# ENGINEERING METHOD TO CALCULATE THE HEAT RADIATION ON FAÇADES DUE TO A POOL FIRE

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## ABSTRACT

All around the world, the density of buildings near industrial sites and roads is increasing. Consequently, introducing fire risks and therefore the need for extra fire safety requirements around these newly built structures. Some of these new risks that need to be considered around industrial sites are pool fires. A pool fire is caused when spilled flammable liquid ignites. Façades of buildings constructed in an area which could be affected by heat radiation of a pool fire need to be fire-resistant to protect the building and the people inside. However, application of fire-resistant materials is expensive and often redundant as the area defined as a risk of a pool fire does not take various elements like the surroundings into account. Therefore, this paper is written to combine the research on pool fire models and presents a method to calculate the receiving heat radiation on a façade. Based on the Yellow book and Poolfire6, a two-zone model of pool fires is proposed to describe the fluid flow and flame properties of the fire. It consists of combustion and plume zones, providing a model to determine the diameter, total flame length, visible flame length, flame tilt and the surface emissive powers. The receiving heat radiation is often computed for a single point and the view factor of a whole façade and orientation is not considered. These models aim to gain insight into the maximum heat radiation at a certain distance and are not constructed to analyse a complete façade. Using a calculation tool developed for calculating heat fluxes according to a national standard for external fire propagation NEN 6068:2020 The view factor of the whole building's façade is calculated. Combining this with the two-zone model results in a more detailed analysis of heat radiation received on a façade. This allows for determining the fire resistance on the necessary parts of the façade and configuring the optimal design in a preliminary design stage. Leading to a more economically feasible design.

## INTRODUCTION

Flammable liquids are transported on roads, rail- and waterways. In case of an accident, liquid can escape from the container itself. Consequently, forming a liquid pool which could potentially ignite, triggering a large fire. As a result of the heat, liquid from the pool vaporizes, resulting in a buoyancy-controlled turbulent diffusion flame. Such an incident could have catastrophic consequences for surrounding people, buildings and nature due to the heat release of the flame. The possibility of this incident is low, but not zero. For example in the Netherlands, a pool fire containing petrol occurred near Gouda after a car crashed into a petrol station, and in April 2025[1] a pool fire happened at a highway in Brazil after a truck crashed[2]. Both incidents resulted in multiple casualties and buildings and roads were damaged after the resulting fire. So, the possibility of an incident is rather small, but may result in significant consequences.

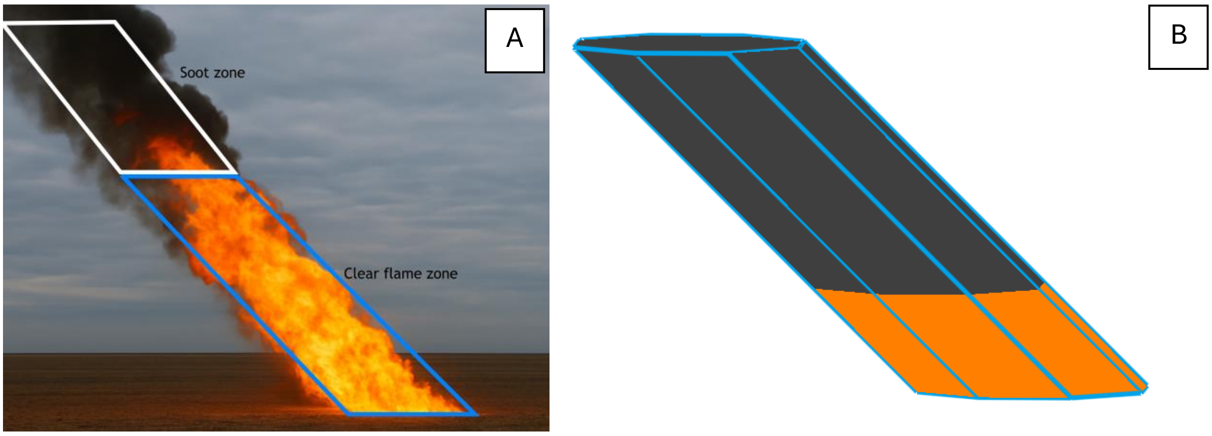
The Dutch government has analysed all the main transportation routes and defined an area around these roads that should be considered as potentially impacted during a pool fire incident. At first, an analysis was done to map out which type of liquid was transported on the various roads. However, this data is not publicly available, and one can only find the total amounts of transportation that have taken place for certain categories. For each type of transportation route typical incident scenarios were defined and published in '*scenario's externe veiligheid*'[3]. Secondly, areas were stipulated in which the heat radiation of a pool fire is considered dangerous. This area was determined to include everything within 30 meters from the centre of those road/water and train tracks. However, effects from height difference and (fire-resistant) obstructions within these 30 metres were not taken into account. Based on this investigation, Dutch regulations were drafted. These regulations oblige entire facades of buildings located in this area to be 60 minutes fire resistant (irrespective of the height) and to meet the fire class requirement A1 or A2[4]. As a result, this newly drafted regulation limited the possible building materials of façades to non-burning materials such as brick and aluminium. This method is a rough estimation towards the area a pool fire effects the environment but is not very specific to a building itself.

