NUMERICAL SIMULATION OF POOL HYDROCARBON FIRES AND THEIR EFFECT ON ADJACENT TANKS

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1. SUMMARY

This paper addresses the problem of the thermal response of steel fixed-roof oil storage tanks that are heated during pool fires. The first objective is to identify the parameters that describe the burning tanks and calculate the geometric characteristics of flames. Then, numerical models are developed, which include both burning tanks and the heated tank, in order to calculate the temperature distribution on the heated tanks. The problem is solved numerically using the Finite Element Method. The behaviour of the heated tank is examined for multiple pool fire scenarios. First, the case of one unique burning tank is examined. In the rest scenarios the fire spreads to adjacent tanks, thus, in those scenarios the examined tank is heated by multiple sources (burning tanks). Parametric analyses are conducted to study the influence of various parameters which are the diameter of the burning tank, the type of stored fuel (gasoline or ethanol), the incidence of wind, the separation distance between tanks and the number of burning tanks involved. Furthermore, the study aims to propose an index for the evaluation of risk for the autoignition of fuel and subsequently the spread of fire from the burning tank to the adjacent one.

2. INTRODUCTION

Tank fire incidents take place mainly in petroleum refineries, oil terminals or storage tanks facilities and they can prove to be catastrophic. 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 the thermal radiation. Current regulations (API [1], NFPA [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 the fire spread. In case of a fire engulfed tank, that contains flammable liquids such as oil, it can be easily foreseen that the tank will collapse at elevated temperatures. However, the fire engulfed tank is also a heat generator for the adjacent tanks. The heat is transferred mainly through radiation and becomes the thermal load for the neighbor tanks. In this case the temperature distribution of the adjacent tanks is non-uniform in both the circumferential and the axial direction and depends on several factors e.g. the position of the fire engulfed tank, the burning fuel etc.

In order to minimize the risk of fire propagation that could lead to domino effect, several organizations (e.g. API [1], NFPA [2] etc) propose guidelines regarding the tank layout in the oil depot. The suggested layout takes into account the accessibility of fire-fighting teams. Recent research activity in this area (Santos and Landesmann 2014 [3], Fontenelle 2012 [4]) demonstrated that the temperature on the target tank can be up to 800°C depending on the type of stored fuel (gasoline or ethanol), the structural tank side wall material (steel or concrete) and the incidence of wind. Moreover, the study of Santos and Landesmann (2014) [3] indicated that the minimum safety distances are changing rapidly with the wind and that the present NFPA30:2012 [2] design recommendations need to be modified, in order to achieve a satisfactory failure prediction for different storage fuels (e.g. ethanol).

The previous studies indicate that the risk of domino effect during pool fires is high, and, thus, is very important to examine the main factors that affect the conditions of fire spread to adjacent tanks and sequentially, the temperature fields induced on them.

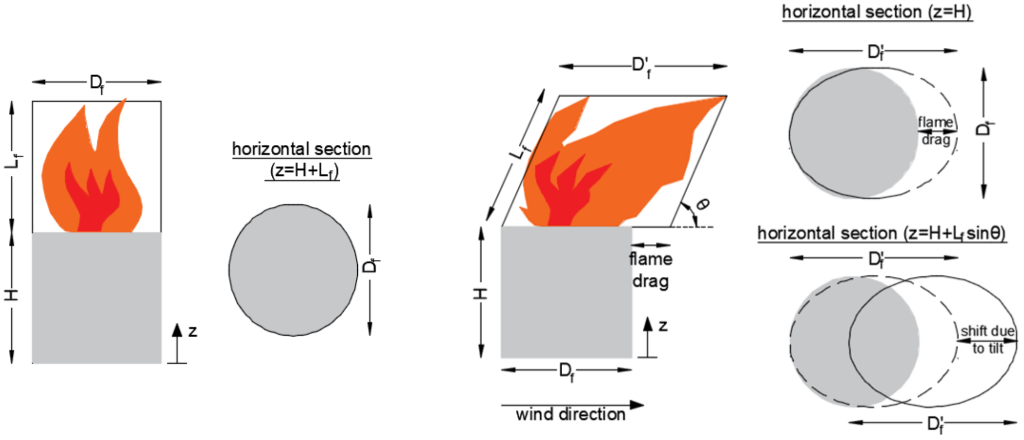
This paper studies the temperature response of a fixed-roof storage tank for multiple pool fire scenarios. The goal is to evaluate the temperature filed of the tank and to find the maximum temperatures that arise. Parametric studies are conducted, to take account of the most important parameters that affect the problem (i.e. burning fuel, wind conditions, separation distance etc). Moreover, the study proposes a fire risk index for the evaluation of the possibility of fire-spread from the burning tanks to the adjacent ones.

