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Implementation of Low-Pressure Water Mist System for Fire Suppression inside a Model of Road Tunnel

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Abstract: ***Previous studies have proven the performance of certain water mist system in general or in suppressing certain tunnel fires. The southern tunnel under the Suez Canal in the province of Ismailia length of 4 kilometers and 800 meters is serving the movement from Ismailia to Sinai through the Suez Canal old and new, while serving the northern tunnel movement from Sinai to Ismailia through the two channels. This tunnel in Ismailia is the largest in the world, with outer diameter of 12.6 meters, the internal 11,40 meters, the length of the tunnel is 4830 meters and reaches 6830 meters with the entrances and exits, the distance between the north and south tunnels 12 meters, and the maximum depth of the tunnel 45 meters down both Suez Canals. Since completing this project in the begin of 2019, this Tunnel did not experimentally test. This paper describes an experimental study of a low-pressure water-mist system (LPWMS) used in a scaled fire test conducted in a section of a scaled down road tunnel. The length, width, and height of the tunnel were 6 m, 2.4 m, and 2 m, respectively, which are in a ratio of 1:4 to the dimensions of an actual tunnel. The LPWMS used a pump pressure of 5.5 bar, and the system configuration was designed according to the pressure generated by the pump. Without a ventilation fan, the fire suppression time was 275 s, and amount of water required to fully suppress the fire was 696.67 L. When a ventilation fan was used, the maximum temperature location was moved from the center of the 6 m long tunnel toward the air inlet end of the tunnel (upstream). While this study will find the performance of the LPWMS in suppressing a fire in a small section of the Ismailia tunnel, determining the times spent and the amount of water consumed in the various stages of fire suppression, and in addition to studying the effect of the ventilation fan on These results and the location of the maximum temperature in the tunnel.***

Key Words: ***Ismailia-Sinai tunnel; water-mist; fire safety; Froude scaling***

I. INTRODUCTION

There are many previous studies dealing with the low-pressure water mist system, and others dealing with the use of the water mist system to suppress fires in compartments or tunnels (other than the Ismailia tunnel). Some studies also addressed the idea of scaling down the space in which the fire is suppressed. The novelty of this study is that it is combining all those studies ideas adding to it the effect of the ventilation fan on the maximum temperature location, all these in the largest road tunnel which never tested before (in a scaled down section of the Ismailia tunnel), which none of the previous studies touched upon the study of the effect of using a ventilation fan on the location of the fire center (the location of the maximum temperature).

Tunnels are used to connect various locations (cutlers and economy). However, tunnels are prone to fire accidents such as those that occurred in the Channel Rail Tunnel in 1996 and Mont Blanc Road Tunnel in 1999. During such accidents, the temperature inside the tunnel increases rapidly by hundreds of degrees, and consequently, there is huge loss of life and property damage. Furthermore, the insulation of some tunnel areas is damaged, which requires time and money to be repaired. Therefore, understanding, controlling, and improving fire-fighting systems in tunnels have received considerable attention from researchers and specialists [1]. In this study, the effect of a low-pressure water-mist system (LPWMS) on fire suppression in a 6 m long section of a 6 m × 2.4 m × 2 m scaled down road tunnel [2] [3] was experimentally investigated; the dimensions are scaled down at a ratio of 1:4 from those of an actual tunnel. Measurements were obtained under the same fire scenario to determine the location of the maximum temperature in the tunnel with and without a ventilation system. Furthermore, the time and amount of water required to fully suppress the fire were determined. The LPWMS consists of a water tank connected to a high-pressure water pump with a pressure of 5.5 bar and flow rate of 40.15 gpm. The pump distributes water at a low pressure of 175 psi (12.1 bar) or less [4] into two pipes with a diameter of 1 in; the distance between the pipes is 1500 mm. Each pipe has four low-pressure water-mist nozzles at a height of 1800 mm from the ground. The low-pressure nozzles used are designed with $\emptyset_{mist} = 170°$, orifice K-factor = 7.18, and water particle size of 323µm. There are five jets per nozzle, and the nozzle working pressure and the flow rate are 0.7 MPa and 19 L/min, respectively. The ventilation fan used was also scaled down at a ratio of 1:4 of the actual size to provide an airflow of 2295 cfm at a flow velocity of 2.374 m/s. The ventilation fan was suspended from the ceiling of the tunnel at a distance of 750 mm from the tunnel end. During testing, the fire was produced using wood pallets (European Standard), which were also scaled down at a ratio of 1:4 from the actual size to obtain a heat release rate (HRR) of 2.7375 MW [5]. The experimental results were analyzed using physical suppression mechanisms. The design of the water-mist system was based on comprehensive fire tests carried out by an internationally recognized laboratory, as recommended in FM Approvals, Class Number 5560 (Approval Standard for Water Mist Systems).

