Formation of Dangerous Zones Due to Accidental Release of Liquefied Naturl Gas in Egypt

O. Badr and O. Al-Farouk

***Abstract*—The main objective of the present investigation is to study the environmental impact due to accidental spill of toxic and flammable liquefied natural gas (LNG) on land. Different case studies of possible accidents in Egypt were considered. US EPA-approved dispersion models were used to estimate the size and location of the formed dangerous zones at different elapsed times from the accident. The growth and decay of the dangerous zones for different concentration levels were also obtained showing them in downwind, crosswind, and vertical directions. In this study the toxicity of natural gas is measured by its concentration causing suffocation to humans while flammability is measure by its lowest concentration in air to cause fire in the presence of an ignition source. Two accidental scenarios of LNG spill from an instantaneous full rupture of a storage tank or a rupture of an external pipe connected to it have been considered. In both cases, constant area or constant thickness of the formed LNG pool were studied. Parametric studies were performed to investigate the effects of wind speed, atmospheric stability, and vertical height on the size of formed dangerous zones.**

***Index Terms*—Risk assessment, LNG accidents, toxic zones, flammability limits.**

I. Introduction

Worldwide, natural gas has become one of the major sources of energy particularly in Egypt. Having a large amount of reserves, Egypt utilizes natural gas widely in its industrial and economical development plans. Natural gas is used to a great extent as a domestic fuel as well as for most industrial combustion equipment and to a lesser extent for automobiles. Moreover, NG is used heavily as a feed stock to many petro-chemical industries. In addition to such local utilization, Egypt exports a large percentage of its production in the form of compressed natural gas (CNG) through pipelines and LNG via large shipping vessels.

On the other hand, health, safety, and environment (HSE) are extremely important issues in oil, gas, and petro-chemical industries. Presently, the risk in dealing with such chemicals is very high due to the substantial increase in producing, transporting, and/or utilizing them. Abnormal situations such as equipment commissioning, emergency shutdowns and accidental situations may lead to gas release and/or liquid spill of these dangerous chemicals leading to health hazards and/or explosions. There are many examples of such accidents which took place all over the world. For instance, the Bhopal disaster was a gas leak incident in India, at the Union Carbide pesticide plant in which over 500,000 people were exposed to methyl isocyanate gas that ended by immediate death toll of 2,259 [1]. Another example is the explosion of a road tanker transporting LNG in Catalonia (Spain) in which one person killed and two injured [2]. A third example is a complete failure of a road tanker containing 19 tones of ammonia resulted after the tanker had fallen from an elevated roadway in Houston, Texas, USA in1976. There was a rapid formation of a large cloud which slumped to ground level and spread over the surrounding area. Six people were killed [3].

The simple logic dictates that preventing such accidents is much better than curing their impact after they happen.

In order to control the environmental impact of such abnormal situations, a risk assessment analysis should be conducted in which the size of the problem and the consequences of the propagation should be studied. For example, the US EPA Clean air Act (section 112 r) requires facilities that manufacture, process, use, store, or otherwise handle certain amounts of toxic substances to submit a Risk Management Plan (RMP) to local emergency management authorities [4]. An important element of the RMP is the determination of consequence distances for worst case and alternative release scenarios. Risk assessment of an accident combines many elements in determining the size and probability of harm, which could result from that accident. The main objective of this investigation is to determine the size and location of toxic and flammable zones formed in the atmosphere due to accidental spills of LNG on land in Egypt. Since worst case scenarios are dealt with, the study considers the maximum possible extent of damage which could occur due to the accident.

II. Problem Statement

This study applies to a typical LNG plant located in Damietta industrial city north east of Egypt. It considers a typical LNG storage tank with 85 meter diameter filled with 50 meter-high liquid at almost atmospheric pressure. The study also considers a 0.5 meter diameter pipe among the many different size pipes connected externally to the tank.

