Calculation of Liquefied Natural Gas (LNG) Burning Rates

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Abstract

A set of small-sized experiments were carried out at Texas A&M University's Brayton Fire Training Field (BFTF) to determine the radiative heat transfer of LNG pool fires. This set of experiments was designed to study how the heat feedback from the fire to the pool surface is subsequently distributed through the liquid volume. Burning rates of LNG pool fires are driven mainly by radiative heat transfer from the fire for diameters larger than 1m. However, it is known that factors such as the gas layer on the liquid surface, liquid refractivity, and other factors affect the amount of heat that, in reality, is used for evaporation. Therefore, to determine the real amount of heat that is being absorbed by the liquid undergoing evaporation, we will take into account the gas layer and the heat loss to the surroundings in our analysis.

Further validation will be made through a series of experiments in a laboratory setting. Quantitative data will be collected in these experiments to further understand the absorption characteristics of LNG as a function of wavelength of thermal radiation.

Introduction

Previous research has shown that the accurate description of parameters such as flame height, mass burning rates, and emissive power of the flame will result in a more precise calculation of the thermal exclusion zones [1, 2]. During the series of tests performed in Montoir, France in 1987, different methods were used to determine the evaporation rates due to fire. Moreover, it was shown that mass burning rates were highly dependent on the assumptions used for the calculations and the impact of the calculated values in the hazard zones [2-4]. Raj [1] had suggested three possible paths for further investigation to understand the discrepancy found during these sets of tests: absorption of thermal energy by soot particles in the lower region of the fire, optical (absorption or/and reflection) effects due to the gas layer above the liquid pool, and transmission of energy through the lower layers of the liquid pool.

Theoretically, pool fires scenarios can be described by semi-empirical models and computational models. Babrauskas [5] and Burgess [6] have proposed semi-empirical correlations for the calculation of mass burning rates of cryogenics based on experimental data. Conversely, computational models such as Fluent and Phast are being introduced for this, but are still not widely used. Both of these models have only been validated in a limited range and are subjective to errors when extrapolating results [7]. Therefore, a credible scenario of the hazards posed by LNG pool fires, will be attained if the available models take into consideration phenomena that has been observed in real scenarios, such as those seen through experiments.

Overview of 2009 LNG field test

In December 2009 three tests were performed over two days at the Brayton Fire Training Field. LNG was spilled into a small pit 1.03m x 1.03m x 0.23m (40½in x 40½in x 9in) made of cellulose concrete, to limit the heat transfer through conduction. The pit was positioned on the concrete ground of the test facility and filled to a specific height. The actual initial height varied with the volume of LNG spilled. LNG was discharged with a 52.4 m (172 ft) long, 10.16 cm (4 inch) OD aluminum pipe supported on a wood frame, which provided control over the discharge point. Free evaporation lasted until a thermally stable state was attained between the liquid and the concrete surface (boiling decreased). After this, ignition of the flammable vapors was performed with a torch. Combustion lasted until the fuel was consumed for the first two tests and extinguished in the last test. Figure 1A shows a photograph of the dike area.

A B

Figure 1. Concrete pit and sensors set up

The set up encompassed a number of sensors positioned mainly inside the pit, as well as outside the containment area. A weather station mounted on a tripod 2m above the ground was set up in the upwind direction of the facility. Parameters, such as the ambient temperature, wind direction and speed, and humidity and atmospheric pressure, were measured every 60 seconds. During test 1, 16 k-type thermocouples were spaced out on a metal bar inside the pit to measure the temperature of the liquid and gas interface and to obtain a direct measurement of the evaporation rate of LNG. During tests two and three, nineteen additional thermocouples were used. Two of them were positioned at the same level as the water-cooled radiometers to calculate the theoretical value of the thermal radiation reaching the sensor. Two water-cooled, nitrogen purged radiometers were located inside the pit at two different elevations from the liquid surface to measure radiative heat transfer between the flame and the liquid pool. Cooling water flow was used to maintain the integrity of the sensor when exposed to high temperature environments. Nitrogen purge was used to reduce soot deposition from combustion products on the radiometer window. Sapphire windows were used to account only for radiative heat without the interference of convective heat. This feature limited the view angle of the radiometer to 150 degrees. Figure 1B shows an overview of the set up used during one day of experiments.

