

CFD SIMULATION BASED ON THE RELATIONSHIP BETWEEN ABSOLUTE HUMIDITY AND INFLUENZA SURVIVAL RATE

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Abstract

In this research, Harper's previous experiment data on survival ratio of the influenza virus was re-analyzed from a viewpoint of absolute humidity according to Shaman. Consequently, it was confirmed that the survival ratio of the influenza virus was more correlated with absolute humidity than relative humidity. Moreover, survival change model using the half lifetime of an influenza virus based on Harper's data was found to explain experiment results very well. The virus survival model and diffusion of a virus as a Lagrangian model was incorporated to CFD, and the case study which changed the air-conditioning system was carried out. Consequently, a possibility that indoor influenza infection would be controllable was shown by combining humidification and ventilation.

Keywords: influenza, absolute humidity, survival rate, CFD

1 Background and purpose of research

At present, blocking the spread of novel influenza infection is regarded as an important public health goal, and the effectiveness of air-conditioning indoor environment conditions in inhibiting infection is garnering attention. As shown in Table 1, there are various conceivable routes for influenza infection—contact infection, droplet infection and airborne infection – and droplet infection due to saliva particles produced by the coughing of infected persons is regarded as particularly prevalent.

However, since the scope of action of coughing is less than 2m, pandemics cannot be explained through droplet infection alone. Therefore, in order to examine inhibition of infection, it is also necessary to consider infection routes other than droplet infection. On the other hand, previous research has reported that there is a relationship between survival of the influenza virus and relative humidity, but recently Shaman et al.¹⁾ have attempted to reanalyze this issue, focusing on absolute humidity, and as a result have shown that there is an even more marked relationship. Thus, in this research, experimental results where Harper²⁾ found the survival rates of the influenza virus for a wide range of temperature and humidity conditions based on the findings of Shaman et al. were reanalyzed from the standpoint of absolute humidity. Furthermore, the obtained results were used in describing the results of studies conducted using CFD of the risk of influenza infection in air-conditioned indoor environments.

Table 1: Routes for influenza infection

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- (1) Infection due to physical contact with an infected person
 - (2) Contact infection via an intermediate object
 - (3) So-called "droplet infection" where a person inhales droplets expelled by an infected person due to coughing etc.
 - (4) Airborne infection due to aerosols containing viruses
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2 The relationship between absolute humidity and virus survival rate

Harper released virus solution into the air using an atomizer under a wide range of temperature and humidity conditions, investigated the relationship between elapsed time and virus survival rate, and concluded that the virus survival rate increases under conditions of low relative humidity. Table 2 shows the results of newly adding absolute humidity to these experimental results. Fig. 1 shows the results of plotting data on the survival rate after 1 hour in Table 2, taking temperature, relative humidity and absolute humidity as independent explanatory variables. The R2 values of the respective coefficients of determination are ordered: absolute humidity > temperature > relative humidity (the same also holds for other elapsed times). The results indicated that absolute humidity is important for the virus survival rate, as reported by Shaman et al.

Table 2: Routes for influenza infection

Case No.	Temperature [°C]	Relative Humidity [%]	Absolute Humidity [g/Kg(DA)]	Influenza Survival rate						
				0	1/12	1/2	1	4	6	23 [h]
A-1	7.5	24.0	1.54	100	98.9	90.9	88.6	77.3	71.6	69.3
A-3	7.5	51.0	3.28	100	74.2	113.6	92.4	59.1	63.6	28.8
A-5	7.5	82.0	5.28	100	95.2	56.3	55.6	31.0	27.8	2.4
B-1	22.25	21.0	3.49	100	102.7	86.7	85.3	98.7	88.0	29.3
B-2	22.25	35.0	5.85	100	108.1	67.4	68.6	76.7	61.6	16.3
B-3	22.25	50.5	8.47	100	73.8	58.3	34.5	7.6	5.0	-
B-4	22.25	64.5	10.86	100	58.4	37.7	19.5	8.6	4.2	-
B-5	22.25	81.0	13.70	100	82.1	32.8	19.4	9.6	7.5	-
C-1	32.0	20.0	5.92	100	80.5	64.4	51.7	20.7	19.5	1.5
C-3	32.0	49.5	14.86	100	45.9	22.4	13.3	2.8	0.7	-
C-5	32.0	81.0	24.70	100	54.9	16.5	7.3	-	-	-

