CFD Analysis of the Inhaled-Air Quality for the Inpatients in a Four-Bed Sickroom

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Abstract

This study examined the effects of the position and number of the supply openings (SOs) and exhaust openings (EOs) on the inhaled-air quality of inpatients using Computational Fluid Dynamics (CFD) analysis. The positions and number of SOs and EOs were selected to create mixing ventilation, displacement ventilation for a calm indoor environment, and personal ventilation for each inpatient's ventilation. The effect of the installation of a curtain in the sickroom on the inhaled-air quality for inpatients was also examined. The inhaled-air quality of the inpatients was evaluated using the age of air, residual life of air, contribution ratio of nostril-exhaled air, and contribution ratio of the pollution source from the sickroom floor. CFD analysis showed that displacement ventilation, which uses a large SO with a low airflow velocity, supplied better air to the inpatients than the other ventilation methods, but pollution from the sickroom floor made a significant contribution. Overall, in general sickrooms and intensive care units, low-airflow-velocity displacement ventilation can supply high-quality air to the inpatients but the sickroom floor must be cleaned thoroughly.

Keywords: sickroom; inpatient; inhaled-air quality; CFD

1. Introduction

Sickrooms are inhabited for a long time by inpatients, who have impaired natural immunity. Therefore, careful attention must be paid to nosocomial infections in multibed sickrooms. Nosocomial infections occur via a range of routes. Beggs et al.\(^1\) explained that nosocomial infection occurs when bacterial, fungal, or viral etiologies propagate via the airborne route. Beggs\(^2\) reported that the number of cases of airborne nosocomial-infections is increasing. Therefore, nosocomial infections must be controlled by ventilation not only in isolation wards but also in general sickrooms.

In Korea, there are no regulations or design guidelines for the airflow rate or air change rate in hospitals, and ventilation is planned according to ASHRAE Standard 62, USA\(^3\) or HEAS-02, Japan\(^4\). These two standards stipulate only the airflow rate or air change rate according to the required cleanliness, and do not suggest appropriate ventilation methods.

The ventilation systems applied to sickrooms have not been unified in many countries, and many designers and researchers have examined them in a variety of ways. Cheong \textit{et al.}\(^5\) combined the supply openings (SOs) and exhaust openings (EOs) into three types to evaluate their decontamination performance in sickrooms. Chau \textit{et al.}\(^6\) proposed local exhaust ventilation, and evaluated the ventilation efficiency to ensure the safety of healthcare workers, who work in the sickrooms of SARS inpatients. Yuguo \textit{et al.}\(^7\) evaluated the ventilation performance in nine hospitals in Hong Kong that have SARS isolation wards, etc.

The above studies used different evaluation indices as well as the ventilation and air-conditioning methods that were limited to different sickroom structures to examine the ventilation efficiency. Consequently, the ventilation efficiency for each sickroom could be examined, but could not be compared with those under different conditions. Moreover, previous studies did not involve the inpatients. Inpatients form a thermal plume as heating elements. The reproducibility of the thermal plume of inpatients influences the inhaled-air quality of the inpatients significantly because the low velocity airflow is dominant in sickrooms. This study describes precisely the shape of an inpatient lying on a bed for the purpose of CFD analysis. In addition, this study reviewed the inhaled air quality by reproducing the metabolic rate of the human body and generating a thermal plume around the inpatient.

The author examined the effects of the positions and number of EOs on the air inhaled by inpatients when one SO was fixed using CFD, as in a previous study\(^8\). The present study further develops the previous study by examining the effect of the positions and number of SOs and EOs on the inhaled-air quality of inpatients...
using CFD to provide basic data on the ventilation design. The positions and number of SOs and EOs were determined based on the data obtained from other studies, and from the authors’ visits to three hospitals in Korea. Four-bed sickrooms were selected as the subject spaces, where the air exhaled by an inpatient can affect the other inpatients in the room. A curtain that can influence the indoor airflow was installed in the sickrooms to examine its effect on the inhaled-air quality.

2. Overview of CFD Analysis

2.1 Subject Space

The subject spaces for CFD analysis were 6×5×3 m four-bed sickrooms. As shown in Fig.1., a 3×5×3 m subject space with four beds, where a symmetry plan was installed at the center considering the symmetry of airflow, was prepared. Two inpatients were placed in the subject space. The inpatients were formed by simulating an accurate human-body shape, which was called 'human-shape model (HSM)' in this study. HSM is a modification of the HSM used in the author's previous study in the shape of an inpatient.

