RESEARCH ARTICLE

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Simulation of LPG Pressure Vessel under Fire Engulfment

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Liquefied Petroleum Gases [LPG] are flammable mixtures of gases such as propane and butane mainly which is transported and stored in liquid phase in storage vessels under amply pressure. These industrial processes are of high fire and explosion hazard. When a vessel carrying LPG is damaged, an abrupt drop in pressure may release colossal quantities of evaporating gas and energy that has a destructive effect on the vessel itself and its surroundings. When comes in contact with ignition source, BLEVE phenomenon is developed. Elevated temperature environment outside the LPG pressure vessel can cause vessel explosion due to the pressure mount inside the tank and drop in strength of the tank walls. This catastrophic rupture will lead to BLEVE phenomenon which when ignited will again lead to a vapor cloud explosion. Most common scenario is when the pressure vessel partially filled with liquid form of LPG is exposed to a fire. The primary focus of the paper is to analyze the LPG storage pressure vessel under thermal loading condition. For this Finite element modeling approach is used and the analysis is carried out in ANSYS™ software.

Introduction

Liquefied Petroleum Gas (LPG) is a widely used fuel which is environment friendly for domestic, industrial and commercial purpose. LPG is stored and transported in special fire-resistant tanks but whenever highly flammable gases like LPG is either stored or transported there is a risk of leakage which can be ignited by any other ignitable source. LPG vessels being the cause of many accidents with fire and explosions have been reported in the past. Scientists have been interested in investigating [**1-4**] thermal protection of LPG/petroleum transport containers which are engulfed in fire. In such accidents propagation of primary accident may cause or trigger severe domino scenarios that involves nearby process units and storage areas which will lead to the escalation of fire and explosion. The secondary scenario that is associated with a catastrophic rupture of pressurized LPG storage vessel is Boiling Liquid Expanding Vapor Explosion (BLEVE) and toxic dispersions (for non-flammable substances) or consequent fireballs (in the case of flammable substances) [**5**]. This may be caused by catastrophic rupture of LPG pressure vessels, exposed to fires while transporting or during loading & unloading stage as a outcome of accidental event.

Over the last few years, in order to minimize the risk associated with transportation, most of the attempts made were focused on structural safer design of pressurized tanks used primarily for transporting LPG and other hazardous contents. Considering the risk, substantial amount of research work had been carried out in the past for safeguarding the LPG tanks under fire engulfment condition.

The fire protection system in case of pressure vessels is activated only when the temperature of the vessel's surface goes beyond a critical value [**6**]. Kramer *et. al.*, [**7**] in his study carried out experiments to find out the surface temperature and heat transfer taking place inside of a tank which is engulfed in a pool fire by using numerical methods for predicting the temperature. Birk *et. al.*, [**8**] in his work provided comprehensive data relevant to the thermal response of a tank containing propane under hydrocarbon pool fire engulfment. Their work uncovered different parameters which influences the failure of a propane tank under fire. Aydemir *et. al.*, [**9**] in the year 1988 published their research in which a numerical model was developed for tanks containing LPG under fire engulfment. Their main work was comparison of data from computer predictions to the data obtained from field test; this approach clearly shows the ability of the code in simulation and prediction of LPG tank's response under fire. Beynon *et. al.*, (1988) [**10**] originated a model called "HEATUP" which predicts the response of a tank containing flammable liquid under fire engulfment scenario. Landucci (2009) in his experimental work carried out two diesel pool fire tests on tanks with intumescent coating containing LPG for determining the coating's effectiveness to minimize the risk of BLEVE in road and rail transportation. Hang (2019) in his study highlighted the use of CFD for simulation of large hydrocarbon pool fires for predicting the surface emission and radiation emitted from the LPG pool fire, the model was validated by comparing the results with existing experimental data. Scarponi (2018) conducted experimental tests on LPG storage tanks in case of remote source radiation by forest fire to analyze the behavior of tanks. The outcome of the experiment was used to validate a CFD model for determining critical exposure scenario for tanks.

The analysis presented in this paper deals with the response of LPG tank engulfed in a pool fire condition. Temperature and the resulting stress distribution on the tank surface under a pool fire engulfment condition is analyzed. The response of a LPG tank in terms of temperature and stress distribution under a pool fire engulfment condition is evaluated further the time to failure is determined by comparing the stress induced on the tank surface with the maximum allowable stress of the tank material.

