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Liquefied Natural Gas (LNG) Plume Interaction With Storage Tanks

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ABSTRACT

A wind-tunnel test program was conducted on 1:250 scale models to determine the effects of storage tanks on the dispersion of LNG plumes. The tests were conducted for an equivalent continuous prototype LNG boiloff rate of 30 m^3/min, and at 4 and 7 m/sec wind speeds at 10m height. The highest concentrations were observed without any surface obstacles. Tanks created additional turbulene intensity in the wake, resulting in enhanced mixing, with corresponding reduction in distances to lower flammability limit (LFL) concentration of the heavy gas. For an LNG spill without tank, a wind speed of 7 m/sec resulted in higher concentration as compared with a 4 m/sec wind speed. However, the 4m/sec wind speed gave higher concentrations as compared to the 7 m/sec wind speed for an LNG spill when the storage tank interacted with the plume. The ratios of distance to a specific concentration with no obstacle to that with obstacle ranged from one to seven under identical wind speed and boiloff conditions. Mean concentrations measured in a neutral density plume were about three to five times smaller than those observed with the simulated LNG plume.

INTRODUCTION

Natural gas is a highly desirable source of energy for consumption in the United States. Its conversion to heat energy for home and industrial use is achieved with very little environmental impact. Recent efforts to expand natural gas supply include the transport of natural gas in a liquid state from distant gas fields. Liquefied natural gas (LNG) is stored and transported at about -162°C. If a storage tank were to rupture and the contents spill out, rapid boiling of the LNG would ensue and liberation of a potentially flammable vapor would result.

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Studies [1-5] have demonstrated that the cold LNG vapor plume will remain negatively buoyant for most conditions during the dispersion of concern. Thus, it represents a ground-level hazard. This hazard extends downwind from the spill until the atmosphere has diluted the LNG vapor below the lower flammability limit (LFL), a local concentration for methane below 5 percent by volume. Some experts assume that considerable mixing takes place during the gravity driven vapor spreading stage of LNG spills; whereas others assume no dilution of vapor during this stage. None of these formulations currently incorporate the additional complications of surface obstacles. Such interference may cause additional plume dilution or temporary pooling of high gas concentrations. This paper develops an empirical appreciation of the physics of the LNG plume interaction with surface obstacles using atmospheric boundary-layer wind tunnel experiments.

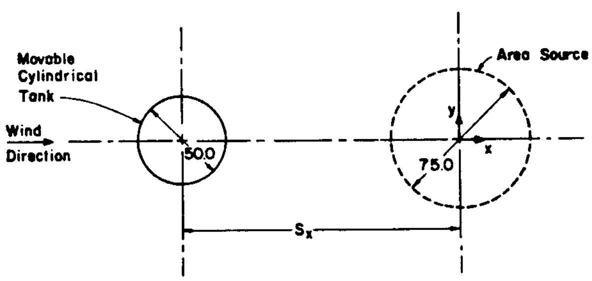
EXPERIMENTAL FACILITIES AND SIMULATION METHODS

Wind-tunnel: The Environmental Wind Tunnel (EWT) at Colorado State University was used for all tests performed. This tunnel incorporates special features such as an adjustable ceiling, rotating turntables, transparent boundary walls, and a long test section to permit reproduction of micrometeorological behavior at large scales. Mean wind speeds of 0.10 to 12 m/sec can be obtained in the EWT. For the present set of test data vortex generators and a trip at the tunnel entrance were followed by 8.8 m of smooth floor upwind of the 1:250 scaled area source model.

Model: Based on the previous atmospheric data from sites similar to that of the present idealized site it was decided that the best reproduction of the surface wind characteristics would be at a model scale of 1:250. Also Cemak [6] has shown that the velocity profiles and spectra and scales of motion observed in the atmospheric boundary layer can be adequately simulated in the wind tunnel at the length scale ratios in the range of 200 to 500. A circular area source having an equivalent diameter of 75 m and cylindrical tanks having an equivalent height and diameter of 50 m were constructed from Plexiglas. The source gas, 100 percent Argon or a mixture of 10 percent Ethane, 4 percent Carbon Dioxide, and 86 percent Nitrogen, was stored in a high pressure cylinder and directed through a flowmeter into the circular area source mounted in the wind-tunnel floor. The area source was constructed so that the discharging gas would exit uniformly through it.