The positions and number of SOs and EOs were varied in each analysis case. The standard case is where a curtain is installed between the beds. The subject space for CFD analysis was divided into approximately 350,000 to 400,000 cells to establish the analysis geometry.

2.2 Analysis Cases

Fig.2. shows a total of 6 cases as well as the analysis geometry. Case A-1 involved general mixing ventilation, and displacement ventilation was applied to cases A-2 and A-3. Case A-3 was obtained by increasing the size of the SO in case A-2 to reduce the supplied wind velocity. In case B, both the SO and EO were installed individually for each inpatient, which denotes personal ventilation. In cases B, the SO or EO was installed at the ceiling or wall above the HSM head, or at the ceiling above the HSM foot. In Case B-1, the EO was installed on the wall above the HSM's head so the contaminated air supplied to the interior can be exhausted immediately through the nostrils of the HSM. In Case B-2, the SO was installed on the ceiling above the HSM's legs to prevent a cold draft caused by the intake air supplied through the SO. In Case B-3, the SO was installed on the ceiling above the HSM's head to allow direct supply of fresh air to the air inhalation region.

These were done to examine the inhaled-air quality for the inpatients according to the positions of the SO and EO. The size of the SO and EO that were installed for each case was 0.3×0.3 m, but a SO of 0.6×0.6 m was applied to cases A-3.

2.3 Boundary Conditions

Table 2. shows the boundary condition for CFD analysis. The commercial code Star-CD was used for CFD analysis. The renormalization group (RNG) k-ε model was used as the turbulence model, the SIMPLE method was used as the algorithm, and the first upwind scheme was used as the scheme for the study. The convective and radiative heat transfer was calculated by CFD analysis.

The rate of the airflow supplied to the subject space through the SO was determined to be 0.075 m³/s, corresponding to 3 ACH (air changes per hour), which is the minimum air change of outside air per hour in an intensive care unit (ICU) stipulated in HEAS-02, Japan. The EO was determined to be the free-slip against velocity and temperature. The wall, curtain and bed were subjected to the generalized log law and were adiabatic against velocity and temperature. The curtain actually allows air or heat to flow because it is made of textile, but this was not considered in this study. The active level of the HSM was determined to be 0.7 met (=40.74 W/m²) in the sleeping state. The equation used by Tanabe et al. for the heating of a thermal manikin was used for this conversion (Equation 1). Assuming that the body surface area was 1.5 m², the 0.7 met resulted in 32 W of sensible heat transfer.

\[ Q_m = 1.96 \times Q_t - 21.56 \]
The HSM emits heat through its 'head' and 'center of blanket', and the area ratio of these two regions is 6.8:93.2. The sensible heat transfer rates of the 'head' and 'center of blanket' were set to 22.0 and 23.7 W/m$^2$, respectively, considering the area and area ratio. The emittances of the head of the HSM and blanket were set to 0.95 and 0.9, respectively.

The breathing of the HSM was determined to be the steady inhalation model of Hayashi et al.$^{13)}$. This model was used to examine the effect of the air exhaled by the HSM on the neighboring HSM. The curtain was made from actual fabric, enabling air and heat to transfer. This study did not take this feature into consideration. The emittances of all the walls and curtains were set to 0.9.

### 2.4 Index for Inhaled-Air Quality

In this study, the inhaled-air quality was evaluated using the scales for ventilation efficiency (SVEs) proposed by Kato and Murakami,$^{14)}$ and the contribution ratios of the pollution source (CRPs) proposed by Hayashi et al.$^{15)}$.

\[
SVE3(X) = \frac{C_{x}(X)}{C_{S}} \quad (2) \quad SVE4(X,n) = \frac{C_{a}(X)}{C_{no}} \quad (3)
\]

\[
SVE6(X) = \frac{C_{1}(X)}{C_{o}} \quad (4) \quad CRP_{i} = \frac{q_{i}}{Q_{i}} \quad (5)
\]

The age of the air in the room was calculated using $SVE3$, which evaluates the average time that it takes for fresh air supplied in the room to reach a specific point. $SVE3 = 1$ means that the fresh air reaches a specific point through the SO during the time equivalent to 1 ACH.

