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A Study on fire smoke behavior in a submerged floating tunnel

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ABSTRACT

The demand for submerged floating tunnels has been increasing worldwide, and related key technologies are being actively developed. In the event of a disaster, submerged floating tunnels that travel across the sea may result in serious human casualties. Thus, thorough preparation for potential disasters is required. In this study, smoke and thermal airflow diffusion characteristics were numerically investigated in a single, submerged floating tunnel, which can be used as both a railway and road in the event of a fire. The seawater temperature outside of the tunnel was considered for the analysis, and the smoke and thermal airflow diffusion characteristics, according to fire intensity, were analyzed for the road and railway tunnels. The minimum distance between evacuation safety facilities was obtained by performing an evacuation simulation. This study is significant as a basic study to prepare for disasters that may occur in submerged floating tunnels.

1. INTRODUCTION

An underwater tunnel is a tunnel floating in the sea, which has been installed underwater between the sea level and seabed. It is also referred to as a submerged floating tunnel or Archimedes bridge. The demand for submerged floating tunnels is increasing with the rapid increase in exchanges between countries, as well as the interest in securing new transportation infrastructure, due to abnormal weather conditions and related key technologies that are being developed. Such technologies, however, are in the beginning stage of development worldwide, and they require various studies to promote safety, especially against disasters.

Fires that may occur in tunnels, due to vehicle collisions and electrical accidents, have the potential to cause massive social and economic losses, as they may lead to structural damage and even human casualties. For submerged floating tunnels, in particular, massive damage can be caused in the event of a fire because the exterior of the structure is exposed to high-pressure seawater. Thus, it is necessary to perform detailed examinations and establish countermeasures against possible fire accidents. In this study, thermal airflow and smoke diffusion characteristics were numerically analyzed in the event of a fire within a submerged floating tunnel, which may be utilized as both a road and railway tunnels. To this end, a fire simulation was performed for various fire intensities by applying the fire growth curves suggested in the literature. An evacuation simulation was also performed separately to assess the distance of damage that may cause human casualties, and propose optimal distances between the shelters, according to the fire intensity.

2. ANALYSIS METHOD

2.1 Dimensions of the submerged floating tunnel

The submerged floating tunnel used in this study was a typical shield tunnel with an outer diameter of 23 m and a wall thickness of 1 m, as shown in Fig. 1. The top section of the tunnel was used as the road tunnel and the bottom section was used as the railway tunnel. The total cross section was assumed to be a concrete structure and transverse air ducts were applied to the road and railway tunnels for ventilation. The cross-sectional areas of the road and railway tunnels were set to 63.2 and 27.3 m^2, respectively.

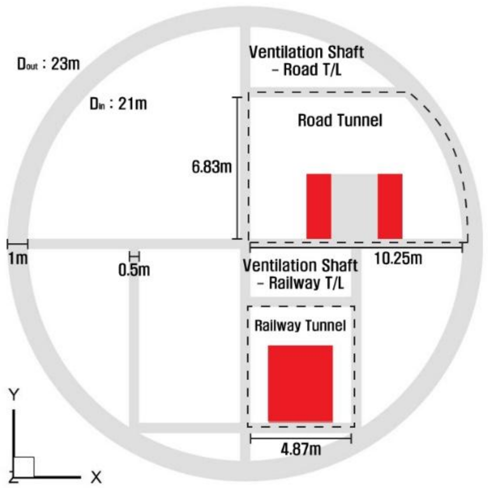


Fig. 1 Dimensions of the submerged floating tunnel

2.2 Modeling of the numerical simulation

To analyze thermal airflow diffusion characteristics inside the submerged floating tunnel in the event of a fire, the cross section was modeled using ANSYS-FLUENT, which is a commercial, three-dimensional, fluid analysis software program. As for the grids of the tunnel, both tetrahedral and hexahedral cells were used. Hexahedral cells were generated for the external wall of the tunnel, considering the convergence of the analysis, and tetrahedral cells were generated for walls between each space. The tunnel was analyzed for a distance of up to 1 km from the point of the fire occurrence in both directions. The gradient was set to 0% to investigate the representative diffusion characteristics of the fire smoke, according to the fire intensity and tunnel use (road or railway tunnel). Additionally, the wind speeds, due to the traveling vehicles and trains (1.45 m/s for the road tunnel and 2.23 m/s for the railway tunnel), were set as the initial input values for the main lanes of the road and railway tunnels before the occurrence of a fire.

