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Domino Effect by Pool Fire Radiation on Pipelines: an Applicative Case-study

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An important feature of tank pool fire is that the targets of interest for critical effects may include other plant units, such gas pipelines, storage sites, process sections, with heat transfer modes not limited to radiation. This paper, which takes inspiration from a recent work of the same authors, considers the physical model of a rectangular pool-fire to provide an analytical trend of the surface emissive power depending on the flame height. The capability of the approach is proved by an applicative case-study where the possible escalation from pool fire to a coke oven gas pipeline failure is analysed, within the context of a coal dry distillation plant. The possibility of escalation with pipeline damage is thoroughly discussed, in order to develop a detailed design of the emergency response capability considering the provision of human and logistical resources.
Keywords: accident escalation, coal, coal tar, coke oven gas, explosion, pool-fire

1. Introduction

As demonstrated by high profile accidents in the process industry, accidental fires may lead to damages to equipment, with severe consequences and possible accident escalation (Bagster and Pitblado, 1991). Statistics evidence as well that the process accident history is dominated by fire scenarios (Fabiano et al., 2012). Also for this evidence, pool fire represents one of most explored scenario in the scientific literature and a number of different modelling approaches were developed over the years, namely field CFD models, integral models, zone models and semi-empirical models. The last ones characterize the geometry and radiative characteristic of pool fire by using correlations based on dimensionless modelling. The reader is addressed to the review provided by Rew et al., (1997) for burning rate and surface emissive power database for a broad range of liquid hydrocarbon fuels and for uncertainty in the application of semi-empirical pool fire modelling. An analytical model suitable for different geometries was proposed by Palazzi et al. (2017) and validated for different hydrocarbons, utilizing both laboratory and full scale experimental runs. Domino effect is defined in accordance to CCPS (1999), as “an incident which starts in one item and may affect nearby items by thermal, blast, or fragment impact, causing an increase in consequence severity, or in failure frequencies”. Owing to its low probability high severity consequence the last implementation of Seveso III Directive requires inclusion of domino scenarios in developing safety management of industrial process plants (Fabiano et al., 2018). In the tested industrial context, domino effects denoting an accident propagating in the neighbouring unit and triggering escalation of the accident (De Rademaeker et al., 2014, Zeng et al., 2020) is referred to possible escalation to coal pile storage and complex pipeline infrastructure, mainly transporting coke oven gas (COG). The latter is a valuable but flammable and explosive by-product obtained during coal carbonization to produce coke in the steel industry. Improper operation in the production process, transportation or storage can easily lead to combustion and explosion, posing a serious threat to lives and assets. The topic is up-to-date as the current unfavourable situation on the coke oven tar (COT) market imposes to look for alternative methods of recycling COT, in the direction of process safety, environmental protection and extending coke production (Makgato et al., 2019). Additionally, the increased attention on low carbon energy transition attracts research in the direction of alternative and less hazardous energy sources (Vairo et al., 2014), as well as towards new

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technologies in energy storage, as exemplified by transition metals applications (e.g. vanadium) which are in the hotspot for their unique properties in redox processes (Reverberi et al., 2016).

2. Modelling framework

This section explains key aspects of the calculation methods utilized to determine the possible escalation following the development of the given pool fire, constrained by a rectangular bund.

2.1 Pool fire model

The pool fire model is founded on a conservative analytical approach originally described in Palazzi and Fabiano, (2012), whose validity as short-cut method was verified also under in confined environment (Vianello et al., 2012). Under simplifying and conservative hypotheses, pool fire behavior was subsequently described starting from following Eqs:

$$\dot{m}_a = \frac{2}{3}\frac{1}{K}\delta\eta z^{3/2} \qquad (1) \qquad \dot{m}_v = \frac{2}{3}\frac{K-1}{K}\delta\eta z^{3/2} \qquad (2) \qquad A_F = \frac{2}{3}\frac{\delta}{\rho}z \qquad (3)$$

where:

$$\delta = Kf\rho P_r \qquad \eta = \left(\frac{2K}{K+6}\theta\right)^{1/2} \qquad \theta = \left(\frac{\rho_a}{\rho} - 1\right)g$$