The contribution ratio of the SO in the room was calculated using $SVE4$. When there are many SOs in

| Table 2. Boundary Conditions |
|-----------------------------|
| Object                      | Conditions                                      |
| Supply openings             | • Airflow rate: 0.075 m$^3$/s • Air change rate: 3 ACH • Turbulence intensity: 10% • Turbulence scale: 0.01m • Temperature: 297 K • Standard opening - Size: 0.3m x 0.3m - Velocity: 0.8333 m/s • Large opening (Case A-3) - Size: 0.6m x 0.6m - Velocity: 0.2083 m/s |
| Exhaust openings            | • Velocity and temperature: free slip • Size: 0.3m x 0.3m |
| Surrounding walls and Curtain | • Velocity and temperature: generalized log law • Adiabatic |
| Human shape models(HSM)     | • Velocity and temperature: generalized log law • Active level: 0.7 met [19] • Sensible heat transfer: 32 W • Head: 22.0 W/m$^2$ • Center of blanket: 23.7 W/m$^2$ |
| Inhalation and exhalation of HSM | • Size of nostril: 2.94E-4 m$^2$ • Airflow rate: 2.4E-4 m$^3$/s • Velocity: 0.8163 m/s • Temperature*: 305 K • Turbulence intensity*: 10% • Turbulence scale*: 0.001m |

* is the case of application to exhalation of HSM A
the room, $SVE4$ evaluates the effect of the air supplied by a specific SO on the air in the room. In this study, the air exhaled from the nostrils of HSM A was assumed to be contaminated, and its contribution to the inhalation of HSM B was evaluated. The concentration of contaminated air exhaled by HSM A was determined to be 1 (kg/kg'). If the contribution to HSM B, or $SVE4$, is close to 1, the degree of exposure to the contaminated air exhaled by HSM A is higher.

The residual life of the air in the room was calculated using $SVE6$, which evaluates the mean time for the air at a specific point in the room to be discharged through the EO. $SVE6 = 1$ means that the air at a specific point is discharged through the EO within the time equivalent to 1 ACH.

$CRP1$, the human inhalation of a contaminant from a certain source was evaluated as a percentage. A low $CRP1$ means a low contribution of the contaminant, and a better inhaled-air quality. In this study, it was assumed that 1 kg/(m$^2$·s) contaminant was generated from the sickroom floor. The floor comprises the largest area of the sickroom and is close to the occupied zone and a patient's air inhalation region. Therefore, a sickroom requiring high purity is quite sensitive to the impact of pollution coming from the floor.

The contaminated air from the HSM and the contaminant from the sickroom floor were analyzed using the passive scalar method, which is passive against the airflow in the room. The passive scalar method uses the transport equation for gas-phase contaminants. Liu et al.\textsuperscript{16} and Annis\textsuperscript{17} reported that the bacterial and viral particles can be analyzed using the transport equation for gas-phase contaminants because their diameters are 20 μm or less. In addition, they reported that the small bio-aerosol generated by coughing or sneezing can be analyzed using this method.

Gas-phase contaminants do not target any specific gas. A range of gas-phase contaminants arising from a construction space generally do not show enough emissions and concentrations to alter the indoor airflow. In this study, the contaminant concentrations of 20 μm-or-less particles and unspecified gases were estimated and evaluated using the passive scalar method. Therefore, the contaminated air from the HSM and the contaminant from the sickroom floor point to 20-μm-or-less particles or gas-phase contaminants.

3. Results

3.1 Distribution of Airflow

Fig.3. (standard cases without a curtain) and Fig.4. (curtain installation cases) present the 6 analysis results for each case in this study. In case A-1, the fresh air supplied through the SO collided with the
floor at HSM B's side and propagated towards HSM A while surrounding HSM B. Accordingly, the thermal plume of the HSM was broken. In case A-2, the air supplied through the SO collided with the wall at HSM A's side, covered HSM A, and returned to HSM B's side. Accordingly, the thermal plume of the HSM was broken. Even if displacement ventilation was applied to case A-2, the strong circulation airflow in the room led to the same results as those of mixing ventilation. In case A-3, where fresh air was supplied at a low airflow velocity through a larger SO, there was no strong circulation airflow, which is in contrast to that generated in case A-2. Therefore, a calm airflow environment was formed in the room, and the thermal
plume of the HSM was produced.

In case B, one SO and one EO were installed for each HSM to create a positional change. In case B-1, the airflow that was supplied through the EO and the thermal plume of the HSM were mixed in the airflow around the head because the EO was installed at the wall at the side of the HSM's head. In all cases, the airflow rate around the HSM was lower than the 0.25m/s recommended by ASHRAE Standard 55th.