Test Program: The goal of the test series was to determine the effect of surface obstacles on the dispersion of LNG and neutral density plumes. All tests were conducted at an equivalent continuous LNG spill rate of 30 m^3/min., two wind speeds, 4 and 7 m/sec at 10 m equivalent height, and with neutral atmospheric stability. The experiments were performed with a single cylindrical model tank at a scale ratio of 1:250.

A right-hand coordinate system with the origin at the center of the area source was utilized. Configuration 1 is the plane area source case. Ground-level concentration measurements were performed for all tests. Configurations 2 to 8 are described in Figure 1. A summary of the test



Configuration	Displacement in x Direction S_x, meters
2	0.0
3	-250.0
4	-150.0
5	-50.0
6	50.0
7	150.0
8	250.0

Note: All Dimensions in meters

Figure 1 Configurations 2 to 8 Identification

program identifying run numbers, prototype wind speeds, various configuration numbers, and source density is given in Table 1. The model wind speed and flow rate were calculated, as per the discussion in the following section, using equality of Froude number and volume flow rate, respectively.

Atmospheric boundary layer simulation: The atmospheric boundary layer is the portion of the atmosphere extending from ground-level to a height within which the major exchanges of mass, momentum, and heat occur. This region of the atmosphere is described mathematically by statements of conservation of mass, momentum, and energy [6]. It has been determined [7,8] that kinematics and dynamics of flow systems above a certain minimum Reynolds number are independent of its magnitude. Halitsky [9] reported that for concentration measurements on a cube placed in a near uniform flow field the Reynolds number required for invariance of the concentration distribution over the cube surface and downwind must exceed 11,000. Reynolds numbers based on the diameter of the cylinder ranged from approximately 6000 to 12000 for the present study. Since the flow scale being modeled is small, the turning of the mean wind with the height is unimportant; hence the Rossby number equality can be neglected. The experiments were performed with isothermal tunnel air which implies equality of Richardson number to neutral prototype conditions.

Simulation of plume: In addition to modeling the turbulent structure of the atmosphere, it is necessary to scale the LNG plume source conditions properly. The method of similitude [10] obtains scaling parameters by reasoning that the mass force, energy, and property ratios should be equal for both model and prototype. The dynamics of gaseous LNG plume behavior then leads to specifying equality of Froude number, volume flux ratio, and specific gravity.

The buoyancy of a LNG plume is a function of both the mole fraction of methane and temperature. If the plume entrains air adiabatically, then the plume would remain negatively buoyant for its entire lifetime. If the humidity of the atmosphere were high then the state of buoyancy of the plume will vary from negative to weakly positive. Since

Table 1 Summary of Tests

Configuration Number	Source Density-Neutral				Source at Specific Gravity of LNG at Boiloff Temperature			
	Prototype Wind Speed @ 10 m height	Run Number	Prototype Wind Speed @ 10 m height	Run Number	Prototype Wind Speed @ 10 m height	Run Number	Prototype Wind Speed @ 10 m height	Run Number
1		1		23		45		67
2		2		24		46		68
3		3		25		47		69
4	4.0 m/sec	4	7.0 m/sec	26	4.0 m/sec	48	7.0 m/sec	70
5		5		27		49		71
6		6		28		50		72
7		7		29		51		73
8		8		30		52		74

Note: 1. LNG boiloff rate from area source = 30 m^3min.
2. Neutral density source runs were performed with the equivalent amount of vapor generation from 30 m^3/min LNG, but with neutral density.

the adiabatic plume assumption will yield the most conservative downwind dispersion estimates, this situation was simulated. Several investigators [11-13] have confirmed that the Froude number is the parameter which governs LNG plume spread rate, trajectory, plume size, and entrainment during initial dense plume dilution. Froude number is defined as $U^2/((\rho_s/\rho_a - 1)Lg)$. U is the wind speed, ρ_s/ρ_a is the source specific gravity (S.G.) of gas, L is the length and g is acceleration due to gravity. Equality of the Froude number results in the following relationship between prototype and model wind speed:

$$(U_a)_m = \left(\frac{S.G._m - 1}{S.G._p - 1}\right)^{1/2} \left(\frac{1}{L.S.}\right)^{1/2} (U_a)_p \qquad (1)$$

where, m and p indicate model and prototype conditions, respectively. L.S. is the length scale given by L_p/L_m and was equal to 250 in this study. Equality of model and prototype specific gravity was relaxed slightly so that pure Argon could be used, and Froude number equality was maintained by adjusting reference wind speed.