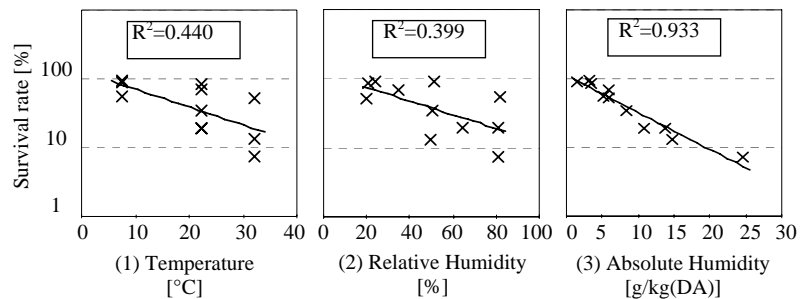


Figure 1: Survival rate relationship

3 Examination of changes over time in virus survival rate

The virus halving time is defined as the time needed for the virus survival rate to drop to 50% or less. For each case in the experimental results of Harper, the halving time was estimated by performing linear regression using the upper and lower 2 or 4 points of data sandwiching the survival rate of 50%. As shown in Fig. 2, a strong correlation was evident in the relationship between absolute humidity and halving time.

Next, the elapsed time (actual time) was made dimensionless using the halving time, and data relating to changes over time in survival rate was arranged as shown in Fig. 3. Fig. 3 shows that the survival rate rapidly drops to about 10% for almost all data, but after that it declines at a slower pace.

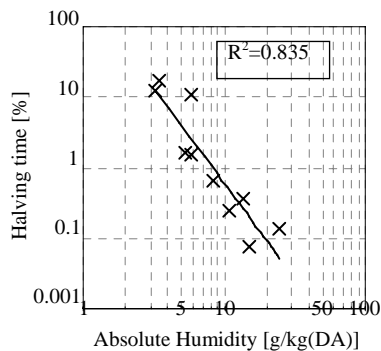


Figure 2: Relationship between absolute humidity and halving time

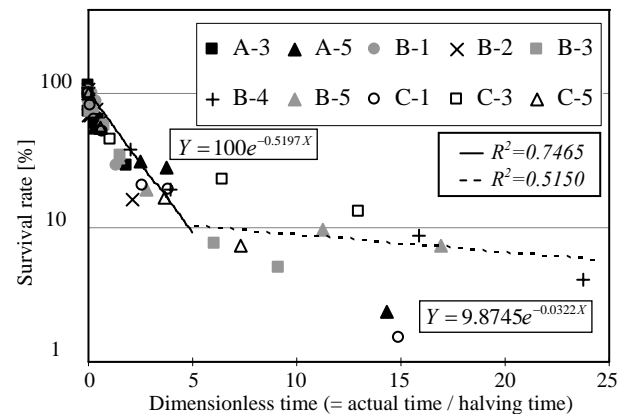


Figure 3: Relationship between survival time and dimensionless time

4 Examination of indoor infection risk using CFD

Assuming a typical 4-bed hospital room (Fig. 4, Table 3), the room was divided into 5 zones: zones A-D consisting of the spaces from floor to ceiling enclosed by the curtain around each bed, and zone E outside those zones. It was assumed that a patient is lying in each bed, and a convective heat value of 33.8 W was assigned to each bed surface. The examined cases are as shown in Table 4. In Case 1, an air supply opening ① and an air exhaust opening ③ are used. The air exhaust opening is provided in the ceiling surface above the bed, and thus it is likely to be effective in eliminating contamination. In Case 2, curtains are provided for Case 1, and this should enhance effectiveness in inhibiting the spread of infection. In Case 3, an air supply opening ② and air exhaust opening ④ are used; the ventilation rate and blowing speed are the same as in Case 1, but the ventilation path is different and the air exhaust opening is located at a position separated from the source of infection. In Case 4, the ventilation path is the same as Case 1, and the ventilation rate is reduced to 1/3 by reducing the blowing speed. Calculation was done using the conditions shown in Table 3, but in 4-1 the calculation takes into account a uniform distribution of absolute humidity in the space, and in 4-2 it takes into account humidification due to coughing in addition to humidification due to air-conditioning. In both cases, the indoor environment was roughly 23°C, with a relative humidity of 50% and an absolute humidity of 8.7 g/kgDA.