Two different sources of the accidental spill were considered. The first is a full rupture of the storage tank which may occur due to an earthquake, explosion, war situation, or a terrorist attack. The second is a rupture of one of the pipes connected to the tank that may occur due to corrosion of a valve or direct impact by any moving vehicle within the plant. The pool formed by the spilled LNG may be contained in a limited surface area due to the presence of nearby buildings or fences. Otherwise the spilled liquid

Manuscript received May 30; revised September 3, 2013.

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DOI: 10.7763/IJESD.2014.V5.446

spreads on land with almost a constant thickness (1 cm). Accordingly, three accidental scenarios are investigated in this article; namely 1- a pipe rupture with a constant thickness pool, 2- a tank rupture with a constant thickness pool, and 3- a tank rupture with a constant area pool. All case studies deal with a typical Egyptian natural gas having 81% Methane, 5.1% Ethane, 2.0% Propane, and other non combustible gases. The saturation temperature at atmospheric pressure [112 K] of pure methane [5] is taken as the initial pool temperature.

The meteorological conditions in the considered location are: outside Temperature 35°C, wind speed 0.5 - 8.0 m/s, wind direction 270° from north, and variable atmospheric stability. Atmospheric stability is a measure of turbulence level in the atmosphere near earth surface and thus the intensity of mixing of evaporated NG with ambient air. It is usually classified as [6]: A: extremely unstable, B: moderately unstable, C: slightly unstable, D: neutral, E: stable, and F: very stable.

In addition to the above-mentioned three cases, parametric studies of effects of wind speed and atmospheric stability on results of worst case scenario are also conducted.

III. Modelling of the Situation

The LNG spill from either the storage tank or one of the pipes connected to it forms a pool on the ground. The pool area and liquid temperature as well as the rate of evaporation from the pool as function of time are essential input data to the dispersion software that is used to determine the size and location of the dangerous zones. Therefore a mathematical model was developed to determine such data using the "Surface Temperature" method [7]. This method considers the coupled equations of mass transfer and energy to determine the evaporation rate and the bulk temperature of the pool by an iterative procedure.

As shown in Fig. 1, the energy balance per unit time and area of the pool of the spilled liquid may be written in the following form [7]:

$$Q\text{sol} + Q\text{atm} - Q\text{sur} - Q\text{evp} + Q\text{sen} + Q\text{grd} = Q\text{total}$$

where, Qsol is the net solar radiation, Qatm is the long-wave radiation from the atmosphere absorbed by the pool, Qsur is the long wave radiation emitted by the pool, Qevp is the evaporation energy, Qsen is the net sensible heat transferred into the pool from the atmosphere by convection, Qgrd is the heat conducted from the ground, and Qtotal is the increase in energy stored in the pool.

In case of having a ruptured pipe connected to a storage tank, the rate of change in the pool liquid mass is determined by the difference between the inlet flow rate from the leaking pipe and the rate of evaporation. The evaporation rate was calculated from the above-mentioned energy equation while the leaking pipe flow rate was calculated from the simple Bernoulli equation based on the transient height difference between the top level of LNG inside the tank and the level of the rupture point.

Consider the first scenario of a ruptured pipe with constant thickness pool where the accident started at 4:00AM and took 6 hours to be under control and stopping the spill completely. Despite being a function of many parameters, the evaporation rate is strongly dependent on the pool surface area as shown in Fig. 2 and Fig. 3. Once the pipe flow stopped, the huge evaporation rate reduced the pool area to zero almost instantaneously.

