Combustion and Flame 162 (2015) 4497–4513

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

The phoenix series large-scale methane gas burner experiments and liquid methane pool fires experiments on water

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ARTICLE INFO

Article history:
Received 1 May 2015
Revised 28 August 2015
Accepted 30 August 2015
Available online 22 October 2015

Keywords:
LNG
Methane
Gas burner
Pool fire
Heat flux
Flame height

ABSTRACT

This paper summarizes a series of large-scale outdoor and indoor LNG pool fire experiments conducted at Sandia National Laboratories in Albuquerque, New Mexico. Two outdoor LNG spills on water with resulting pool fires of 21 m and 56 m in diameter were conducted to improve hazard predictions by obtaining measurements of flame height, smoke production, and burn rate. The experimental data indicates that LNG pool fires on water display different behavior than those on land by producing less smoke. Surface emissive powers of up to 286 kW/m^2, flames heights of up to 146 m, and burn rates of about 0.147 kg/m^2 s were measured. Discussion is provided on the observed behavior of the two outdoor tests with regards to smoke production, wind effects, and hydrate production. The large-scale indoor experiments used a 3-m diameter gas burner with methane fuel to assess flame height to fire diameter ratios as a function of non-dimensional heat release rates for extrapolation to large-scale LNG fires. A flame height correlation was developed from this data.

1. Introduction

Liquefied natural gas (LNG) is imported and exported at ports across the US in ships with capacities ranging from about 150,000 m^3 to 250,000 m^3. Due to the extremely large capacity of these carrier ships, there are concerns over the impact that accidental spills could have on public safety and property. In the early 2000s, as LNG imports started to increase in the US, a number of LNG hazard studies were conducted that resulted in widely varying consequence and hazard estimates resulting in broad public concern over the adequacy of current hazard and consequence analysis techniques. Subsequent Sandia analyses [1,2] highlighted some primary knowledge gaps that were limiting the fidelity of site-specific risk assessments due primarily to the lack of large-scale LNG fire data. Experimental data used by the early 2000s studies were taken from pool fires 10–100 times smaller in scale than that anticipated from LNG ship incidents (~100s of meters) [3]. The greatest uncertainty regarded the surface emissive power and the amount of smoke production. There were some studies speculating that a 100 m diameter pool fire would have significant smoke shielding, similar to other hydrocarbons, to result in significantly reduced predicted thermal hazard distances. It was uncertain if this was the case.

Thus, in order to reduce uncertainties, two large-scale tests were conducted at Sandia National Laboratories (SNL) in 2009, resulting in pool fire diameters of 21 m and 56 m. The parameters pertinent to empirical models used to calculate thermal hazard distances are the burn rate, flame height, and surface emissive power (SEP). Thus, these measurements were obtained in order to improve the accuracy of thermal hazard evaluations. The 56 m test is the largest LNG pool fire performed on water or land to date. The details of the test series and recommendations for hazard analysis are provided in Sandia reports [4,5]. In addition to the outdoor tests, an indoor test series was performed utilizing a 3-m diameter gas burner in order to develop a flame height correlation. The following first provides a summary description of the experimental facilities and instrumentation. Then the data from the outdoor and indoor tests is presented as well as discussion of the behavior of LNG pool fires on water.

2. Large scale LNG pool fire experiments on water

2.1. Site and infrastructure

Conducting cost-efficient tests at the required scale of around 100 m posed several challenges, such as, designing a containment system for the LNG that prevents complete evaporation and leakage before test execution, provision of a suitable water reservoir, and design of a delivery and diffuser system.

The most cost effective design for the containment system or reservoir consisted of an above-ground, dome-covered, truncated

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http://dx.doi.org/10.1016/j.combustflame.2015.08.025

Fig. 1. Large-scale LNG facility: (a) side view and (b) top view.

Fig. 2. Reservoir construction (a) and water pool excavation (b).

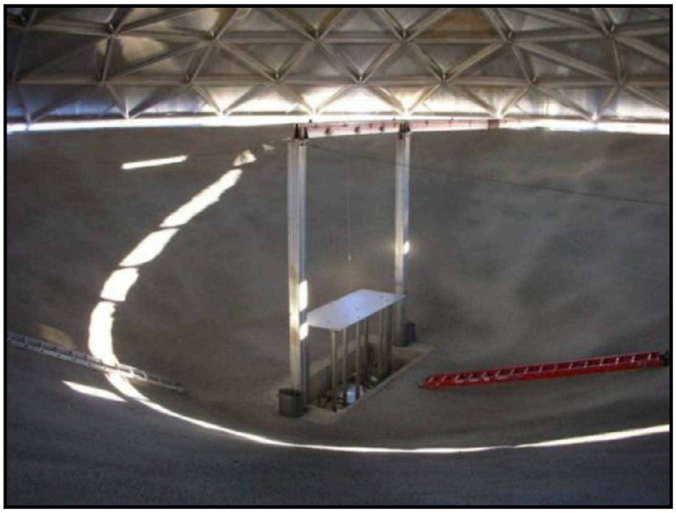

Fig. 3. Lifting of plugs at drainage junction between reservoir and concrete pipes.

cone structure constructed with compacted soil (Fig. 1a). The LNG in the reservoir was gravity driven through a pipe that delivered the fuel to the center of a water pool (Fig. 1b). A diffuser was constructed at the end of the pipe for uniform dispersal.

