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Exposure of a liquefied gas container to an external fire

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Abstract

In liquefied gas, bulk-storage facilities and plants, the separation distances between storage tanks and between a tank and a line of adjoining property that can be built are governed by local regulations and/or codes (e.g. National Fire Protection Association (NFPA) 58, 2004). Separation distance requirements have been in the NFPA 58 Code for over 60 years; however, no scientific foundations (either theoretical or experimental) are available for the specified distances. Even though the liquefied petroleum gas (LPG) industry has operated safely over the years, there is a question as to whether the code-specified distances provide sufficient safety to LPG-storage tanks, when they are exposed to large external fires.

A radiation heat-transfer-based model is presented in this paper. The temporal variation of the vapor-wetted tank-wall temperature is calculated when exposed to thermal radiation from an external, non-impinging, large, 30.5 m (100 ft) diameter, highly radiative, hydrocarbon fuel (pool) fire located at a specified distance. Structural steel wall of a pressurized, liquefied gas container (such as the ASME LP-Gas tank) begins to lose its strength, when the wall temperature approaches a critical temperature, 810 K (1000 °F). LP-Gas tank walls reaching close to this temperature will be a cause for major concern because of increased potential for tank failure, which could result in catastrophic consequences.

Results from the model for exposure of different size ASME (LP-Gas) containers to a hydrocarbon pool fire of 30.5 m (100 ft) in diameter, located with its base edge at the separation distances specified by NFPA 58 [NFPA 58, Liquefied Petroleum Gas Code, Table 6.3.1, 2004 ed., National Fire Protection Association, Quincy, MA, 2004] indicate that the vapor-wetted wall temperature of the containers never reach the critical temperature under common wind conditions (0, 5 and 10 m/s), with the flame tilting towards the tank. This indicates that the separation distances specified in the code are adequate for non-impingement type of fires. The model can be used to test the efficacy of other similar codes and regulations for other materials.

Keywords: Flammable liquid fire; LPG tank; Pool fire; Separation distance; Tank-wall temperature; Thermal radiation; View factor

1. Introduction

Many pressurized, liquefied gas tanks containing ambient temperature liquids are located in urban areas zoned for industrial activities. Many of these storage facilities abut other storage facilities storing hydrocarbon fuels such as gasoline, diesel and jet fuel. One of the safety concerns to the liquefied gas tanks is the detrimental effect of an external, non-impinging, hydrocarbon liquid pool fire on the tanks. The size of the pool fires could be large in comparison to the size of the liquefied gas tanks. Thermal radiation from the fire will heat the steel wall of the tanks. The wall in contact with vapor heats up faster than the wall in contact with the liquid due to the lower heat-transfer coefficient between the steel wall and vapor. The liquid-wetted tank wall will remain essentially at the liquid temperature because of high (boiling) heat-transfer rates between the wall and the liquid. Liquid temperature will increase (but not by a very large value) due to internal boiloff, the consequent increase in pressure of vapor inside the tank and the fact that, in general, the liquid and vapor are in saturation equilibrium.

Codes and regulations governing the location of pressurized liquefied gas in storage facilities and bulk plants have recognized the potential adverse impact of exposure of tanks to external fires. Many of the codes/regulations have strict

