure fluctuations can be more complicated. The air in all rooms is connected; hence, pressure change in one room may lead to a pressure change in the entire infectious disease department, and in severe cases, it may even cause the air to flow from the contaminated area to the semi-contaminated area, resulting in the leakage of pollutants. Therefore, model validation is required for the complete infectious disease department. The model of the infectious disease department in CONTAM is shown in Fig. 6. The verification of the simulated and design room pressures of the entire infection disease department is shown in Figs. 7 and 8.

3. Result

Based on the above parameters and verification, a set of ventilation design methods for buildings with differential pressure control requirements can be obtained. Firstly, an area must be selected as the baseline pressure area. The corridors (PC and MC) that have connection relationships with multiple rooms were selected. Then, the required supply air volume for each room and the pressure gradient within the building are determined based on pollutant control needs and regional contaminated
Fig. 6. The verification of the pressure differentials in the single isolation room model.

Fig. 7. The model of infectious disease department in CONTAM.

levels. The next step is to separately calculate the active infiltration air volume between the two rooms according to the pressure gradient of the adjacent rooms and the area of the leakage area (the height of the door gap). Exhaust air volume can be determined according to the existing air supply volume. Finally, the air volume parameters of each room are input into CONTAM, and the air supply and exhaust systems of different rooms are connected to different air handling units according to different partitions to obtain the pressure gradient distribution of the entire building and the air supply and exhaust volume of each partition. After the simulation results were obtained in CONTAM, the parameters of each room were verified to determine whether they meet the design requirements. If errors exist, such as pressure confusion or reverse airflow direction, the flow direction of the airflow channel and the pressure difference on both sides can be checked in the graphical interface of CONTAM to check and adjust the input parameters. Fig. 9 shows the flow chart of the design process.

The relationship between infiltration of airflow and the pressure difference across the leakage is represented by a Eq. (1)[25], which is based on the Bernoulli equation in condition of steady-state, incompressible fluids. This equation was used to design the active infiltration air vol-
ume at different t of door gap height.

\[ Q = C_d A \sqrt{\frac{2\Delta P}{\rho}} \]  

(1)

Where \( Q \) (m³/s) is the volumetric flow rate, which is also the air infiltration volume to control pressure gradient in this research. \( C_d \) is the discharge coefficient, \( A \) (m²) is the area of orifice opening, \( \Delta P \) (Pa) is the pressure difference, \( \rho \) (kg/m³) is the density of air, 1.181 kg/m³ in this study. Theoretically, the value of the flow exponent should lie between 0.5 and 1.0. Large openings are characterized by values very close to 0.5, whereas values near 0.65 have been found for small crack-like openings [25]. Guo et al. also prove that \( C_d \) = 0.64 is reasonable in the calculation of the door crack of the hospital. The independent model (single set of isolation room) mentioned above was selected in this study to explore the influence of door gaps on air supply and exhaust volume and the control strategy of pressure gradient. Moreover, an entire infectious disease department model was used to verify to obtain appropriate pressure difference control strategy. Path A to E represents the air path between each room. Cases 1–3 represent the three scenarios in which the heights of all door gaps are modified, and Cases 4–8 represent the scenarios in which the height of a certain type of door gaps is individually modified. The details are shown in Table 4.

### Table 4
The specific height of door gaps in different cases.

| CASE | Path A | Path B | Path C | Path D | Path E |
|------|--------|--------|--------|--------|--------|
|      | Gap TR to NPIW | Gap NPIW to BR | Gap BR to MC | Gap NPIW to PC | Gap MC to Clean zone |
| Case 1 | 20 | 20 | 20 | 20 | 20 |
| Case 2 | 15 | 15 | 15 | 15 | 15 |
| Case 3 | 10 | 10 | 10 | 10 | 10 |
| Case 4 | 10 | 20 | 20 | 20 | 20 |
| Case 5 | 20 | 10 | 20 | 20 | 20 |
| Case 6 | 20 | 20 | 10 | 20 | 20 |
| Case 7 | 20 | 20 | 20 | 10 | 20 |
| Case 8 | 20 | 20 | 20 | 20 | 10 |

