



Predicting the flammable region reach of propane vapor clouds



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ABSTRACT

Liquefied gas fuels are widely used around the world, and the growth of LNG and LPG consumption continues to increase. However, using these fuels can lead to accidents if they are released to the environment. Consequently, the challenge to control and predict such hazards has become an objective in emergency planning and risk analysis. In a previous article the “Dispersion Safety Factor” (DSF) was proposed, defined as the ratio between the distance at which the lower flammability limit concentration occurs and that corresponding to the visible contour of a vapor cloud. Its interest was demonstrated by applying it to the specific case of an LNG spill. With the appropriate modifications, this factor may be applied to the dispersion of other substances; in this communication it is applied to the atmospheric dispersion of propane, and two expressions are proposed to estimate it. Due to the similarity between the properties of both gases, these expressions could probably be applied as well to the dispersion of propylene.

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1. Introduction

Liquefied Petroleum Gas (LPG) is a mixture of hydrocarbon gases composed mainly of propane and butane. LPG has numerous applications: it is used in transportation, in commercial business, industry, agriculture and domestic heating and cooking, among other purposes. The domestic sector is one of the most notorious applications for LPG, with almost 45% of the global demand. However, transportation is one of the fastest growing sectors and represents almost 9% of total world LPG consumption, with 23.7 million tons in 2011 (Hart, Gist, & Otto, 2011).

Global LPG consumption has increased significantly in recent years; the increase in 2000 over 1990 was 45% (Hart et al., 2011). Among the countries with the highest consumption in the world are the United States and Canada, with approximately 50.9 million tons consumed in 2010. In 2006, the consumption in China was 19 million tons, while in Japan was 18.2 million tons (Hart, Gist, Otto, & Whitley, 2008). By region, Asia is already the world's largest consumer with 63.4 million tons, and the global LPG market is expected to increase substantially in the next decade in this region. In 2011 the world LPG production reached a new record of 269 million

tons (World LP Gas Association, 2012) and the production is expected to increase to 275 million tons in 2014 (Hart et al., 2011).

LPG is a co-product of natural gas and crude oil production and usually goes by underground pipeline or by railroad to storage terminals and by trucks to storage facilities. LPG is stored in large tanks at various distribution points, and in smaller tanks at residential homes.

LPG can be stored either under pressure or refrigerated. Selection of the storage option depends on different factors such as safety, product distribution supplies and cost. As an estimated guide, pressurized storage tends to be used up to 3200 m³, semi-pressurized from 2400 m³ to 6400 m³ and refrigerated for volumes above 6000 m³ and up to 100,000 m³ (Brook & Chodorowska, 2005).

With the objective of minimizing the storage volume of LPG, it is often stored as a liquefied gas. For large quantities the most economical option is to store it at atmospheric pressure to minimize the number and capital cost of the tanks.

A main component of LPG is propane, and this study focuses on this component. Propane boiling temperature at atmospheric pressure is −42 °C; at room temperatures it can be liquefied at a pressure of about eight atmospheres. Under normal temperature and pressure (1 atm and 20 °C), propane is in gaseous state; it is heavier than air and therefore, in case of leakage it tends to accumulate in low places.

The lower (LFL) and upper (UFL) limits of flammability are respectively the minimum and maximum concentrations of propane that must be present in a propane/air mixture to support its combustion in air. These are very important values concerning the

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flammability of a propane cloud dispersing in the atmosphere. The lower and upper flammability limits of a propane/air mixture are 2.1% and 10.1% (volume) respectively.

Potential hazards related with a propane spill are diverse and vary depending on several factors: the size of the spill, storage conditions, environmental conditions and characteristics of the place where the spill occurs.

A substance which is relatively similar to propane is propylene. Propylene is a key component of the petrochemical industry; the materials that are derived from propylene are polypropylene, acetone, phenol, cumene (epoxy resins), acrylonitrile (acrylic fibers and coatings), propylene oxide, isopropyl alcohol, etc.

Propylene is produced mainly as a by-product of petroleum refining and of ethylene production by steam cracking of hydrocarbon feedstocks. But there are also a number of technologies for producing propylene directly from other feedstocks; thus, the increasing demand for propylene and the availability of low-cost feedstock make propane dehydrogenation an economically attractive chemical method (American Chemistry Council, 2007).

Propane and propylene share physical and chemical properties that make them very similar substances (see Table 1) and the processing and storage facilities are commonly interchangeable for both substances. Based on this fact, it is possible to extrapolate some predictions for propane (including correlations) also for propylene.

Some events that can occur associated to a release of propane are a jet fire, a flash fire, a pool fire or even a BLEVE, usually followed by a fireball.

