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MODELING LARGE LIQUEFIED NATURAL GAS FIRES

Kevin McGrattan

National Institute of Standards and Technology
Gaithersburg, Maryland, USA
email: kevin.mcgrattan@nist.gov

ABSTRACT

This paper describes the numerical simulation of large liquefied natural gas using the Fire Dynamics Simulator (FDS). The cases include trench fires, jet fires, and fireballs.

INTRODUCTION

In 2022, Sandia National Laboratories published "Model Evaluation Protocol (MEP) for Fire Models Involving Fuels at Liquefied Natural Gas Facilities" in cooperation with the Pipeline and Hazardous Materials Safety Administration (PHMSA) of the U.S. Department of Transportation [1]. As stated in the document:

> The purpose of the MEP is to provide procedures regarding the assessment of a model's suitability to predict heat flux from fires. Three components, namely, a scientific assessment, model verification, and model validation comprise the MEP. The evaluation of a model satisfying these three components is to be documented in the form of a model evaluation report.

Among its other requirements, the MEP lists a series of large-scale experiments conducted over the past 40 years that are to be used for the validation of any fire model that is to be used for LNG facilities. These experiments include the following:

1. BGC/GRI LNG Fires (1982) Thirteen LNG trench fires conducted by the British Gas Corporation (BGC) and the Gas Research Institute (GRI)
2. Montoir LNG Fires (1987) Three 35 m LNG pool fires conducted by Gaz de France in Montoir de Bretagne, France
3. Shell Fire Balls (2014) Four LNG fire ball experiments conducted by Shell Research Ltd, UK
4. Sandia Methane Burner (2009) Twenty-eight 3 m diameter methane burner fires conducted by Sandia National Labs, USA
5. Phoenix LNG Fires (2009) 21 m and 83 m diameter LNG pool fires conducted by Sandia National Labs, USA
6. Loughborough Jet Fires (2012) LNG jet fire experiments conducted by GL Noble Denton in Cumbria, UK, in collaboration with Loughborough University, UK

The results of the simulations of these experiments are included in the FDS Validation Guide. The input files are kept under version control at https://github.com/firemodels/fds and the cases are rerun with each minor release of FDS. Those interested in applying FDS for an LNG facility may be asked by the regulatory authority to provide evidence that FDS is appropriate for this application. The simulations alone are not sufficient, typically, but they do provide a good start.

DESCRIPTION OF EXPERIMENTS

The experiments are briefly described here. Further information can be found in the cited test reports and the summary document written by Anay Luketa of Sandia National Laboratories [2].

BGC/GRI LNG Fires

In 1982 and 1983, P.A. Croce and K.S. Mudan of Arthur D. Little, Inc., and J. Moorhouse of the British Gas Corporation (BGC) supervised 13 liquified natural gas (LNG) trench fire experiments conducted by BGC on behalf of the Gas Research Institute (GRI) [3]. Thirteen experiments were performed with nominal trench sizes ranging from 0.8 m by 4.4 m to 3.9 m by 52 m and aspect ratios ranging from approximately 5 to 30. Wind speeds varied from approximately 1 m/s to almost 10 m/s. Measurements made during the tests included flame geometry, radiative heat flux, emissive power, burning rate, LNG liquid and vapor compositions, and meteorological data. The fires were observed to exhibit substantial flame drag and flame breakup, unlike low aspect ratio pools. Steady burning was achieved in all tests.

Montoir LNG Fires

In 1987, British Gas, British Petroleum, Shell, Elf Aquitaine, Total CFP, and Gaz de France conducted 35 m diameter LNG pool fire experiments [4]. The construction of the test facility was carried out by Gaz de France near the Montoir de Bretagne methane terminal. Three fire experiments were performed under different wind conditions. The Montoir site was selected because the ground is level and obstruction free. Wide angle radiation measurements were made at various locations around the fires, extending outwards approximately 300 m. A bund constructed of lightweight concrete and sand, approximately 1 m tall, surrounded the 35 m pool.

