Experimental Study on Fixed Water Mist Fire Protection in an Underground Train Carriage

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Abstract

The purpose of this paper is to describe and demonstrate a Fixed Water Mist Fire Protection System in an underground train carriage. It attempts to examine a full-scale compartment (2m×2.5m×11m) fire test simulated in an underground train carriage. Fire scenarios use large pool fires of a flammable liquid (Heptane pool fires). The fire scales are changed to various sizes (1.2MW ~ 4MW). Finally, this paper describes the effectiveness of water mist fire suppression in an underground train carriage.

1. Introduction

In urban areas, in addition to the ground and the air, the underground is used. So many public institutions including underground trains are built and they are available for the urban inhabitant. Moreover, as underground space is very precious when considering environmental load reduction and urban renewal, the effective use of space is a big concern. The tendency is to build deeper, larger, and use more complex combinations.

The fire accident in S. Korean Daegu has made safety management and safety guards in underground institutions an urgent subject. Also various technical issues have surfaced. [1]

The current fire safety guard for the train carriage is based on several past fire accidents. [2,3,4] On the other hand, the fireproof performance of the train carriage is based on small-scale fires caused by negligence and electric leakage and doesn't cover intentional fires. Usually, fire extinguishers are installed in each carriage and they are effective for incipient fires. However, in the case of rapidly spreading fire, if correspondence activities are overdue, it is difficult to extinguish.

Fire tests on full-scale train carriages were done in tunnels, and were reported to evaluate structural and material

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performance against a fire. [2] Once the flames became small, the fire was put out spontaneously and did not spread. Therefore, it was almost never dangerous in regard to inner temperature, radiant heat, smoke concentration, or toxic gas. Other fire tests were done in a full-scale train carriage. However, they were not carried out using fuel that burns intensely like gasoline. [4]

Water mist fire suppression systems are known as an effective system, because of good fire suppression capability, no environmental impact, and no toxicity, with minimal water use. Water mist systems can also extinguish fires of flammable liquids, such as gasoline. In enclosed fires, larger fires will be easier and faster to extinguish than smaller fires. This is related to the consumption of oxygen by the fire, the generation of water vapor, and the turbulence created by the fire. Water vapor is known as a kind of inert gas for suppression of fire. [5] Expanding the water vapor displaces the oxygen available for combustion. The larger heat capacity by increased water vapor is also one of the suppression mechanisms. [6,7,8]

Water mist systems also rapidly reduce the compartment temperature and prevent fire from spreading to adjacent compartments. The lower temperatures also tend to reduce the airflow through openings. [9]

Water mist uses less water than traditional sprinklers and spray heads. Therefore, it is well suited for keeping onboard each train carriage as a self-contained unit.

In this paper, a full-scale compartment, which simulates an underground train, is tested to evaluate the water mist fire suppression system. Then the water mist fire suppression effectiveness in an underground train is described.

2. Experiments

Figure 1 shows the outline of a full-scale test compartment and instrumentation. The test compartment is a steel structure with dimensions of 2m wide × 2.5m high × 10m long. The cross section of the compartment is simulated as an underground train and the length is approximately half of the actual length. Therefore, one side of the cross section is opened (natural ventilation). The area of the opening is $2m \times 2.5m = 5m^2$.

The water mist nozzles have been installed on the ceiling. The type of water mist is the twin-fluid system. The spacing between nozzles is 1.5m.

The compartment is equipped with the thermocouples on the ceiling and two thermocouple trees. The ceiling thermocouples are located 100mm below the ceiling and at 1m intervals horizontally. The thermocouple tree #1 is set up in the middle of the compartment (3.5m from the fire source) and the thermocouple tree #2 is also set up near the opening side (8.5m from the fire source). Each thermocouple tree contains ten thermocouples placed 0.1m, 0.2m, 0.3m, 0.4m, 0.5m, 0.6m, 0.75m, 1m, 1.5m, and 2m below the ceiling. In addition, to monitor extinguishment of the fire, the thermocouples are also placed at the fire source location.

A gas sampling line for Oxygen(O_2), Carbon Dioxide(CO_2), Carbon Monoxide (CO), and Water Vapor concentration measurements is located 0.5m above the floor and 0.3m far from the wall. The water vapor concentration is measured with a heated sampling tube, keeping the temperature above the boiling point of water, and using a humidity sensor probe. This equipment makes it possible to measure real water vapor concentration during a fire test. And then, gases are drawn through an electric cooler to remove water vapor and measured by a gas analyzer for O_2, CO_2, and CO concentrations in dry conditions.