According to Palazzi et al., (2017) the flame area A(z) is analytically described as a function of the vertical coordinate z and the effects of non-complete oxidation of hydrocarbons entrained into the flame due to oxygen depletion are accounted for in the pool model. The refined pool model is based on the energy balance referred to the flame region F:

$$\Delta\dot{H}_u + \Delta\dot{H}_c = \dot{Q}_F \qquad (4)$$

where:

$$\Delta\dot{H}_u = \dot{m}_v \sum \Delta\tilde{H}_i\,\hat{n}_i \qquad (5) \qquad \Delta\dot{H}_c = \Delta\hat{H}_{c,298}\dot{m}_v X \qquad (6)$$

$$\dot{Q}_F = \dot{q}''_F A_F = \dot{q}''_F P_r h \qquad (7) \qquad \dot{q}''_F = -\varepsilon\sigma T^4 \qquad (8)$$

Under the conservative hypothesis of radiation feedback from the flame to the pool fully enhancing hydrocarbon (HC) vaporization rate, the energy balance yields:

$$\dot{m}_v \Delta\hat{H} = \dot{q}''_F P_r h \qquad (9)$$

being:

$$\dot{m}_v = -\frac{\dot{q}''_F A_v}{\Delta\hat{H}_v} \qquad (10) \qquad \Delta\hat{H} = \sum \Delta\tilde{H}_i\,\hat{n}_i + \Delta\hat{H}_{c,298}X \qquad (11)$$

By combining Eqs. (9) and (10), it follows:

$$h(T) = \frac{A_v}{P_r}\frac{-\Delta\hat{H}}{\Delta\hat{H}_v} \qquad (12)$$

At last, by imposing the condition z=h and by replacing Eqs. (10) and (12) into Eq (2), it follows:

$$-\dot{q}''_F = \frac{2}{3}(K-1)\eta f\rho\left(\frac{A_v}{P_r}\frac{1}{\Delta\hat{H}_v}\right)^{1/2}\left(-\Delta\hat{H}\right)^{3/2} \qquad (13)$$

The logic steps of the considered approach can be summarized as follows:

- determine from Eq. (13) by numerical method the temperature T, having properly accounted for the dependence of flame thermal flux and fuel density upon temperature, by pertinent formulae;
- determine by Eqs. (10) and (12) respectively the vapour flow rate and the flame height as a function of T;
- determine the surface emissive power;
- determine the heat radiation at the target, by adopting a geometric view-factor and atmospheric transmissivity, mainly depending upon humidity, distances and viewing angles between the radiation source and the receiver, according to:

$$\dot{q}''_{i,m} = \dot{q}''_{F} F_{FC} \tau_m \tag{14}$$

2.2 Consequence and escalation assessment

An approximated estimate of the possible escalation of the combustion process to the coal storage was performed considering the energy balance in the peculiar situation corresponding to the parallelism between the flame axis and the slope of the coal pile surface exposed to radiant heat from the pool-fire (Palazzi et al.,2017). In this way, a conservative estimate of the surface temperature attained for time extensions characteristics of the full development of the pool fire scenario was performed, evidencing that coal ignition and combustion towards the inner layer is an escalation to be included in setting-up an effective design of fixed/mobile mitigation systems. The further scenario here analysed is the possible escalation to a pipeline failure due to thermal load from pool fire. The calculation of temperature T_t of the pipeline exposed to fire is developed under the hypothesis of its constancy on the segment of pipeline at stationary conditions.
The energy balance for the segment of pipeline can be written as:

$$\dot{q}''_{in} DL = \dot{Q}_f + \dot{Q}_e \tag{15}$$

where:

$\dot{Q}_f = \dot{n}\tilde{c}_p\left(T_{fu} - T_{fe}\right)$ Heat flow between the pipeline and the fluid [W] (16)