The reservoir is approximately 7 m tall, with a base diameter of approximately 73 m and a top diameter of approximately 44 m. The cavity of the reservoir is an inverted truncated cone, designed to contain a maximum of 1172 m^3 of LNG. Since LNG is a cryogenic fluid with a saturation temperature of −160 °C, the cavity wall was insulated with 4 in. of sprayed polyurethane foam to reduce boil-off and LNG usage. The foam was covered with 2 in. of “shotcrete” concrete with carbon mesh reinforcement (Fig. 2a).

The body of water which LNG spilled onto was created by excavating nearby soil to construct a water pool with a diameter of ∼120 m, a depth of approximately 2 m at the center 43 m radius, and an upward slope to the pool edge (Fig. 2b). The depth of the pool was chosen to prevent significant freezing, so that the water could maintain a constant supply of heat to the LNG.

The delivery and diffuser system consisted of three concrete pipes with diameters of 0.38, 0.61, and 0.91 m. The pipes had matching mating plugs, designed to achieve the desired LNG pool spread. The plugs were lifted using SS wire rope and sheaves on a SS A-frame attached to a concrete thrust block (Fig. 3).

Reinforced concrete pipe (2.44 m sections) was used to construct pipe runs (∼1% slope) approximately 91.5 m long, with the first 30.5 m under the reservoir and the last 61 m inside a dirt berm constructed during the water pool excavation. The three reinforced concrete pipes terminated in a mating stainless steel Y-connector inside a diffuser near the center of the water pool. The diffuser converted the horizontal momentum of the LNG liquid discharge to a near uniform radial spread onto the water pool. The diffuser was 1.83 m tall and had an inner diameter of 2.44 m.

Three igniters, two of which were propane flares, and one a highway emergency flare, were installed on top of the diffuser located at the center of the water pool. The igniters were used to remotely ignite the methane exiting the LNG discharge pipe at the start of the spill.

A concrete slab, transport container, and thermal shield located at ground level outside the reservoir comprised the pool data acquisition system (DAS) station. This station housed a majority of the support systems – winches and batteries for lifting the LNG discharge plugs, propane and flare igniter systems at the diffuser, reservoir and discharge pipe gas sampling systems, gas bubbler systems for LNG liquid level, and the DAS for the pool and reservoir instrumentation.

2.2. Measurements and instrumentation

Measurement locations were along four cardinal axes or spokes, where the North spoke (also called the 0 spoke) has a magnetic heading of 340°. Three heat flux instrument towers on each spoke were located approximately 110 m, 160 m, and 210 m from pool center. Cameras located on the end of each spoke (∼226 m) focused on the pool vertical centerline. Some spokes contained additional instrumentation, such as IR cameras, spectrometers, and meteorological instrumentation. The heat flux instruments were water-cooled and the towers were thermally insulated.

The instrument towers, approximately 1.5 m tall, were embedded in concrete slabs to provide a stable platform. Tower 1 of each quadrant was the primary tower, supporting five narrow-angle (also called narrow-view or NV) radiometers for spot intensity measurements and one wide-angle (also called wide-view or WV) radiometer for computing overall flame surface emissive power (SEP). Towers 2 and 3 each supported one narrow-angle radiometer and one wide-angle radiometer, which were used to determine heat flux variation with distance. Note that the spot diameter for the 5.5° narrow-angle gauges at a distance of 110 m (to pool centerline) is about 10.6 m, at 160 m is 15.4 m, and at 219 m is 20.2 m.

The data acquisition system (DAS) consisted of five PCs (one on each spoke and 1 pool/reservoir) with 16-bit data acquisition cards connected to a National Instruments (NI) SCXI-1001 chassis. LabView® software interfaced with the NI cards to both control systems and record data. During pretest and post-test periods, data from all five field computers was monitored and recorded at 1 Hz. Immediately before ignition, the field computers were programmed to record individual spoke and pool high-speed data locally at 200 Hz.

Twenty eight narrow-angle radiometers measured the spot incident heat flux at various heights of the flame plume surface (Medtherm Schmidt-Boelter sensors, 12 mV nominal at 300 kW/m^2, 5.5° view angle, with zinc selenide window, water cooled, 63.2% time constant is 35 ms). Note that narrow-angle heat flux can be considered as a spot-average surface emissive power if the relatively small spot is completely filled with flame. The relative angle of the narrow-angle gauges (to the ground plane) was adjusted to measure the flame plume heat flux at different heights (approximately equal spacing) with the line of sight for each gauge passing through the vertical centerline of the pool.