One side-wall of the compartment also has a glazing for observation purposes (3m wide and 2m high, heat-resistant glass). A video camera is set up outside the test compartment to obtain visual records of the water mist discharge and the behavior of the fires during suppression.

The heptane pool fire is located on the floor. The fire pan sizes are $0.6m^2$(round-pan 0.87m in diameter), $1m^2$(square-pan dimension of 1m×1m), and $2m^2$ (square-pan dimension of 2m×1m).

Water mist is discharged to extinguish the fire after a 60seconds free burning period. (When the fire pan size is 1m×2m, the free burning period is 45seconds.)

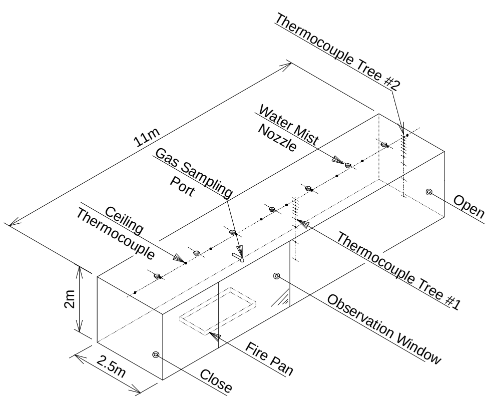

Figure 1. Outline of full-scale test compartment

Figure 2. Photograph of test compartment

3. Results and Discussions

The full-scale tests are divided into two phases: The Free Burning Test and the Water Mist Fire Extinguishing Test.

3-1. Free Burning Test

Gasoline is used as the testing fuel and various quantities are carried out. The size of the fire pan is decided by the quantity of the gasoline. The amounts of gasoline are 1L, 2.5L, 4L, and 5L, which is poured into the fire pans of $0.25m^2$, $0.6m^2$, $1m^2$, and $2m^2$ respectively. And the depth of the gasoline in the fire pan is approximately 4mm (When the fire pan is $2m^2$, the depth of fuel is 2.5mm).

Table 1. Results of Free Burning Test

Test No.	Gasoline	Fire Pan Size	Heat Release Rate
F-1	1L	$0.25m^2$	0.4MW
F-2	2.5L	$0.6m^2$	1.2MW
F-3	4L	$1m^2$	1.7MW
F-4	5L	$2m^2$	4MW

Table 1 shows the test results of the free burning test. The second row shows the quantity of gasoline. The third row shows the surface area of the fire pan. The fourth row shows the heat release rate of the fire.

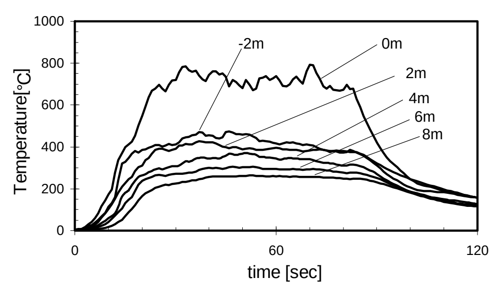

Figure 3. Ceiling temperature in Test F-3

Figure 3 shows the ceiling temperature time history of the compartment with the various distances from the fire source in Test F-3 (1.7MW).

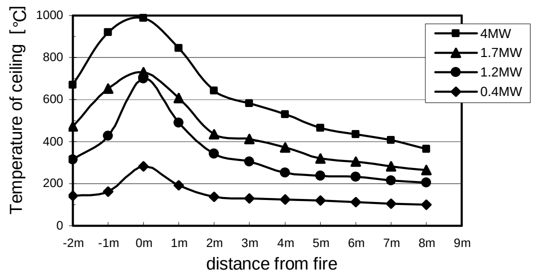

Figure 4. Maximum ceiling temperature in Free Burning Test

Figure 4 shows the maximum ceiling temperature profiles in the compartment at the free burning test.

It seems that the ceiling temperatures decreased exponentially.

When the fire size was 0.4MW, the maximum ceiling temperature ranged from 100°C to 280°C. It seems that, when the fire size is 0.4MW, it is hard for the fire to spread to the ceiling because of lower temperatures below the flash-point of a flame retardant material.

When fire size was larger than 1.2MW, the maximum ceiling temperature reached higher than 800°C. And areas with a temperature over 500°C, which might be over the flash-point of a flame retardant material, ranged from 1m from the fire source at 1.2MW, 1.5m from the fire source at 1.7MW, and 4.5m from the fire source at 4MW.

These results might suggest that if the quantity of gasoline is large it may spread a fire to the ceiling if any using a flame retardant material.