3.1. Case of single set of NPIW

The verified model of the single set of isolation room (NPIW) was used as the baseline model. The height of the door gaps in the baseline model (Case 1) is 20 mm, and the room pressure of the baseline model was verified to be in good agreement with the designed pressure in the above study. Therefore, the state of the baseline model can be considered the design state. After the height of the door gaps was changed, the air supply and exhaust volume of each room in the baseline model was kept unchanged to evaluate the pressure fluctuation of each room. A new variable \( R_o \) is defined to represent the degree of deviation between the simulated pressure and design pressure, which reflects the severity of the room pressure fluctuation before and after the change in door gap height. The definition of \( R_o \) is shown in Eq. (2).

\[ R_o = \left| \frac{P_c - P_b}{P_b} \right| \]  

(2)

where \( P_c \) is the room pressure in the different cases, and \( P_b \) is the pressure in the baseline model and the design pressure. Fig. 10 shows the pressure change and deviation rate when changing the door gap height without adjusting the air volume.

The results in Fig. 10 show the working conditions (Cases 2 and 3) when all the height of the door gaps were modified. The smaller the door...
gap height, the larger the value of negative pressure in all rooms, and the higher the deviation rate \( R_D \). However, the deviation rate \( R_D \) is close to uniform for different rooms in Case 2 and 3. Additionally, when door gap height was modified, the negative pressure in some rooms increased, whereas the negative pressure in some rooms decreased. For example, in Cases 2, 3, 4 and 8, the negative pressure of some rooms dropped after the height of the door gap dropped. Under these circumstances, the pollutants in the room may not be well controlled, and leaks may occur. Combined with the analysis of Fig. 11, the influence of the change in door gap height on the pressure can be analyzed more clearly.

Fig. 11 illustrates the magnitude of the pressure deviation rate of each room when the height of the door gaps at different positions decreases. In Case 4, reducing the height of Path A (Airflow path between TR and NPIW) increased the negative pressure in TR, whereas the pressure in other rooms had almost no change, and the pressure deviation rate was very low. At this time, if the pressure needed to be restored to the design pressure, only the air supply and exhaust volume of one room of TR needs to be modified, whereas the other rooms do not need a major modification. In Case 8, the pressure of each room changed drastically after the height of Path E (Airflow path between MC and Clean zone) was changed. Although the pressure deviation was not as large as that in Case 3, the large difference in the pressure deviation rate \( R_D \) between rooms was observed in this case. Repeatedly adjusting the airflow volume of multiple rooms, which is difficult to accomplish, is necessary to achieve the goal of restoring the design pressure. From the right picture in Fig. 11, the trends of pressure deviations in different rooms when the height of the door gaps change has a certain similarity. The pressure of each room can reach the design pressure again by changing the air supply and exhaust volume of the room. Fig. 12 shows the pressure deviation of each room after adjusting the air supply and exhaust volume.

Fig. 12 shows that the pressure deviation rate \( R_D \) still fluctuated, and the similar trends of the pressure changes in different rooms when the height of the door gaps changed still exist. However, in the five rooms...
Fig. 10. Pressure and deviation rate $R_O$ in 5 rooms for seven cases.
of all cases, the pressure deviation rate $R_q$ remained below 0.0045. At this time, the pressure of the five rooms in these cases has reached the design pressure of the baseline model in Case 1. In this situation, a further analysis of air volume can be carried out. As mentioned above, the pressure in the room will be controlled by the active infiltration volume, which is released by the difference between the air supply volume and air exhaust volume. Variable $\Delta Q$ is defined as the active infiltration air volume, which was used to represent the difference between the supply and exhaust air volumes. The definition of $\Delta Q$ is shown in Eq. (3).

$$\Delta Q = Q_E - Q_S$$

(3)

Where $Q_E$ is the exhaust air volume (or return air volume), and $Q_S$ is the supply air volume. The results in eight cases are shown in Fig. 13.

In the infectious disease hospital, the ventilation systems in the contaminated and semi-contaminated areas are relatively independent, and the air in the contaminated and semi-contaminated areas needs to be handled separately. Therefore, in Fig. 13, the active infiltration air volume $\Delta Q$ is divided into three main parts. The positive value indicates that the area has more air supply volume than exhaust, and a negative value does the opposite.