$\dot{Q}_e = \pi D L h_e (T - T_a)$ Heat flow between the pipeline and air [W] (17)

The heat flow between the pipeline and the fluid [W] can be also expressed as:

$$\dot{Q}_f = \pi D L h_f \left(T - \frac{T_{fo} + T_{fi}}{2}\right) \tag{18}$$

where the logarithmic mean temperature difference is approximated by the arithmetic mean. Thermal conductivity and other physical propriety of the fluid are referred to the mean value of temperature of fluid in the pipeline, T_{fm}=400K. The heat transfer coefficient between pipe and air is assumed equal to 15 W·m^{-2}·K^{-1} (Faggiani, 1992) in the case of thermal radiation and natural convection condition (corresponding to wind velocity u ≤ 0.5 ms^{-1}). In the case of forced convection, the coefficient can be expressed as:

$$h_e = 0.021\, Re^{0.6} \tag{19}$$

The heat transfer coefficient between flow and pipe surface has been calculated by means of Nusselt number:

$$Nu = \frac{h_f D}{k} = 0.023\, Re^{0.8} \tag{20}$$

The analytical expression of the outlet temperature of the fluid in the segment of pipeline is easily obtained by combining equations (18), (19) and (20)

$$T_{fo} = \frac{\frac{2\dot{q}''_{rn}}{\pi h_e} + T_{fi}(\chi - 1) + 2T_i}{\chi + 1} \tag{21}$$

where:

$$\chi = \frac{2\dot{n}\tilde{c}_p}{\pi D L}\left(\frac{1}{h_e} + \frac{1}{h_f}\right) \tag{22}$$

3. Results and discussion

The capability of the methodology is verified referring to an industrial case study to discuss the importance of assessing effects on equivalent absorbed thermal dose, rather than fixed thermal radiation threshold.

3.1 Case-study definition

Reference is made to a coal dry distillation plant where the accident scenario is a multi-component hydrocarbon pool fire arising from a major LOC in the coke tar storage park. Nearly half of coke oven gas is directly sent to the combustion chamber to heat the coke oven, while the remaining can be conveniently utilized for the deep processing in producing high-valued chemical products. The vulnerable pipeline system conveys COG from coke batteries at a minimum distance of 32 m from the edge of the bund, at a height from the ground equal to 5.5 m (see Fig. 1). The steel pipeline sections of potential interest for accident escalation are characterized by length L=12 m diameter D= 1.2, 1.3 and 1 m all with a thickness of 10 mm. Thermal conductivity and other gas properties are calculated considering the average COG composition and constant T_f = 400 K. COG percentage composition (v/v) was evaluated by standard UniChim methods on samples collected in the plant : O_2 = 0.54; N_2 = 15.28; CH_4 = 22.30; CO = 4.5; CO_2 = 2.38; C_2H_4 = 1.96; C_2H_6 = 0.93; H_2 = 49.89; H_2O = 1.53; C_nH_m = 0.69.

3.2 Safety considerations

Starting from the previously outlined pool fire model, the calculation of the thermal load on the target pipelines due to heat radiation from a rectangular pool fire under different atmospheric conditions and flame tilt was comparatively performed according to three approaches. As detailed in the following we comparatively utilized:

- refined surface emitting source (SS) and incident thermal flux obtained by local energy balance, as for the model originally described in Palazzi et al.(2017);
- point source (PS) located in the centre of the rectangular dike at half flame height;
- radiating view factor (RVF), as for analytical expressions provided by Howell (1982) and allowing to obtain the average incident thermal flux on a given target.

Every model was applied under several atmospheric conditions: the worst conditions coincide to a direct wind from the centre of the pool to the projection on the ground of the pipeline. The most significant atmospheric scenarios explored in the study are summarized in Table 1, while the maximum and minimum values of heat radiation load attained under the explored atmospheric conditions are summarized in Table 2.