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Nomenclature

A_e area of the elemental surface on the tank (m^2)
A_{VWF} area of the vapor-wetted wall exposed to the fire (m^2)
A_{VWT} total surface area of the vapor-wetted tank wall (m^2)
b thickness of steel wall of the tank (m)
c_p specific heat of the steel of which the wall is made (J/(kg K))
D_F diameter of the base of the hydrocarbon liquid fuel fire (m)
D_T outer diameter of the tank shell (m)
L_F length of (or the height for a non-bent) visible fire (m)
L_T axial length of the tank shell (m)
E_F mean radiance ("emissive power") of the fire (W/m^2)
f curve-fit constant to equivalent radiative heat-transfer coefficient (Eq. (7))
F geometric view factor between the elemental surface on the tank and the radiating part of the fire
H_T height of pedestal holding the tank (m)
H_F height of the base of the fire above ground (m)
h_c convective heat-transfer coefficient ($W/(m^2\,K)$)
h_{eff} effective (convective and radiative) heat-transfer coefficient ($W/(m^2\,K)$)
h_R equivalent radiative heat-transfer coefficient ($W/(m^2\,K)$)
k fraction of tank volume occupied by liquid
m total mass of the VWW (kg)
m_e mass of the elemental area of the tank (kg)
$\dot{q}''$ radiant heat flux from fire absorbed by the wall, $\alpha_S \dot{q}''_F$ (W/m^2)
$\dot{q}''_F$ radiant heat flux from fire incident on the exposed area (W/m^2)
$\bar{\dot{q}}''_F$ mean fire radiation heat flux incident on fire-side VWW surface (W/m^2)
Q $\frac{A_{VWF}\alpha_S \bar{\dot{q}}''_F}{h_c T_a A_{VWT}} = \frac{\text{incident fire radiative heat input rate}}{\text{convective cooling rate at a temperature difference } T_a}$
R_T radius of the tank shell (m)
S_D separation distance between line of adjoining property that can (m) be built upon and the tank shell surface nearest to boundary line
t_{ch} characteristic cooling time (s) $= (\rho_s b c_p T_a)/(h_c T_a)$ = [time to reduce the VWW sensible heat from a temperature of T_a to zero with a constant convective cooling with a temperature difference of T_a]
T temperature of the elemental wall surface (K)
T_a ambient air temperature (K)
$\bar{T}$ average temperature of the VWW (K)
α_S absorptivity of the tank surface element for fire radiation
β $\frac{\varepsilon_S f T_a}{h_c} = \frac{\text{effective radiative heat-transfer coefficient at a tempeature difference of } T_a}{\text{convective heat-transfer coefficient}}$
ε_F emissivity of the fire (set to 1 for optically thick fires)
ε_S emissivity of the (painted) VWW surface
ϕ angle with X-axis subtended by the radiation receiving elemental area on the tank-wall surface (rad)
ϕ_{Liq} angle (w.r.t. horizontal axis) subtended by the liquid surface at the tank center (rad)
ν_1 angle w.r.t. to the base plane of the unit hemisphere made by the line connecting the elemental area on the tank wall and the center of fire base (rad)
ν_2 angle w.r.t. to the base plane of the unit hemisphere made by the line connecting the elemental area on the tank wall and the point on the fire axis at the top of visible fire (rad)
Θ dimensionless temperature $= \frac{\bar{T}-T_a}{T_a}$
θ_F angle the axis of the fire makes with the vertical due to wind bending of the fire (positive if bending away from tank) (rad)
ρ_s density of steel (constituting the tank wall) (kg/m^3)
σ Stefan–Boltzmann constant (5.6697×10^{-8}) ($W/(m^2\,K^4)$)
τ dimensionless time for heating the VWW surface $= t/t_{ch}$
τ_{Atm} transmissivity of the atmosphere to thermal radiation
ω_1 half angle of the tangent to the fire base from the elemental area measured in the plane containing the lines from the elemental area to the center of fire base and the tangent at fire base (rad)
ω_2 half angle of the tangent to the fire top from the elemental area measured in the plane containing the lines from the elemental area to the fire axis at the tops and the tangent to fire top (rad)
ψ $\frac{A_{VWF}}{A_{VWT}} = \frac{\text{area of VWW over which radiant heat is incident}}{\text{total surface area of VWW}}$

requirements for minimum inter tank distances and between the tank that is nearest to the edge of the plant property and the line of adjoining property that can be built upon. One such code is the National Fire Protection Association (NFPA) 58 Liquefied Petroleum Gas (LPG) Code [1], which requires a minimum distance of 7.6 m (25 ft) for containers of water capacity 500–2000 gal, 15.2 m (50 ft) for tank sizes between 2001 and 30,000 gal and 22.9 m (75 ft) for tanks of 30,001 to