In addition, two heat flux sensors with associated thermocouples were positioned on the concrete-LNG interface at the bottom of the pool and 1.3 cm under the concrete surface (embedded) to measure the heat transfer between the concrete floor and the liquid fuel and to measure the temperature at the bottom of the pool. Finally, a nitrogen-purged dip tube was used at the bottom of the pool to measure the hydrostatic pressure on the column of liquid and obtain the change of the liquid level, and subsequently the LNG burning rate.

Results and discussion

Weather conditions

Table 1 contains a summary of the conditions observed during the three experiments. The lowest wind speed was seen during the last test, which was performed at nighttime under calmer conditions. Maximum flame heights and radiative heat fluxes were observed during the third experiment.

Table1. Summary of test conditions

Parameter	Test 1	Test 2	Test 3
Temperature [˚C]	9.01 ± 0.17	10.74 ± 0.75	10.05 ± 0.05
Wind speed [m/s]	2.90 ± 0.62	1.28 ± 0.55	0.50 ± 0.35
Wind direction	S & SSE	SE & ESE	ESE
Relative humidity [%]	49.53 ± 0.68	64.97 ± 4.11	69
Solar radiation [W/m^2]	60.2 ± 10.85	0	0
Methane [%]	99.9	99.9	99.9
Starting time [h:min:s]	16:18:01	17:28:50	18:30:00

Heat transfer

Conductive heat to the liquid pool was an important parameter monitored to observe any appreciable change in flux direction during the experiments. Figure 2 shows the heat flux at the liquid-concrete interface as well as ½ in deeper into the substrate. The following analysis is focused on the behavior observed for the sensor labeled “on the surface” (upper plot). As can be seen in the figure, the abrupt changes in heat flux were noticed when the ΔT was larger, both during the liquid layer formation and the disappearance of the liquid due to the fire. At the beginning of the filling operation, LNG reached the sensor as a gas with low cooling power. As time went by, the pipe and the surroundings cooled down and therefore we started to observe an increase in heat input to the bottom of the pool due to LNG. Once the liquid layer had been formed, the temperature remained basically constant on the concrete surface, and the heat transfer decreased due to the thermal equilibrium that was being reached between the liquid and the concrete layers. At approximately 1700 seconds, the pool was ignited and no appreciable change in trend was observed in the heat flux. This lack of change infers that the radiative heat reaching the pool surface was consumed in ways other than transmission within the liquid layers. Therefore, it seemed that the heat flux transfer from the concrete to the pool is never affected by the radiative heat feedback from the fire to the liquid pool.

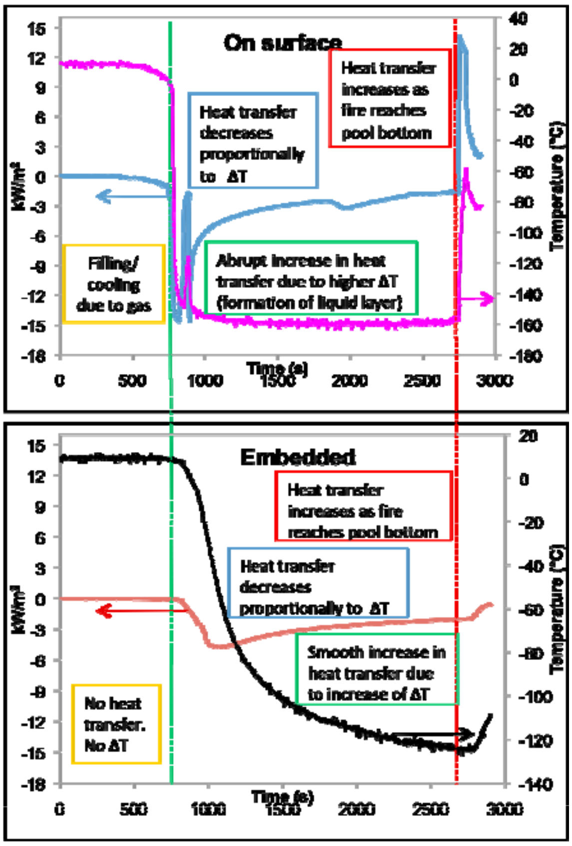

Figure 2. Thermocouple reading

<u>Mass burning rates</u>

Mass burning rates were calculated using different approaches. First, we obtained local mass burning rates and an average value from the thermocouple readings by knowing the location for each thermocouple. We were able to obtain the time (ΔT) that it takes for the liquid layer to pass from one thermocouple to another since the abrupt change in the temperature implies when the liquid has vaporized at a given location. Figure 3 shows the behavior of the thermocouples during experiment 2. The same trend was observed for the other experiments.