4.1 Examination of ventilation efficiency due to the indoor air current structure

The mouth of a human body was simulated at part of bed A, and the spatial concentration distribution was found for the case of constant release assuming that the exhaled air was contaminated. In Figs. 5-7, the values are made dimensionless by dividing by the exhaust concentration for Cases 1-3 where the ventilation rates are equal. In Cases 1 and 2, the path from the mouth to the air exhaust opening, and the area around the path, exhibited high concentration, and furthermore, a fair degree of

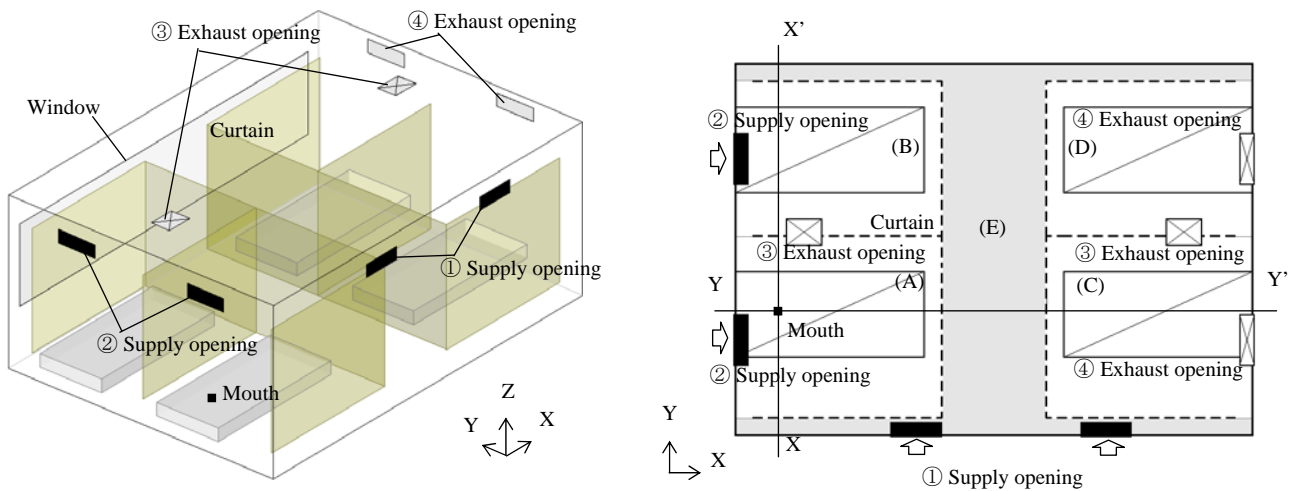


Figure 4: Object of analysis

Table 3. Analysis conditions

Room size	6.0 (X) × 4.3 (Y) × 2.5 (Z) [m]	
Inlet	Supply opening	① 0.6 × 0.2 [m]
		② 0.4 × 0.3 [m]
	Mouth	0.025 × 0.025 [m] Velocity 0.16 [m/s]
Outlet	Exhaust opening	③, ④ 0.4 × 0.3 [m]
Window	5.8 × 1.2 [m], Temperature 5.8[°C]	
Bed	2.2 × 1.0 [m], Convective heat flux 33.8[W]	
Turbulence model	Standard Reynolds number $k-\epsilon$ model	

Table 4. Case analyzed

	Supply opening	Velocity [m/s]	Exhaust opening	Air exchange late [times/h]	Curtain
Case 1	①	0.45	③	6	Not installed
Case 2	①	0.45	③	6	Installed
Case 3	②	0.45	④	6	Not installed
Case 4	①	0.15	③	2	Not installed

Table 5. Computational model for particles

Calculation model	Lagrangian model	
Particle size distribution	300 : 100 : 30 : 5μm = 1 : 1 : 3 : 15, Total 160 [number / min]	
Evaporation limit	Diameter	Over 5μm : evaporable
		Under 5μm : Not evaporable

change in the concentration distribution was evident due to the presence/absence of curtains. In Case 3, the air exhaust opening is located at a position away from the contamination source point, and thus the contamination spreads over a wider range than in Case 1 and 2.