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II. EXPERIMENTAL APPARATUS

To better characterize the LPWMS used to suppress the fire, a 1:4 scaled down test model of a road tunnel at the college of engineering at El Mataria- Helwan University is used.

The dimensions of the scaled tunnel are 6 m × 2.4 m × 2 m. Scaling corrections based on Froude scaling were used to extend the small scale test results to a full scale fire test [6] [7]. The tests were conducted twice under a scaled fire scenario (based on Froude scaling) in a 6 m long section of the scaled model. The tunnel was constructed outdoors using a steel structure covered with 2 mm galvanized steel sheets. Wood pallets were used to produce the required scaled fire of 2.7375 MW. The pallets were divided into three piles comprising five pallets each [5]. One pile was placed at the center of the tunnel with a distance of 150 mm between the pile, and the other two piles (one before and the other after the centralized pile), they were used as the source of fire. Figure (1) shows the schematic of the tunnel.

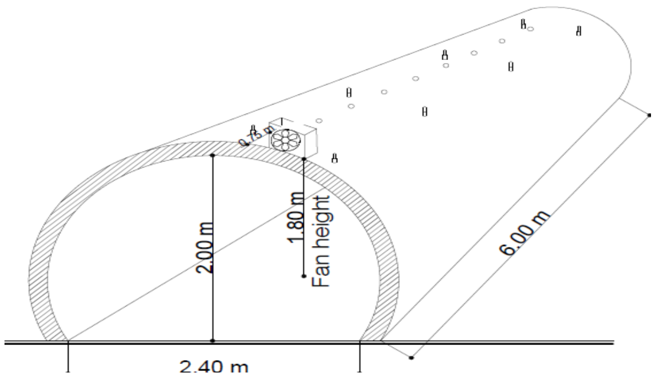

Figure 1 Schematic diagram of road tunnel.

Figure (2) shows the locations of the water-mist nozzles and thermocouples within the tunnel.

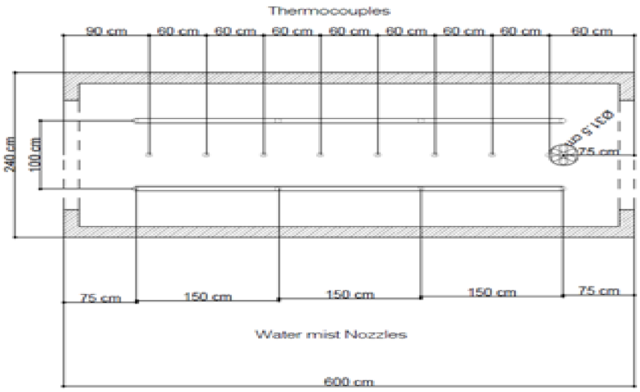

Figure 2 Top-view schematic diagram of tunnel with thermocouples and water-mist nozzles.