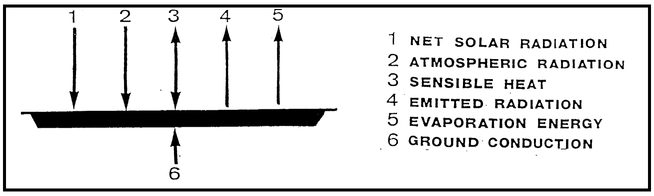


Fig. 1. A schematic diagram of an evaporating pool with all energies involved

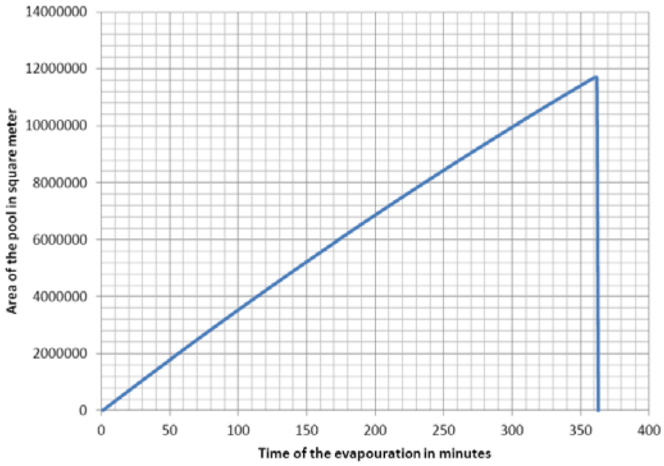


Fig. 2. Variation of LNG pool area with respect to elapsed time from an accident of a pipe rupture for case study #1 (ruptured pipe – constant thickness pool)

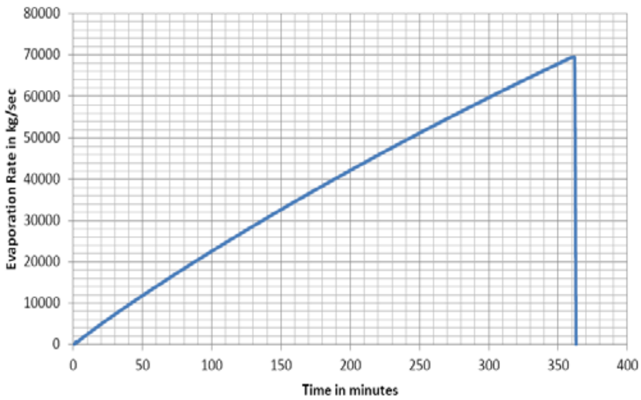


Fig. 3. Variation of LNG evaporation rate with respect to elapsed time from an accident of a pipe rupture for case study #1 (ruptured pipe – constant thickness pool)

Toxic and Dangerous Limits: The dangerous zone for a certain limit is defined as the 3D contour surface of constant level of concentration equal that limit. The important concentration limits used in this study were mainly set by NIOSH [8]. In this investigation three limits were considered; namely the toxic TWA limit which is the Time Weighted Average concentration for a normal 8-hour workday and a 40-hour workweek to which all workers may be exposed without adverse health effects. The other two limits were the Lower Flammability Limit (LFL) and the Upper Flammability Limit (UFL). Despite being nonflammable, zones with concentrations higher than UFL are hazardous since they become flammable after a while due to mixing with atmospheric air. For the natural gas under consideration, these limits were reported as 6666, 33000, and 98356.67 mg/m3 for TWA, LFL, and UFL, respectively [8].

IV. Prediction of Dangerous Zones

The EPA based dispersion model (DEGADIS+) was used to predict the size of the dangerous zone in the downwind, crosswind, and vertical directions. This model is developed for the dispersion of heavier than air gases. In this study the temperature of evaporated NG is assumed to be very close to the boiling point of methane at atmospheric pressure (112 K) which makes its density greater than ambient air.

In addition to the pool area, temperature, and evaporation rate previously discussed, DEGADIS+ software requires input parameters such as the accident location, meteorological data, and liquid properties. Wind speed, atmospheric stability or stability class, and height of interest were varied (one at a time) to determine the worst situation.

It should be emphasized that the results of the size and location of the dangerous zones are purely theoretical and have not been verified with experiments. However, some experiments in China Town, Nevada, USA were performed and verified successfully the DEGADIS+ Model [9].