In the late '80s and early '90s, calculation methods were developed for the geometry and radiation from pool fires of various liquids. Currently, there are several computer programs that can calculate heat radiation as a function of the distance. However, all these available programs still do not take any surrounding objects into account. DGMR has extended an existing model that follows the method of the pool fire calculation defined by the Yellow book[5] and Poolfire6[6]. The only adoption done on the existing model is based on the view factor so one can calculate the receiving heat radiation on a façade and add objects in the surrounding. In this model, the pool fire itself is based on a two-zone concept, containing a bottom with a clear flame and a high temperature, and the resulting heat radiation. The top section of the model contains the smoke layer, where a flame is obstructed by smoke, causing decreased heat radiation. Finally, to define the size of a pool fire, the total amount of liquid, type of liquid and the wind speed needs to be entered. As a result, flame height and heat radiation are calculated. In combination with the orientation of the building, the heat radiation on the façades is determined. The model is available in the software package Gebouwprestatie. The paper is structured as follows: in Section II, the characteristics of pool fires are described. Moreover, in Section III, the model of the heat radiation is discussed, followed by Section IV with a case study. At last, the conclusions are provided in Section V and discussed in Section VI.

## POOL FIRE CHARACTERISTICS

All flames contain soot particles. The smaller particles in the combustion zones produce the heat radiation. In colder regions incomplete combustion leads to large soot particles which shield most of the flame's radiative power. The total thermal radiation from a pool fire therefore depends on how much soot is produced. This total amount of soot is influenced by air entrainment rate, turbulence in the flame, and fuel type. In a well-ventilated hydrocarbon pool fire, fuel vaporizes from the liquid surface, as a result of the thermal radiation feedback. Above the fuel surface, there is a clean burning flame layer with high radiative emissive power. This is followed by an obscured flame zone where smoke shields the clean burning flame below, which occasionally appears as 'blumes'. Higher in the flame, smoke obscuration increases until no clear flame is visible. This flaming body can be modelled in a computational fluid dynamic program. However, the time to construct such a model is a large investment and limits the total amount of variations that can be calculated. An alternative model is the two-zone model of Rew and Hulbert[6]. This model describes the structure of a pool fire in two phases, as shown in Figure 1. Next to this figure, a screenshot from the model is placed to show the comparison.

*Figure 1: A: the two zones of a flame of a pool fire, constructed with AI[7], B: the flame from the DGMR model, modelled in Gebouwprestatie.*




The two-zone model is a semi-empirical model which are generally used to characterize the geometry and radiative properties of pool fires through correlations using simplified formulas. The formulas used for the semi-empirical models are derived from extensive experimental data, providing reasonable predictions as long as they are applied within their validated range. Various examples of such models are documented in the literature. In this paper, the two-zone model is highlighted. However, other type of models will be discussed in the subchapter on the heat radiation. The main parameters of this two-zone model are explained in the subsections below.