Several models and approaches [**7**] were proposed for the calculation of the time to failure of LPG tanks under fire engulfment scenario. In the present analysis, Finite Element Method (FEM) is considered and implemented as shown in **Fig. 1** to analyze the problem.

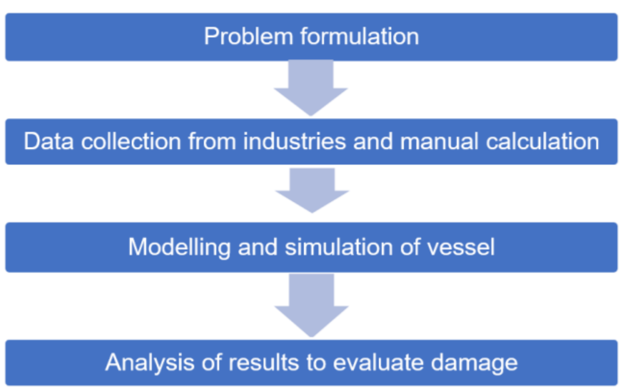

Fig. 1. Overview of modeling approach used

Finite element model

The tank model under diesel pool fire engulfment was based on Finite Element approach summarized in **Fig. 2**. ANSYS™ software was used to implement the FEM simulation on the pressure vessel. Comprehensive temperature and stress distribution on the tank shell were obtained by finite element modeling. Initially, with time and external thermal load as a function, thorough computation of the temperatures on the tank shell was done. The body of the vessel shell was modeled as a cylinder with spherical heads. No insulating coating was considered in the model.

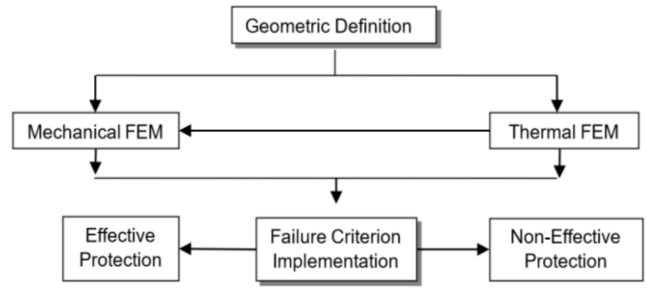

Fig. 2. Overview of the methodology.

The model used in this paper solves the basic transient heat balance equation at each point during simulation, expressed in cylindrical coordinates as [**20**]:

$$c\rho \frac{\partial T}{\partial t} = \left[\frac{1}{r}\frac{\partial}{\partial r}\left(k_r \frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(k_\varphi \frac{\partial T}{\partial \varphi}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right)\right] \quad (1)$$

where,
c: Heat capacity
T: Temperature
t: Time
ρ : Density
K: Thermal conductivity

Assuming uniform thermal conductivity throughout the material,

$$c\rho \frac{\partial T}{\partial t} = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(\frac{\partial T}{\partial \varphi}\right) + \frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right)\right] \quad (2)$$

A steady heat load Q_{rad} on the external surface of the vessel shell was taken on the account of radiating heat from the outdoor fire, surface emission and convection to or from the ambient environment [**20**]:

$$Q_{rad} = k\frac{\partial T}{\partial r}\bigg|_{ext} \quad (3)$$

From the standard data available the value 110 kW/m^2 was taken for further calculations for large diesel pool fires [**6**].

For internal boundary condition, due to convective heat transfer to the fluid, a variable heat load Q_{conv} on the internal shell surface was considered [**20**] the value of which depends on the wall temperature & on the fluid temperature.

$$Q_{conv} = h\,(T - T_a) \quad (4)$$

In the next step, taking local temperature and other loads present on the shell as a function, the calculation of the transient stress field was done. In this, mechanical analysis in steady state is applied to get the transient advancement of the stress field on the tank walls. The values of local temperature determined in the thermal simulation were used to find the local stresses. The strain due to local temperature variation is given by [**20**]

$$\epsilon_T = \alpha(T_n - T_{n-1}) \quad (5)$$

where,
α: Thermal dilatation coefficient,
n & n-1: Consecutive time steps

Parameters	Value
Temperature conductivity coefficient	1.34×10^{-5} m²/s
Thermal conductivity coefficient	54 W/mK
Temperature of solid	310 K
Thermal flow to the liquid phase	46.7 W/m²
Evaporation intensity	108.7 kg/m²s
Nusselt no.	26.6
Absorption capacity of flame	0.9
Atmospheric absorption coefficient	20
Stefen-Boltzman constant	5.67×10^{-8} W/m² K
Flame Temperature	1100 K
Angle coefficient	0.8
Thermal radiation intensity	110 kW/m²

Parameters used for thermal simulation and properties of vessel material (SA-516 Gr 70) are shown in **Table 1**.

