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Thermal performance-based analysis of minimum safe distances between fuel storage tanks exposed to fire

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ABSTRACT

This paper presents a numerical investigation aimed at assessing the safety of fuel storage tank farms subjected to elevated temperatures caused by fire conditions. In particular, the work addresses the ways of given pool-fire scenarios, occurring from the fuel ignition of pre-defined source tanks, are able to propagate to adjacent target tanks, *i.e.*, examining the possibility of a domino effect. The proposed analysis involves a sequential two-step procedure, corresponding to the application of: (i) a semi-empirical model—to obtain the equivalent temperature of the large pool-fire flame (source tank), assumed as a solid cylinder with a homogeneous and constant temperature distribution, dependent on the smoke ratio generated from fuel burning, with determined geometric flame features based on data extracted from literature and, (ii) Abaqus finite element transient heat transfer model—to determine the temperature variation on the target tank sidewall as a function of fire elapsed time. After validating the numerical model adopted, through the comparison with results of simulations reported in the literature and based on CFD (Computational Fluid Dynamics) model, the paper presents results concerning the safety assessment of a proposed case study corresponding to two adjacent tanks (source and target). The analysis considered the influence of a combination of various parameters: (i) type of stored fuel (gasoline or ethanol), (ii) structural tank sidewall material (steel or concrete), (iii) incidence of wind and (iv) several distances between the tanks. Finally, the temperature field evolution and ultimate temperature (mostly) resulting from the target tank sidewall data gathered in this study indicate that the current NFPA 30:2012 design recommendations need to be modified in order to achieve a satisfactory failure prediction for different ethanol and wind incidence.

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1. Introduction

The fire hazard is one of the main concerns associated with fuel storage tanks [1,2]. Accidents related to the occurrence of fire in storage farms composed by several tanks are recurrent [3–6]. Especially the grouped layout of the units makes them fairly prone to the so-called “domino effect”[1] and its probability tends to rise with an increasing production, urban densification around industrial complexes and other factors that may result in larger storage volumes and smaller distances between tanks, buildings and equipment. The proposition of minimum safety distances between nearby storage units in tank farms is a common “passive” approach used to reduce risks of fire propagation between adjacent tanks and, also, to allow sufficient time for users' evacuation and firefighting procedures. Therefore, several published technical guidelines and regulations for the construction, material selection, design and security of fuel storage facilities have been published in the last years [8–13]. However, the proposed recommendations are prescriptive-based, in the sense that the suggested minimum distances between tank façades do not take into account different key factors, such as tank sidewall materials and stored fuels. Recently, Sengupta [14] stated that the minimum fire safety distances specified in current design codes (*e.g.*, NFPA 30 2012 [8]) do not guarantee the safety of tanks from a fire.

The rather large number of fire accidents registered every year [5] has motivated the use of Computational Fluid Dynamics (CFD) models to assess the risk of a domino effect in tank farms [15–18]. However, although the CFD approach allows the analysis of fairly complex fire scenarios, including the effectiveness evaluation of firefighting systems and minimum safety distance estimates between units, the computational effort and the large amount of data produced make this approach inadequate for current design applications. On the other hand, *finite element method* (FEM) thermo mechanical analyses have been used as an alternative to

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[1] The domino effect is a chain reaction that occurs when a small change causes a similar change nearby, typically refers to a linked sequence of events where the time between successive events is relatively small. In the present application it is related to the occurrence of successive damage to adjacent tanks (targets) caused by fire propagating from a particular source tank [7].

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Nomenclature

A	curve-fitted constant dependent on tank's height
A_i	emitter surface area
A_j	receiver surface area
B	curve-fitted constant dependent on tank's shell material, flame fuel and wind speed
c	specific heat
D	liquid pool/tank diameter
d	distance between flame and target
dA_i	area of an emitter infinitesimal plane
dA_j	area of an receiver infinitesimal plane
d_m	minimum safety distance between source and target tanks
E	flame emissive power
E_{av}	flame average emissive power
E_b	black body emissive power
E_{soot}	smoke emissive power (20 kW/m^2)
F_{ij}	configuration factor
Fr	Froude number ($Fr=u_w^2/gD$)
g	acceleration of gravity (9.8 m/s^2)
H_0	tank height
h_{ext}	coefficient of heat transfer by convection for the external surface of the tank
H_f	flame height
h_{int}	coefficient of heat transfer by convection for the internal surface of the tank
H_R	relative humidity
L	oblique flame length
m_∞	the mass burning rate per unit area of the liquid surface
P_w	vapor pressure of water
P_{wa}	vapor pressure of water at room temperature
q_{re}	radiative heat fluxes emitted
q_{ri}	radiative heat fluxes that strike a facet on a target
Re	Reynolds number ($Re=u_wD/1.57\times10^{-5}$)
S_{i-j}	distance between emitters' and receivers' planes
t	fire elapsed time
T_a	air temperature/fluid temperature
T_{ext}	temperature on the external face of a target tank
T_f	flame radiation temperature
T_{fe}	equivalent flame temperature
T_{ig}	autoignition temperature of the storage fuel
T_{int}	temperature on the internal face of a target tank
T_u	ultimate temperature
u_w	wind speed