**Burning rate**

An important parameter in the flame geometry is the mass burning rate. Often the formula found by Babrauskas[8] is used to compute the mass burning rate:

$$m'' = m''_{\infty}\left(1 - e^{-k\beta D}\right) \tag{1}$$

The burning rate is dependent on the type of fuel and the diameter of the pool. $m''_{\infty}$, $k$ and β are factors that depend on material characteristics. These values can be found in literature like the Yellow book[5]. A small summary of these values is given in Table 1. Note that the burning rate is dependent on the size of the pool which can be explained following an example: for a relatively small pool with a diameter of 2 meters fresh air can easily reach the centre, resulting in a faster burning rate. So, the opposite is true for a larger pool fire: no fresh air will reach the centre and therefore the burning rate is lower. As less air will reach the centre of the flame, the total smoke production increases. This is further discussed in the subsection elaborating on the clear flame length.

**Pool diameter**

Liquid spills can occur under various scenarios. Spills may be classified based on the activity during which they occur (such as from storage tanks, process installations, or transfer and transportation operations), the environment into which the liquid is spilt (on land or water surfaces), or based on the rate, quantity, and duration of the spill. The classification based on the release rate and duration includes three categories:

1. Instantaneous spills, all the liquid is released within a very short period, often used in calculating pool fires;
2. Continuous spills, the liquid is released over time (e.g. a pipeline);
3. Quasi-continuous, at first a given volume of liquids is released from the container and over time the redundant liquid will drip from the container.

The differentiation between "short time" and "long time" depends upon various factors, including the size of the spill, the properties of the liquid and the surrounding environment. Although most spills might fall into the category of quasi-continuous spills, it is very hard to define such a scenario analytically as many assumptions must be made. Therefore, it becomes more intuitive to make a calculation based on instantaneous spills. When spilled liquid ignites, a pool fire occurs. The diameter of the pool fire is influenced by the mode of release, the quantity (or rate) of release, and the burning rate. An expression for the spreading and burning of an instantaneous spill of liquid is formulated by Rai and Kalekar[9]. This formula is based on the gravitational spreading force and the burning rate of the fuel and is therefore independent of the surface:

$$D = 2 \cdot R = 2(V_L^3 \cdot \frac{g}{m''^2})^{1/8} \tag{2}$$

Using this formula, the assumption is made that all the liquid will burn, so there is no absorption in the surface area. This is accurate if the incident occurs on water, however, on roads and especially railways a part of the liquid will be absorbed. It was found that for roads this effect is small for oil spillage, however, no data is found for gravel beds on railways. Probably a part of the spillage will leak into the gravel beds itself and therefore will not contribute to the pool fire itself. To make a conservative assumption this positive effect is not considered in the calculations. For a continuous spill the diameter can be determined by assuming an equilibrium condition between the burning rate and the liquid spill rate:

$$D = 2 \cdot (\frac{V_L}{\pi m''})^{0.5} \tag{3}$$

From these two formulas, one calculates the maximum diameter. This diameter will realistically only occur for a short period, as the pool diameter decreases rapidly while on fire. Using this maximum pool diameter will lead to conservative outcomes, giving insight into the maximum resulting heat radiation on the object in the environment. Another assumption in applying this formula is that the surface of the incident is flat and there are no obstructions like trenches or walls. When there is an incline, for example on a road for the rainwater, liquids will flow downward, causing the pool fire to deviate from a perfectly round shape. The burning rate is influenced by the pool diameter, which in turn is affected by the burning rate. Therefore, an assumption must be made regarding one of these parameters. Often the diameter is assumed based on a pool thickness of 2 mm, as noted in the Yellow book[5.] Given the volume of the spill, it is possible to calculate the area and consequently determine the resulting diameter. The software package allows users to define the free shape of the pool itself, and by using the above formulas, the maximum area of the pool can be determined. Therefore, various shapes can be computed, and the influence of different object in the surrounding can be analysed.