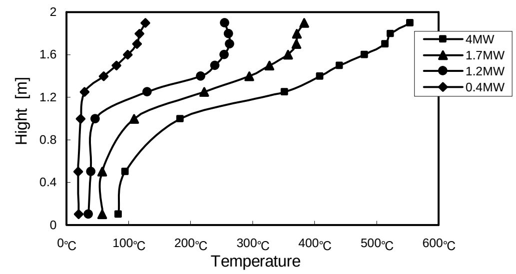

Figure 5. Maximum temperature of thermocouple tree #1 (distance from the fire source is 3.5m)

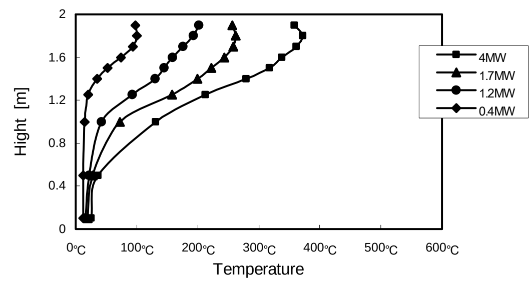

Figure 6. Maximum temperature of thermocouple tree #2 (distance from the fire source is 8.5m)

Figure 5 shows the temperatures measured at thermocouple tree #1 that is located 3.5m from the fire source (middle of the compartment). Figure 6 shows the temperatures measured at thermocouple tree #2 that is located 8.5m from the fire source (near the opening). The hot gases from the fires tended to concentrate in the upper part of the compartment. The gases could be characterized in terms of two layers, an upper layer with hot combustion products and a lower layer with less affected air. The thickness of the upper layer is from 600mm to 800mm in the middle of compartment and from 500mm to 700mm near the opening. The thickness of the upper layer increased as the fire scale grew.

3-2. Water Mist Fire Extinguishing Test

Heptane is used as the testing fuel for fire extinguishing tests. A sufficient quantity of fuel is required for a fire extinguishing test, and too much gasoline may cause an explosion due to its volatility. The depth of heptane in the fire pan is 10mm.

Table 2. Results of Fire Extinguishing Test

Test No.	Fire Pan Size	Ext. Time	Min. O_2 (Dry)	Max. Water Vapor
E-1	$0.6m^2$	47sec	16.5 vol%	11.4 vol%
E-2	$1m^2$	28sec	15.9 vol%	15 vol%
E-3	$2m^2$	42sec	5.5 vol%	37.6 vol%

Table 2 shows the results of the fire extinguishing test. The third row shows the extinguishing time, which is defined as the time interval between activation of the water mist system and the instant of fire extinguishment. Fire extinguishment is determined by visual observation and fire temperatures. The fourth row shows the minimum oxygen concentration, which is measured by a gas analyzer in dry conditions (removed water vapor). The fifth row shows the maximum water vapor concentration, which is measured by a humidity sensor through a heated probe.