Fig.4. shows the change in the airflow in the room according to the curtain installation. In case A-1, the fresh air supplied to HSM B's side was blocked by the curtain, and strong circulation airflow was formed in the curtain region at HSM B's side. A part of this circulation airflow was supplied via the lower part of the curtain at HSM A's side. In case A-2, the fresh air supplied to HSM A's side was blocked by the curtain and was supplied via the lower part of the curtain at HSM B's side. Accordingly, a thermal plume of HSM B was formed, which is in contrast to the standard case. In case A-3, where a larger SO was applied, the results did not differ significantly from those of the standard case. In addition, the thermal plume of the HSM was also produced.

In case B, the results did not differ significantly from the airflow characteristics of the standard case. This suggests that with personal ventilation, curtain installation in a sickroom does not greatly affect the airflow characteristic.

3.2 Distribution of SVE3 and SVE6

In this chapter, only the distributions of SVE3 and SVE6 for specific cases are stated because there were many cases. Fig.5. shows the SVE3 distribution in case A-1 according to whether or not a curtain was installed. In the standard case, the SVE3 around HSM B was somewhat lower than that around HSM A due to the effect of the SO. The SVE3 around the face of HSM A was 0.7-0.75, and that around the face of HSM B was 0.65-0.7. In the curtain installation case, the fresh air supplied to the region partitioned by the curtain did not propagate to the other spaces but remained around HSM B. Therefore, its SVE3 was lower than that in the standard case. The SVE3 around the face of HSM A the face of HSM B was 0.65-0.7 and 0.6-0.65, respectively.

Fig.6. shows the SVE6 distribution in Case A-1 according to curtain installation. The SVE6 around HSM A was lower than that around HSM B because the EO was installed at the ceiling at HSM A's side. In the standard case, the SVE6 around the face of HSM A and HSM B was 0.6-0.65 and 0.7-0.8, respectively. In the curtain installation case, the fresh air supplied to HSM A could not proceed to HSM B due to the curtain, and was exhausted directly through the EO. Therefore, the SVE6 at HSM A's side was much lower than that at HSM B's side. The SVE6 around the face of HSM A and HSM B was 0.5 or less, and 0.8-0.9, respectively. Therefore, curtain installation led to a large difference between the SVE6 values of HSM A and HSM B.

3.3 Evaluation of Inhaled-Air Quality of HSM

1) SVE3

Fig.7. shows the SVE3 analysis results. The blue bars represent the standard cases, the red bars represent the curtain installation cases, and the green lines represent the average of all cases. The SVE3 values in the graph were obtained by averaging the time that it takes for the fresh air supplied through the SO to reach the nostrils of HSM A and HSM B, and by converting it to the air change rate.

In cases A-1 and A-2, the SVE3 decreased by 0.1 and 0.2, respectively, due to curtain installation. In the other cases, the changes in the SVE3 due to curtain installation were less than 0.1. In case A-2, the fresh air supplied to HSM A collided with the wall and was trapped in the curtain, resulting in a low SVE3 of HSM A.

In case A-3, the SO size was larger than that in case A-2 to supply low-airflow-velocity fresh air and create a calm indoor environment. The SVE3 in case A-3 was lower than that of case B. They were even lower than that in cases B-3, where the SO was installed at the ceiling above HSM's head to supply fresh air directly to the HSM. In case A-3, the SVE3 was 0.28 and 0.3 in the standard and curtain installation case, respectively.

2) SVE6

Fig.8. shows the SVE6 analysis results. In this study, the SVE6 of the first cell of the HSM face was presented in a graph in terms of the volume-weighted average.

In cases A-1 to A-2, where the indoor air was well mixed, curtain installation led to a 0.1-0.4 decrease in the SVE6 value. This is because the curtain reduced the mixed air and increased its exhaust rate. In the other cases, the change in the SVE6 value was less than 0.1 according to curtain installation.

In case A-3, the SVE6 value was the second lowest, following that in cases B-1, where the EO was installed at the wall above the HSM's head. As the indoor airflow in case A-3 was under a calm environment, the indoor air was guided to the upper part of the sickroom by the thermal plume of the HSM, and was exhausted rapidly through the EO at the upper wall without propagating to the other spaces. In cases B, the SVE6 value was low when the EO was installed around the HSM'S head, which is in contrast to the SVE3 values obtained.