The utilized dispersion software determines the concentration profiles of the evaporated LNG at different heights and different times elapsed from the start of the accident (e.g. Fig. 4). At each time, such concentrations are used to generate sets of results including output data files for the maximum downwind distance for each dangerous limit, 2D diagrams for the dangerous zones in the downwind and crosswind directions superimposed on a plain map of the affected city (Fig. 5), and finally a side view of the dangerous zones in the downwind and vertical directions (Fig. 6). In Fig. 5, the dangerous zone (a contour line for a given limit) always extends from the source edge in the downwind direction. However, a circular zone with a radius equals the maximum distance from the source center is considered to be hazardous since the wind is erratic and may change its direction suddenly.

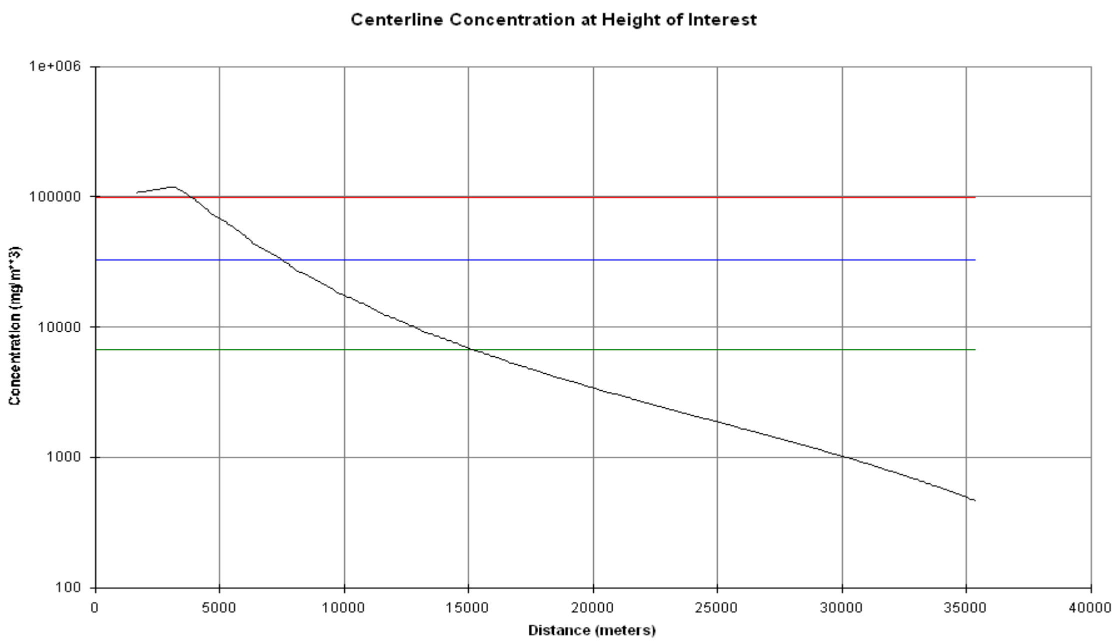


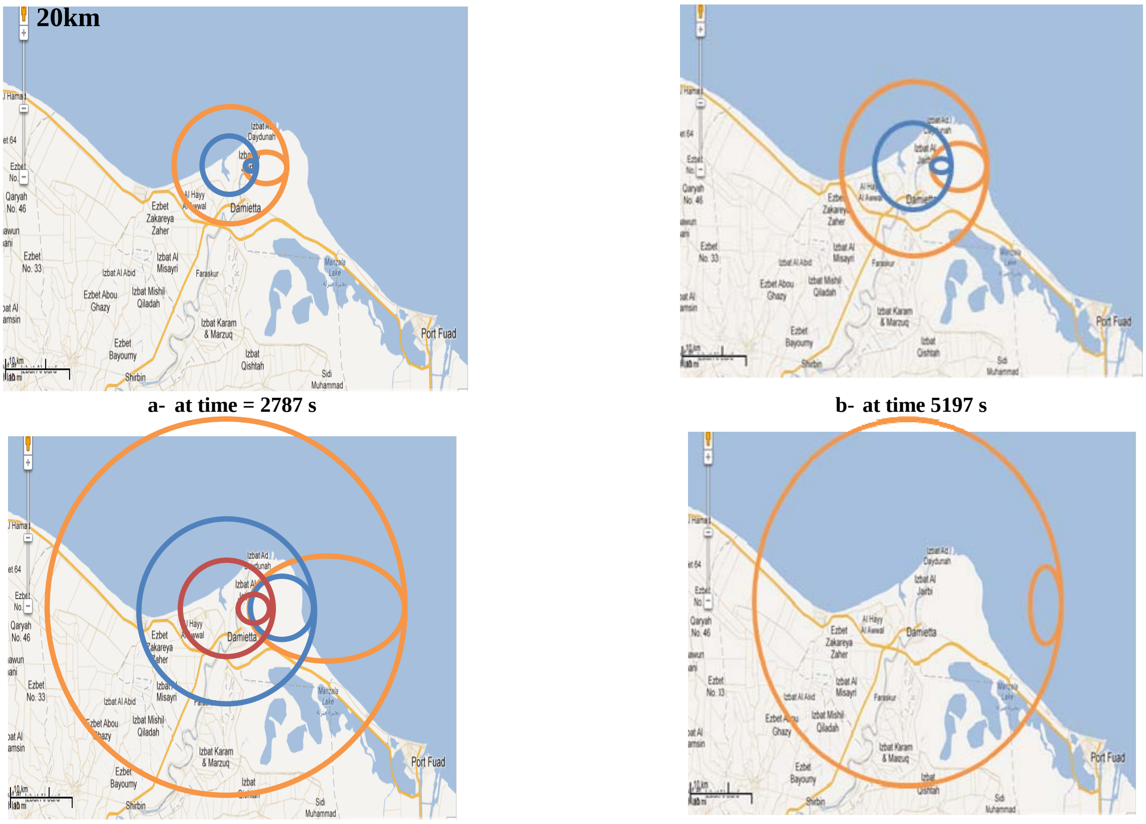
Fig. 4. A typical concentration profile of NG in air after 7,700 s for case study #1 showing three dangerous limits (TWA green, LFL blue, and UFL red)

V. Results and Discussion

Fig. 5 clearly shows the phenomena of growth and decay of the dangerous zones with respect to time elapsed from the start of the accident. This phenomenon is explained in the schematic diagram of the variation of the concentration profile with time, Fig. 7. During the early stages of the accident (t0), the evaporated LNG has a high concentration over a small downwind distance that produces a short dangerous zone (X0). As time passes (t1, t2) and due to dispersion, the gas concentration peak decreases but it covers a larger distance producing a larger dangerous zone (X1, X2). During the late stages of mixing (t3), however, the gas spreads over a much larger distance with lower peak concentration and shorter distance above the dangerous limit (X3). Finally at time (t4), the gas spreads over an extremely large area but with concentration less that the limiting value and thus no dangerous zone (X4= 0).

Fig. 5-d indicates that even after the end of evaporation, the dangerous zone keeps moving with the wind until mixing process with atmospheric air reduces the concentration below the limit and thus the entire area becomes safe.