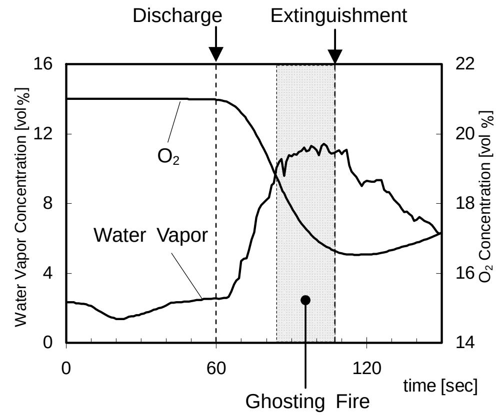

Figure 7. Water vapor and Oxygen concentrations in Test E-1

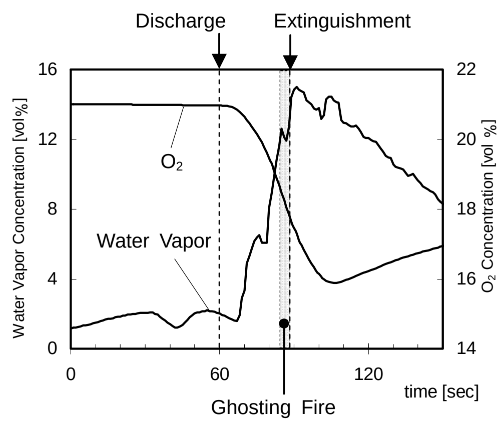

Figure 8. Water vapor and Oxygen concentrations in Test E-2

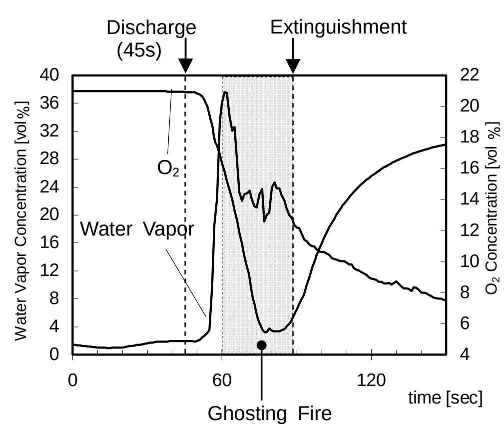

Figure 9. Water vapor and Oxygen concentrations in Test E-3

Figures 7, 8, and 9 show the time history of the water vapor concentration and dry oxygen concentration during a fire extinguishing test. As the oxygen concentration is measured in dry conditions, the oxygen in these Figures is decreased due to consumption by the fire.

A ghosting fire is defined as a phenomenon in which the fire pulls away from the base of the flame, and wafts into the compartment.[10] The shaded region in these figures shows that the ghosting fire phenomenon occurring.

Figures 10, 12, and 14 show the time history of the temperatures at thermocouple tree #2 that is located close to the opening during fire suppression. Figures 11, 13, and 15 show the photographs of the fire behavior at that time.

Before water mist discharge, the temperature profiles could be characterized in terms of two layers. After water mist system activation, the water mist evaporated in the upper layer of the compartment, and then water vapor and combustion products in a hot layer near the ceiling pushed downward near the floor of the compartment. Water mist created a strong dynamic mixing in the compartment, and blocked fresh air from entering into the fire plume. As shown in Figures 7, 8, and 9, the water vapor concentration increased and the dry oxygen concentration decreased. As a result, the oxygen available for combustion is significantly reduced due to both the consumption of the oxygen by the fire and dilution of the oxygen by water vapor.

In Test E-1, approximately 25 seconds after water mist discharge, the ghosting fire phenomenon was observed. After the ghosting fire phenomenon appeared, the water vapor concentration stabilized, and then, 47 seconds after water mist discharge, the fire was extinguished (Fig.7).

In Test E-2, approximately 24 seconds after water mist discharge, the ghosting fire phenomenon was observed. In this case, the water vapor concentration increased during the ghosting fire phenomenon. Immediately after that, 28 seconds after water mist discharge, the fire was extinguished.

In Tests E-3, the water mist was discharged directly into the fire because the fire pan size (2m) was larger than the nozzle spacing (1.5m).

Immediately after water mist was discharged, a large momentary fire flare-up was observed, because initial water mist discharge increased turbulence and stirring around the fire and brought more fresh air into the fire plume, resulting in increased temperature profiles (Fig.14). At the same time, water vapor was dramatically increased (Fig.9), and the ghosting fire phenomenon occurred. The flame wafted into the upper layer near the ceiling, and then the fire was extinguished (Fig.15).

5. Conclusion

These test results indicate that the water mist system effectively extinguishes flammable liquid fires in a compartment with minimal water use. Water mist quickly controls the fire and cools the atmospheres of the compartment. Discharged water mist blocks fresh air from entering into the fire plume and generates a large quantity of water vapor. As the size of the fire increases, the oxygen concentration available for combustion decreases due to both the consumption of oxygen by the fire and the dilution of oxygen by water vapor. Therefore, in enclosed fires, larger fires will be easier and faster to extinguish. The water mist fire suppression system is suitable for protecting an underground train carriage against large flammable liquid fire such as gasoline.

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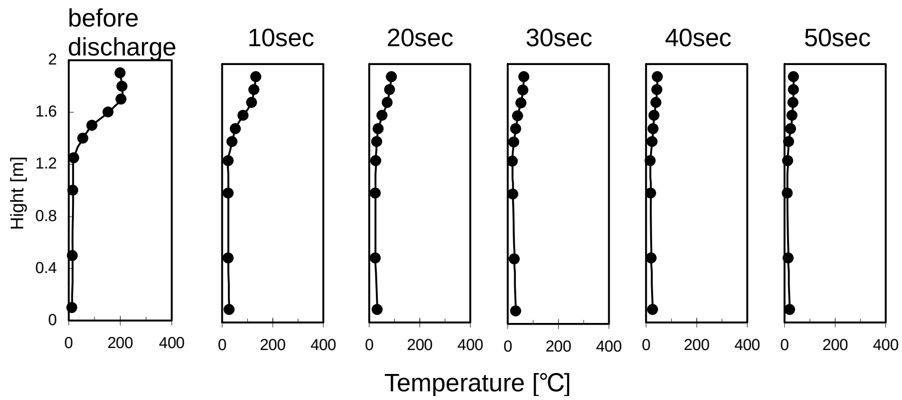