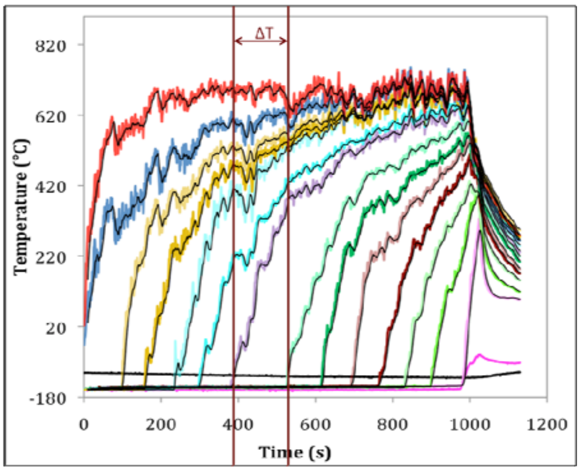

Figure 3. Thermocouple reading

The second approach involves the prediction of an average value by the use of the differential pressure transducer. This method is more straightforward and involves less subjective error. The transducer's output gives the reduction of the liquid column in the pool. The average regression rate (m/s) was then converted to an average mass burning rate. A third approach used for the prediction of mass burning rates included the conversion of liquid regressions rates to mass burning rates and reporting its behavior through the entire burning period. Figure 4 shows the regression rate for experiment 2 and the mass burning rate calculated every second. Table 2 shows the summary of the results for mass burning rates for the three experiments using the methods explained above.

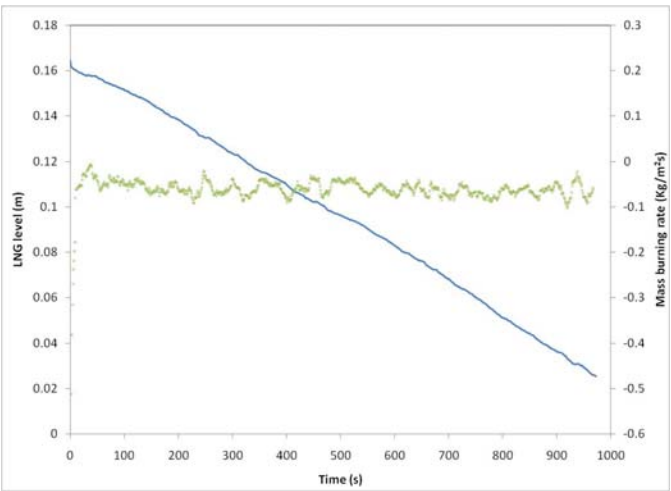

Figure 4. Mass burning rate behavior

Figure 4 shows that the mass burning rate remained constant during the burning period. This curve, unlike others found in literature, did not present a transition period at the initial stage of burning. This is due to the delay of ignition incorporated in all three tests.

Table 2. Comparison of mass burning rates. Methodology A corresponds to the differential pressure transducer data, B to thermocouple readings. Type of parameter is an indicative of the preceding nature of the average shown in this table, where M means an average point value, I means intensive local values, and CB means "complete behavior"

Experiment	Mass Burning rate ($kg/m^2.s$)	Methodology	Type of parameter
1	$0.5181 \pm 7.225*10^{-4}$	A	M
	$0.06221 \pm 1.063*10^{-2}$	B	I
2	$0.06005 \pm 4.250*10^{-4}$	A	M
	$0.06395 \pm 3.581*10^{-2}$	A	CB
	$0.07461 \pm 9.566*10^{-3}$	B	I
3	$0.06466 \pm 2.762*10^{-4}$	A	M
	$0.06802 \pm 3.331*10^{-2}$	A	CB
	$0.07662 \pm 1.417*10^{-2}$	B	I

Table 2 shows reasonable agreement among the calculated mass burning rates, considering the uncertainty. Uncertainties are shown based on the calculated standard deviations. However, it is noticeable that when the average value calculated comes from an instantaneous property, the observed value is higher.

Conclusions

Mass burning rate measurements and calculations were obtained from different methods commonly used. These methods produced similar results and therefore are proven to be viable for reporting LNG evaporation rates for pool fire scenarios. In addition, no heat transfer was observed from the liquid layer to the bottom of the pool, given the indication that the radiative heat that reached the pool surface was used entirely for phase change rather than lost from transmission to the bottom of the pool layer and subsequent transmission to the concrete surface.

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