4.2 Examination of the distribution and survival rate of produced particles

Overview of cough model

Coughing was modelled as a jet with a wind speed of 11.2 m/s and a duration of 0.2 s by referring to previous research⁴⁾ based on visualization of coughing, and coughing was assumed to occur in the vertical direction, once every minute, from the mouth of the human body on bed A. The exhalation air due to coughing was set to 32°C and a relative humidity of 95%. The saliva particles produced by coughing were assumed to be pure water, and evaporation in accordance with the ambient vapor pressure was taken into account. Saliva particles which arrive at the wall surface (including the curtain) were assumed to deposit on the wall surface, and evaporation was assumed to continue there. Details are shown in Table 5.

Determination of particle life expectancy

It was assumed that influenza virus with a risk of infection was mixed into all saliva particles. When a particle was generated, a random number in the range $0 \leq X < 1$ was generated using the multiplicative congruential method given in Equation (1).

$$x_{n+1} = \text{mod}(ax_n, y) / y \quad (1)$$

Table 6. Case analyzed

Particle conditions		Percentage of particles in each zone [%]						Remaining particles [%]	Discharged particles [%]
		A	B	C	D	E	Total		
Case 1	Suspended	5.8	4.7	0.2	0.4	1.8	12.9	76.7	23.3
	Surviving	5.5	4.4	0.2	0.3	1.7	12.1		
	Deposited	40.4	15.4	0.7	1.4	6.0	63.8		
	Surviving	26.6	13.3	0.5	1.1	5.3	46.7		
Case 2	Suspended	11.5	1.6	0.0	0.0	0.4	13.6	68.9	31.1
	Surviving	11.2	1.5	0.0	-	0.4	13.1		
	Deposited	47.0	6.2	0.1	0.1	2.0	55.4		
	Surviving	31.6	5.0	0.1	0.1	1.3	38.4		
Case 3	Suspended	2.8	3.2	0.3	0.3	2.2	8.7	96.5	3.5
	Surviving	2.7	3.1	0.3	0.2	2.1	8.4		
	Deposited	44.3	20.4	1.1	1.2	20.7	87.8		
	Surviving	28.9	17.5	0.9	1.0	17.4	65.6		
Case 4	Suspended	3.2	5.7	0.4	0.3	2.4	11.9	94.2	5.8
	Surviving	2.8	5.5	0.4	0.3	2.1	11.1		
	Deposited	37.9	22.4	0.3	0.5	21.3	82.4		
	Surviving	24.7	19.0	0.3	0.3	18.0	62.3		