For the three scenarios mentioned earlier, the worst situations produced dangerous zones (at a height of interest of 1.6 meters) with maximum sizes in the downwind and vertical directions as shown in Table I. It should be noted that the worst situation for each concentration limit does not occur at the same time elapsed from the start of the accident.



a- at time = 2787 s

b- at time 5197 s

c- at time 22067 s

d- at time 24477 s

Fig. 5. Growth and decay of dangerous zones (downwind and crosswind directions) with respect to time elapsed from the accident in Damietta city in Egypt for case study #1 (ruptured pipe – constant thickness pool)

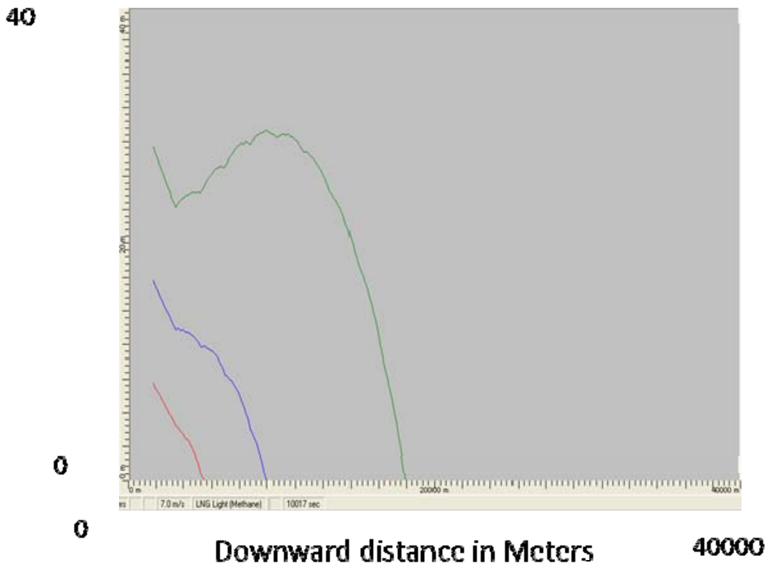


Fig. 6. Side view of the dangerous zones in the downwind and vertical directions after 20,000 s for case study #1 (ruptured pipe – constant thickness pool)

Fig. 8 and Fig. 9 present the results of parametric studies of the effects of atmospheric stability class and wind speed on the size of the dangerous zone. Both parameters are directly related to the mixing intensity of the evaporated LNG in ambient air. For a low wind speed (0.5 m/s) and highly stable atmosphere (F) in Fig. 8, the mixing intensity is very low. As atmospheric instabilities increase (E, D) mixing increases and thus the size of the dangerous zone increases. However, much higher instabilities (C, B, A) substantially increase mixing of the gas with much larger volumes of air and thus reduces the size of the dangerous zone. For higher wind speeds (4 m/s and 8 m/s) the mixing intensity is already high. Thus, any increase in the atmospheric instabilities (F, E, D, C, B, A) decreases the size of the dangerous zone continuously.

Fig. 9 confirms the same phenomenon. For highly stable atmosphere (F), the increase of the wind speed from 0.5 to 2.5 m/s slightly increases the mixing intensity and thus produces a larger dangerous zone. However, for much higher wind speeds (> 2.5 m/s), mixing intensity becomes very high and thus reduces the size of the dangerous zone. On the other hand, for extremely unstable atmosphere (A) the mixing intensity is already high and any increase in the wind speed increases mixing substantially causing continuous reduction in the size of the dangerous zone.

