Mechanical Ventilation Strategy for Subway Cabins
Using Numerical Simulations

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Abstract: Seoul metropolitan subway network is known to be the one of the most heavily used transportation means in the world. The subway cabins are naturally ventilated when the cabin doors are opened and through the gaps caused by the incomplete air-tightening of cabin bodies. Although, subway trains are equipped with a mechanical exhaust fan, the apparatus is rarely operated due to the problem of heating/cooling efficiency especially in the summer and winter seasons. In this study, we analyzed the transient CO₂ (carbon dioxide) concentration level during the journey of a subway cabin when a heavy load of passengers of up to 200% of designed capacity using a CFD (computational fluid dynamics) analysis. With an increased journey time, the CO₂ concentration increased by up to 5,000 ppm depending on passenger load. Through the operation of a mechanical exhaust fan, the high concentration of CO₂ decreased down to 1,500 ppm. The effect of the exhaust fan operating on the dilution of indoor air was estimated by comparison with a closed cabin. In addition, the energy consumption for cooling in summer time was assessed for exhaust fan operations.

Key words: Subway cabin, ventilation, carbon dioxide, CFD, exhaust fan.

1. Introduction

The SMS (Seoul Metropolitan Subway) is an important transportation means as it transports an average of 7.4 million passengers on 5,697 subway trains journeying 736.6 km a day as of 2009 [1]. Modern people spend most of their day indoors, and the air quality of the subway, the key transportation means, has gained much attention because it is related to quality of life issues. The indoor air quality of the subway becomes more important with the installation of PSDs (platform screen doors). Although the installation of PSDs has helped to improve the air quality on the platform and waiting areas [2], the pollution inside the tunnel is expected to have become relatively worse. As such, deterioration of the air quality inside the subway cabins of the urban subway operating in the tunnel zones has been a major issue.

Air-tightening the cabin to prevent the inflow of polluted air from the outside can cause discomfort and cause drowsiness because of the increased carbon dioxide coming from the breathing of the passengers inside the cabin [3]. This study intends to numerically analyze the ventilation of cabin air using the forced exhaust outlet on the change of carbon dioxide concentration indoors and to predict the change of thermal comfort of the indoor space at the same time. The study’s purpose is to obtain the reference material for a ventilation strategy for subway cabins and the development of air quality improvement technology in the future.

2. Methods

2.1 Subway Cabin Air Conditioning System

The subway trains operating in the metropolitan area have two air conditioners on top of the vehicle roof and uniformly supplies air to the subway cabin through two rows of air ducts. The circulated air is fed to the return grill at the center of the subway cabin for
return. The outside air flows into the subway cabin through the outdoor air inlet, and the same amount of air is discharged through the exhaust outlet. If there is no outside air flow, there will be no air discharge through the exhaust outlet. Fig. 1 shows the air flow pattern in the subway cabins when the air conditioner using the outside air is in operation. The exhaust outlet located at both ends of the subway cabin has the role to naturally vent out the outside air that has been pumped into the cabin by the air conditioner and is designed under the condition that the vehicle is maintained with positive pressure based on the newly manufactured vehicles on the Seoul Metro Line No. 2. The exhaust outlet can be divided into the natural exhaust outlet without a fan and the forced exhaust outlet with a fan. Its installation location somewhat differs according to the vehicle type. It is reported that, in the case of the natural exhaust outlets installed at both ends of a subway cabin, the polluted air inside the tunnel flows into the subway cabin due to the acceleration/deceleration of the vehicle [4]. In addition to the standard air conditioner, a line flow fan is installed on the ceiling to increase the mixing with the indoor gas and increase local cooling. Operation of the line flow fan makes the actual air flow inside the subway cabin more complicated.

2.2 Numerical Simulation Model

The shape used for the interpretation was a subway vehicle from Line No. 2 as shown in Fig. 2. Applying the symmetric condition, only 1/4 of the vehicle was created as the interpretation model. Although all passengers in the cabin could not be simulated, ten passengers sitting on chairs were reflected in the model. For the interpretation, it is assumed that the air condition was running but not the line flow fan. Since the line flow fan sprays the air by rotating its discharge unit, it is very difficult to define the condition of air spray to be reflected in the interpretation. Furthermore, there can be many interpretational situations according to the operating conditions, and the transient interpretation must be performed since the air flow inside the cabin changes with time. Since the main purpose of this study is to analyze the carbon dioxide concentration distribution in the subway cabin when the forced exhaust fan operates and when it does not, it reviewed the effect of the exhaust fan operation on carbon dioxide distribution rather than simulating all complex flow conditions. Therefore, this study interpreted the situation of only the air conditioner operating to interpret the steady state of flow field.

Using commercial software ICEM CFD (ANSYS), the unstructured mesh was generated. The number of the meshes was around 4.6 million. Fig. 3 shows the generated mesh shape.