Shell LNG Fireball Experiments

Shell Research Ltd. commissioned four large-scale BLEVE (Boiling Liquid Expanding Vapor Explosion) experiments using LNG (Liquified Natural Gas) at the DNV (Det Norske Veritas) GL test facility at Spadeadam, UK [5]. For Experiments 2-4, the cylindrical containment vessel was constructed of 6 mm stainless steel plates and had a length of approximately 6.5 m and diameter of approximately 1 m, with a total volume of 5.055 m^3. The mass of LNG for Experiments 2-4 was approximately 681 kg, 1306 kg, and 1251 kg, respectively. The LNG consisted of 96.7 % methane, 3.0 % ethane, 0.2 % nitrogen, and 0.1 % propane, by volume. The reservoir pressure for Experiments 2-4 was maintained at 13.01 bar, 6.07 bar, and 13.62 bar; and the temperatures were −115 °C, −131 °C, and −115 °C, respectively.

Figure 1: (Top) Pressure vessel used in the Shell LNG Fireball experiments. (Bottom) Photographs of Tests 2, 3, and 4, respectively [5].

The rupture of the vessel was initiated by an explosive cutting charge designed to rip open the vessel from end to end. Commercial fireworks were ignited just prior to the explosive charge to ensure ignition of the released gas. In the FDS simulations, the specified mass of LNG is injected uniformly for 0.2 s at the ground over an area 4 m long and 4 m wide. An inert obstruction that is 1 m long by 1 m wide and 1 m tall is suspended 1 m above the spill region to represent the remains of the containment vessel. No attempt is made to model the destuction of the vessel or the subsequent spill of LNG.

Sandia Methane Burner

A series of 3 m diameter methane gas burner experiments were conducted in the Fire Laboratory for Accreditation of Models and Experiments (FLAME) facility in the Thermal Test Complex at Sandia National Laboratories [6]. The test chamber (Fig. 2) is cylindrical with an inner diameter of 18.3 m and a height of 13.1 m at the perimeter. The ceiling slopes upwards to a height of 15.2 m at the center. The perimeter walls are made of steel channel sections that are water-cooled. The gas burner is surrounded by a 12.7 m diameter steel spill plate. Beyond the spill plate is steel grating through which air can flow from the basement.