Firstly, a total active infiltration air volume analysis was performed. Cases 1–3 reflect that the smaller the height of door gaps in all positions, the lesser the active infiltration air volume. The total active infiltration air volumes of Cases 4–7 were the same as the baseline model in Case 1. The door gaps in Cases 4–7 have a common feature, that is, their height-reduced door gaps are in the interior of the building, and the areas connected on both sides of these door gaps are all inner zones. In Case 8, the height-reduced door gap is located at the place connecting the inner and outer zones (clean zone), and its total active infiltration air volume is the same as when all door gaps are 10 mm high in Case 3. Therefore, a preliminary conclusion can be drawn. The effect of reducing the height of the door gaps between the inner zone of the building and the outside zone is the same as reducing the height of all door gaps in the building on the total active infiltration air volume $\Delta Q$, whereas changing the height of the door gaps inside the building has no obvious effect on the total active infiltration air volume.

In terms of the active infiltration air volume in the contaminated and semi-contaminated zones, the most remarkable differences appeared in Cases 1, 2, 3 and 8. In Cases 1–3, the active infiltration air vol-
ume $\Delta Q$ in the contaminated zone gradually decreased by the height of the door gaps, whereas the active infiltration air volume in the semi-contaminated zone did not change. Compared with Case 3, the active infiltration air volume in the contaminated zone of Case 8 increased slightly, whereas that of the semi-contaminated zone decreased. This result shows that compared with Case 3, although the total active infiltration air volume of Case 8 was the same, more air was drawn into the contaminated zone from the semi-contaminated zone inside the building.

Therefore, for a single set of NPIW, the total active infiltration air volume is gradually reduced when all the door gaps of the building are reduced. The total active infiltration air volume does not change if the height of the door gaps located in the inner part of the building is reduced and the door gaps only connect the interior rooms. In comparison, the total active infiltration air volume is the same as that in the case 3, which reduces the height of all door gaps in the model, when only the height of the door gaps where the interior and exterior zones of the building are connected was reduced. Case 3 had the lowest level in the simulation.

### 3.2. Case of entire infectious disease department

After the single set of NPIW was analyzed, the entire infectious disease department model was analyzed. The analysis method for the single set of NPIW was also applied to the following research. Table 5 shows the ventilation rates of supply air and exhaust air of an entire infectious disease department. Fig. 14 shows the magnitude of the pressure deviation rate of each room when the height of the door gaps at different positions were reduced.

As shown in Fig. 14, the trend of pressure deviation after decreasing the height of door gaps in the entire infectious disease sector was similar to that in the single set of NPIW. The pressure deviation rate was the largest when all the door gaps were reduced to 10 mm. Notably, the deviation is beneficial because the negative pressure in all rooms increases, resulting in the lesser pollutant escape. The larger pressure deviation in MC relative to the other rooms were found in most cases. This result shows that in the whole department, the pressure of MC was more difficult to control than the other rooms. The air supply and exhaust volume of the room were adjusted to make the room pressure reach the design value, and then the change in air volume was studied. Fig. 15 is the deviation rate after adjustment.

| CASE   | NPIW | TR  | BR  | PC  | MC  |
|--------|------|-----|-----|-----|-----|
|        |      |     |     |     |     |
|         |      |     |     |     |     |
|         |      |     |     |     |     |
| Case 1  | 540  | 150 | 2340| 810 |
| Case 2  | 540  | 112 | 2340| 810 |
| Case 3  | 540  | 75  | 2340| 810 |
| Case 4  | 540  | 0   | 2340| 810 |
| Case 6  | 540  | 225 | 2340| 810 |
| Case 7  | 540  | 150 | 2340| 810 |
| Case 8  | 540  | 150 | 2340| 810 |

According to the results in Fig. 15, except for the situation of MC in Cases 4 and 8, the pressure deviation rate $R_p$ of the other rooms in all cases was below 0.01, and the deviation rate of MC was higher than those of the other rooms. All rooms had a deviation rate $R_p$ below 0.02. At this time, all room pressures were considered to have reached the design pressure value in the baseline model (Case 1). Air volume analysis was performed on the entire infectious disease department, and the results are shown in Fig. 16.