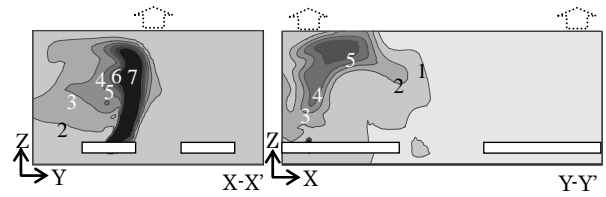


Figure 5: Case 1 nondimensional concentration distribution

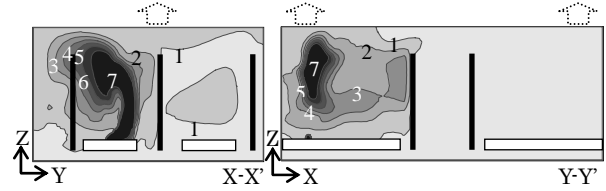


Figure 6: Case 2 nondimensional concentration distribution

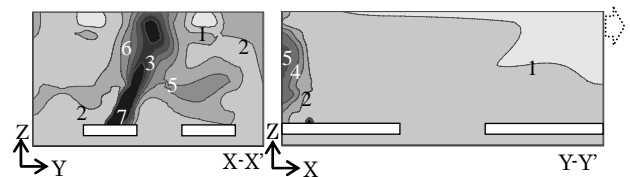


Figure 7: Case 3 nondimensional concentration distribution

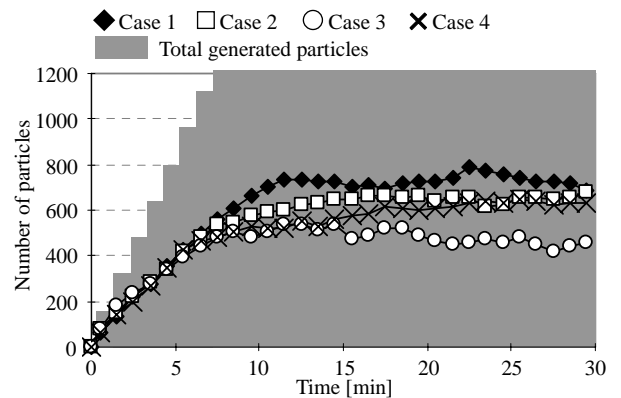


Figure 8: Time changes of Number of suspended particles

A dimensionless life expectancy was assumed in accordance with the expression relating dimensionless time and survival rate in Fig. 3. It was assumed that each particle loses expected life in accordance with the ambient absolute humidity, and that the influenza virus ceases to survive in particles whose life is 0 or less. For example, if the random number assigned to a certain particle is assumed to be 0.5, then based on Fig. 3 the dimensionless life of that particle becomes about 1.33. If this particle is exposed for 1 minute to an environment with an absolute humidity of 8 g/kgDA, it loses about 0.015 of its dimensionless life expectancy based on Fig. 2, and if that state continues it will cease to survive after approximately 90 minutes.

Number of suspended particles at each unit time

A total of 4800 particles were generated for each Case 1-4. Fig. 8 shows the relationship of elapsed time and number of suspended particles for each case, and the percentage of particles in each zone and the percentage of those which are surviving are shown in Table 6 and Fig. 9. As can be seen in Fig. 8, the number of suspended particles in the room does not depend on the ventilation path or ventilation rate in this study, and it continues to increase in the same way until about 10 minutes after the start. However, during this period some of the particles deposit on the walls or are discharged outside the room. Subsequently, from roughly the 15 minute mark, the number of suspended particles remains at a constant value, but in Case 4 where the ventilation rate is low, there is a trend where the number increases somewhat after 30 minutes. It was also found that differences arise in the number of suspended particles due to the ventilation path and ventilation rate.

Percentage of particles discharged

Looking at the percentage of particles discharged based on Table 6, the percentage of all generated particles in Case 1 was 23% and the percentage in Case 2 were 31%. In contrast, the percentage was 3.5% in Case 3 where the ventilation path is different, and 5.8% in Case 4 where the ventilation path is the same as Case 1 but the ventilation rate is low. Thus there were marked differences due to the ventilation path and ventilation rate. In terms of the particle distribution in each zone, there was almost no spread of particles to zones C and D in any of the cases, but whereas the spread of particles to zone E was 7.8% in Case 1 and 2.4% in Case 2, it was 23% in Case 3 and 24% in Case 4.

Spread of particles from the generation source

Looking at the spread of particles from zone A where the infected person is located, in Case 1 the total of the number of particles in zone A and the number of discharged particles was 70%, and the total in Case 2 with the curtain installed was 90%. Thus although the spread of particles from zone A was effectively prevented, the total was 51% in Case 3 and 49% in Case 4, and the percentage of all generated particles outside of zone A stayed at roughly 50%.