3. POOL FIRE MODELING

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 modeling and experimental data predictions and they are divided into two types: point source models and solid flame models. According to the literature, the most efficient models are the solid flame models. In this case the flame shape is determined from experiments and it can be a cylinder or an ellipse, dependent on factors such as fuel type and wind speed. The main parameters that describe solid flame models are flame size and shape, mass burning rate, average flame emissive power and atmospheric transmissivity.

This study is based on the findings of literature and uses the solid flame model. The shape of the flame depends on the wind conditions. In the case when the wind is not considered, the flame is simulated through a cylinder (Figure 1a). When wind is present, it affects the flame's geometry and SpecRew and Helberd (1996) [5] claimed that a sheared elliptical cylinder describes the real flame length more accurately and can be used to give reasonable predictions. Thus, the flame is simulated according to *Fig. 1b*.



a) *b)*

Fig. 1: Geometric characteristics of flame

The geometric properties and the parameters of the flame simulation are described below. First, it is important to note that the pool fire has the same diameter (D_f) as the source tank. The estimation of the flame length is based on Thomas' (1963) [6] proposal:

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

where L = flame length (m), $\dot{m}^*$ = dimensionless mass burning rate of the fuel. Flame tilt in this study is dependent on Froude number, as proposed at least square fit method and is based on (2).

$$\tan\theta / \cos\theta = 3.13\mathrm{Fr}^{0.431} \tag{2}$$

where Fr = Froude number of pool fire. Flame drag, according to Moorhouse (1982) [7], is calculated as follows:

$$D'_f / D_f = 1.5(\mathrm{Fr}_{10})^{0.069} \tag{3}$$

Based on Mudan's (1984) [8] qualitative experimental data of pool fires, the luminous zone for gasoline is taken as 20% of the flame surface area. In the ethanol fire, according to Santos (2014) [3] the fraction of visible parts is 80%.

The flame average emissive power is predicted using the unobscured ration (U_R) as:

$$E_{av} = E \times U_R + E_s \times (1 - U_R) \tag{4}$$

where E= emissive power of flame and E_s= emissive power of smoke, (taken as $20 kW/m^2$). Therefore in agreement with Landesman and Santos (2014) [3] the following values for ethanol and gasoline are obtained: $E_{av,ethanol}$= 164,93 kW/m^2 and $E_{av,gazoline}$=42,74 kW/m^2.

Transmissivity (5), according to Casal (2008) [9] is calculated as a function of the distance between the flame and the target:

$$\tau = \begin{array}{l} 0.976 \times d^{-0.06}, d < 5m \\ 1.028 \times d^{-0.06}, 5 \le d \le 55m \\ 1.159 \times d^{-0.12}, d > 55m \end{array} \tag{5}$$