For fire occurrence scenarios, the standard fire growth curves of the road and railway tunnels used in South Korea were applied (MOLIT, 2016; KRRI, 2011). In the case of the road tunnel, fire characteristics vary depending on the traveling vehicles, and thus thermal airflow diffusion characteristics were analyzed for the fire intensities of 5-, 10-, 20-, and 200-MW, considering various vehicle types. In the case of the railway tunnel, an analysis was conducted after setting the fire intensity to 20 and 15 MW, considering general and high-speed trains. For the fire analysis, the linings and walls of the submerged floating tunnel was assumed to be concrete with a density of 2,240 kg/m^3, a specific heat (C_p) of 900 J/kg·K, and a thermal conductivity of 1.95 W/m·K. In addition, the temperature of the outer wall of the tunnel was set to 12℃, considering the seawater temperature (Kim et al., 2006). As the main purpose of this study was to investigate the diffusion characteristics of fire smoke inside of the submerged floating tunnel in the event of a fire, it was assumed that smoke control and ventilation facilities were not operational.

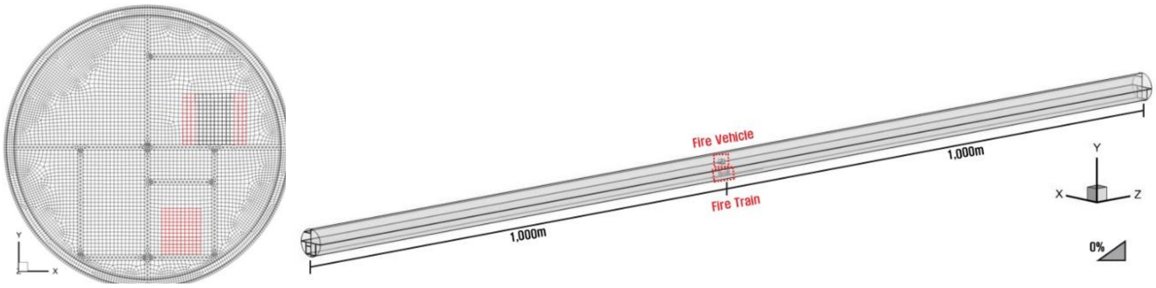


Fig. 2 Modeling of the submerged floating tunnel for the simulation of fire smoke behavior

Table 1. Standard fire intensities used for submerged floating tunnel fire analysis

Purpose	Fire scenario	Fire intensity
Load tunnel	One car	5MW
	Two cars	10MW
	Bus	20MW
	Heavy goods vehicle	200MW
Railway tunnel	Standard train	20MW
	High-speed train	15MW

3. FIRE DIFFUSION CHARACTERISTICS INSIDE SUBMERGED FLOATING TUNNEL

3.1 Fire diffusion characteristics in the road tunnel

Figure 3 shows the fire smoke and thermal airflow diffusion characteristics in the road tunnel at 10 minutes after the occurrence of a fire, according to the fire intensity. As shown in the figure, the smoke and thermal airflow diffusion distances increased as the fire intensity increased, and the fire smoke diffused faster than the thermal airflow. This is because the thermal airflow was generated by the fire smoke. The maximum temperature of the concrete immediately above the point of fire occurrence was found to be 123℃ for the fire intensity of 5 MW, 207℃ for 10 MW, 410℃ for 20 MW, and 3,562℃ for 100 MW. When the fire intensity was 100 MW, the fire-resistant temperatures of concrete and steel materials, which were the main materials used for the tunnel, were exceeded (i.e., 550℃ for steel, 700℃ for concrete). Thus, it is expected that the structure will be seriously damaged in the event of such a fire.