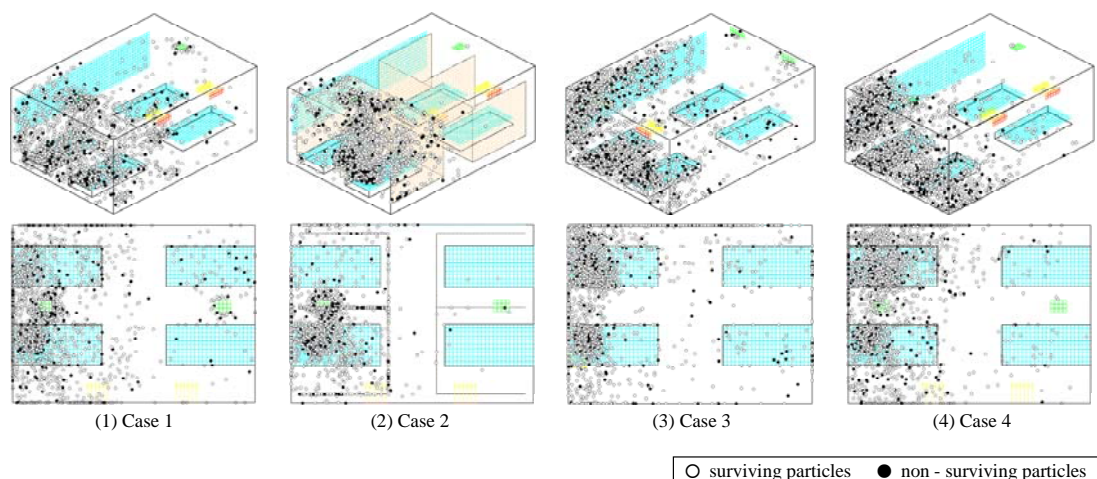


Figure 9: particle distributions

Percentage of particles surviving

Looking at the percentage of surviving particles in each zone, almost all particles, except for the deposited particles in zone A, survived regardless of the zone, suspension or deposition. However, in terms of the percentage surviving relative to remaining particles, roughly 20% were in the non-surviving state in all cases. This is thought to be because the particles which deposit near the mouth (the cough generation point) in zone A are frequently exposed to an extremely high humidity environment (32°C with 95% relative humidity) produced by coughing, and it is more difficult for particles to survive compared to other zones, thus lowering the overall survival rate.

Relative humidity and percentage of particles surviving

Thus, in order to evaluate the effects of the humidity environment in the room on the particle survival rate while excluding the effects of humidification due to the exhalation of the human body on the particle survival rate, it was tentatively assumed that the temperature in the room was a uniform 23°C and the relative humidity was 30, 50 or 70%, and the virus survival rate was found for each relative humidity condition. The results are shown in Table 7. In terms of the particle survival rate itself, almost no differences were seen between cases with the same humidity. The difference in survival rate with a humidity difference of 40% at a relative humidity of 30–70% was 10% for suspended particles and 30% for deposited particles, and the survival rate of particles remaining in the space decreased by about 10% each time the relative humidity increased by 20%, and this change is not due to the ventilation path or ventilation rate. On the other hand, the percentage of surviving particles relative to all generated particles also includes the effect of discharge outside the room shown in Table 5, and thus differences were evident between the different cases. If cases at the same humidity are compared then, for example, whereas the percentage of surviving particles is 66% with a relative humidity of 30% in Case 2, the percentage is 93% in Case 3 and 91% in Case 4. By adding differences in humidity to this, a maximum difference of 45% was evident in the percentage of surviving particles in the space relative to all generated particles.

In the cases examined here, the percentage of particles discharged relative to all generated particles was a maximum of 31% and a minimum of 3.5%, and the results suggest that an inhibitory effect on infection in the room can be achieved by combining discharge through ventilation with a reduction in survival rate due to humidification.

Table 7. Relationship between relative humidity and parentage of particles surviving

	Relative humidity [%]	Suspended particles (surviving)		Deposited particles (surviving)		Surviving particles	
			Survival rate		Survival rate		Survival rate
Case 1	30%	12.7	98.4	61.3	96.0	74.0	96.4
	50%	12.2	94.5	54.5	85.4	66.7	86.9
	70%	11.2	87.2	43.1	67.6	54.4	70.9
Case 2	30%	13.4	98.6	53.0	95.7	66.4	96.3
	50%	13.2	96.9	46.3	83.6	59.5	86.3
	70%	12.1	88.9	36.1	65.2	48.2	69.9
Case 3	30%	8.6	99.0	84.3	96.1	93.0	96.4
	50%	8.4	96.9	75.0	85.5	83.5	86.5
	70%	7.9	90.2	60.0	68.4	67.9	70.4
Case 4	30%	11.6	98.1	79.2	96.2	90.9	96.4
	50%	11.2	94.7	70.3	85.4	81.6	86.6
	70%	10.1	85.1	56.2	68.2	66.3	70.4

5 Conclusion

In this research, experimental results on the survival rate of the influenza virus according to Shaman were reanalyzed from the standpoint of absolute humidity, and there was found to be a stronger relationship with absolute humidity than with the previously cited relative humidity. Changes over time in the virus survival rate were standardized using halving time, and a basic examination of the infection inhibition effect in the room was conducted from the standpoint of ventilation and humidification by endowing particles with a survival rate and using CFD. The results indicated the possibility that combining ventilation and humidification may be an effective way to inhibit the spread of infection indoors.

6 References

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