Since the thermally variable prototype gas was simulated by an isothermal simulation gas, the concentration measurements observed in the model must be scaled. This scaling is required since the number of moles of methane released in a thermal plume are different from the number of moles of methane released in an isothermal plume of equal size. The resulted equivalent concentrations are given by the relationship:

$$\chi_p = \frac{\chi_m}{\chi_m + (1 - \chi_m)\frac{T_s}{T_a}}, \qquad (2)$$

where,

χ_m = volume or mole fraction measured during the model test,

T_s = source temperature of LNG during prototype conditions,

T_a = ambient air temperature during field conditions, and

χ_p = volume or mole fraction in the prototype conditions.

Once geometric and kinematic similarity for the simulated atmospheric boundary layer are achieved, the additional modeling requirements for similar neutral density plumes are equality of density ratio and consistent scaling of all velocities. The actual LNG evaporation rate for 30 m^3/min liquid spill rate was calculated. During the neutral density plume release an equivalent volume flow rate of neutral density gas was emitted from the area source.

RESULTS AND DISCUSSION

Approach velocities: The velocity and turbulence intensity profiles were measured with a ThermoSystems, Inc. (TSI) 1050 constant temperature anemometer and a TSI model 1210 hot-film probe. The calibration standard consisted of a Matheson model 8116-0154 mass flowmeter, a Yellowsprings thermistor, and a profile conditioning section fitted to the nozzle. The mass flowmeter measures mass flow rate independent of temperature and pressure. The profile conditioning section forms a flat velocity profile with very low turbulence at the nozzle exit. Incorporating a measurement of the ambient atmospheric pressure and a profile correction factor permitted calibration for wind speeds from 0.1 to 2.0 m/sec. During calibration of the single film anemometer, the anemometer voltage response values over the velocity range of interest were fitted to an expression of King's law [14] but with a variable exponent. During velocity measurements, the anemometer responses were fed to an analog-to-digital converter and then to a minicomputer for immediate calculation of velocity and turbulence intensity.

The approach flow velocity profiles were measured at the location of the area source center, 8.8 m from the tunnel entrance. The representative mean velocity and turbulence profiles are displayed in Figure 2. The average value of the velocity profile power-law exponent was 0.22. The velocity profile data from the lowest measurement location to approximately 20 cm height were fitted to log-linear profile relationship to determine frictional velocity and surface roughness. The average values of the prototype frictional velocity, u_*, were 0.25 m/sec and 0.44 m/sec corresponding to prototype wind speeds of 4 and 7 m/sec. The average value of the prototype surface roughness parameter, z_o, was 4 cm.

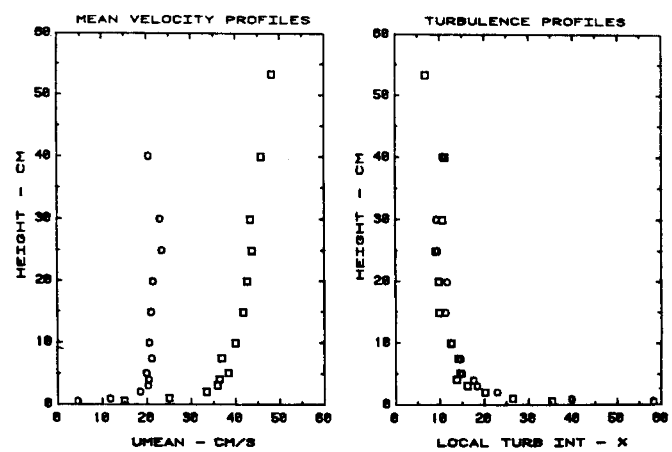


Figure 2 Velocity and Turbulence Profiles Utilized with Negatively Bouyant Plume (LNG)

Concentration Measurements: A rake of eight hot-wire aspirating probes was used to obtain the concentration time histories at points downwind of the spill site. These eight instantaneous concentration sensors were connected to an eight-channel TSI hot-wire anemometer system. The voltages from the TSI unit were conditioned for input to the analog-to-digital converter by a DC suppression circuit, a passive low-pass filter circuit tuned to 100 Hz, and an operational amplifier of gain five.