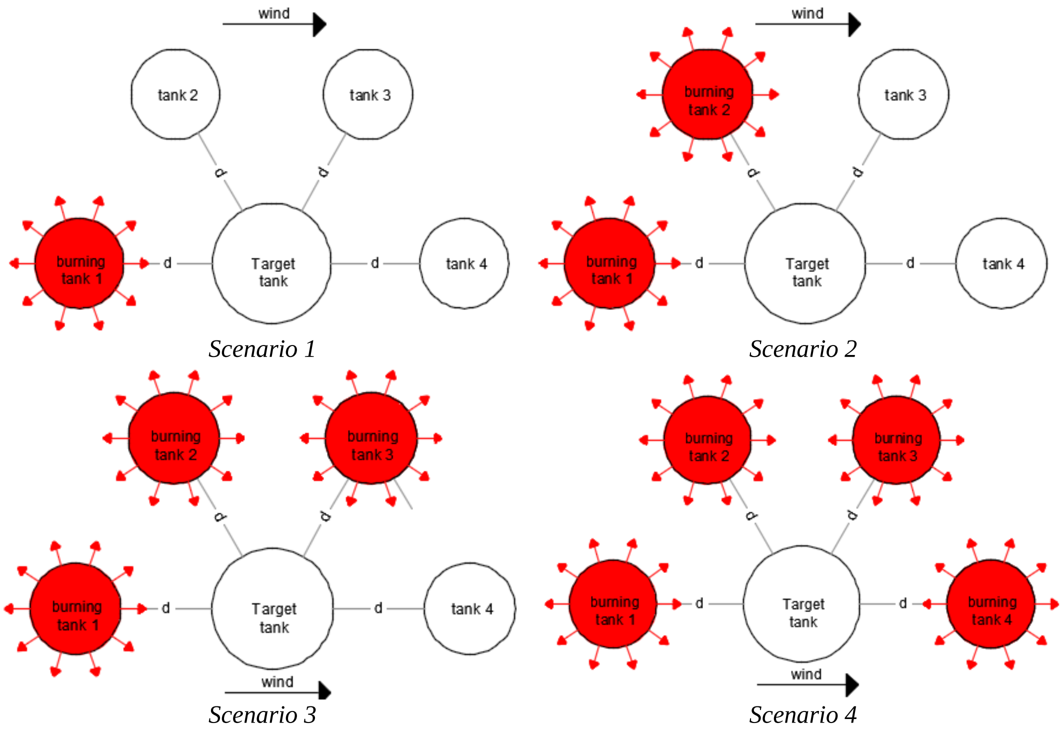
Finally, the flame radiation temperature is given by equation (6):

$$T_{fe} = \sqrt[4]{\frac{e_f \times \sigma \times T_a^4 + E_{av} \times \tau}{e_f \times \sigma}} \tag{6}$$

where T_{fe} is the radiation temperature of the flame, e_f = emissivity, σ is the Stefan – Boltzmann constant and T_a the ambient temperature.

4. CASE STUDIES

The layout of storage tanks that is considered in this paper, is illustrated in *Fig. 2*. Four different scenarios are studied depending on the number of burning tanks. The "target tank" in all cases has the same geometric characteristics and is considered to be empty. The basic goal is to study the fire-behaviour of this tank. In scenario 1, the case of one unique burning tank is examined. Parametric case studies are examined with respect to parameters that may affect the behaviour the of target tank. The parameters that are considered are the geometry of the burning tank, the fuel that is stored (Ethanol or gasoline), the presence of wind and the separation distance between the burning and the target tank. The wind direction is indicated in *Fig. 2*. Scenario 2 corresponds to the case where the fire spreads from tank 1 to the adjacent one (tank 2). The further propagation of fire to more adjacent tanks (tanks 3 and 4) is incorporated in Scenarios 3 and 4. In scenarios with multiple tank fires it is assumed that the fire has already spread to adjacent tanks. The short name of each case study, used in this study, consists of five parts. The first is the diameter of the burning tank, the second is the separation distance, the third is the type of burning fuel (E for ethanol and G for gasoline), the fourth indicates if the wind is considered (W for the case of wind and NW for the wind free case) and the fifth part is the name of the scenario.