The results presented in Fig. 16 are similar to that in the single set of NPIW to a certain degree. Overall, the pattern of the overall active infiltration air volume was consistent with the model in the single set of NPIW. Fig. 15 presents that changing the height of door gaps in Cases 4, 6, and 7 had no effect on the active infiltration air volume in different zones. Compared with Case 1, the changes exist in Cases 3, 5, and 8. Compared with all 20 mm door gaps in Case 3, the air volume that needs to actively infiltrate into the building was reduced by 52.20%. Additionally, the air volume that needs to actively infiltrate into the building in the contaminated area and the air volume that needs to actively flow out in the semi-contaminated area were reduced by 69.02% and 78.32%, respectively. In Case 8, only lowering the height of the door gap between the building and the outside world alone can also reduce the air volume that the door gap needs to actively infiltrate into the building by 52.20%. However, the air volume that needs to actively infiltrate into the contaminated area dropped by 14.46%, and the air volume that needs to actively flow out in the semi-contaminated area increased by 8.35%, which are the remarkable differences between Cases 3 and 8. The position where the height of the door gaps changes in Case 8 was located at the junction of the contaminated and semi-contaminated areas. Compared with Case 1, the air volume that needs to actively infiltrate into the building hardly changed in Case 8. However, the air volumes that need to actively infiltrate into the contaminated and semi-contaminated areas were reduced by 38.04% and 56.65%, respectively, and the air exchange inside the building decreased.

Based on the analysis of the eight scenarios above, optimal strategies for adjusting ventilation volume according to door gap height were obtained. The specific strategies for different scenarios are summarized in Table 6. The table shows the specific position of air volume that needs to be adjusted to stabilize the pressure difference gradient of the entire building in different scenarios. DEC means the air volume needs to be decreased, INC means the air volume needs to be increased.

### 4. Discussion

In this paper, a set of ventilation design methods for buildings with pressure gradient control requirements is proposed. We studied the pressure changes when the height of the door gaps was reduced at different positions of the building and analyzed the strategy and adjustment of the active infiltration air volume to restore the design pressure after changing the height of the door gaps.

Obviously, when the overall airtightness of the building is good, that is, the height of the door gaps connecting each room is low, the active infiltration air volume required to maintain the pressure gradient will be reduced. Currently, reducing the exhaust air volume or increasing the air supply volume in the contaminated area, as well as increasing the exhaust air volume in the semi-contaminated area, is necessary. In the case of a building with only good external airtightness, that is, only when the height of the door gap connecting the building and the external environment is low, the overall active infiltration air volume required to maintain the pressure gradient will be reduced. Only reducing the exhaust air volume or increasing the air supply volume in the polluted area is necessary at this time, and the volume in the semi-contaminated area does not need to be adjusted. When a good airtightness exists between the contaminated and semi-contaminated areas, that is, the height of the door gap between the partitions is low, the exhaust air volume of the semi-contaminated area should be increased, and the exhaust air volume...
Fig. 14. Deviation rate of pressure in infectious disease department for seven cases.

Fig. 15. Deviation rate of pressure in infectious disease department for seven cases after modification.

Fig. 16. Active infiltration air volume for eight cases.
of the semi-contaminated area should be reduced, or the air supply volume should be increased. When the height of the door gaps is changed in other positions, the air volume does not need to be adjusted. Complex recalculation and adjustment process are not necessary to carry out when adjusting the air volume of different functional areas. The original design pressure gradient can be achieved by adjusting the air volume of some specific rooms. Ventilation strategies for different situations are shown in Table 6. In addition, the findings of this study can in turn guide the adjustment of door gap height to achieve the required pressure gradient according to different air volumes. Similar results were also shown in some other studies. Lin et al. [39] concluded that the outdoor environment has a significant effect on airflow rate through openings directly connected with outside such as external doors through the study of air infiltration in the aquatic center. Wang et al. [40] also proposed to reduce air leakage by closing windows between the outdoor environment and the building. However, their research focuses on buildings with the same functional zoning. In such a building, the functions of each zone are similar; therefore, the division of the ventilation system is not based on the function of the zone and does not need to strictly control the airflow direction and room pressure gradient. For air infiltration, their focus is on the infiltration between the entire building and the outside world. The present study proposed a method to reduce door gap height to optimize the total air infiltration of the building and analyzed the ventilation strategy of buildings with strict functional area division and pressure gradient control requirements under different door gap heights through the simulation of the whole building. This study is of great importance for guiding the design and operation of ventilation systems in NPIWs, clean workshops, biological laboratories and other buildings that need to control the pressure gradient to achieve a one-way flow of internal airflow and improve room pressure stability.