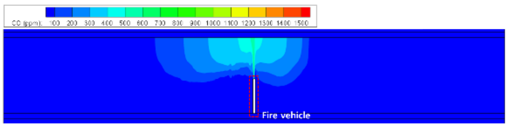
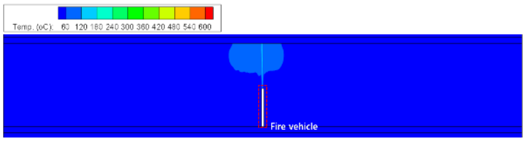
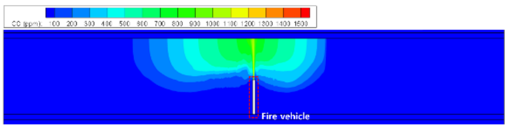
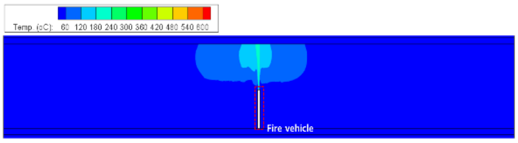
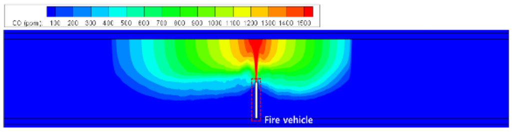
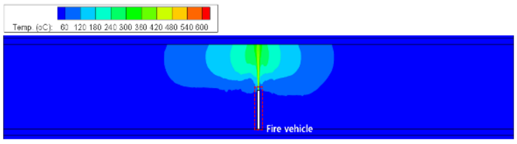
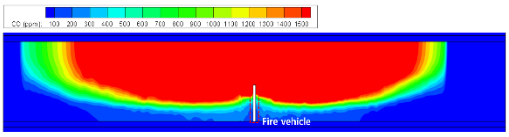
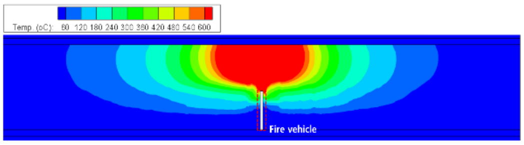
Fire intensity	Smoke diffusion	Thermal diffusion
5MW		
10MW		
20MW		
100MW		

Fig. 3 Diffusion characteristics of smoke and thermal heat after 10 min of fire in the road tunnel

3.2 Fire diffusion characteristics in the railway tunnel

Figure 4 shows the fire smoke diffusion characteristics in the railway tunnel, according to the fire occurrence time by train. As shown in the figure, the smoke and thermal airflow gradually diffused in both directions of the tunnel over time, and the smoke of the high-speed train (15 MW) diffused faster than that of the standard train (20 MW). The maximum temperature of the concrete immediately above the point of the fire occurrence was 462℃ for the high-speed train and 475℃ for the standard train. The maximum temperature of the standard train in the event of fire was higher than that of the high-speed train because the standard train had a higher fire intensity, while the fire growth of the high-speed train was faster than that of the standard train.

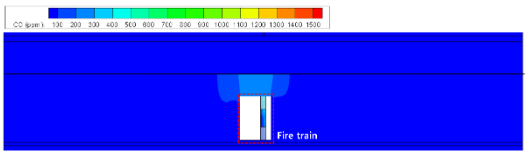
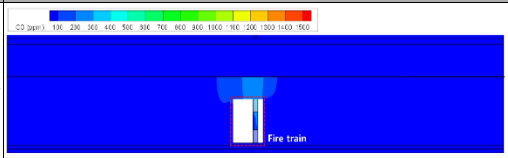
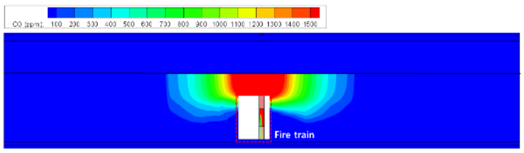
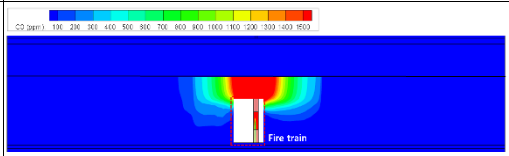
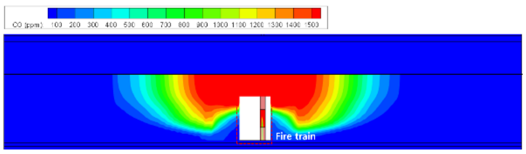
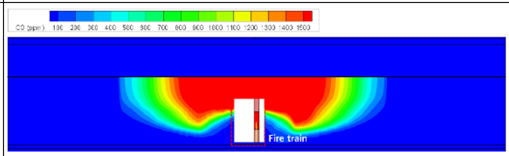
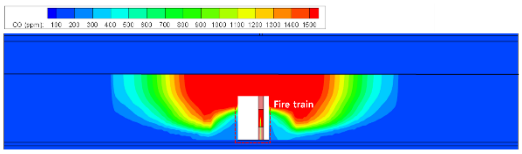
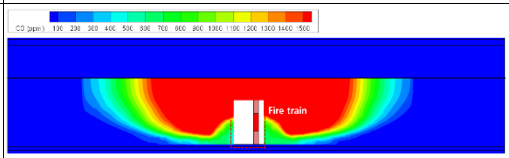
Fire duration	High speed train (15MW)	Standard train (20MW)
10 min		
15 min		
20 min		
25 min		