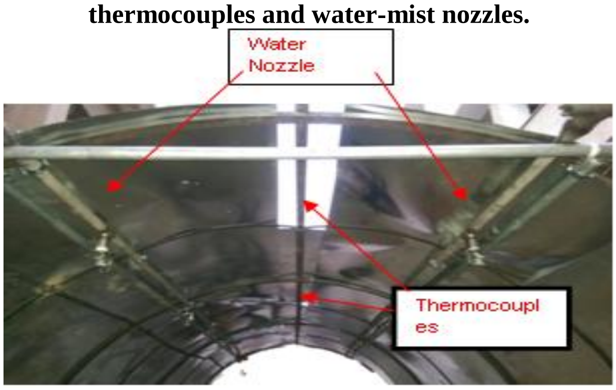

Figure 3 Photo of the tunnel with the water-mist nozzles and thermocouple sensors.

The nozzles were installed on the ceiling of the tunnel and were distributed into two lines at a height of 1800 mm. The separation distance between the nozzles in the same line was 1500 mm. The distance between the nozzles at the ends of the distribution lines and the entrance and exit of the tunnel was 750 mm, respectively. The LPWMS pump pressure was 5.5 bar, and the flow rate was 40.15 gpm. Low-pressure nozzles were used with $\emptyset_{mist} = 170°$ and water particle size of 323 µm. There were five jets per nozzle, and the working pressure and flow rate were 0.7 MPa and 19 L/min, respectively (Figure (4)).

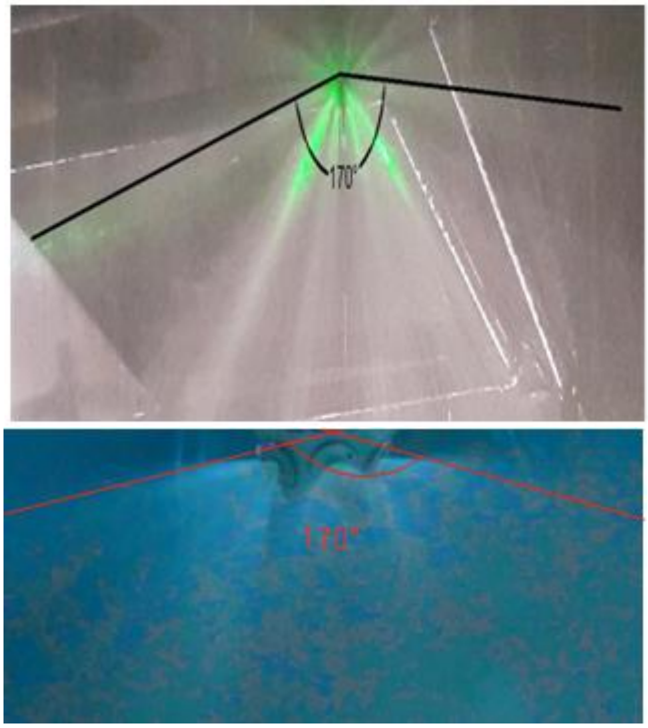

Figure 4 Water pattern for Low-pressure water-mist nozzles.

The schematic of the entire test rig is shown in Figure (5).

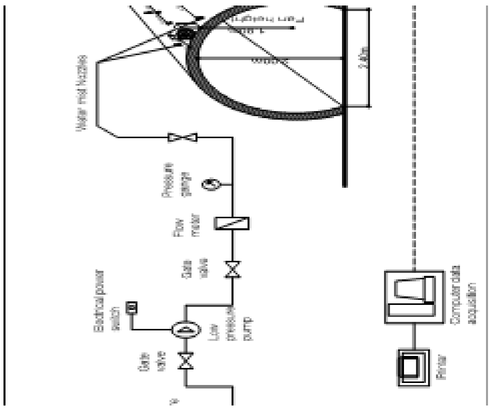

Figure 5 Schematic diagram of test rig.

A. EXPERIMENTAL PROCEDURES

This section details the experimental scenarios to evaluate the performance of the LPWMS to suppress the same fire after it is fully developed in a section of the scaled road tunnel in the presence and absence of a ventilation system.