Noticeably, our study has important limitations. Firstly, our study is based on the hypothesis that the room has good airtightness, and the opening between rooms is only door gaps. In other word, the door gap is the only path for air flow between the two rooms. Moreover, the pressure difference caused by the temperature difference in the room due to different loads was not considered in the scope of this study. This factor may limit the conclusions from this research to buildings with good airtightness and relatively uniform temperature, such as NPIWs and biological laboratories.

Furthermore, our results suggest that MC and PC had larger deviation rates compared with other rooms, and that deviation rate was obvious highly in MC than in PC. This result shows that controlling the pressure stabilization of MC and PC is more difficult than those of the other rooms. We think the reason is that many rooms in the infectious disease department can be indirectly connected to the outside world through the MC and PC. The effect of pressure changes in each room will affect the two corridors that they connect to, that is, the combined effect of the deviation of the pressure values in each room is superimposed, resulting in a larger deviation of the pressure values in these two regions. In addition, the corridor is an area where medical staff and patients often appear. Frequent opening and closing of doors and other behaviors may destroy the original pressure balance, causing pressure fluctuations in the MC and PC. Moreover, the two corridors will become the most vulnerable places for pressure to get out of control in the infectious disease department. Although the buffer room can offset some of these effects, the door on one side of the buffer room can be closed for 1 min before the door on the other side can be opened [41]. However, no literature has reported the quantitative degree of contamination control using a buffer time of 1 min. Hence, a fast control method for behaviors, such as opening and closing doors, is necessary to study to reduce the possibility of pressure imbalance as much as possible and avoid the leakage of pollutants caused by the airflow from the contaminated area to the semi-contaminated area. Therefore, a rapid response control method for air volume in the pressure fluctuation area will be the direction of future study.

5. Conclusion

Multizone indoor air quality and ventilation analysis computer program CONTAM is applied in this study to investigate the effect of height of door gaps on pressure difference and active infiltration volume. The multizone network model of the entire infection disease department was established and verified in CONTAM. Based on the results, a set of ventilation design methods for buildings with requirements of controlling pressure gradient was proposed. Moreover, a ventilation strategy was obtained when the height of the door gap at different positions changes. This strategy does not require the recalculation and redesign of the ventilation of the entire building when air tightness changes cause the pressure gradient to be chaotic. Ordely pressure gradients can be regained with only air volume adjustments made at specific locations. The simulation results will be useful in understanding air infiltration and guiding the design and operation of ventilation systems in NPIWs, buildings remodelled to isolate the close contacts of patients with COVID-19, clean workshops, biological laboratories and other similar buildings.

The main conclusions can be summarized as follows:

1. A ventilation design for buildings that require a strict control of pressure gradients is proposed. The method is designed for complete buildings with multiple zones, avoiding the problems that may occur when the design calculations are performed for individual rooms of the building.

2. The simulation results show that the ventilation strategies for controlling the pressure gradient are not the same under different conditions. A ventilation strategy is proposed to control the infiltration air volume in different areas to achieve an orderly pressure gradient according to the height of door gaps at different positions (different air tightness) in a complete building.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
CRediT authorship contribution statement

Mingyao Ma: Writing – original draft, Formal analysis, Methodology, Changsheng Cao: Formal analysis, Resources. Yukun Xu: Data curation. Zhijian Liu: Investigation. Lingjie Zeng: Writing – review & editing. Chengquan Zhang: Methodology. Jun Gao: Supervision, Methodology, Resources, Investigation.

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