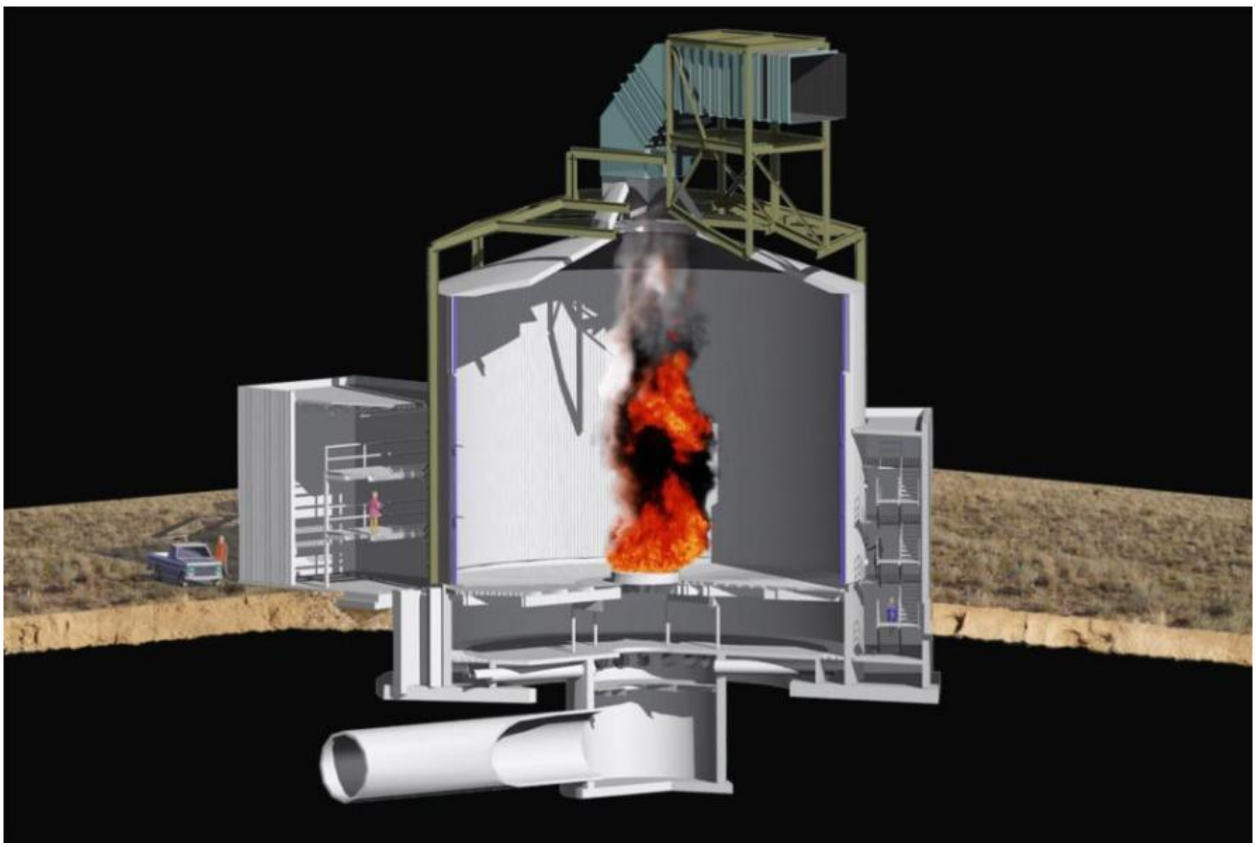

Figure 2: Cutaway view of the Sandia FLAME test cell.

Phoenix LNG Fires

In 2009, Sandia National Laboratories conducted two large-scale LNG pool fire experiments in a 120 m diameter pond in its Area III test complex in Albuquerque, New Mexico [6]. The fires were approximately 21 m and 83 m in diameter. Measurements of flame height, smoke production, burn rate, and heat flux were performed. A photograph of Test 2 is shown in Fig. 3.