The location of the maximum temperature is determined in the tunnel with the fan. In both scenarios, the nozzle distribution was the same. In the second scenario, a fan with a scaled flow rate was fixed at the mid-point of the tunnel ceiling at a distance of 750 mm from the end of the tunnel, where the suction direction from the begin side and plow to the end of tunnel side.

The HRR of the actual fire selected to be simulated was 10–11.64 MW, which is representative of a bus or truck fire [8] [9]. Wood pallets were used to simulate the actual fire and scale it down at a ratio of 1:4 to obtain an HRR of 2.64–2.91 MW. Each pallet could produce an HRR of 176 to 194 KW when the fire was fully developed [5], and thus 15 pallets were used in this experiment to simulate the HRR of the actual fire. The pallets were distributed into three piles of five pallets each at the center of the tunnel at a height of 3” from the ground. The distance between the piles was 150 mm. Figure (6) shows the manner in which the wood pallets were arranged in the tunnel before the fire was started.

Figure 6 Arrangement of wood piles and pallets in road tunnel.

B. Burning of Wood Pallets

Burning was started by laying down the pallets in the configuration described earlier. The separation clearance between the pile and the tunnel wall was 650 mm, and 1500 mm from the last pile and the entrance of the tunnel and the same distance from the other side of the piles to the exit of the tunnel. The distance from the top of the piles to the nozzles was 1080 mm. As the open type water-mist system was used, the pump was turned on when the fire was fully developed to ensure that the required HRR of 2.64–2.91 MW could be achieved. The ambient conditions in the experiments were 36 °C, RH of 49%, and wind speed of 19 km/h. The influence of the wind was negligible due to the location at which the tunnel was built. The temperatures were recorded by 8 K-type OMEGA thermocouples (Model: TC-TT-K-24-36), which were distributed along the internal center line of the top of the tunnel with equal spacing between each thermocouple. The distance between the entrance of the tunnel and the first couple and that between the exit of the tunnel and the last thermocouple was 900 mm. The temperatures were continuously recorded at intervals of 5 s by using OMEGA Data Acquisition Module (Model: OM-DAQ-USB-2401), the KACISE ultrasonic flow meter (Model: KUF2000) and the AZUD (Model: EN 837-1) pressure gages were used to measure the water flow rate and pressure respectively. Figure (7) shows the burning stage of the experiment when the fire is fully developed before the fire-fighting system is initialized.

Figure 7 Burring stage of the experiment.

III. RESULTS AND DISCOUSSION

Temperature and time were the main parameters affecting the fire suppression in the conducted experiments. The results were characterized with respect to temperature and time for both experimental setups. The volume of water required to suppress the fire was also determined and investigated. Figures 8 and 9 illustrate the change in temperature with time from the time at which the fire begins to the time it is completely suppressed in both experimental setups. The temperature prole is divided into distinct zones as follows: Zone A, initiation of fire (interval between f and y); Zone B, fire suppression (interval between y and s); and Zone C, cooling (interval between s and l). The locations of the maximum temperatures in the tunnel are shown for both experimental setups. The behavior of the fire in each of the zones is as follows:

- Zone A: The initiation on the fire results in a rapid increase in the temperature from ambient temperature at line f to the maximum temperature at the line y. The temperature increases owing to the hot gases exhausted from the combustion of the pallets.
- Zone B: The fire suppression phase is initialized manually (to ensure that the fire is fully developed and that the required HRR can be achieved) at line y; the fire-fighting system starts spraying water at this time. The fire is fully suppressed at line s. The water evaporates due to the generated heat, and the oxygen level in the tunnel is reduced.
- Zone C: The cooling process results in a gradual decrease in the temperature the tunnel (interval between line s and line l) due to reduction in the difference between the temperature of the water droplets and that of the combustion gases; this also reduces the evaporation of the water.