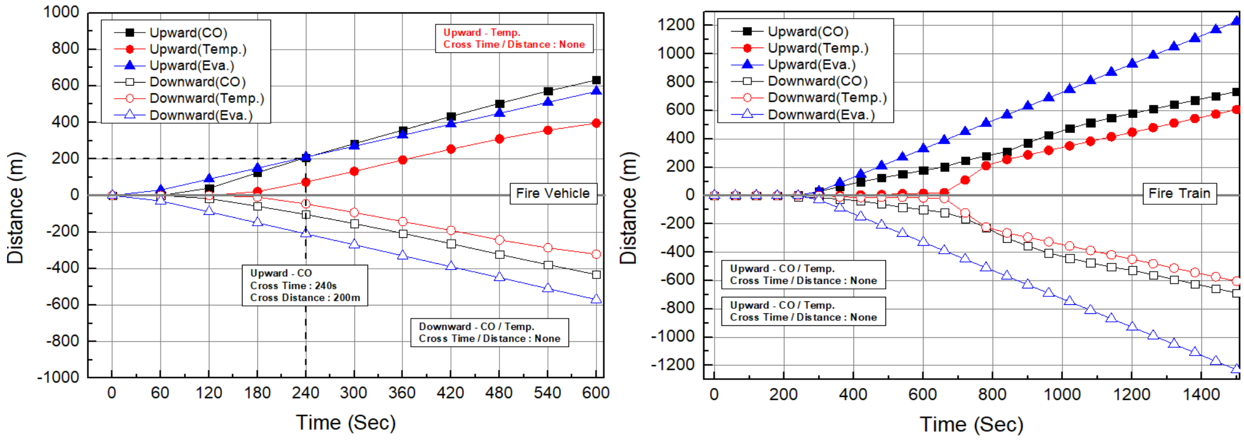
Fig. 4 Diffusion characteristics of fire smoke in the railway tunnel

3. EVACUATION SAFETY ASSESSMENT

It is necessary to assess evacuation safety in the event of a fire in the road and railway tunnels and to prepare countermeasures, such as the installation of cross passages for evacuation and shelters, to prevent human casualties. For the assessment of evacuation safety, it is important to examine the maximum evacuation distance for evacuees to withdraw faster than the fire smoke by comparing the fire smoke diffusion speed with the evacuation speed. To this end, evacuation safety was assessed using SIMULEX, which is a commercial, two-dimensional, evacuation software program that considers the psychological factors and behavioral characteristics of humans in the event of a fire.

Figure 5a shows the smoke diffusion distance and the evacuation distance over time when a fire intensity of 20 MW occurs in the road tunnel. At a distance of 200 m from the fire point, the travel distance of the smoke and the travel distance of the last evacuee were crossed, which indicates that minimum evacuation safety measures (e.g. distance between shelters) need to be established at 200 m intervals in the event of a 20 MW class fire. For 5 and 10 MW, it was confirmed that a safe evacuation environment could be generated for the entire tunnel because the evacuation speed was faster than the diffusion speed of fire smoke. For the fire intensity of 100 MW, the smoke diffusion distance and the evacuation distance were crossed at a 50 m distance from the fire point.

Figure 5b shows the smoke diffusion distance and the evacuation distance over time when a fire occurs in the high-speed train within the railway tunnel. As shown in the figure, the smoke diffusion distance and the evacuation distance were not crossed, which indicates that the safety of evacuees is secure in the event of a fire in the railway tunnel. Similar results could be found for the standard train. For safety's sake, however, it is deemed necessary to install evacuation shelters at regular intervals to follow appropriate evacuation safety measures.



(a) road tunnel (b) railway tunnel

Fig. 5 Measuring the time of smoke diffusion and evacuation distance from the fire point in the road tunnel and railway tunnel

3. CONCLUSIONS

In this study, smoke and thermal airflow diffusion characteristics, according to fire intensity, were simulated in the event of a fire within a submerged floating tunnel, and the evacuation safety measures were assessed. As a result, the study found that the smoke and thermal airflow diffusion speeds increased as the fire intensity increased. In the case of the road tunnel, the study found that minimum evacuation safety measures must be established at the minimum intervals of 200 and 50 m for the fire intensities of 20 and 100 MW, respectively. In the case of the railway tunnel, regardless of the train types, the safety of evacuees was secured because the evacuation distance was longer than the smoke diffusion distance. For safety's sake, however, it is deemed necessary to establish minimum evacuation measures at regular intervals in the tunnel. It is expected that the results of this study will be used as a basic data set for establishing safety measures to combat fire disasters. Further research is required, however, because smoke and thermal airflow diffusion characteristics, as well as evacuation safety measures, are affected by the cross section of the tunnel, gradient of the tunnel, average wind speed, wind tunnel design, and the presence of obstacles in the event of a fire.

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