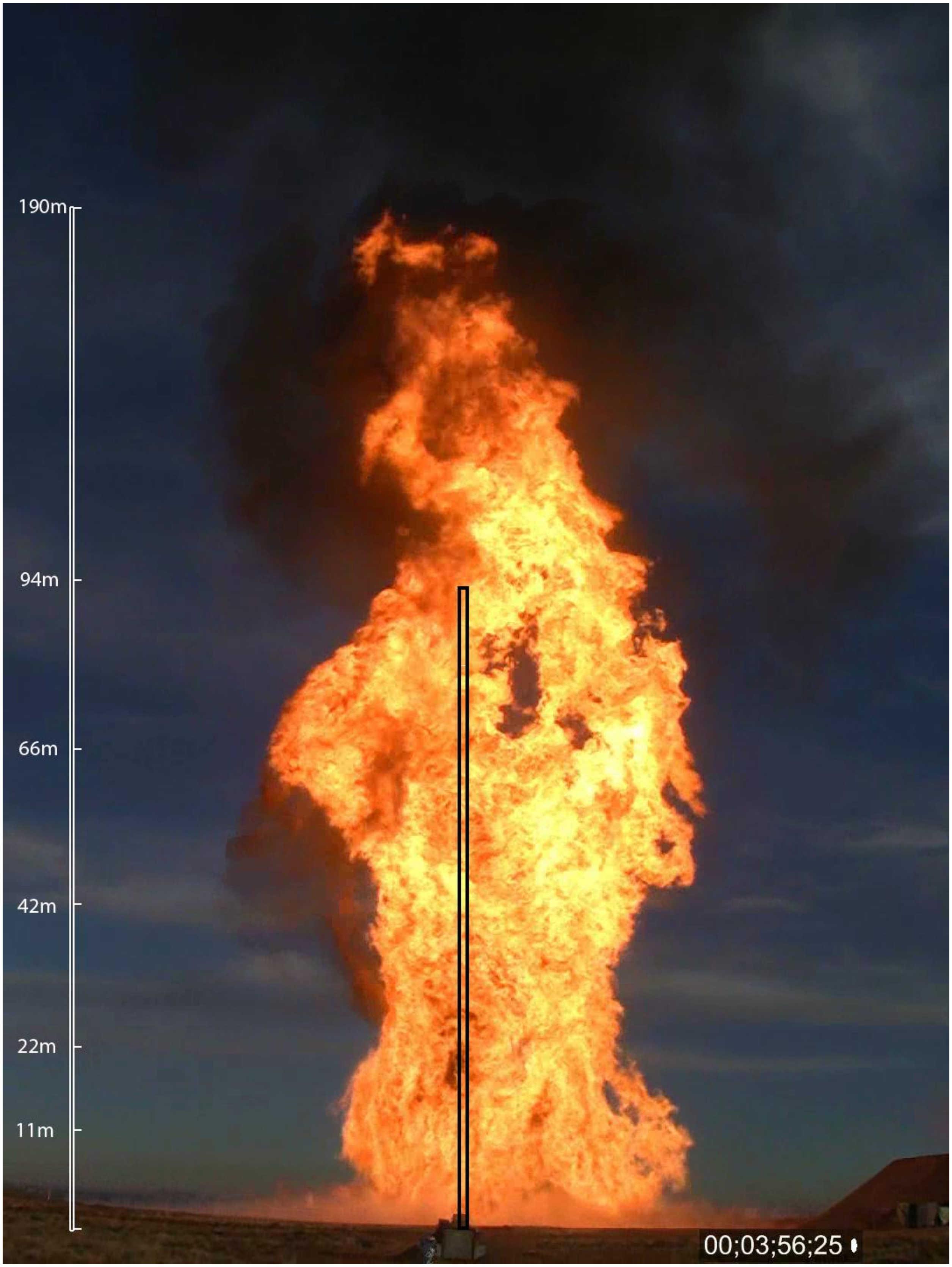

Figure 3: Photograph of Phoenix LNG Fire Test 2 [6].

Loughborough Jet Fire Experiments

Researchers at Loughborough University, UK, conducted a series of six large-scale, high pressure jet fire experiments using natural gas and natural gas/hydrogen mixtures at the GL Noble Denton Spadeadam Test Site in Cumbria, UK [7]. For each fuel, the gas was released horizontally at high pressure (approximately 60 bar) through 20 mm, 35 mm and 50 mm diameter holes at the end of a 15 cm diameter pipe. The jet fires engulfed a 0.9 m diameter, 16 m long pipe section perpendicular to the flow direction. Heat flux measurements were made at various locations on the pipe and further afield. A typical jet fire experiment at the facility is shown in Fig. 4.

Figure 4: Photograph of a jet fire experiment at the Spadeadam Test Site.

MODELING CONSIDERATIONS

As mentioned in the discussion of each set of experiments, there are several important considerations for the user when modeling large LNG fires. Each is discussed briefly below, and further details are found in the FDS User's Guide. Table 1 lists some of the special parameters used to model the experiments discussed above.

Angular Resolution of Radiation Solver

By default, FDS uses approximately 100 solid angles to discretize the unit sphere when solving the radiation transport equation. That is, the radiant energy from a hot object or fire is transported outward in 100 discrete directions. This is usually sufficient for compartment fires, but when the target is relatively far from the radiation source, the number of angles should be increased. The easiest way to determine how many angles are sufficient is to include in your input file several "slices"

Table 1: Summary of the Loughborough Jet Fire Experiments.

Experimental Series	Soot Yield	Radiative Fraction	Number of Angles	Path Length (m)
BGC/GRI LNG Fires	0.005	0.25	600	50
Montoir LNG Fires	0.01	0.14	600	300
Shell Fire Balls	0.005	0.30	600	100
Sandia Methane Burner	0.01	0.35	600	10
Phoenix LNG Fires	0.01	0.25	1200	250
Loughborough Jet Fires	0.01	0.14	600	100

(contour plots) of the quantity `'INTEGRATED INTENSITY'`. This quantity is the angular integral of the radiant intensity, $I(\mathbf{x},\mathbf{s})$, which is a function of position, $\mathbf{x}$, and angle, $\mathbf{s}$:

$$U(\mathbf{x}) = \int_{4\pi} I(\mathbf{x},\mathbf{s}')\,\mathrm{d}\mathbf{s}' \tag{1}$$

The actual value of this quantity is not important; rather, it is the shape of its spatial contours. The contours of U should become more and more smooth with distance from the hot source. However, the angular discretization of the radiation field produces a star-like pattern that becomes more pronounced with distance, as seen in Fig. 5. In this particular case, `NUMBER_RADIATION_ANGLES=600`. The increase in cost for the radiation solver can be partially offset by updating the radiation field less often, or the heat flux to a given location can be taken as a spatial average.