**Flame length**

From literature, the flame length can be calculated in several ways. The basic formula for determining the flame length of a pool fire is based on the formula of Thomas[6] and the wind is not considered. However, the wind is a very important factor as it not only influences the tilt of the flame but also influences the combustion dynamics inside the flame. The Yellow book[5] proposed the following formula:

$$L = D \cdot 55 \cdot (\frac{m''}{\rho_{air} \cdot \sqrt{(g \cdot D)}})^{0.67} \cdot (\frac{U_w}{U_C})^{-0.21} \tag{4}$$

With this formula the length of the length is based on the windspeeds, and the user of the model can compute the total length of the flame for various wind speeds.

**Visible (clear) flame length**

The flame is divided into two separate parts and the total flame length has to be split. Part one exists where the flame is visible/clear and part two where the flame is shielded by the smoke. The modelling of the visible flame length has been studied by Considine[10], Pritchard and Binding[11], and Ditali[12]. A starting point is the research of Considine[10] as he indicated that the total length of the clear flame ranged from 30% of the maximum flame length for fires up to 25 meters in diameter to 0% for fire diameters of 50 meters or more. This variation can be explained as result of the airflow rate into a pool fire this strongly impacts soot particle production, as evidenced by increased soot production with larger pool diameters due to reduced air entrainment at the centre of the pool. Two separate formulas have been formulated by Pritchard and Binding and Ditali to calculate the visible clear length and both have been compared to clear flame data. The conclusion was that the formulae of Pritchard and Binding matched the data at most. However, for small fires (D<1.5 meters) the deviation of the test data and this formula is rather large. But for this study, only rather larger pool fires (D>20.0 meters) are considered as the total volume transported is big resulting in a larger diameter. The formula formulated by Pritchard and Binding:

$$L_C = D \cdot 11{,}404 \cdot m^{*1.13} \cdot U_9^{*0.179} \cdot \left(\frac{C}{H}\right)^{-2.49} \tag{5}$$

$$m^* = \frac{m''}{\rho_a \cdot (g \cdot D)^{0.5}} \tag{6}$$

**Tilt**

The tilt of the flame as a result of the windspeed can be calculated with the following formula found by Welker and Sliepcevich[13]:

$$\frac{\tan\theta}{\cos\ \theta} = c \cdot Fr^a \cdot Re^b \tag{7}$$

$$Fr = \frac{U_w}{g \cdot D}^2 \tag{8}$$

$$Re = \frac{D \cdot U_w}{\mu} \tag{9}$$

This formula is dependent on the windspeed and the diameter of the pool. There are 3 constants in this formula, which were found by validating the results of various tests and plotting of the formula. Pritchard and Binding [11] formulated the following: a= 0.333 b= 0.117 and c= 0.666. Using these values the angle of the flame can be calculated.

## HEAT RADIATION

After determining the shape and size of the fire, it is essential to find its heat characteristics to compute thermal radiation. From literature, various models can be summarized as follows:

1. Point model;
2. Solid flame model;
3. Two-zone model.

The point model is the most simplified option. The flame geometry is not taken into account and the heat radiation is calculated for a single point of the flame, neglecting most of the above-discussed topics, resulting in a single point that radiates heat. The second option is the solid flame model. For this option shape of the flame and size are considered, however no further distinction is made between the smoke layer and the clear flame. Therefore, the complete flame model has the same heat radiation over the total surface. Mudan[14] proposed a formula to calculate the average heat radiation of the flame, based on observations on how much of the flame is visible through the smoke layer. This percentage was determined to be 30%. With this percentage an average radiation can be calculated, 30% clear flame and 70% smoke layer. For this paper the two-zone model was used, dividing the flame into two separate parts. So, one has to determine the heat radiation of the clear flame and the heat radiation of the smoke layer.