The basic principles governing the behavior of aspirating hot-wire probes are discussed in [15-17]. A vacuum source sufficient to choke the flow through the small orifice just downwind of the sensing wire element was applied. The sensing wire was operated in a constant temperature mode at a temperature above that of the ambient air temperature. A feedback amplifier maintained a constant overheat resistance through adjustment of the heating current. A change in output voltage from this sensor circuit corresponds to a change in heat transfer between the hot-wire and sampling environment. The heat transfer rate from a hot-wire to a gas flowing over it depends primarily upon the wire diameter, the temperature difference between wire and gas, thermal conductivity and viscosity of gas, and gas velocity. For a wire in an aspirated probe with a sonic throat, the gas velocity can be expressed as a function of the ratio of the probe cross-sectional area at the wire position to the throat area, the specific heat ratio, and the speed of sound in the gas. The latter two parameters as well as the thermal conductivity and viscosity of the gas are functions of composition and temperature. Hence, for a fixed geometry and wire temperature, the heat transfer rate or the related voltage change across the wire is a function of only the gas composition and temperature. Since all tests performed were in an isothermal flow, the wire's response was a function of gas composition only.

The experimental measurements of concentration with neutral density source were performed with a gas chromatograph having a flame ionization detector (FID). The electrical conductivity of a gas is directly proportional to the concentration of charged particles within the gas. The ions in this case are formed by the sample gas mixed with hydrogen and then burned with air. The ions and electrons formed enter an electrode gap and decrease the gap resistance. The resulting voltage drop is amplified by an electrometer and fed to an integrator.

The tracer gas sampling system used for neutral plume releases consisted of a series of fifty 30 cc syringes mounted between two circular aluminum plates. A variable-speed motor raised a third plate, which in turn raised all syringes simultaneously. A set of check valves and tubings was connected such that airflow from each sampling point passed over the top of each designated syringe. When the syringe plunger was raised, a sample from the tunnel was drawn into each syringe. A sample from each syringe was injected into the gas chromatograph, and output was converted to concentration.

This paper describes mainly the experimental measurements of LNG and neutral density plume dispersion in the wake of a single cylindrical obstacle. Additional experiments with added tanks, buildings, and a shelterbelt are described elsewhere [3]. The neutral density plume results are presented as mean concentrations, whereas LNG plume data are given as both mean concentrations and peak concentrations.

Figures 3 and 4 show plots of ground-level mean concentration versus downwind distance for neutral density and LNG source gas, respectively. The highest concentrations were observed without any surface obstacle (configuration 1). The storage tank generated excess turbulence intensity [18-22], which resulted in additional mixing and corresponding plume dilution. For an LNG spill without tank, a wind speed of 7 m/sec resulted in higher concentration as compared to 4 m/sec wind speed data. However, the 4 m/sec wind speed gave higher concentrations as compared to 7 m/sec wind speed data for an LNG spill when the storage tank interacted with the plume. The mean concentrations measured with neutral density plumes were about 3 to 5 times smaller in magnitude than those observed with LNG plumes. When the cylindrical tank was located upstream of the spill area, the initial

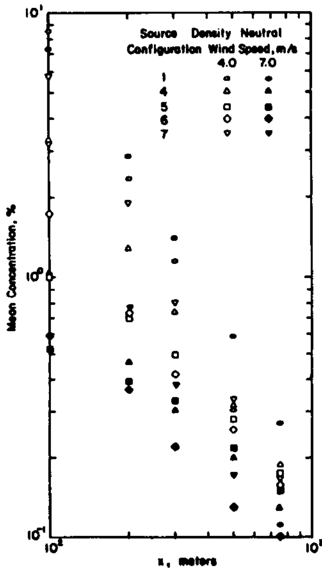


Figure 3
Mean Concentration vs. x (Neutral Density Plume)

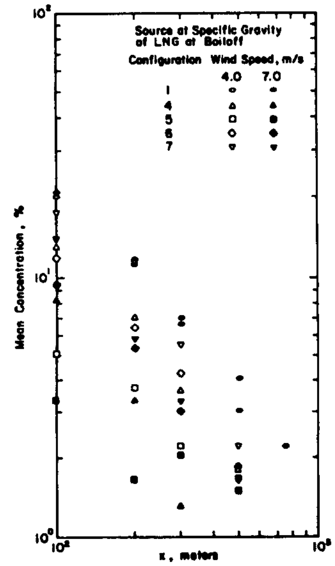


Figure 4
Mean Concentration vs. x (LNG Plume)

dilution for LNG plume (measured at 100 m downwind) was generally 2 to 3 times smaller than that for the neutral plume data. With the cylindrical tank upstream but close to the spill area the highest plume dilution was observed.