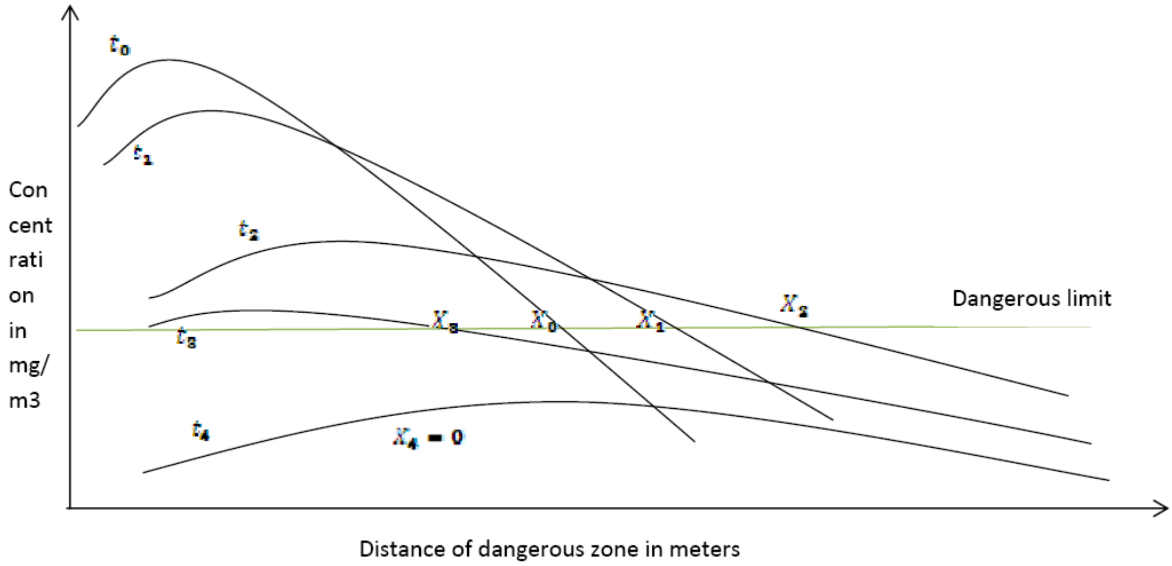


Fig. 7. Schematic diagram of concentration profiles at different times elapsed from the start of an accident

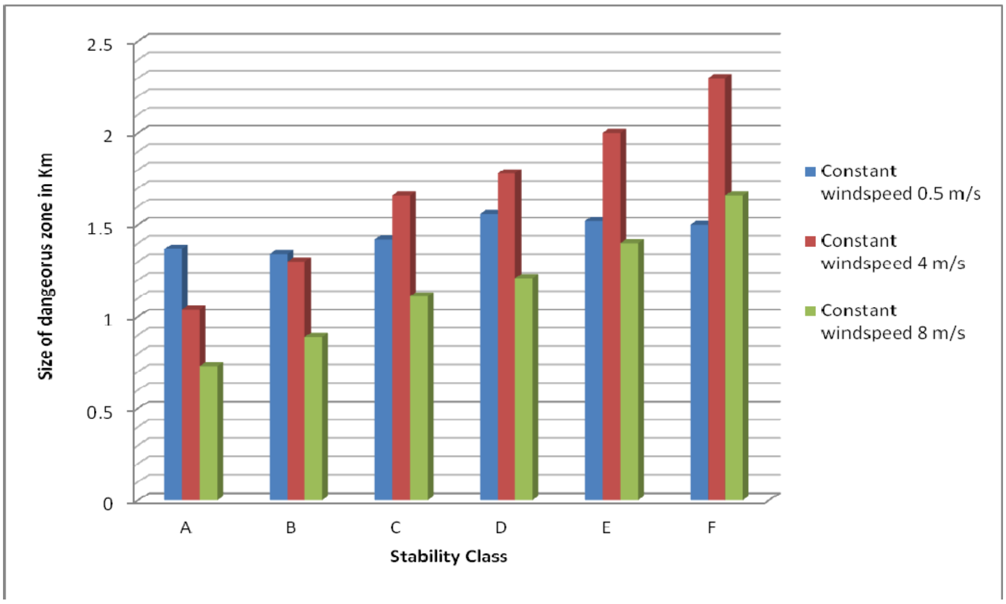


Fig. 8. Parametric study of the effects of stability class on the size of dangerous zones for case study #3 (ruptured tank – constant area pool - TWA)

TABLE I: DANGEROUS ZONE SIZES FOR THE THREE CONSIDERED SCENARIOS.