Greek letters

α	angle between the vector normal to the emitting surface and the direction of the radiation flux emitted
ΔD	lateral displacement of the flame
ε_f	flame emissivity coefficient
ε_t	surface emissivity coefficient for steel and concrete sidewalls (0.7)
θ	inclination angle of the flame
λ	coefficient of thermal conductivity
ρ	density of the material
ρ_a	air ambient density (1.2 kg/m^3)
ρ_v	fuel vapor density ($\rho_{\text{v,gasoline}}=3.94$ kg/m^3 and $\rho_{\text{v,ethanol}}=1.59$ kg/m^3)
σ	Stefan–Boltzmann constant (5.67×10^{-11} kW/m^2/K^4)
τ	atmospheric transmissivity
φ	angle along the target tank surface circumference
χ_{lum}	percentage of visible flame

CFD models to perform a fire safety analysis of tank farms—either on the structural or on the temperature domains [19–23]. One notices that, while in the former materially and geometrically nonlinear thermo mechanical analyses are performed, in the latter, one compares the temperatures of the tank sidewall with fuel self-ignition, which is a more straightforward approach. Nevertheless, all FEM thermo mechanical reported works dealt exclusively with steel structural facilities and liquid products derived from petroleum (and/or petrochemicals) (*e.g.*, gasoline).

1.1. Motivation and objective

According to the authors' best knowledge, it was not possible to identify any research paper that explores the burning behavior of alternative liquid fuels (*e.g.*, ethanol) and/or compares the fire performance of storage tanks made of non-steel sidewalls. Although steel tanks[2] are widespread and predominate in the oil industry—Fontes [24] argued recently that concrete tanks are more durable and, also, present lower construction and operating costs when compared with steel counterparts. Moreover, Van Breugel and Ramler [25] concluded that prestressed concrete tanks are able to considerably reduce the probability of domino effect, since they are less susceptible to failure due to large fire accidents than steel ones. Furthermore, differences in fuel combustion processes present a fundamental factor in the fire safety of storage tank farms—recalling the distinction on the emitted radiation intensity of gasoline and ethanol fires. While the former generates a large amount of smoke, thus blocking most visible parts of the flame and consequently reducing its radiation emission, the latter are nearly smoke free, hence exhibiting more intense radiation fluxes. Persson and McNamee [26] stated that the use of unique design criteria for gasoline and ethanol could represent a serious risk to the safety of tank farm facilities, and suggested to adopt more appropriate firefight measures and/or safety distances between storage units. These findings provided the motivation for the present work, which aims at contributing towards the establishment of specific recommendations for a performance-based analysis of storage tanks exposed to fire conditions. Different factors are considered in the analyses for several distances between tank units: storage fuels, structural tank's sidewall materials and the incidence of wind. Accordingly, this paper addresses the ways that pool-fire[3] scenarios, occurring from the fuel ignition of pre-defined source tanks, are able to propagate to adjacent target tanks, *i.e.*, one assesses the possibility of domino effect. The adopted numerical analysis involves a sequential two-step procedure, corresponding to the application of: (i) a semi-empirical model—to obtain the equivalent temperature of the large pool-fire flame (source tank), assumed as a solid cylinder with a homogeneous and constant temperature distribution, dependent on the

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[2] Indeed, the use of (i) high-strength steels and (ii) very slender cross-sections are responsible for making steel tank construction particularly vulnerable to fire conditions—recalling that the heating rate of a steel cross-section depends on its dimensions, namely perimeter exposed to fire and area.

[3] A pool fire is defined as a buoyant diffusion flame that burns above a fuel horizontal surface [27].

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