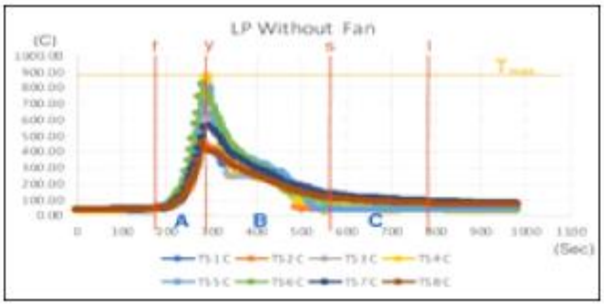

Figure 8 Temperature vs. time for LPWMS without ventilation fan.

The following observations can be made from Figure (8):

- The duration between f and y (Zone A) is approximately 105 s. The maximum temperature of 873.47 ºC is observed at thermocouple 4 (TS4), which was almost at the center of the tunnel (at 2700 mm from exit).
- The time required to suppress the fire is 275 s (Zone B).
- The duration of the cooling stage (Zone C) is 210 s.
- The total water consumption from line y to l (Zones B and C) is 696.67 L + 532 L = 1228.67 L.

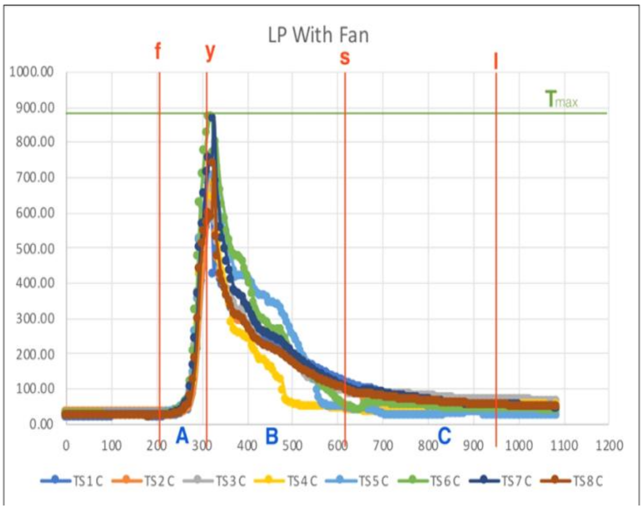

Figure 9 Temperature vs. time for LPWMS with ventilation fan.

From Figure (9), the following observations can be made:

- The duration of Zone A is approximately 100 seconds. The maximum temperature is of 870.48 ºC is found at thermocouple 6 (TS6), which was located at almost 1/3 of distance from the tunnel entrance and the air suction direction (at 3900 mm from exit).
- The duration of Zone B is 320 s.
- The duration of the cooling stage (Zone C) is 310 s.
- The total water consumption from line y to l (Zones B and C) is 810.67 L + 785.33 L = 1596 L.
  Figure (10) shows the variation in the location of the maximum temperature in both experimental setups.

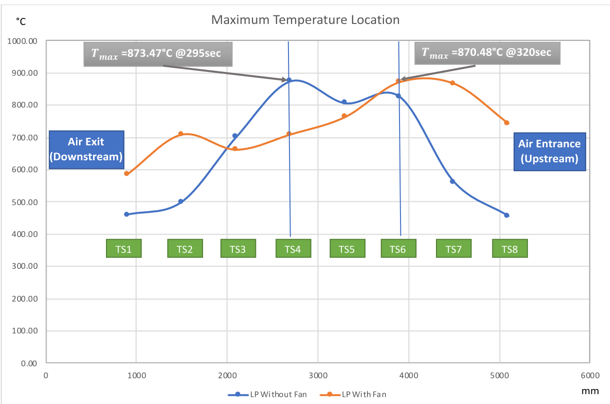

Figure 10 Maximum temperatures vs. distance for LPWMS setups with and without ventilation fan.

Table (1) presents a comparison between the two LPWMS setups based on the maximum temperature, suppression and cooling times, water consumption, and location of the maximum temperature.