2.3 Interpretation Conditions

This study interpreted the case of the fresh air flowing into the cabin with the forced fan operating (Case 1) and the case of no fresh air and no operation of the forced fan (Case 2). The number of passengers was set to 120 in both cases. Since the passenger model was not fully deployed in the cabin and only sitting passengers were simulated, the simulation of the heat and carbon dioxide generated by the passengers needed to be simulated. Applying the
symmetric condition to a total of 120 passengers, the heat source and carbon dioxide generation by 30 passengers, or 1/4 of total, is needed. First, 100 W of heat generated by each of the 10 seated passengers was divided by the surface area of the passenger model to configure the heat flux per unit area. For the heat generated by the remaining 20 passengers, the heat flux per unit volume up to the height the passenger can reach inside the cabin was assigned. For the carbon dioxide generated by passengers, the points presented by spheres in Fig. 4 were assigned as the carbon dioxide generation source. The amount of carbon dioxide generated through breathing by an adult was set to $1.015 \times 10^{-5}$ kg/s [5]. The carbon dioxide is generated by total of 30 points by the seated and standing passengers as shown in Fig. 4. For the interpretation, the flow field result obtained after the steady state interpretation through the thermal environment assessment under the condition of the outside air flowing in and air condition operating was interpreted. For the mean age of air, which is the residence time of the carbon dioxide and fluid, a total of 180 seconds with an interval of 1 s were interpreted after an unsteady state interpretation.

The capacity of the air conditioner was 3,300 m$^3$/h, and the outside air flowing in was 960 m$^3$/h. The temperature of air exhausting air conditioner was set constant 18°C. In the case of outside air flowing in and the exhaust fan operating, a total of 4,260 m$^3$/h (sum of air conditioner capacity and outside air flowing) of air flows into the cabin. Of this, 960 m$^3$/h is discharged by the exhaust fan while the remaining 3,300 m$^3$/h is recycled by the return grill (Table 1). In the case of there being no outside air flowing in, 960 m$^3$/h discharged by the exhaustion fan was treated to be recycled by the return grill. Therefore, the total volume of air supplied by the air conditioner does not change. However, the carbon dioxide concentration of the air supplied by the air conditioner will be lower in the case of outside air flowing in since the air containing the carbon dioxide concentration is at the level of the outside reference concentration. On the other hand, if the exhaustion fan is not operating, the carbon dioxide concentration of the subway cabin will be recycled.
Table 1 Air flow condition of subway cabin.

<table>
<thead>
<tr>
<th>Case</th>
<th>Air conditioner flow (m³/h)</th>
<th>return grill flow (m³/h)</th>
<th>exhaustion fan flow (m³/h)</th>
<th>Number of passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>3,300+960</td>
<td>3,300</td>
<td>960</td>
<td>120 persons</td>
</tr>
<tr>
<td>Case 2</td>
<td>3,300+960</td>
<td>3,300+960</td>
<td>0</td>
<td>120 persons</td>
</tr>
</tbody>
</table>

3. Results

3.1 Thermal Environmental Conditions

Figs. 5–8 show the results of velocity, temperature, PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) interpretations. Since the volume of air supplied by the air conditioner is the same for the Case 1 and Case 2, there was not much difference in the overall velocity ranges. Although the streamlines of Fig. 6 also do not show much difference, the temperature profiles in Fig. 7 shows Case 2 to be higher. That is because Case 1 has the exhaust fan in the front and the rear of the return grill and it is easy to discharge the air in the subway cabin while in Case 2, the air discharge occurs only in the cabin center where the return grill is located and thus the air circulation is poor. As such, the temperature profile is formed at about 2°C higher in Case 2, and thus PMV and PPD in the cabin in Case 2 are somewhat warmer and less comfortable than in Case 1, as shown in Figs. 7 and 8.

3.2 CO₂ Concentration Distributions

Fig. 9 shows the carbon dioxide concentration after 180 s. To show the distribution after removing the carbon dioxide in the air, the interpretation was
performed so that the carbon dioxide concentration was set to 0 initially and increases only with the carbon dioxide discharged by the passengers. Since the carbon dioxide discharged to the return grill is returned to the entry, the carbon dioxide concentration increases with time. In Case 1, the carbon dioxide concentration is high only in the source area where it is discharged from human exhalation. In Case 2, the high concentration area is expanded, and the area below LCD (liquid crystal display) was particularly high because the passengers were concentrated but the carbon dioxide was not removed by the exhaust fan unlike in Case 1. As shown in Fig. 10, the carbon dioxide concentrations continuously increase with time. The increase of carbon dioxide concentration inside the subway cabin in Case 1 is more gradual than in Case 2 due to the inflow of fresh air. The bulk mean carbon dioxide concentration of the whole cabin after three minutes was 589 ppm for Case 1 and 845 ppm for Case 2, meaning Case 2 showed about a 42% higher carbon dioxide concentration than Case 1.
4. Conclusions

The urban subway is the key transportation means in the metropolitan area. Since the installation of PSD, the air quality inside the subway cabin has gained attention, and the authorities are investing great efforts in reducing the polluted air and maintain a comfortable environment. The numerical simulation was performed on newly manufactured vehicles of the currently operating Subway Line No. 2 to observe the impact of the forced exhaust outlet on the air ventilation and carbon dioxide concentration in the subway cabin. At the same time, the change of the indoor thermal environment was predicted. When the mechanical ventilation was not operated, indoor CO\textsubscript{2} level tends to increase linearly with subway operating time and indoor thermal condition was warmer and less comfortable. It is strongly recommended to use a mechanical exhaust fan for reducing indoor CO\textsubscript{2} level at a certain level and also increasing thermal comfort of passengers.

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References