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A dispersion safety factor for LNG vapor clouds

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HIGHLIGHTS

- ► We proposed a new parameter: the dispersion safety factor (DSF).
- ► DSF is the ratio between the distance reached by the LFL and that reached by the visible cloud.
- ► The results for the DSF agree well with the evidence from large scale experiments.
- ► Two expressions have been proposed to calculate DSF as a function of H_R.
- ► The DSF may help in indicating the danger of ignition of a LNG vapor cloud.

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ABSTRACT

The growing importance of liquefied natural gas (LNG) to global energy demand has increased interest in the possible hazards associated with its storage and transportation. Concerning the event of an LNG spill, a study was performed on the relationship between the distance at which the lower flammability limit (LFL) concentration occurs and that corresponding to the visible contour of LNG vapor clouds. A parameter called the dispersion safety factor (DSF) has been defined as the ratio between these two lengths, and two expressions are proposed to estimate it. During an emergency, the DSF can be a helpful parameter to indicate the danger of cloud ignition and flash fire.

1. Introduction

As the industrial, residential and power sector demand for natural gas increases yearly, annual natural gas production is expected to rise. To give just an example, about 25% of the energy used in the United Sates came from natural gas in 2009, and LNG demand in the USA is expected to increase from 2.4×10^{10} m^3 in 2009 to 3.1×10^{11} m^3 in 2030 [1]. According to a report prepared by the Center for Energy Economics [2], the USA has the largest number of LNG facilities in the world, scattered throughout the country and often located near population centers where natural gas is needed.

Natural gas consumption has also increased steadily in the European Union. According to the European Union of the Natural Gas Industry, it is expected to increase from 9.9×10^{10} m^3 in 2010 to approximately 2.54×10^{11} m^3 in 2030 [3].

Typical LNG facilities today range from huge base-load liquefaction plants to small satellite storage units. Natural gas is transported in specially designed ships as liquefied natural gas, which is cooled to −160 °C, a temperature at which the gas becomes a liquid at atmospheric pressure. In this compact form (the specific volume of LNG is 600 times smaller than in its gaseous condition at the same pressure), LNG can be shipped in special tankers to receiving terminals, where it is stored in insulated tanks without any pressurization. Then, it can be transported in cryogenic road tankers, or regasified and transported by pipeline to distribution companies.

Natural gas consumption is also expected to rise rapidly in other countries such as China and India. Consequently, public authorities have increased their warnings about the possibility of large-scale LNG spill hazards caused by accidental events or intentional attacks. For this reason, there is now significant interest in the possible risks associated with the storage, treatment and transportation of liquefied natural gas (LNG) and in accurate hazard prediction.

Therefore, methods to ensure the safety and reliability of current or future LNG facilities and LNG shipments are important from both public safety and property perspectives.

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Nomenclature

A to F	atmospheric stability class
b	half width of the middle part of the cross wind concentration profiles, m
c	concentration, kg m^{-3}
c_A	centerline ground level concentration, kg m^{-3}
DSF	dispersion safety factor, dimensionless
H_R	relative humidity, %
LFL	lower flammability limit, % vol
R^2	coefficient of determination, dimensionless
S_y, S_z	horizontal and vertical dispersion coefficients, m
T	ambient temperature, °C
T_{dew}	dew point temperature, °C
UFL	upper flammability limit, % vol
u_w	wind speed, m s^{-1}
X_{LFL}	length of the flammable cloud at the lower flammable limit (LFL), m
X_{VIS}	length of the visible cloud, m
z_r	surface roughness, m
β	function of the parameter in the wind profile, $\beta = 1 + \alpha$, dimensionless

1.1. LNG hazards

The potential hazards associated with an LNG spill are diverse, and vary depending on the release features, the size of the spill, the environmental conditions and the site at which the spill occurs. To assess whether a given facility implies a certain hazard, knowledge is required on the LNG properties and their behavior when released.

The density of LNG is roughly half the density of water, and at its boiling point at atmospheric pressure its vapor density is 1.5 times the density of air. When LNG is spilled on land or water, the underlying spill surface is initially very hot compared to the temperature of the LNG. Due to the high heat transfer rate from water or ground, the natural gas will vaporize rapidly, producing a low-lying white vapor cloud which is visible due to the condensation of water vapor from the atmosphere.