Radiation Path Length

By default, FDS uses a gray-gas model for radiation; that is, the thermal radiation is assumed independent of wavelength. Of course, the radiant energy from a hot object or a fire is distributed over a range of wavelengths, and water vapor and carbon dioxide in the atmosphere absorb the energy at different rates depending on the wavelength. However, when computing the absorption coefficients for various gas mixtures, a single path length must be chosen, and in FDS that value is 10 cm. Again, for compartment fires this value has been shown to work reasonably well, but for large outdoor fires, an adjustment must be made. In the cases discussed above, the path length chosen for the calculation of the radiation absorption coefficient is comparable to the distance between source and target.

Radiative Fraction and Soot Yield

The fraction of the fire's energy that is emitted as thermal radiation is usually specified by the user of FDS. There is an option to allow FDS to calculate the value automatically, but this calculation is complicated by grid resolution issues and the composition of the emitting and absorbing gases. Most sooty compartment-scale fires emit about 35 % of their energy as radiation, but natural gas is closer to 20 %. The reason is that natural gas fires produce little soot, and soot is a significant source of thermal radiation. However, for very large natural gas fires, soot is produced, as evidenced by visible smoke. This tends to increase the radiative fraction. At the same time, however, the soot within the flame zone reabsorbs some of the emitted thermal radiation, leading to lower overall values of radiative fraction.

The values of Radiative Fraction listed in Table 1 were chosen based on point source estimates from the experiments. The values range from 0.14 to 0.35, indicating that the size and configuration of the fire has a significant impact on the radiation emission. There is still no simple "rule of thumb"