Figure 10. Time history of temperature at thermocouple tree #2 in Test E-1

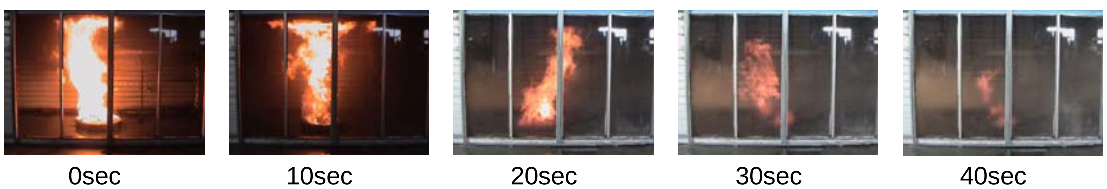

Figure 11. Photographs of behavior of fire during fire suppression in Test E-1

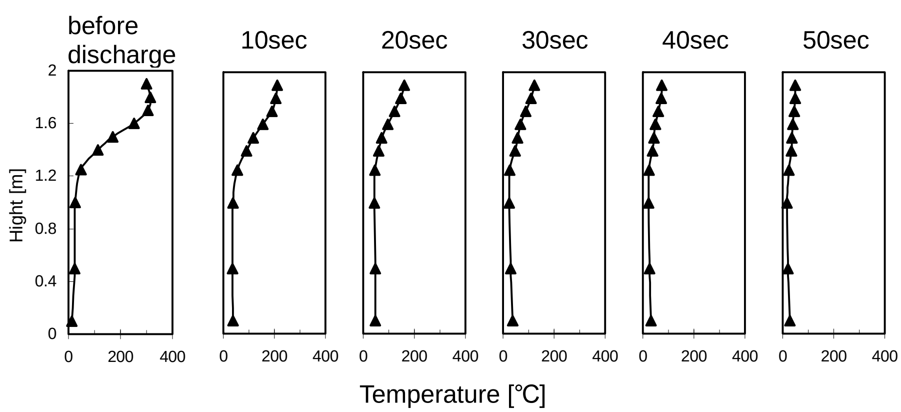

Figure 12. Time history of temperature at thermocouple tree #2 in Test E-2

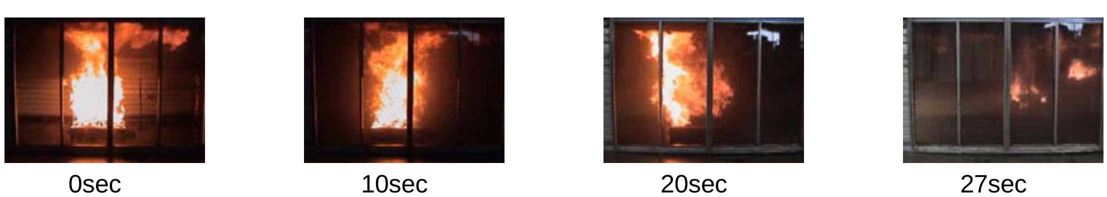

Figure 13. Photographs of behavior of fire during fire suppression in Test E-2

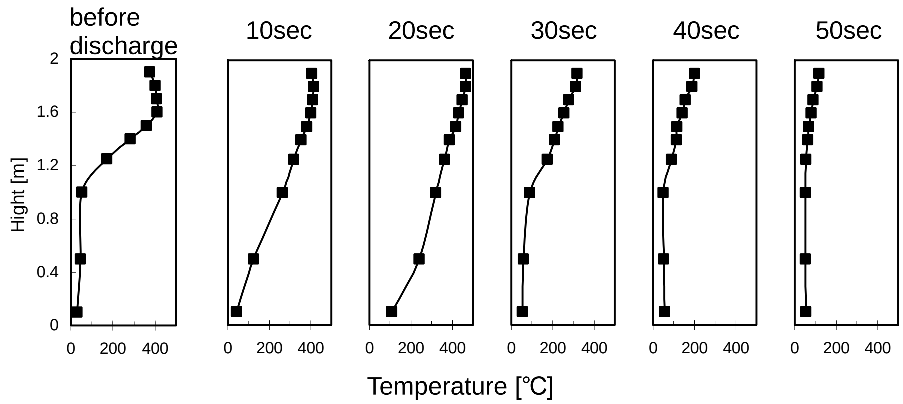

Figure 14. Time history of temperature at thermocouple tree #2 in Test E-3

Figure 15. Photographs of behavior of fire during fire suppression in Test E-3