Scenario 1

Scenario 2

Scenario 3

Scenario 4

Fig 2: Layout of tanks and the fire scenarios

5. NUMERICAL SIMULATION, MESHING SIZE AND MODELING VALIDATION

The problem is solved numerically through the Finite Element (FE) method and the non-linear code MSC-Marc (2014) [10] is used. Three-dimensional models are developed for the simulation of the behavior of steel storage tanks, using shell elements.

Thermal transient analysis is used. An open cavity is defined for the treatment of the heat transfer problem from burning tanks to the target tank through radiation. The calculation of view factors is based on the Pixel Based Modified hemi-cube method. The emissivity of fire and steel are taken equal to 1 and 0.8 respectively. The environmental temperature is set equal to 20ºC. The temperature of the flame, which is simulated as a radiating surface, remains constant during the analysis. The material properties are temperature dependent as it is defined in EN 1993-1-2 [11].

6. RESULTS & CONCLUSIONS

As it can be seen in *Fig. 3 & 4*, the temperature distribution on the tank wall of the adjacent tank is not uniform. The highest temperature rise takes place on the side of the tank wall which is opposite of the source tank (180°), while the back side is not affected by the pool fire. This pattern becomes more complex as more burning tanks are added.

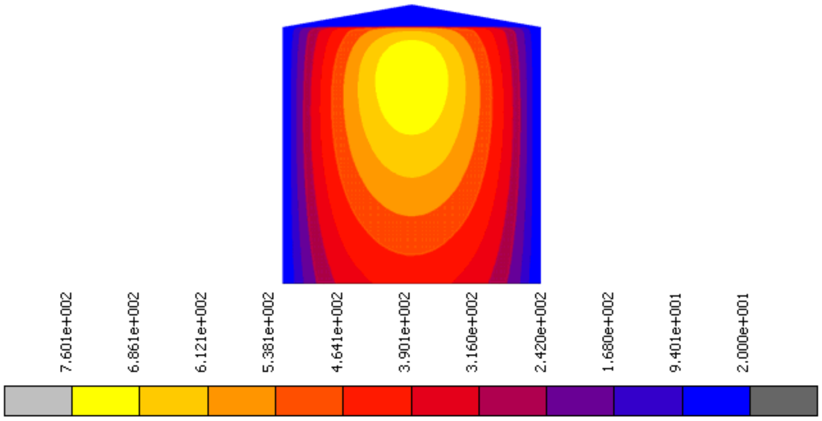
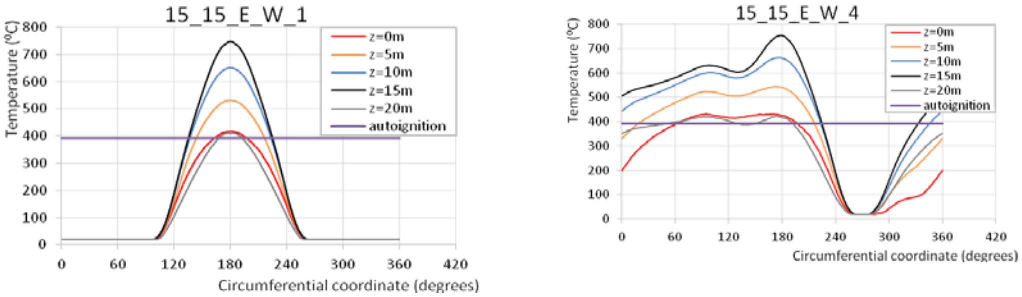


Fig. 3: Temperature distribution on the target tank on side facing the burning tank



a) *b)*

Fig. 4: Temperature distribution along the circumferential plane for a scenario with one burning tank (a) and four burning tanks (b)