Immediate hazards can include cryogenic damage caused by direct contact, and a pressure wave due to rapid phase transition that can occur if there is mixing between the LNG and water.

An LNG spill on ground or water gives rise to a pool that simultaneously spreads and evaporates; this spreading pool can result in a pool fire if it is ignited. If it is not immediately ignited and a vapor cloud is formed, a flash fire will occur if it meets an ignition source, followed by a pool fire in the spill.

The dominant component of LNG is methane; hence, LNG vapor is flammable in air in a range from approximately 5% (LFL) to 15% (UFL) by volume. When the fuel concentration is below the lower flammability limit (LFL), the vapor cloud cannot burn because too little methane is present. When the LNG concentration exceeds the upper flammability limit (UFL), the cloud is too rich in LNG for ignition.

If the flammable vapor cloud progressing from an accidental LNG spill reaches a confined area, a gas explosion may occur.

2. Large scale LNG release experiments

A series of experimental trials were performed in the early 1980s to study the behavior of LNG when spilled. The available data sets are limited. This type of experiment is expensive and difficult to carry out and is therefore necessarily limited in terms of the number of experimental programs and the cases studied in each one. The set of available trials includes releases in various atmospheric conditions. All test releases were on unobstructed terrain, and the range of materials was restricted to LNG (or methane) and LPG. Table 1 summarizes the most significant vapor cloud dispersion trials for which data are available and relevant to this study. All these trials involved spillage of LNG on water, which produced dense vapor clouds.

The Burro series tests [4,5] involved eight releases of approximately 40 m^3 of LNG on water, with a spill duration ranging from 1.3 to 3.2 min. A large array of equipment was used including gas, temperature, heat flux, humidity, and turbulence sensors.

The primary objective of the tests conducted on water at Maplin Sands [6] was to obtain data on dispersion and radiation due to fire, from 20 releases of LNG and 14 of propane, for both instantaneous and continuous spills. From these tests, it was found that the fuel type and the release mode affected the behavior of the vapor clouds. It was noted that the area covered by a flash fire was approximately the same as that contained within the flammable region of the cloud before ignition.

Coyote series tests [7] were performed with the same setup as that used in the Burro tests. The main purpose of this test series on water was to study the rapid phase transition phenomenon.

Several authors [8–12] have commented and analyzed the main features of large LNG spills.

3. Vapor dispersion modeling

There are different types of heavy gas dispersion models, including empirical models, box/integral models such as those applied in SLAB, HEGADAS and DEGADIS codes, and CFD (Computational Fluid Dynamics) models. In this study, we applied the DEGADIS code, because it is widely used for environmental impact and risk assessment, due to the fast computational time, the ease of use and the fact that it is freeware. This model has been demonstrated to give predictions consistent with a wide range of field tests data involving different substances on flat terrain. In addition, DEGADIS predictions of the flammable cloud extent are close to the observations reported by different authors for the release of propane and LNG [13,14]. Finally, an additional reason to use DEGADIS in this paper is that it calculates the temperature of the cloud along the distance, and this value can be used in order to establish the atmospheric humidity condensation and therefore the contour of the visible cloud.

DEGADIS is a one-dimensional integral model which predicts ground level dispersion. The initial dispersion is characterized by a box model with an initial width and height. Subsequently, the vapor cloud will disperse in the prevailing wind direction. It will be diluted as it mixes with air and will become less dense. The cloud will spread with an exponential profile in the vertical direction, becoming smoother in the direction perpendicular to the wind until it reaches a Gaussian distribution in the horizontal direction. The concentration can be calculated from the following equations:

$$c(x, y, z) = c_A \exp\left\{-\left[\frac{z}{S_z(x)}\right]^{\beta}\right\} \quad \text{for } |y| < b \tag{1}$$

$$c(x, y, z) = c_A \exp\left\{\left[\frac{|y| - b(x)}{S_y(x)}\right]^{2} - \left[\frac{z}{S_z(x)}\right]^{\beta}\right\} \quad \text{for } |y| > b \tag{2}$$

where

c is the concentration, kg m^{-3}
c_A is the centerline ground level concentration, kg m^{-3}
b is the half width of the middle part of the cross wind concentration profiles, m
S_y, S_z are the horizontal and vertical dispersion coefficients, m