### Heat radiation of the clear flame

The heat radiation of the clear flame is defined as the maximum surface emissive power and can be calculated with the following formula[5]:

$$E_{max} = \frac{m'' \cdot Hc}{1 + 4 \cdot \frac{L}{D}} \tag{10}$$

The total radiation depends on the size of the flame itself and the liquid. The burning rate is discussed as part of the flame length. For the heat of combustion, the Yellow Book[5] gives various values in table 6.6 depending on the substance.

### Heat radiation smoke layer

In literature, it was found that the smoke layer emits heat radiation of 20.0 kW/m$^2$ [15]. However, from visible observations by Rew and Hulbert the smoke of the flame was not constantly covered over time. In addition, blumes of the clear flame were visible over time as a consequence of the wind and fire dynamics inside the flame. In literature, this phenomenon is described as the unobscured ratio of the flame[12]. It is defined by comparing the ratio of the total area of visible flame in the upper region to the total area of the upper region. For fires which produce little smoke, for example LNG fires, the unobscured ratio will be high, whereas low values will be obtained for fires involving significant soot production, for example kerosene and petrol fires. A summary of values given in the literature is shown in Table 1.

*Table 1: fuel property data[6 11].*

| **Fuel** | $m''_\infty$ **(kg m$^{-2}$ s$^{-1}$)** | $k\beta$ **(m$^{-1}$)** | **C/H** | **$U_R$, D> 20 m (m$^2$ m$^{-2}$)** |
|---|---|---|---|---|
| Benzene | 0.085 | 2.700 | 1.000 | 0.02 |
| Diesel | 0.054 | 1.301 | 0.540 | 0.05 |
| Petrol | 0.067 | 1.480 | 0.430 | 0.02 |
| Heptane | 0.081 | 1.394 | 0.438 | 0.08 |
| LPG | 0.118 | 0.500 | 0.375 | 0.106 |

The formula of the surface emissive power of the smoke layer based on the unobscured ratio is as follow[6]:

$$E_u = U_R * E_{max} + (1 - U_R) \cdot E_S \tag{11}$$

**Atmospheric transmissivity**

Atmospheric transmissivity accounts for the partial absorption of emitted radiation by the air between the radiator and the target object. Water vapour and carbon dioxide are the main absorbers within the heat radiation's wavelength spectrum, leading to the following approximation[5]:

$$\tau_a = 1 - \alpha_{w-}\alpha_c \tag{12}$$

These factors depend on partial vapour pressure, radiation length, radiator temperature, and ambient temperature. A simplified formula was formulated by Bagster[16];

$$\tau_a = c_7 * (p_w \cdot x)^{-0.09} \tag{13}$$

For example, the atmospheric transmissivity is for an outside temperature of 15 °C (Pw is 1705 N/m$^2$) and a pool fire is at a 20-meter distance, $\tau_a$ =0.79 (-).

**VIEW FACTOR**

The view factor can be defined as the visible area of the flame that can be seen from a certain point. This can be calculated according to the principle of the Yellow book[5]. In the case of the two-zone flame model, two calculations are required: one for each zone. The Dutch regulations require proof that a fire in a building fire compartment will not spread to another building. The standard NEN 6068:2020[17] provides a calculation procedure based on the external flame model of Law & O'Brien. That model assumes the flame temperature decreases over the flame height. The flame emissivity is assumed to depend on the flame thickness as seen from the target point. NEN 6068 extends the original radiation model to allow calculating the radiant heat flux in arbitrary locations and directions. This more detailed approach was used in this study to gain more insight into the distribution of incident heat radiation on building facades.

**Threshold factor**

In the Netherlands, the possibility for fire to spread to adjacent buildings is assessed according to NEN 6068:2020[17], which allows heat radiation below 15.0 kW/m². This threshold value is established on the premise that cellulose materials will undergo piloted ignition when exposed to this level of heat radiation in a short period. In other countries and disciplines, this threshold value is often lower; for instance, industrial models typically use 10.0 kW/m². Generally, adopting a lower threshold value reduces the likelihood of fire spreading. However, in the case of pool fires, it is recommended to use the 15.0 kW/m² threshold, as many calculated parameters assume the maximum effects which one occur for a brief period.

