Thin-Walled Structures 131 (2018) 577–594

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Numerical study on thermal buckling of empty thin-walled steel tanks under multiple pool-fire scenarios

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ARTICLE INFO

Keywords:
Thin-walled tanks
Pool-fire
Thermal loading
Thermal buckling
Numerical analysis

ABSTRACT

Fire incidents at fuel storage tank farms are high risk incidents due to the fact that can result in severe socio-economic losses, injuries, deaths and have a serious environmental impact. In the case of a tank fire, there is a serious possibility that the fire will spread to adjacent tanks. The research activity in this area is mainly focused on the prediction of the heat transfer characteristics of pool fires, the thermal response of neighbouring tanks (or target tanks) and the potential of fire spreading. On the contrary, the research for the structural integrity of tanks involved in pool fire scenarios is limited. This paper aims to study the thermal buckling behaviour of fixed-roof tanks in the case of pool fire scenarios, considering one or more burning tanks. To this end, different scenarios are examined, aiming to study the key factors (the burning fuel, the wind, the separation distance between tanks and the size of the burning tanks) that may affect the thermal buckling response of the target tanks. Semi-empirical models, available in the literature, are used for the calculation of the characteristics of flames that arise from burning tanks. Then, the problem is solved numerically, through the Finite Element Method. The heat transfer from the burning tanks to the target tank is treated through the open cavity option, and the response of the target tank is predicted in the same thermo-mechanical analysis. The basic objective is the investigation of the inherent fire resistance of thin-walled tanks and to predict their failure.

1. Introduction

Current regulations (API 650 [1], NFPA 30 [2]) present strict guidelines for construction, material selection, design and the safe management of storage tanks and propose active fire protection measures in order to minimise the risk of fire and to prevent the fire spreading. Although most companies follow the current regulations, fire accidents at tank farms still happen. Most of the accidents recorded have taken place at petroleum refineries, terminals and pumping stations [3]. Crude oil, gasoline, and fuel products (fuel oil, diesel, kerosene, lubricants) were the principal contents involved in most cases. It is noted that the structural design of storage tanks under thermal loading is not covered by existing codes.

Tank fire incidents may start due to several reasons such as operating errors, equipment failure, lightning, poor maintenance and static electricity. The fire may be limited to one tank, however, there is a serious possibility that the fire will spread to the adjacent tanks due to fuel leakage or due to thermal radiation. In the case of a fire in a fixed-roof tank that contains flammable liquid, it is possible that the volatiles in the vapour space above the liquid in the interior of the tank will ignite if the conditions allow. The ignition may result in structural failure, as it is possible that the roof will partially detach from the cylindrical wall of the tank (failure known as large ‘cod's mouth's rupture) leaving its contents exposed. Under these circumstances, a full surface fire will break out, in which case, it is very difficult to suppress and will continue until the total volume of the flammable liquid is consumed. The duration of such fires varies between one and three days, depending on the available volume of the stored liquid. If the fire does not spread to the neighbouring tanks, the burning tank constitutes a heat generator for the adjacent tanks. The heat is transferred mainly through radiation.

Over the last decades, the researchers were mostly focused on, the prediction of the heat transfer characteristics of pool fires. The research was mainly based on experimental investigations of both laboratory and field fires of a number of different fuels. A great deal of research has been published in this area [4–12] and it puts forward a number of mathematical expressions to describe and model pool fires. Moreover, several studies have focused on the effect of pool fires on adjacent tanks, the thermal response of the liquid stored in these tanks and the potential of the escalation of fire [13–16]. Most of the studies published agree that the safety distances between the tanks, as proposed in the current regulations, should be reconsidered. Specifically, as indicated in the study of Silva Santos and Landesmann [15], the minimum safety distances change rapidly, depending on the wind, and therefore the

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https://doi.org/10.1016/j.tws.2018.07.025
Received 16 January 2018; Received in revised form 12 June 2018; Accepted 17 July 2018
0263-8231/

present NFPA30:2012 design recommendations need to be modified to achieve a satisfactory failure prediction for different storage fuels (e.g. ethanol).

The thermal buckling of cylindrical shells under uniform heating and temperature gradients through the thickness was studied in the past [17–21], but the thermal loading generated by a fire is more complicated than these patterns. The research concerning the structural performance of thin-walled steel tanks due to heat from a fire has only recently begun and, consequently, is limited [22–26], according to Godoy [27]. Most of this research is focused on isolated tanks, but the review presented in [27] explains that it is very important to consider the factors that are introduced in the case of tank farms (or tanks in groups). Specifically, it is stressed that current research into the thermal buckling behaviour of thin-walled tanks is based on thermal loading generated by one burning tank and that the cases in which there are two or more sources such as those found in tank farms during domino effects, are still to be considered.

The doctoral thesis of Liu [22] is the first and most complete study in this area and presents a systematic exploration of the potential thermal and structural behaviours of an oil tank when one of its neighbouring tanks is on fire. One of the main objectives of this thesis was to reveal the thermal distribution patterns developed in an oil tank when heated by an adjacent tank fire. The study proposes a simplified temperature distribution that follows a cosine function along the circumferential coordinate, while in the vertical direction the distribution is uniform. Moreover, the thesis reveals the underlying mechanisms responsible for the buckling of a tank structure and examines the influences of various thermal and geometrical parameters on the buckling temperature of the tanks.

