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Fuel pool development in tunnel and drainage as a means to mitigate tunnel fire size

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ABSTRACT

One of the most dangerous fire events that can happen in road tunnels is a fuel tanker fire, when flammable or combustible liquid fuel spills on the tunnel roadbed and catches fire. The fire develops extremely fast, with its size directly dependent on the size of the liquid pool on the roadbed surface. The tunnel roadbed is typically not flat and is usually sloped both longitudinally and transversely (cross slope). There have been some attempts to evaluate the fuel pool size on a flat or longitudinally sloped surface, whereas there is a lack of methodology for evaluation of fuel pool size, fire zone length and fire heat release rate on a sloped roadbed surface. While there is some controversy as to the exact heat release rate for a given fuel type and fuel pool depth, very little experimentation has been performed or documented on fuel flow across an unbounded sloped surface. This paper presents results of the scaled tests that measured the size and shape of water and fuel on a sloped road surface as well as attempts to verify CFD analysis. The estimated results from the measured data extrapolated to 12 l/s are compared against the CFD model and previously published papers. A 1.2 m × 1.2 m (4 ft × 4 ft) section of concrete surface representing a concrete road was built, and flow tests were performed on the sloped surface with water and gasoline at different flow rates, different surface slope and different surface roughness. The test data was used to determine the liquid pool area based on the flow rate. This data shows that the geometrical shape of the pool remains proportionate for the different parameters of slope, flow rate, and surface roughness that were tested. Since this is an unbounded experiment the test results can be directly applied to a fuel spill on a sloped surface (roadway) by adjusting the fuel flow rate. This flow pattern and flow dynamics were then used to calibrate a CFD model that emulated the flow pattern of the liquid fuel across an inclined concrete road surface. Using the calibrated CFD model and standard drainage calculations the drainage system can be designed to limit the size of the pool of liquid fuel. This paper addresses the pool size and the area of the pool on a sloped concrete surface.

1. Introduction

The Tunnel Fire in California at Interstate 5 and Highway 2 happened on July 13, 2013, when flammable liquid fuel estimated at 28,390–32,933 l (7500–8700 US gal) of gasoline spilled and burned for 2 h. This event reminded us of the high risk of such fires and the need to study the liquid fuel spill fire dynamics.

Two problems can be identified from a liquid fuel spillage causing fire in the tunnels:

- Fuel pool development, fire size and fire dynamics which were also studied by Ingason [7] and Mealy et al. [5].
- Tunnel drainage as a mitigation means to reduce fire size by capturing fuel spill is addressed in more detail in this paper.

There has been previous research conducted to understand the spill and fire dynamics of these types of scenarios [2,3,7]. It is well known that the size of a liquid fuel pool fire is proportional to the pool area. Ingason demonstrated that the pool and fire size are mainly controlled by the flow rate of fuel from a damaged tanker, the flow characteristics, the slope and roughness of the road surface and design of the drainage system [7]. The heat release ratio, and thus the size of the liquid fuel fire, also depends on the depth of fuel layer, but this phenomenon is out of the scope of this paper. NFPA 502 [1] recognizes that drainage system can be very effective in capturing spilled fuel and can aid in reduction of the fire size. There is experimental data and the empirical Manning equation also known as the Gauckler–Manning formula [4] developed in 1890, which allow for the evaluation of the drainage once it is channelized (gets to the side of the road) and is being conveyed as gutter flow. There are also

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some known studies on liquid fuel flow when dropped on a flat plate [5], and small scale experiments [7], and unbound sheet flow [8,9], but very little experimentation has been performed or documented on fuel flow across an unbounded sloped surface. For this reason this paper focuses on the development of the area of the flow and its further development based on the slope of the road and flow rate prior to becoming channelized.

In the case of a flammable liquid cargo incident in the tunnel that involves a fuel spill on the roadway that catches fire, it is important to capture spilled fuel within the fire zone in order to prevent fire propagation. The fuel leakage flow depends on the size of the rupture and the fluid pressure at the rupture (fuel flow rate) of the damaged tank. The effect of the leakage fuel flow diameter and the drainage rate on the fire size of fuel tankers was published in the PIARC document [3]. Further design aspects can be found in PIARC (2016) [12]. If a fire suppression system is used to protect the tunnel, the water discharged from sprinklers and hose valves also has to be collected and conveyed through the drainage system without flooding the roadway. A path clear of water has to be maintained for access of emergency vehicles. The drainage conveyance and collection systems are designed based on requirements from NFPA-502 [1] and Urban Drainage Design Manual (HEC-22). Standard hydraulic equations which can be found in HEC-22 are utilized to perform the drainage calculations [2].