Concentration isopleths for selected runs are displayed in Figures 5 through 8. Figure 9 is a plot of the maximum downwind distance for ground-level concentrations versus the displacement of the cylindrical tank at various wind speeds. This figure also indicates the downwind distance to ground-level concentrations for the no obstacle case. Table 2 summarizes the ratios of distance to a specific concentration with no obstacle to that with an obstacle. The ratios ranged from one to seven under identical wind speed and boiloff conditions. The recirculation zone behind an obstacle is approximately 3 to 5 times the height of the obstacle [18-22]. From Table 2, it can be concluded that the effects of the obstacle are major for a distance between 3 to 6 times the height of the cylinder; thus, the present data will be applicable when the plume is within the recirulation zone of the obstacle. In the case of an accidental LNG spill the LNG storage tank is likely to be within 250 m of the spill location. Comparisons of mean and peak concentrations of the same magnitude show that peak concentrations in the wake of cylinders have been effected less than mean concentration.

The entire heavy gas plume is modified by the cylinder wake when the cylinder is upstream of the spill area, whereas the plume divides and is only partly modified by the wake when the cylinder is downwind of the spill area. Greater dilution of the plume occurred with the cylinder upstream of the spill area. However, modifications of the flow structure upstream of the obstacle were also important and resulted in diluting the plume upstream.

For the no obstacle case, the LNG plume spread was larger at 4 m/sec wind speed than at 7 m/sec wind speed. Configurations where the plume is affected by the surface obstacles gave longer LFL distances at 4 m/sec wind speed than at 7 m/sec wind

