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Thermal buckling behaviour of unstiffened and stiffened fixed-roof tanks under non-uniform heating

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ABSTRACT

The problem addressed in this paper is the thermal buckling behaviour of thin-walled steel cylindrical fixed-roof tanks under non-uniform loading, induced by an adjacent tank. This specific type of thermal loading can be triggered by a neighboring tank fire where heat is transferred mainly through radiation. Since the calculation of the temperature field of the heated tank lies in other scientific fields (e.g. Computational Fluid Dynamics), a thermal pattern, proposed in literature, is used for the simulation of the fire-induced load and the investigation of the structural response of the tank due to heating. The study is conducted numerically through the Finite Element method, using coupled thermo-mechanical analysis. The general purpose Finite Element code MSC Marc, is used for the simulation. Three-dimensional models are developed using shell elements. Firstly, a detailed study of the failure mechanisms that take place in case of non-uniform loading is carried out. Furthermore, tanks with different geometries are studied. The main objective is the calculation of the critical temperature i.e. the temperature where the failure appears and the determination of the failure modes. Finally, a parametric study is conducted for the evaluation of the effectiveness of stiffening methods that are commonly used at ambient temperature design (stiffeners and stepwise wall thickness), in the case of the non-uniform heating load. In this study, the heated tanks are considered to be empty, which is the most severe scenario, for their structural integrity.

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1. Introduction

Tank fire incidents take place mainly in petroleum refineries, oil terminals or storage tank facilities and they can be catastrophic. Current regulations (API 650 [1], NFPA 30:2012 [2]) define strict guidelines for construction, material selection, design and safe management of storage tanks and propose active fire protection measures in order to minimize the risk of fire and to prevent fire spreading. Nevertheless, the structural design of storage tanks under thermal loading is not covered by the existing guidelines.

Although most companies strictly follow the regulations, tank fire accidents still occur. According to [3], in total 480 tank fire incidents have been identified worldwide from 1950 until 2003 and the number of incidents increases each decade. International attention was given to the tank fire event that took place in 2005 at the Buncefield Oil Storage Depot in the north of London. This event motivated scientific research in order to better understand the major cause of tank explosions and spreading of fires. Moreover, recently (2015), a massive fire and explosion of oil tanks in a storage facility near Kiev resulted in serious environmental impact.

Storage tanks that are used for liquid hydrocarbons (e.g. oil, diesel etc.), are classified according to the operation pressure and the type of roof that is used. Specifically, the atmospheric tanks can be designed as open or with roofs which can be either floating or fixed. Floating roof tanks are used for storage of liquid hydrocarbons which are characterized by a low ignition point (lower than standard ambient temperature) like light crude oil and light polar compounds (methanol, ethanol, ketones etc.). Fixed-roof tanks are used for heavy oil products (like diesel and mazut) with an ignition point greater than ambient temperature. According to the literature, the floating roof tanks minimize losses and escape of volatiles to the environment and they are considered the safest storage facilities for oil products. Fixed-roof tanks with cone roofs is the most common type of tanks that is used in practice and this study is focused on these types of tanks.

Tank fire incidents may be initiated due to several reasons like operating errors, equipment failure, lightning, poor maintenance, static electricity and so on. Moreover, a domino chain can be triggered in case of earthquake, as e.g. it was reported after the Izmit earthquake of 1999 in Turkey [4]. The fire may be limited to one tank but there is a serious possibility that the fire will spread to the adjacent tanks due to fuel leakage or due to thermal radiation. In case of a fire in a fixed-roof tank that contains flammable liquid, it is possible that the volatiles in the vapor space above the liquid in the interior of the tank, will ignite

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if the right conditions appear. The ignition may result to 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' rupture) leaving the tank wall and its contents exposed. Under these circumstances a full surface fire will be initiated. In this case, the fire is very difficult to be suppressed and the phenomenon 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 will not spread to the neighboring tanks, the burning tank constitutes a heat generator for the adjacent tanks. The heat is transferred mainly through radiation and generates thermal loading.

Nowadays, the interest of the researchers is focused on the prediction of heat transfer characteristics of pool fires ([5,6,7,8]), their effect (radiation, temperature field etc.) on adjacent "target" tanks ([9]), the thermal response of stored liquid in adjacent tanks ([6]) and the potential of escalating fire involving more tanks ([10,11]). Most of the published studies agree that the safety distances between the tanks proposed in the current regulations should be reconsidered. Specifically, in the study of Silva Santos and Landesmann [11] it is indicated that the minimum safety distances change rapidly due to the wind and that the present NFPA30:2012 recommendations need to be modified, in order to achieve a satisfactory failure prediction for different storage fuels (e.g. ethanol).