Table 1 Comparison between LPWMS setups with and without ventilation

	LPWMS Without Fan	LPWMS With Fan
Max. Temp. (ºC)	873.47	870.48
Max. Temp. Location	2700 mm @ TS4	3900 mm @ TS6
Suppression Time (s)	275 (After Max. Temp)	320 (After Max. Temp)
Cooling Time (s)	210	310
Zone B Water Consumption. (L)	696.67	810.67
Zone C Water Consumption. (L)	532.00	785.33
Total Water Consumption (L)	1228.67	1596.00

The maximum temperature almost the same (it was controlled manually) and depending on reaching the well establishment of the fire by physical visual mechanism. The location of the maximum temperature was almost at the center of tunnel (TS4) location in the setup without the fan which is the center of the fire at the center of the tunnel and the center of the wood pallets, while the location of the maximum temperature in the setup with the fan was shifted forward toward the air inlet end (upstream) of the tunnel at 1/3 of the distance from the tunnel entrance (TS6) which is become closer to the fresh air inlet to the tunnel, this is because more oxygen interred and helped in to increase the fire (the burning) at the air entrance of the tunnel and reduce it at the other side of the tunnel due to the increase of the oxygen at this side of the tunnel. The duration for fire suppression was 275 s in the setup without the fan and 696.67 L of water was consumed. Similarly, the time required for fire suppression was 310 s in the setup with the fan, and 810.67 L of water was consumed, which is showing that with ventilation fan increased the suppression time and its water consumed increased with 35 s and 14 L because of the effect of the oxygen blowing. The cooling stage required 532.00 L of water in 210 s in the setup without the fan and 785.33 L of water in 310 s in the setup with the fan, which is showing that with ventilation fan increased the cooling time and its water consumed increased with 100 s and 253.33 L because of the effect of the oxygen blowing.

IV. CONCLUSION

Two LPWMS setups were experimentally investigated in this study. The first setup comprised an LPWMS without a ventilation fan and the second consisted of the same LPWMS with a ventilation fan. The performance of the LPWMS and the effect of the ventilation system on a fire caused by wood pallets fire in a section of a scaled road tunnel were studied. From the previous figures and table, it concludes that:

- The low-pressure water-mist fire-fighting system showed good performance in terms of suppression time in the setup without the ventilation fan (4 min and 35 s) and in the setup with the fan (5 min and 20 s), and here it is cleared the effect of the ventilation fan on the suppression time which increasing air blowing to the fire will help the fire to burns more which will takes more time to suppress.

- In the setup without the fan, the water consumption of the system was 1228.67 L from the time the fire was fully developed to the time that it was fully suppressed. In the setup with the fan, the amount of water required for fire suppression was greater by 1596.00 L, due to the same above reason the water consumption will increase in the with ventilation fan setup.
- The cooling process (Zone C) consumed less water compared with that required for fire suppression (Zone B). due to the lower temperatures in this zoon, the water droplets have large size of the relative to that in suppression zone with the higher temperatures. Because the effect of the heat rate which is affect the evaporate of the water droplets rate.
- The ventilation fan shifted the maximum temperature location from the center of the tunnel to the air inlet end of the tunnel (upstream) as a greater amount of pure oxygen entered the tunnel which helps to shift the fire center forward the oxygen blowing source.

Designing road tunnel firefighting systems shall consider the effect of the ventilation fan -not only on the smoke purging- to the time of fire suppression and this time delay in the fire suppression how much it will increase the losses, also the water storage shall take in consideration the effect of the ventilation fan in increasing the water consumption which must be reflected on the design of the water storage volume. Finally, the fire fighting zoon which will run in the location of the fire shall be taking in consideration that the fire will be moved forward the air entrance side after the ventilation fans switched on. The same experiment shall be conducted under the same conditions using the high-pressure water mist system and compare the results with this study results to find the deference between both water mist systems (high and low pressure) in suppressing the same fire and the ventilation fan effect on the location of the maximum temperature and time with water consumption in the suppression and colling stages, in using LPWMS and HPWMS. Finally making computer code to compere the experimental and computer results to use this code in the future to decide which water mist

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