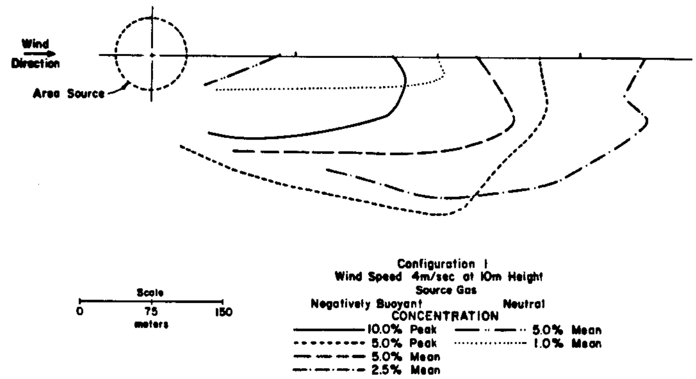


Figure 5 Concentration Isopleths for Configuration 1 and Wind Speed 4m/sec

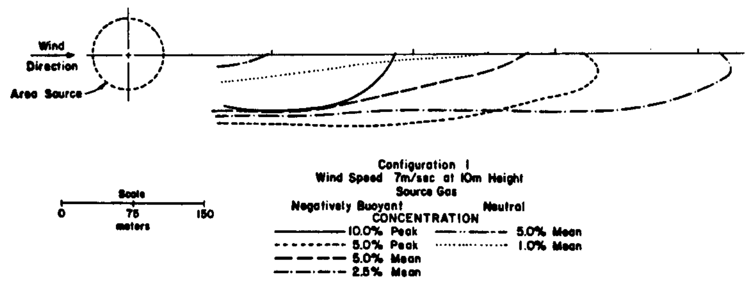


Figure 6 Concentration Isopleths for Configuration 1 and Wind Speed 7m/sec

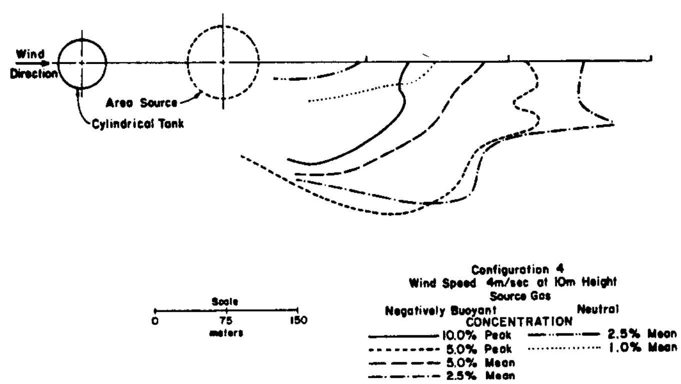


Figure 7 Concentration Isopleths for Configuration 4 and Wind Speed 4m/sec

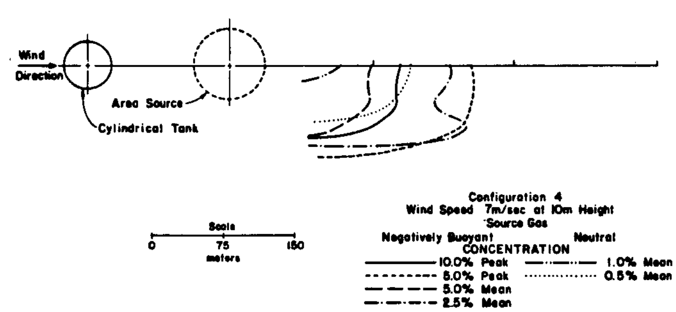


Figure 8 Concentration Isopleths for Configuration 4 and Wind Speed 7m/sec

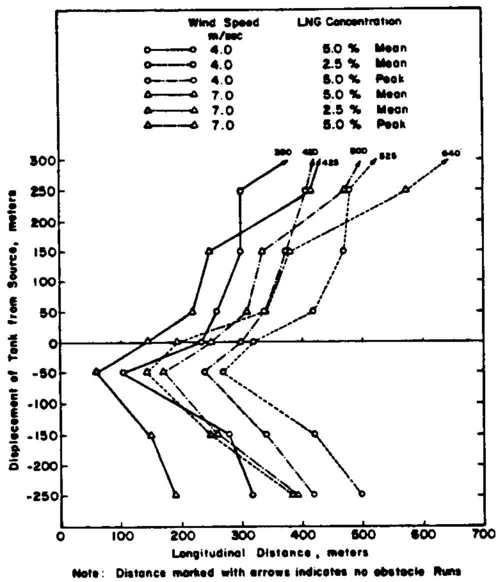


Figure 9 Maximum Downwind Distance for Given Concentrations Versus Displacement of the Cylindrical Tank

CONCLUSIONS

The experimental measurements lead to the following conclusions:

- At the same downwind locations, the highest concentrations were observed without any surface obstacles. Tanks and buildings created additional turbulence intensity in the wake, resulted in enhanced mixing, with corresponding reduction in concentrations.
- For no obstruction, the higher concentration persisted for longer downwind distance at a wind speed of 7 m/sec.
- A 4 m/sec wind speed resulted in higher ground-level concentration when the surface obstacle interacted with the plume.
- Mean concentrations measured with neutral density plumes were about 1/3 to 1/5 of the magnitude of those measured with the LNG plume.
- The ratios of distance to a specific concentration for no obstacle to that with obstacle were in the range of 1 to 7 for identical wind speed and LNG boiloff conditions.
- The greatest plume dilution occurs when the plume is released downstream of the obstacle and close to the obstacle, in the recirculation zone of obstacle wake.

Table 2 Comparison of Longitudinal Distance to a Specific Concentration Against Cylinder Position

Wind Speed (m/sec)	LNG Boiloff Rate (m^3/min)	Concentration	$R^{(1)}$ Cylinder at -250m	-150m	-50m	0m	50m	150m	250m
4	30	5% Mean	1.25	1.37	3.57	1.60	1.45	1.27	1.25
4	30	2.5% Mean	1.08	1.25	1.92	1.64	1.25	1.11	1.09
4	30	5% Peak	1.01	1.23	1.75	1.41	1.23	1.12	1.03
7	30	5% Mean	2.27	2.86	7.14	2.86	1.92	1.69	1.02
7	30	2.5% Mean	1.75	2.56	4.35	3.33	1.89	1.67	1.12
7	30	5% Peak	1.27	1.92	2.86	1.89	1.61	1.49	1.06

(1) $R = \left(\frac{\text{Longitudinal Distance without Obstacle}}{\text{Longitudinal Distance with Obstacle}}\right)$ @ specific concentration limit

speed, although smaller than those observed without obstacles. The LNG plume tends to have its maximum concentration off the centerline. For configuration 1 the deviation from centerline may be attributed to meandering of the plume from the wind-tunnel centerline due to a slight lateral nonuniformity of the flow. However, for the cylindrical tank interaction cases the deviation may be caused by either higher turbulence intensities in the wake of the tank which results in higher entrainment and correspondingly lower concentration in the wake region, or the horseshoe vortices [22] located with their axis in the longitudinal direction on either side of the obstacle deflecting the ambient air downward from the top of the turbulent boundary layer along the centerline of the obstacle, or the defection of the plume laterally by the surface obstacle.

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