The papers by Godoy and Batista [23,24] adopt this thermal pattern, proposed in Liu's thesis [22], and study the structural behaviour of a fixed-roof and open tanks heated by an adjacent fire-engulfed tank. Specifically, in [23], two tanks that buckled due to a huge fire in Bayamon, Puerto Rico in 2009, are investigated in detail. Parametric studies are performed to understand the influence of the shell thickness, the level of fluid stored in the tank, the area affected by fire in the circumferential direction and the temperature gradient through the thickness. Open cylindrical storage tanks are studied in [24]. The results for open tanks show that the location of large out-of-plane displacements attributable to thermal buckling coincides with the heated zone. The importance of thermal gradients in the thickness to the buckling load and mode are shown.

According to the findings of the aforementioned studies, the temperature field of a tank heated by an adjacent tank is non-uniform in both vertical and circumferential directions and depends on several factors such as the distance between them, the diameter of both burning and heated tanks, the type of liquid burning and the speed and direction of the wind. It is concluded that significant compressive stress arise due to restrained thermal expansion that is induced by the roof. Moreover, an important temperature difference between the hottest and coldest part of the heated tank exists and this generates supplementary meridional and circumferential stresses. The reduction of mechanical properties of steel in conjunction with thermal induced stresses may lead to thermal buckling and failure of the tank at relatively low temperatures.

This paper studies the thermal buckling behaviour of thin-walled fixed-roof tanks in multiple pool-fire scenarios. The target tank is subjected to non-uniform heating that is generated from one or more neighbouring fire-engulfed tanks. The simulation of pool fires is based on the solid flame semi-empirical model, available in the literature. This model is capable of estimating the variation in the temperature in the vertical direction and providing more realistic results from previous studies [22–24], where the temperature is only assumed to be non-uniform in the circumferential direction. The basic objective is to determine the fire resistance of target tanks in terms of both time and temperature. To this end, different scenarios are examined, with the aim of identifying the key factors (size of burning tanks, type of fuel burning, wind, separation distance and number of burning tanks) that may affect their resistance.

2. Pool fire modelling

A pool fire is defined as a turbulent diffusion of fire burning above a horizontal pool of vaporizing hydrocarbon fuel. The fuel can be liquid, gas or solid. There is a wide range of mathematical expressions that are used to predict the behaviour of hydrocarbon pool fires that vary from field models (also known as Computational Fluid Dynamics, or CFD models) to empirical models (or semi-empirical models).

Empirical models are based on dimensionless modelling and experimental data predictions and are divided into two types: point source models and solid flame models. Their advantage, compared to the CFD models, is that they are simple, as they do not incorporate the solution of the partial differential equations of fluid flow. The point models assume that all the radiant heat flux from the fire is emitted from a single point located near to the centre of the flame. The solid flame models are more detailed. The flame shape is determined from experiments and it can be a cylinder or an ellipse, depending on factors such as fuel type and wind speed. According to the literature [6,13,28], the solid flame models are more efficient for the prediction of radiant heat fluxes, in terms of targets outside the flame [6].

This study uses the solid flame model. The shape of the used flame depends on wind conditions. In the case where the wind is not considered, the flame is simulated through a cylinder (Fig. 1a). On the other hand, the wind affects flame's geometry and Rew and Hulberd [5] claimed that sheared elliptical cylinder (Fig. 1b) describes the real flame length more accurately and can be used to give reasonable predictions.

Therefore, in this paper the flame is simulated according to Figs. 2, 3. The main parameters describing pool fire are the flame shape, the diameter of the flame D_f (which is the same with the diameter of the burning tank), the length of the flame L_f, the tilt θ, the flame drag D_f' and the average flame emissive power E_{av}.

The following mathematical expressions are used for the determination of solid flame model characteristics. The flame length L_f is calculated using Thomas [29] proposal, according to (1):

$$L_f/D_f = 42\cdot(\dot{m}^*)^{0.61} \tag{1}$$

where, $\dot{m}^*$ is the dimensionless mass burning rate of the fuel and is given by (2):

$$\dot{m}^*=\dot{m}_b/(\rho_\alpha\cdot(g\cdot D_f)^{1/2}) \tag{2}$$

where, ρ_a is the density of air at ambient conditions (kg/m^3), g the acceleration due to gravity (m/s^2) and $\dot{m}_b$ is the mass burning rate of the fuel.

The mass burning rate, is the mass of the liquid fuel consumed by the flame per unit time, per unit area of the pool and is calculated using the equation suggested by Babrauskas [3]:

$$\dot{m}_b = \dot{m}_{\max}\cdot(1 - e^{-k_\beta D_f}) \tag{3}$$

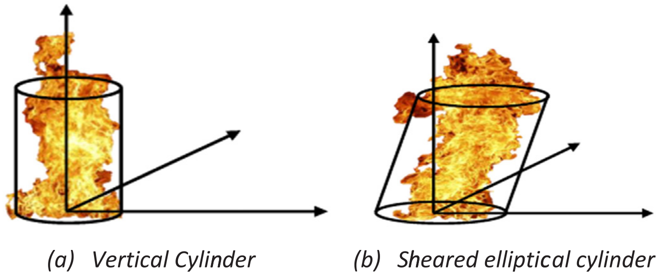
(a) Vertical Cylinder (b) Sheared elliptical cylinder

Fig. 1. Proposed flame shapes ([13]).