One of the most dangerous aspects of a propane leak is the formation of a flammable cloud, which can cause a flash fire and, under certain circumstances, an explosion. A flash fire is the combustion of a vapor cloud resulting from the escape of a flammable gas which, after mixing with the air reaches an ignition source. This type of fire can occur if the ignition does not take place immediately after the escape.

In the event of the atmospheric dispersion of propane, a very important issue is the extent of the region of the cloud which is flammable, i. e. the region where the gas concentration ranges between the two flammability limits. Knowledge of the position of this flammable region with respect to the location of the possible ignition points can be very important from the point of view of managing the emergency. A method has been proposed to estimate the reach of the lower flammability limit as a function of the extent of the visible cloud; this method is based on the so-called Dispersion Safety Factor (Vilchez, Villafane, & Casal, 2013). In this paper, it has been applied to the atmospheric dispersion of propane.

2. Experimental data

The release phenomenon depends mainly on the physical properties of the material, the containment (process or storage)

Table 1
Chemical and physical properties of propane and propylene (American Chemistry Council, 2007).

Property	Propane	Propylene
Molecular formula	C ₃ H ₈	C ₃ H ₆
Molecular weight (g mol ⁻¹)	44	42.08
Normal boiling point (°C)	-42	-47.8
Melting point (°C)	-188	-185.3
Critical temperature (°C)	96.6	91
Critical pressure (bar)	42.5	46.1
Gas density (at 1.013 bar and boiling point) (kg m ⁻³)	2.423	2.365
Autoignition temperature (°C)	470	460
Flammability limits in air, vol. % at 20 °C and 1atm	2.1–10.1	2.0–11.0

conditions, the way the accident takes place and on the possible subsequent mechanical and physical interaction with the immediate surrounding environment, among other factors (Mannan, 2005).

The propane can be initially contained as a liquid cooled at atmospheric pressure or pressurized at ambient temperature, and released in the form of liquid, vapor or vapor–gas mixture (two-phase flow), depending on the location of the aperture and the containment conditions. If the release occurs from a container holding pressurized liquefied gas, the material will normally be liquid if the aperture is below the liquid level and vapor or two-phase mixture if it is above the liquid level.

This study focuses on the case of a spill of liquefied propane gas cooled at atmospheric pressure, assuming that all the propane is evaporated (boiling) taking heat from both the soil and atmosphere, and giving rise to a flammable vapor cloud.

A bibliographical survey has revealed that very few large-scale experimental projects have been performed; this is due to their difficulty and cost. The set of available trials consists of the valuable tests conducted in Maplin Sands in the early 1980s (Hirst & Eyre, 1983). All these test releases were on unobstructed terrain and involved spillage of LPG on water, which produced dense vapor clouds. LPG used in these trials basically consisted of propane (97–98%) with small amounts of ethane. The value of the source radius was reported to be around 10 m, with a constant evaporative flux of 0.085 kg m⁻² s⁻¹.

Here, temperatures of 15 °C and 35 °C have been chosen to provide calculation examples of the dispersion safety factor (DSF), as these are representative of the temperatures during the aforementioned large-scale tests (Table 2) and, furthermore, allowed the comparison of the results with those previously obtained with LNG. The set of available trials with LNG includes releases in several atmospheric conditions with a temperature ranging from 38 °C to 11 °C (Vilchez et al., 2013).

The influence of relative humidity percentages has been analyzed between 5% and 90%; these values take into account coastal areas, desert areas and the relative humidity range in which the trials were conducted (70–85%) at Maplin Sands. Table 2 summarizes the most significant vapor cloud dispersion trials with propane for which data are available and relevant to this study.

3. Application of the dispersion safety factor to propane vapor clouds

In a previous article (Vilchez et al., 2013) a “Safety Factor Dispersion” (DSF) was proposed, given by the following expression:

$$DSF = \frac{X_{LFL}}{X_{VIS}} \quad (1)$$

where

X_{LFL} is the downwind length of the flammable cloud at the lower flammable limit, m, and

X_{VIS} is the downwind length of the visible cloud, m.

Table 2
Summary of large scale propane release experiments (Blackmore et al., 1982; Havens, 1992; Hirst & Eyre, 1983; Puttock et al., 1983).

Test	Spill rate (kg s ⁻¹)	Average wind speed (m s ⁻¹)	Atmospheric stability class	Air temperature (°C)	Atmospheric relative humidity (%)
Maplin 43	19.2	5.5	D	17	70
Maplin 46	23.3	8.1	D	19	71
Maplin 51	46.7	7	D	–	80
Maplin 54	19.2	3.8	C and D	8.5	85

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