Scenario #	Description of Scenario	Dangerous Limit	Maximum Downwind Distance (kilometer)	Maximum height (m)
1	Ruptured pipe Constant thickness pool Wind speed 7 m/s Slightly unstable Evaporation duration 6.1 h	TWA LFL UPL	29.0 13.5 7.2	40.0 13.0 8.6
2	Ruptured tank Constant thickness pool Wind speed 8 m/s Extremely unstable Evaporation duration 2.5 min	TWA LFL UFL	10.0 4.5 zero	50.0 14.3 zero
3	Ruptured tank Constant area pool Wind speed 7 m/s Very stable Evaporation duration 50.0 h	TWA LFL UFL	1.8 0.52 zero	12.5 7.2 zero

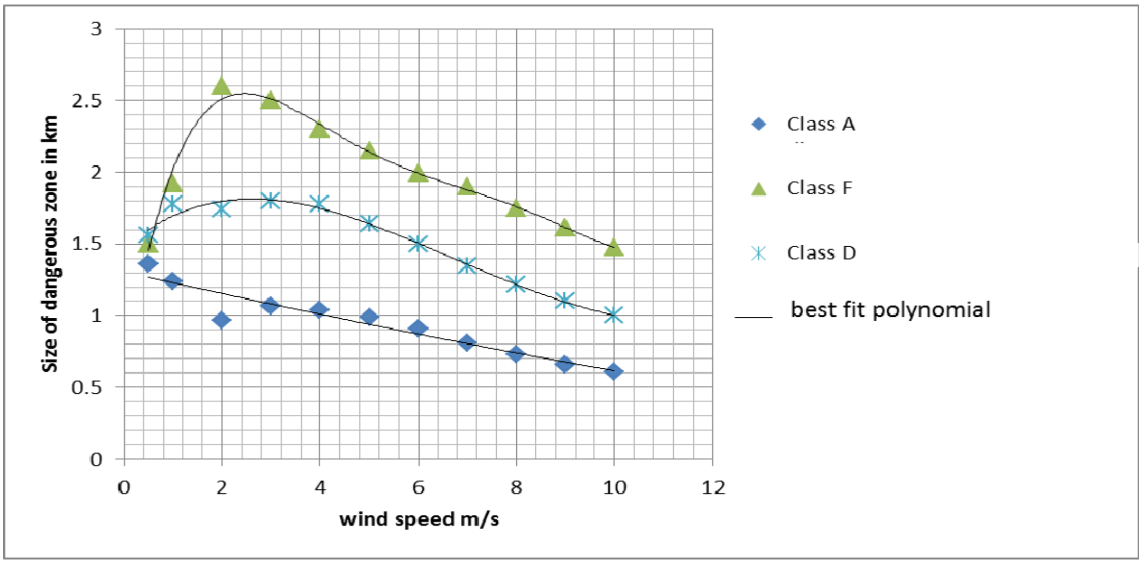


Fig. 9. Effect of wind speed on the size of dangerous zones fore case study #3 (ruptured tank – constant area pool - TWA)

VI. Summary

The main objective of this investigation is to determine the size and location of dangerous zones formed due accidental spill of LNG in Egypt. Toxicity and flammability of evaporated LNG have been considered in case of rupture of a storage tank or a pipe connected externally to it. The two scenarios of constant thickness and constant area pool have been studied. Software based on an EPA-approved dispersion model has been used to predict the dangerous zones at different elapsed times. The growth and decay phenomenon of the formed dangerous zones with time has been also observed. Energy and mass balances of the spilled LNG pool have been solved to determine the dynamic input data for the dispersion software (pool surface area, pool temperature, and evaporation rate).

For the three case studies considered, the worst-case scenarios produced toxic zones extending to 29.0, 10.0, and 1.8 km in the downwind direction, respectively. Similarly, considering lower flammability as a limit, the three case studies produced combustible zones extending to 13.5, 4.5, and 0.52 km in the downwind direction, respectively.

Two parametric studies have been conducted to show the effects of the wind speed and the stability class on the size of the toxic zone.

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