Table 1. Parameters of the pressure vessel.

Tank material characteristics	Value
Thermal conductivity	50 W/mK
Heat capacity	460 J/kgK
Poisson's ratio	0.3
Density	7850 kgf/m³
Surface emissivity	0.4
Thermal dilation coefficient	11.5 ppm/K
Modulus of Elasticity	201.5 GPa

Fire test parameters used in the simulation are shown in **Table 2** [**11**].

Table 2. Parameters of pool fire.

Fire characteristics	Value
Intensity of Pool fire radiation	110 KW/m²
Testing duration	1.86 Hrs
Time steps	20
Initial temperature condition	285 K

Pressure vessel specifications and data input from industrial visit are shown in **Table 3**.

Table 3. Pressure vessel specifications.

Tank characteristics	Value
Capacity	40 MT
Hydraulic Test Pressure	26 kg/cm²
Safety Valve Test Pressure	17.5 kg/cm²
Length	15 m
External Diameter	3 m
Thickness	0.02 m
Storage Pressure	7.5 kg/cm²
Temperature of stored liquid	310 K
Filled Liquid Percentage	79%
Material Specification	IS: 2041 : 1962
Tensile Strength	48 kgf/mm²
Yield Strength	28 kgf/mm²
Stored material density	585 kg/m³
Liquid heat transfer coefficient	400 W/m²K
Vapor heat transfer coefficient	6 W/m²K

The parameters adopted in the mechanical simulation have been summarized in **Table 4**.

Table 4. Parameters used in mechanical simulation.

Results

The directional deformation of the vessel under static structural simulation showing a maximum and minimum deformation is well under the failure range of the vessel which is the maximum allowable stress value of pressure vessel material (120.65 MPa) as shown in the **Fig. 3**. It clearly indicates that the value of directional deformation varies from point to point throughout the surface of the vessel. The maximum directional deformation achieved 0.0001998m is in the zone where there is a liquid-vapor interface during the heat loading condition.

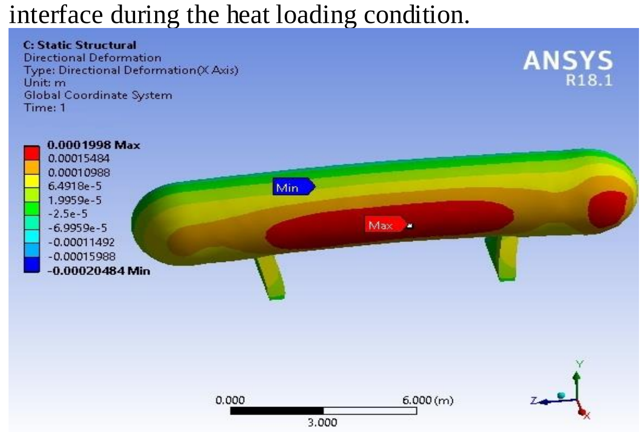

Fig. 3. Directional deformation of the vessel under static structural simulation

The maximum directional deformation obtained is at the portion where there is a liquid-vapour interface with a value of 0.1998 mm for expansion and 0.204 mm for compression. This modeling has been validated by comparing it with the results of simulation done by Larcher *et. al.*, 2010 [**10**].

Fig. 4 shows the equivalent stresses generated in the vessel due to the given loading conditions with maximum value of stress reaching up to 3.941×10^7 Pa and minimum value reaching to 1.782×10^5 Pa. It was observed that the stresses are generated mainly at the end section of the vessel rather than the middle portion of the vessel.