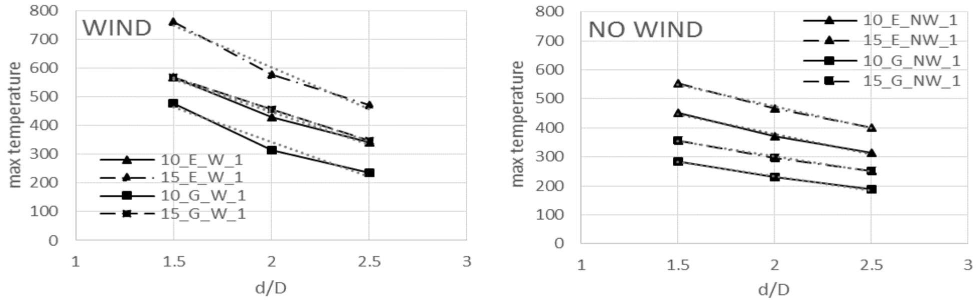


Fig. 5: Max temperature vs the separation distance d/D for wind and no wind conditions

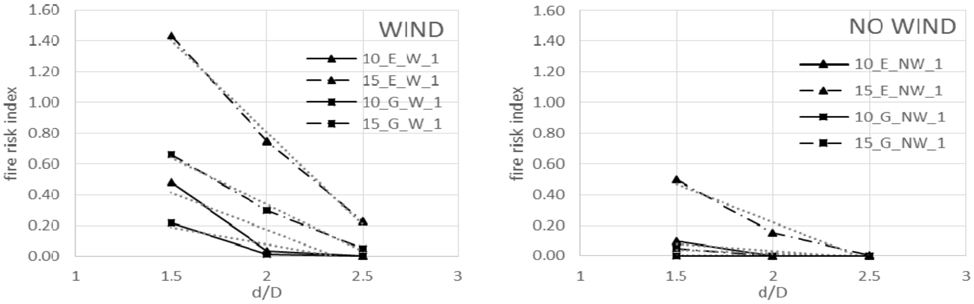


Fig. 6: Fire risk index vs the separation distance d/D for wind and no wind conditions

In *Fig. 5*, it is noted that when the target tank is closer to the burning tank, the maximum temperature is higher, and as the separation distance increases the maximum temperature decreases. This reduction is observed in all cases, regardless of the burning tank diameter, the fuel type, the wind conditions or the number of burning tanks and the rate is found to be linear [12]. Under wind conditions, when the diameter of the source tank is smaller the rate of temperature reduction as the separation distance increases in not affected by the fuel type. In bigger burning tank diameters the fuel type can be a factor. Under no wind conditions, the fuel type has a greater effect on the reduction rate of temperature values, as the separation distance of the tanks increases.

The *fire risk index* is proposed by the authors in order to quantify the temperature distribution on the target tank wall. The fire risk index takes into account both a) the spatial distribution of the temperature values exceeding the autoignition temperature along the external surface of the target tank, and b) the degree that these temperature values exceed the autoignition temperature. Autoignition temperature for Ethanol is 392°C and for Gasoline is 298,9°C. The results of the analysis showed that the higher fire risk indexes occurred under wind conditions. When wind is not present, in the majority of the models analyzed, the fire risk indexes were either very low, or zero, because the autoignition temperature of the fuel is never reached (*Fig. 6*).

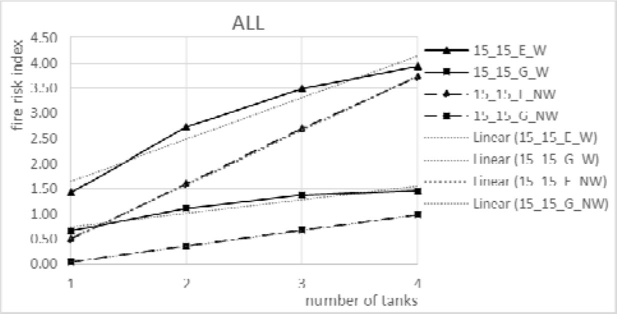


Fig. 7: Fire risk index vs the number of burning tanks for models with 15m diameter fire

In Ethanol models with small burning tank diameters the fire risk rate decreases rapidly as the separation distance of the tanks increases and for distance(d)/diameter(D) ratios >2 becomes zero. For larger burning tank diameters the fire risk index rate decreases linearly as d/D increases, under both wind conditions.