**CASE STUDY**

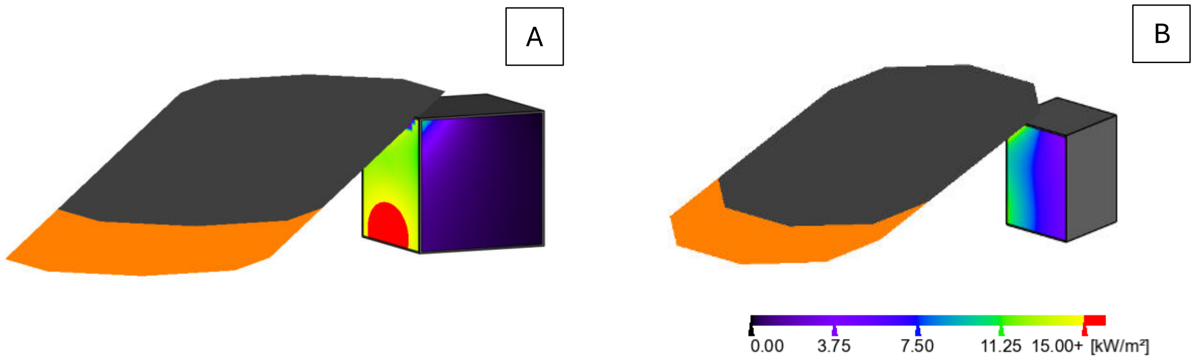
Providing more insight into the advancements of 3D modelling of the pool fire, a case study was formulated. The calculation is done with the software package developed by DGMR Software named Gebouwprestatie. The reference building is a square of 20 meters and is located at a distance of 45 meters from the centre of the highway. The liquid used is benzene, and the total amount of liquid is based on the scenario handbook, which specifies 23,000 kg. The calculations were done with a wind speed of 5 m/s.

Two scenarios were calculated:

A. In the first scenario, the façade of the building is parallel to the pool fire.
B. In the second scenario, the building is turned 45 degrees.

The computed heat radiation on the façade in both scenarios is shown in Figure 2.

*Figure 2: results of the first scenarios.*




When the façade turns red, its heat radiation exceeds 15.0 kW/m², requiring fire resistance. However, if the building rotates, the view factor of the façade reduces, lowering the received heat radiation, and no fire-resistant façade is needed. Note that in both scenarios, the plume's tip hits the façades, but the current model cannot compute the heat radiation of these parts yet. When the façades are within the plume, the heat radiation will exceed the threshold and must be fire-resistant. For the first scenario, a fire-resistant obstruction is placed with a height of 1,0 meter and in the second scenario with a height of 2.5 meters at a distance of 5.0 meters from the edge of the flame, resulting in the following:

*Figure 3: results of adding an obstruction.*

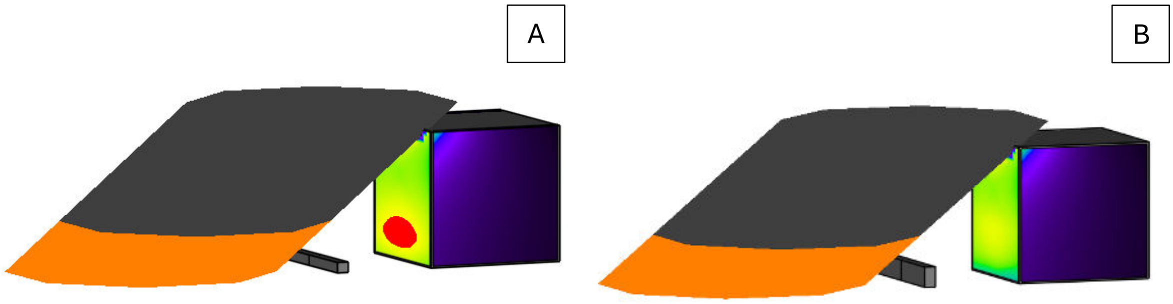
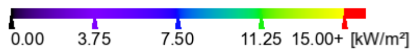



*Figure 4: results of adding an obstruction.*




For the 1.0-meter obstruction, the required fire resistance area is significantly reduced compared to the original scenario. In the case of the 2.5-meter obstruction, the entire red area is eliminated. These relatively straightforward examples provide insight into the extensive possibilities for enhancing our understanding through advanced modelling of pool fires in a three-dimensional manner while considering real façades and objects in the surrounding.