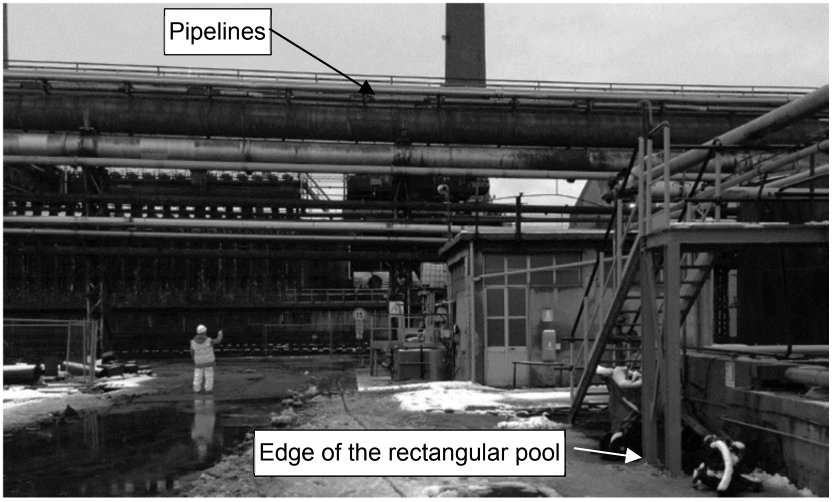

Figure 1: Applicative case-study.

Table 1: Reference atmospheric conditions in the case-study and Pasquill coefficients (Palazzi et al., 2017).

Case	Atmospheric conditions	Stability class	u [m·s^{-1}]	α	β	γ	π
A	Wind absence	B2	0.5	0.40	0.91	0.41	0.15
B	Unstable condition	B2	2	0.40	0.91	0.41	0.15
C	Neutral condition	C	5	0.32	0.78	0.22	0.25
D	Neutral condition	C	10	0.32	0.78	0.22	0.25
E	Neutral condition	C	15	0.32	0.78	0.22	0.25

Table 2: Heat radiation received from the target pipeline as a function of meteorological conditions calculated according to the different approaches.

	Highest heat radiation [kW m^{-2}]			Lowest heat radiation [kW m^{-2}]		
Case	SS	PS	RVF	SS	PS	RVF
A	17	11	19	4.5	2.2	6.0
B	19	13	20	4.9	2.4	6.3
C	23	14	21	5.2	2.7	6.8
D	29	23	25	6.3	3.6	8.2
E	32	41	30	9.5	5.0	10

Table 3: Evaluation of the peak temperature of the COG pipelines under different atmospheric conditions.

	Peak temperature [K]		
Case	Pipeline 1 (D=1.2 m)	Pipeline 2 (D=1.3 m)	Pipeline 3 (D=1 m)
A	454	464	433
B	433	435	421
C	419	418	412
D	427	425	426
E	440	437	444

As shown in Table 2, results by applying a simple point source model tend to underestimate the heat radiation load under all weather conditions. The refined surface emitting source model including enhanced view factor and the radiating view factor f scientific literature yield quite similar results. They are both applied in connection with the novel pool model including variable heat emitting flame area of the pool fire, as a function of the vertical flame axis. A summary of maximum temperature in the exposed pipelines of different sections is provided in Table 3, from which it is evident that the maximum pipe temperature increase is nearly 30 K, compared to steady-state conditions. The refined approach evidences how the minimum values of the highest thermal radiation load (i.e. 17 kW m^{-2} at u = 0.5 ms^{-1}) correspond to the maximum temperature increase rate and the highest peak temperature, exerting the maximum steel pipeline stress. Results are connected to the actual value of h_e that under natural convection conditions is minimum, reaching its maximum in case of forced convection, at u = 15 ms^{-1}. Regarding the assessment for domino effect, it is widely acknowledged a simplified physical effect threshold approach, based on time limit of 10 min exposition to pool fire with 37.5 kW/m^2 for pressurized equipment, or structural elements and 12.5 kW/m^2 for atmospheric equipment, or enclosures. A detailed discussion of the feature of domino effects for different industrial items/apparatuses and thresholds values is reported in Reniers and Cozzani (2013). In the given industrial context, the possibility of escalation to coal pile is possible, while considering pipeline failure a refined approach based on dynamic thermal dose calculation seems advisable. In fact, quantitative results evidence that under natural convection conditions, at the maximum resulting pipeline temperature, COG flow exerts a relevant role in dissipating the additional heat load resulting from the considered pool fire scenario (accounting for nearly 50% heat removal), so that the possible choice of emergency flow shut-down must be carefully considered. In this regard, the combined effects of different active and passive safety barriers on the domino propagations should be evaluated with refined techniques, e.g. by exploring the dynamic temporal evolution as detailed (Zeng et al., 2020). Furthermore, it is advisable an accurate definition of the links between the cause and time to failure and the measures to be enforced to prevent them, considering the effects of management and organizational variables (Milazzo et al., 2010).