In Gasoline models in almost all scenarios, except for large diameter burning tanks with wind conditions, the fire risk index is very small and for d/D >2 it becomes zero.

Under wind conditions, for both fuel types' at large diameters, the fire risk index rate declines in a linear way as d/D increases. In small burning tank diameters for both fuel types the fire risk index reduces rapidly until d/D=2 and then becomes zero. Under no wind conditions in almost every scenario examined, except for larger diameter ethanol burning tanks, the fire risk index is very small and for d/D >2 it becomes zero.

The fire risk index increases as the number of burning tanks rises from one to two, but the rate of increase is much lower when the 3rd and 4th tanks is added (*Fig. 7*). The fire risk index is higher in Ethanol fires than in Gasoline models as the number of burning tanks increases under both wind conditions. Last, but not least, the fire risk index is affected greatly by the fuel type when the number of burning tanks increases while the presence or absence of wind only affects slightly its magnitude.

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ΑΡΙΘΜΗΤΙΚΗ ΠΡΟΣΟΜΟΙΩΣΗ ΠΥΡΚΑΓΙΩΝ ΔΕΞΑΜΕΝΩΝ ΑΠΟΘΗΚΕΥΣΗΣ ΥΔΡΟΓΟΝΑΝΘΡΑΚΩΝ ΚΑΙ Η ΕΠΙΡΡΟΗ ΤΟΥΣ ΣΕ ΓΕΙΤΟΝΙΚΕΣ ΔΕΞΑΜΕΝΕΣ

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ΠΕΡΙΛΗΨΗ

Η παρούσα εργασία εξετάζει το πρόβλημα της θερμικής απόκρισης δεξαμενών αποθήκευσης καυσίμων, σταθερής οροφής, που θερμαίνονται κατά τη διάρκεια πυρκαγιάς. Ο πρώτος στόχος είναι να προσδιοριστούν οι παράμετροι που περιγράφουν τις φλεγόμενες δεξαμενές και να υπολογιστούν τα γεωμετρικά χαρακτηριστικά των φλογών. Αναπτύσσονται αριθμητικά μοντέλα που περιλαμβάνουν τόσο τις δεξαμενές που φλέγονται όσο και τη θερμαινόμενη δεξαμενή. Το πρόβλημα επιλύεται αριθμητικά χρησιμοποιώντας τη μέθοδο των πεπερασμένων στοιχείων. Η συμπεριφορά της θερμαινόμενης δεξαμενής εξετάζεται για πολλαπλά σενάρια πυρκαγιάς. Αρχικά, εξετάζεται η περίπτωση μιας μοναδικής φλεγόμενης δεξαμενής. Στα υπόλοιπα σενάρια η φωτιά εξαπλώνεται σε γειτονικές δεξαμενές, επομένως, η εξεταζόμενη δεξαμενή θερμαίνεται από πολλαπλές πηγές θερμότητας. Διεξάγονται παραμετρικές αναλύσεις για να μελετηθεί η επίδραση ενός συνδυασμού διαφόρων παραμέτρων: διάμετρος της φλεγόμενης δεξαμενής, τύπος καυσίμου (βενζίνη ή αιθανόλη), επίπτωση ανέμου, απόσταση μεταξύ των δεξαμενών και αριθμός φλεγόμενων δεξαμενών που συμμετέχουν. Επιπρόσθετα, η εργασία προτείνει έναν δείκτη επικινδυνότητας, ο οποίος είναι ενδεικτικός της πιθανότητας μετάδοσης της πυρκαγιάς από μια φλεγόμενη δεξαμενή σε μια γειτονική.