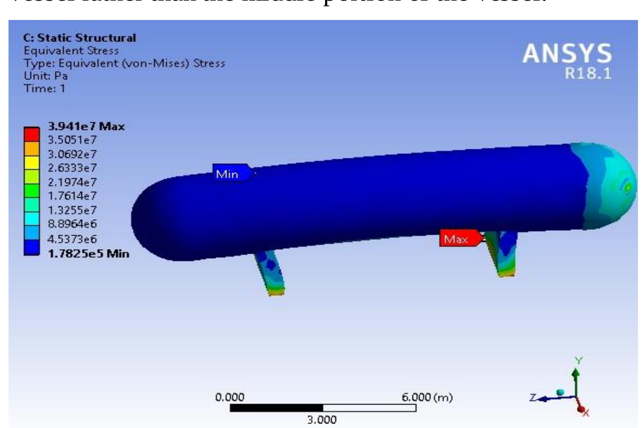

Fig. 4. Equivalent stresses generated in the vessel due to the given loading conditions.

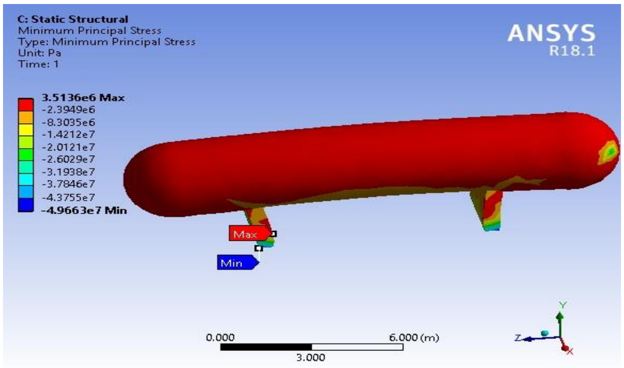

Fig. 5. Maximum Principal Stress around the vessel for the given time period and for given fire loading condition.

Fig. 5 shows us the profile of Maximum Principal Stress around the vessel for the given time period and for given fire loading condition. It has been observed that the maximum value obtained is again fairly spread around the region of liquid vapour interface. The maximum value obtained is 3.513×106 Pa. which is well within the safe permissible limits of 120.65 MPa obtained from the ASME Section VIII Div-1 [**11**] for the carbon steel plate considered in this analysis.

Fig. 6 shows the directional deformation profile on the vessel under the loading boundary condition. It can be observed that the maximum deformation obtained is at the end of the vessels making those portions vulnerable to rupture in case of any mishap. The maximum value obtained for deformation is 0.6987 mm at the end section of the vessel.

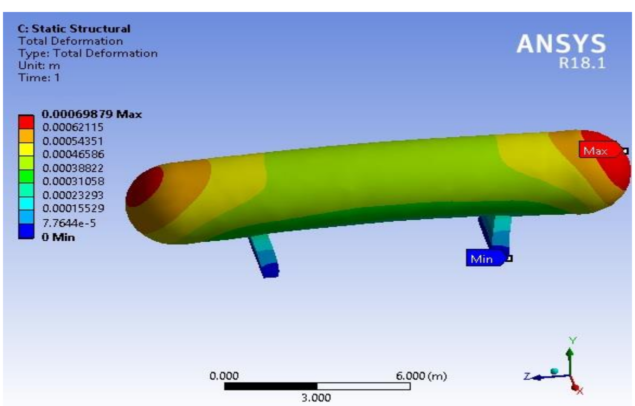

Fig. 6. Directional deformation profile on the vessel under the loading boundary condition.

Conclusion

In the present work, FEM based approach is used to determine the response of LPG tanks under pool fire scenario. The outcome of the FEM based simulation using ANSYS software shows the temperature and stress mapping along the tank surface. On the basis of the simulation results obtained in terms of stress distribution, comparison of maximum induced stress on the tank wall was done with the maximum allowable stress of the tank material. This comparison led to the final outcome which helps to predict whether the tank will survive or not for particular time duration. The output of simulation carried in this work shows that for a given time duration of 6270 seconds the LPG tank sustained the fire load by the engulfed pool fire without failure. The maximum stress induced on the tank surface is below the maximum allowable stress of tank material (SA-516 Gr 70). It is very essential for a LPG pressure vessel which is engulfed under a pool fire to sustain itself long enough so that the emergency response team could reach the hazard zone and prevent further escalation of hazard that might result into a secondary hazard.

Keywords

Pressure vessel, FEM, BLEVE, fire, temperature distribution.
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