2. Scale test description

The scaled test module was designed to emulate a concrete road. A 1.2 m × 1.2 m (4 ft × 4 ft) section of concrete pavement mounted on an adjustable table was constructed (see Fig. 1). The table size was selected due to constructability constraint and requirement that it be of sufficient size to evaluate the fully developed flow (asymptotic width). The table was constructed with a concrete pavement surface that was adjustable from 0% to 10% representing different road slopes. A level and leveling blocks were used to set the slope of the table. The surface was originally finished with a broom finish to emulate a rough, worn road surface. After the rough surface tests were completed, a smooth (troweled finish) concrete surface was added, and the tests were repeated.

The table was built with sufficient stiffness (plywood and wood braces) to maintain a flat surface without sagging. 5.04 m × 10^{-2} (2 in) of concrete was poured on top of the surface and a broom finish was applied. A 2.54 m × 10^{-2} (1 in) by 2.54 m × 10^{-2} (1 in) grid was placed above the surface so that the flow pattern could be accurately measured. Nails and string were used to form the grid for repeatability and accuracy of measurements. Slots were cut in all four legs with washers and bolts so that each leg could be raised independently, and a level was used to ensure proper slope. The slope height for the length of the level was calculated, and blocks of wood were cut at the precise height; each time the table was releveled the blocks were used for accuracy and repeatability.

In order for the liquid fuel flow to be calibrated and repeatable several items had to be configured. For consistent flow, a bucket attached to a guillotine at a fixed height was used for every experiment. In addition a 1.27 m × 10^{-2} (0.5 in) diameter hose was connected to two ball valves in a series. The first ball valve was used as a shut off valve and the second one was used as a flow regulating valve. The regulating valve, a calibrated rod and a stopwatch were used to calibrate and set the flow rate. The flow discharge valve system was held in place by a brace that could be rotated 180 deg. By rotating the brace to the back, the flow could be emptied into a bucket, while using a calibrated rod (tick marks every 1.27 m × 10^{-2} (0.5 in)) and a stopwatch, the regulating valve was adjusted until the correct flow was achieved. Once the flow rate was calibrated the brace could be rotated back to the test table to run the tests.

Initial tests were performed with water, and the results were recorded. The tests were repeated with unleaded gasoline that contained 10% ethanol. All data was recorded, plotted (See Figs. 5–11) and used for calibration of the CFD model.

Building the table level Using wood blocks to ensure slope is consistent.

Once the table slope and the flow rate were set, the fluid was released at 2.5 m × 10^{-2} (1 in) above the surface to simulate the potential failure of a small diameter fuel line or damage to a delivery hose flange on the bottom of a fuel tanker. This does not represent a complete destruction of a delivery hose that would give a hole diameter of 100 m × 10^{-3} (3.9 in). Each test was repeated a minimum of 3 times and the data recorded (see Table 1 and Table 2).

3. Experimental results

Scale tests of fuel flow across an unbounded sloped surface were performed to measure size, shape and depth of water and fuel. The resultant wetted area can be seen in Figs. 2 and 3. Fig. 2 shows results of tests at 5% road slope with water flowing at 0.063 l/s (1 gpm) on rough and smooth surfaces. It appears that the wetted surface area for the smooth surface is wider than for the rough surface. While the increase in width is not significant, the smoother surface is better defined and slightly more conservative, which is why the following figures and graphs are based on the smooth surface data instead of the rough surface data. From Fig. 2 one can see that the back flow of 12.7 m × 10^{-2} (5 in) is similar for both rough and smooth surfaces. However, 12.7 m × 10^{-2} (5 in) down from the discharge point the pool development is wider for the smooth surface than for the rough surface (55.9 m × 10^{-2} (22 in) vs. 43.2 m × 10^{-2} (17 in) respectfully). Note that the hydraulic jump and the backflow of the fluid when it impacts the sloped surface, as well as the development of the flow pattern, are very similar to the results obtained by Ingason [7].

Fig. 3 shows gasoline test results at 5% and 7% slopes. The results show that a flatter slope produces a wider wetted area, which results in a larger pool area. The pattern of the gasoline pool is similar to the water pool, however, the difference in wetted area width is slightly less.

Table 1 provides the water test empirical data used for developing relations between flow and the wetted area (width) as a function of slope (Figs. 4–7). Ingason [7] concluded that the width of the flow is dependent on the diameter of the hole (flow rate), however, it is nearly independent of the roadway slope and the surface roughness. Experimental results are

Building the table level   Using wood blocks to ensure slope is consistent

Fig. 1. Small scale test set-up.