## CONCLUSION

The objective of this study was to improve calculation method of the heat radiation from a large pool fire on a façade. Commonly used methods only provide heat radiation data in a 2D area, based on a circular measurement around the flame. By modelling a pool fire in 3D, it is possible to compute the heat radiation impact on a façade more accurately. This capability enables the design of optimal fire-resistant façades that are both effective and economically feasible. Additionally, this approach provides insights into which parts of the façade need to be fire-resistant, including the option to take objects in the surrounding into account. The flame model used in this study is based on the two-zone model described in the Yellow Book[5], commonly known as Poolfire6[6]. The formulas of this method have been validated and are considered reliable representations of real situations, ensuring safe application. This method allows for the calculation of necessary safety measures tailored specifically to the project. Consequently, this ensures a safe and cost-effective design.

## DISCUSSION

Various formulas in the two-zone model used to compute flame values are conservative. For example, the height of the flame is the maximum height and occurs for a short period. Another conservative parameter is the diameter of the pool, which shrinks during a fire. As a result of these conservative parameters, the outcome is also conservative. The 3D modelling option is not limited to the two-zone model and the model itself offers an option to define the flame parameters. Thus, one can use the same software package to calculate point models or solid flame models. When defining a pool fire scenario, it should be considered that it can occur on any part of the road, rail, or waterway, necessitating to calculate multiple scenarios. Additionally, the tilt of a road and therefore the possibility of fluid moving downhill should be taken into account, as the liquids can flow towards a building. In conclusion, a significant part of reliable output depends on defining the appropriate scenarios and locations of the normative pool fire, which varies in each project. The outcome of the two-zone model is conservative, but applying this 3D modelling already optimizes the necessary safety requirements and represents an improvement over the current situation.

## LIST OF SYMBOLS

$\alpha_c$ = Absorption factor for carbon dioxide in the atmosphere
$\alpha_w$ = Absorption for water vapour in the atmosphere
C/H = Carbon to hydrogen atomic ratio in fuel
c7 = 2.02 $(N/m^2)^{0.09} \cdot m^{0.09}$
D = Pool diameter, in m
$E_{max}$= Surface emissive power of the flame in $kW/m^2$
$E_s$= Emissive power of smoke, approximately 20.0 kW/m
$E_u$= Surface emissive power of upper flame zone
Fr = Froude number of pool fire
g= Gravitational constant, 9,81 m/s
$H_c$ = Heat of combustion, in J/kg
$k\beta$ = Mean beam length corrector extinction coefficient product, $m^{-1}$
L = Total length of flame, in m
$L_C$ = Clear flame length, in m
m" = Burning rate, in $kg/(m^2 \cdot s)$
$m''_\infty$ = Maximum mass burning of fuel, in $kg/(m^2 \cdot s)$
$m^*$ = Dimensionless mass burning rate of fuel
$p_w$ = Partial vapour pressure of water in air at a relative humidity RH, in $N/m^2$
$\rho_{air}$ = Density of air, in $kg/m^3$
R= Radius, in m
Re= Reynolds number of fire source

$\tau_a$= Atmospheric transmissivity
$U^*$ = Dimensionless wind speed
$U_w$= Wind velocity, in m/s
$U_c$= Characteristic wind velocity, in m/s
$U_9^*$ = Dimensionless wind speed measured at a height of 9 m, 2 (-)
$U_R$ = Unobscured ratio of upper flame zone
$u_w$ = Wind velocity, in m/s
$u_c$ = Characteristic wind velocity, in m/s
$V_L$= Volume of the total spill, in $m^3$
x = Distance from the flame surface to the object in m

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