3) SVE4

Fig.9. shows the SVE4 analysis results. The SVE4 in case A-3 was the lowest. The change in the SVE4 value according to curtain installation was quite low (0.07%). This is because the air that had been exhaled from the nostrils of HSM A was guided to the upper part of the sickroom by the thermal plume of the HSM, and was exhausted rapidly through the EO at the upper wall without mixing to the other spaces. In cases B-1, the SVE4 value was higher in the cases where the EO was installed around the HSM's head than in the other
The air that was exhaled from the nostrils of the HSM propagated around the room via the torso of the HSM, and was exhausted through the EO. When the EO was installed around the HSM's head, the exhaled contaminated air was exhausted through the EO, affecting the air inhalation region of HSM B and increasing the SVE4 value. The change in SVE4 value according to curtain installation was highest (0.41%) in case A-2, and was 0.1% or less in the other cases.

4) CRP1

Fig. 10. shows the CRP1 analysis results. Case A-3 showed good inhaled-air quality in SVE3 to SVE6, but had the worst inhaled-air quality in CRP1. In case A-3, fresh air was supplied at a low airflow velocity from the SO installed at the floor so it could not mitigate the contaminant, and was supplied to the air inhalation region of the HSM. In cases A-1 and A-2, the CRP1 value was lower than that in case A-3. The CRP1 was lowest in case B-3, where fresh air was supplied directly to the air inhalation region of the HSM, and where good inhaled-air quality could be ensured.

4. Discussion

As mentioned above, displacement ventilation, where fresh air is supplied at a low airflow velocity through a large SO, supplied better air to the inpatients than the other ventilation methods. Therefore, in general sickrooms and ICUs, displacement ventilation with a low airflow velocity can supply high-quality air to the inpatients. This method, however, can be the most dangerous ventilation method, and the sickroom floor must be kept clean when there is contamination on it.

In addition, even with displacement ventilation, the inhaled-air quality decreased when the high-airflow SO was selected, and produced strong circulation airflow in the sickroom. Therefore, the air supply velocity must be at a level that would not break the thermal plume of the inpatient. For this, the circulation airflow in the sickroom must be examined accurately using CFD analysis or experiments from the design stage.

5. Conclusion

1) With mixing ventilation, curtain installation in the sickroom produced a change in the airflow characteristics. The changes in personal ventilation were not significant. In low-airflow-velocity displacement ventilation, the thermal plume of the inpatient was not broken and rose up in the room.

2) The SVE3 was analyzed to examine the age of the air in the sickroom. The displacement ventilation, where fresh air was supplied at a low airflow velocity through a large SO, was found to be the most efficient method for improving the inhaled-air quality. The second most efficient ventilation method involved the installation of the SO at the ceiling above the head of the inpatient.
3) For SVE6, the inhaled-air quality was best when the EO was installed at the wall of the inpatient's head. The displacement ventilation with a low airflow velocity was the second best.

4) The analysis results of SVE4 showed that the displacement ventilation with a low airflow velocity had the lowest contribution ratio.

5) For CRP1, the displacement ventilation with a low airflow velocity had the highest contribution ratio. The contribution ratio was lowest when the SO was installed at the ceiling above the head of the inpatient.

6) The nozzle type diffuser was selected as the supply opening in this study. The indoor spread of supplied air differs according to the type of diffuser. Nevertheless, further research on the air quality inhaled by an inpatient according to the type of diffuser is needed.

**Symbols**

1) \( CRP_i \) : contribution ratio of the pollution source \( i \) (%)
2) \( C_{c}(X) \) : concentration at point \( X \) where the tracer is uniformly generated through a room in total generation rate \( q \) (kg/s)
3) \( C^{vir}(X) \) : virtual concentration at point \( X \) where the tracer is uniformly generated through a room in total generation rate \( q \) (kg/s) and time pass in reverse
4) \( C_{um}, C_e \) : concentration under perfect mixing conditions,
   \( C_{um} = q/Q \)
5) \( C_{ve} \) : concentration of the tracer at the nth supply opening,
   \( C_{ve} = q/Q \)
6) \( SVE3(X) \) : age of air at position \( X \) in the spatial room
7) \( SVE4(X,n) \) : contribution ratio of the nth supply opening at point \( X \)
8) \( SVE6(X) \) : residual life time of air at position \( X \) in the spatial room
9) \( q \) : tracer generation rate (kg/s)
10) \( q_i \) : pollutant (i) inhaled by a human (mg/s)
11) \( Q \) : total airflow rate (m/s)
12) \( Q_i \) : amount of pollutant (i) generated (mg/s)
13) \( Q_{ve} \) : airflow rate at the nth supply opening (m/s)
14) \( Q_{ve} \) : total heat transfer rate (W/m²)
15) \( Q_{se} \) : sensible heat transfer rate (W/m²)

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