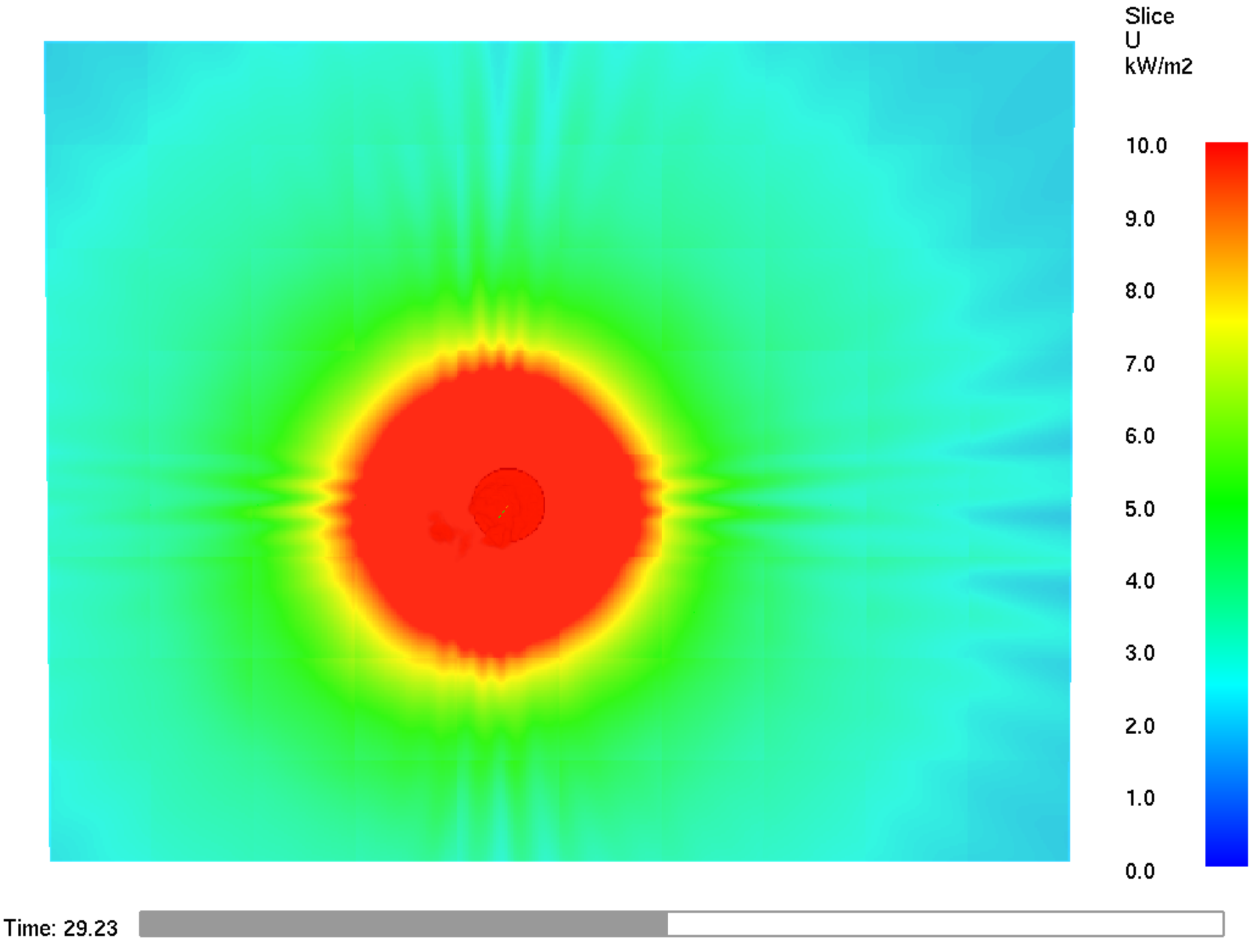

Figure 5: Radiation integrated intensity near the ground in one of the Montoir simulations. The size of the computational domain is 500 m by 400 m.

for specifying this parameter, and predicting it is even more challenging. The values of Soot Yield are simply order of magnitude estimates.

Narrow-Angle Radiometer Measurements

In some of the experiments described above, both wide-angle and narrow-angle radiometers are used to measure the heat flux from the fire to distant targets. Wide-angle radiometers are commonly used in fire experiments and measure the incoming thermal radiation over nearly the entire field of view. Narrow-angle radiometers, on the other hand, measure the incoming radiation over a very limited field of view, typically aimed at the visible flame region. To approximate a narrow-angle measurement, FDS chooses the nearest discrete radiation angle to represent the narrow-angle heat flux. At such large distances, it is difficult to "find" an angle that emanates from the fire to the location of the device. In the simulations of the Phoenix experiments, the location of the targets are shifted slightly so that at least one ray emanating from the fire hits the target.

Atmospheric Conditions

All of the experiments described above were conducted over relatively flat terrain. Typically, wind speeds and a qualitative description of the surface conditions are given in the test report. From this information one can choose appropriate Monin-Obukhov parameters to estimate the vertical temperature and wind speed profiles.

Jets and Fireballs

FDS is a low Mach number code and cannot model directly the supersonic flow at a pipe orifice or gas leak. Instead, cold methane droplets are injected with a high initial velocity and relative narrow spray angle. These droplets evaporate readily to form methane gas. No attempt is made to model the stand-off distance because there is no mechanism in FDS to account for flame suppression due to high shear. Of course, there is some trial and error involved in prescribing a jet. The most important consideration is to match the mass flux and qualitatively capture the spray angle. The droplet size and initial velocity are essentially modeling assumptions because the details of the orifice flow cannot be modeled directly in FDS.

Like a jet, a fireball resulting from a BLEVE (Boiling Liquid Expanding Vapor Explosion) cannot be modeled in FDS directly. For the Shell experiments, the specified mass of LNG liquid is simply introduced at the ground of the computational domain as cold methane gas. The size of the "vent" over which the gas is injected is comparable to the size of the containment vessel. The injection time is on the order of 1 s. A sensitivity study should be done to determine which of these parameters is important.

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