4. Conclusions

In this paper, a non-standard approach is presented to calculate, under different meteorological conditions, the resulting heat radiation of the flame surface on the vulnerable target pipeline, for time extensions characteristics of the full development of the primary pool fire scenario. A variable heat emitting flame area of the rectangular pool fire, depending on the vertical flame axis and a refined assessment of the view factor allow proper evaluation of the possibility of accident escalation. The model was applied utilizing different approaches for assessing thermal damage on the sensitive target. Globally, the results evidence that the escalation of pool fire towards COG pipeline failure and the required time should be carefully included in emergency planning in terms of human and logistical resources, training and assessment. Additionally, the enhanced evaluation of wind effect may help in designing different configurations of thermal barriers e.g. by heat shielding, or water curtains.

Nomenclature

A_F = flame surface [m^2]
A_v = effective vaporization area [m^2]
$\tilde{c}_p$ = gas molar heat capacity [$J \cdot mol^{-1} \cdot K^{-1}$]
f = entrainment constant [-]
F_{FC} = view factor [-]
h = flame height [m]
h_e = heat transfer coefficient between pipe and air [$W \cdot m^{-2} \cdot K^{-1}$]
h_f = heat transfer coefficient between flow and pipe surface [$W \cdot m^{-2} \cdot K^{-1}$]

K = flow rate ratio [-]
$\dot{m}_a$ = flow rate of air entering the flame region [kg s^{-1}]
$\dot{m}_v$ = flow rate of HC entrained in the inner flame region [kg s^{-1}]
$\dot{n}$ = gas molar flow [mol·s^{-1}]
$\hat{n}_i$ = moles of i-th component per unit mass of HC [kmol·kg^{-1}]
P_r = flame outer perimeter [m]
$\dot{q}_F''$ = thermal flux emitted by flame [kW m^{-2}]
$\dot{q}_i''$ = thermal flux on the surface unit [kW·m^{-2}]
$\dot{Q}_F$ = thermal power irradiated by the flame [kW]
T_{fi} = inlet fluid temperature in the segment of pipe [K]
T_{fo} = outlet fluid temperature in the segment of pipe [K]
X = fuel fractional conversion within the flame [-]
z = distance from the source on the vertical axis [m]
$\Delta\dot{H}_c$ = HC molar combustion enthalpy [kJ·$kmol^{-1}$]
$\Delta\hat{H}_{c,298}$ = HC combustion enthalpy [kJ·kg^{-1}]
$\Delta\dot{H}_{c,298}$ = HC molar combustion enthalpy [kJ·$kmol^{-1}$]
$\Delta\tilde{H}_i$ = molar enthalpy of the i-component [kJ·$kmol^{-1}$]
$\Delta\dot{H}_u$ = fume sensible heat at flame turning off [kJ s^{-1}]
$\Delta\hat{H}_v$ = HC vaporization enthalpy at boiling temperature [kJ kg^{-1}]
ε = flame emissivity [-]
ρ = density [kg·m^{-3}]
ρ_a = air density [kg·m^{-3}]
τ_m = average atmospheric transmissivity [-]

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