The thermal buckling of cylindrical shells was studied in the past for uniform heating and temperature gradients ([12,13,14,15,16,17]). But the thermal loading generated by fire is more complicated than the patterns studied previously. According to Godoy [18] the research concerning the structural performance of thin-walled steel tanks has recently been started and is limited ([19,20,21,22]). The doctoral thesis of Liu [19] was the first and most complete study in this area and presents a systematic exploration of the potential thermal and structural behaviour of an oil tank when one of its neighboring tanks is on fire. One of main objectives of this thesis was to reveal the thermal distribution patterns developed in an oil tank under the heating from 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 tank structures and examines the influences of various thermal and geometrical parameters on the buckling temperature of the tanks.

The papers of Godoy and Batista ([20,21]) adopt this thermal pattern, proposed in Liu's thesis [19], and study the structural behaviour of fixed-roof and open tanks heated by an adjacent fire-engulfed tank. Specifically, in [20], two tanks that buckled under 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. The open cylindrical storage tanks are studied in [21]. 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 of the tank walls to the buckling load and mode are shown.

According to the findings of the aforementioned studies, the temperature field of a tank that is 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 the burning and the heated tank, the type of burning liquid, the speed and the direction of the wind and so on. Thus, there exists an important temperature difference between the hotter and the colder part of the heated tank and significant compressive stresses may arise due to restrained thermal expansion. The reduction of mechanical properties of steel in conjunction with the thermal induced stresses may lead to thermal buckling and failure of the tank in relatively low temperatures.

The basic objective of this paper is to study thoroughly the behaviour of thin-walled steel tanks with fixed roof under non-uniform heating that is generated from an adjacent fire-engulfed tank. Specifically, first a detailed research is conducted in order to understand the failure mechanisms of tanks during non-uniform heating. Then, thin-walled tanks with different slenderness (height to diameter ratio) that are commonly used in practice are studied, in order to reveal the effect of several parameters (initial imperfections, boundary conditions etc.) in the response of heated tanks and to investigate the effectiveness of the strengthening methods that are commonly used at ambient temperature design (stiffeners and stepwise wall thickness) in the case of non-uniform heating load. The heated tanks are considered to be empty, which is the most severe scenario, according to the findings of literature. The problem is solved numerically through the Finite Element method.

2. Description of the problem - the case studies

The problem considered in this paper is the study of the behaviour of a heated fixed-roof tank when the thermal loading is generated from a fire-engulfed adjacent tank and the dominant mechanism of heat transfer is radiation. In the case where the thermal loading, it is expected that the temperature distribution of the heated tank will be non-uniform. Actually, the study lies on the scientific area of the behaviour of thin-walled shells. As it is well known, these shells are commonly used in many applications of engineering sustaining the loading mainly through the membrane actions. Even though, they are very efficient, they are vulnerable to buckling failure due to the compressive forces that may appear. In this case, important displacements arise and the membrane energy is transformed to bending energy. This type of failure can be induced by mechanical or thermal loading. The present study investigates the thermal buckling of thin-walled cylindrical shells for non-uniform thermal loading.

Specifically, the side of the tank which is facing the source tank (which is on fire) is hot, compared to the opposite face which is not affected by the fire. The higher temperature of the heated tank is detected at the meridian of the tank which is closest to the fire and the temperature decreases at the meridians that are further away along the circumference. Moreover, it is logical to assume that the level of the stored liquid can affect the temperature pattern in the vertical direction. In particular, the upper part of the tank which is not in contact with the stored liquid is heated more than the lower part, due to the fact that the heat transfer coefficient of air is low (in the upper part) and the thermal inertia of the stored liquid is high (in the lower part). As it is indicated in other studies, the tank is more vulnerable when it is empty, since the stored liquid (due to the high thermal inertia) affects the temperature of the walls of the tank and prevents the stability phenomena that may lead to failure. Thus, this paper studies only the case of empty tanks.

The phenomenon is complicated and it is difficult to predict the temperature distribution of the heated tank. Pool-fire semi-empirical models, available in the literature, can be used to determine the characteristics of flames generated at the fire-tank. Then, the temperature distribution of the heated tank walls can be found numerically through Computational Fluid Dynamics analysis or through the Finite Element method. Since the evaluation of the temperature field of the heated tank lies on another scientific area, it is out of the scope of this paper. Liu [18] conducted a detailed numerical study and the results are found to be reasonable and describe adequately the complicated phenomenon. This study adopts the simplified model proposed in [18]. The temperature distribution of the heated tank is described by the pattern of Fig. 1 and Eq. (1). In this study it is assumed that the source tank is of the same diameter as the target tank and that the distance between them has also the same magnitude. In this

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