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A Dynamic Heat Transfer Model to Predict the Thermal Response of a Tank Exposed to a Pool Fire

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Large scale storage of bulk flammable fuels is necessary for distribution of fuel and also provides an opportunity to take advantage of and minimize market risk due to price fluctuations. Due to the inherent flammable properties of fuels, process safety is a key factor in the design of large scale fuel storages, in terms of instrumentation, detail design, emergency preparedness and site layout. In this paper we will describe a method to calculate important input data for the site layout, fire cooling water requirements and the time one can expect will elapse until a fire spreads from one tank to another. To achieve this, a model to calculate emitted radiation from a fire, and the dynamic response and effect on exposed targets is derived.
Much data and models, in terms of emitted radiation, is available on traditional fossil fuels, less is available for ethanol and other renewable biofuels. In this paper reviewed experimental data of both fossil fuels and recent data of biofuels is used to fit a radiation model that takes into account type of fuel and size of pool fire to calculate emitted radiation. When it comes to determine the tar gets received radiation, several view factor models are available in the literature. In this paper a modified view factor model is derived to enable calculation of the effect of both wind speed and site topography. Finally a first principle heat transfer model is derived to calculate the thermal response on affected nearby storage tanks in the vicinity of a pool fire. This model takes the following heat transfer mechanisms into account: received radiation, cooling by convection, cooling by radiation on the inside of the tank and cooling by radiation on the outside of the tank.
Finally, the model is compared to reviewed experimental data and similar models to evaluate the accuracy in terms of response times for fire spread and radiation levels.

1. Introduction

In order to communicate with neighbors, for land-use planning tasks and emergency preparedness the users of large scale oil depots need to predict the possibility of a fire spreading from one storage tank to another.
In current literature models to derive the heat flux from a pool fire is available, e.g. as described by Mudane (1984). However, fewer models are available to calculate the thermal response of exposed objects, such as exposed tanks. Results from heat flow simulations has been made available by Rebec et al (2014) and experimental data has been generated and compared to simulations by Mansouri (2012). In addition some simulation software such as PHAST and FRED exist. These data and simulations are however difficult to generalize from and there is a need for a more generic simplified model.
In this paper a spreadsheet model to determine the thermal response of a storage tank exposed to an adjacent pool fire is derived. Also a modified view factor model is derived in order to take different wind speeds and site topographies into account. Finally, recent data on the emitted radiation from ethanol fires is used in the model to show the significant difference from a hydrocarbon fire.

2. Model

Here follows the derivation of equations used in the model.

2.1 Pool fire model

The total emitted energy (Q_{rad}) from a pool fire is calculated as

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$$Q_{rad} = \chi Q_{tot} \tag{1}$$

Where χ is the portion of the total heat of combustion (Q_{tot}) emitted as radiation. χ is affected by pool size and obscuring smoke. Using the solid flame model, the radiated energy is then considered distributed across the whole flame surface to give a radiation intensity:

$$Q_{rad,flam} = \frac{Q_{rad}}{\pi DH} \tag{2}$$

Received heat flux is then calculated as

$$Q_{rad,fire,recieved} = \tau F Q_{rad,flam} \tag{3}$$

Where τ is the transmission through air and F is the dimensionless view factor.
The view factor is a dimensionless relation between the emitting and exposed surfaces, i.e the flame and the exposed tank. In order to account for tilted flames due to wind and different topographies, an adapted view factor model has been developed.
In Figure 1, L_1, H_b and H_a is calculated as:

$$L_1 = \cos(\theta)\,(L_0 + h_0 tan(\theta)) \tag{4}$$

$$H_b = \sqrt{L_0^2 + h_0^2 - L_1^2} \tag{5}$$

The view factor between the top left corner of the tank, closest to the flame, and the flame is then calculated using the superposition rule:

$$F = F(H_a + H_b, L_1, D) - F(H_b, L_1, D), \tag{6}$$

where F(H,L,D) is the view factor for a target at ground level located a distance L from a burning pool with a vertical flame of height H and diameter D. Models for the calculation of F for vertical flames and targets at ground level can be found in many text books, e.g. SFPE Handbook of Fire Protection Engineering (2002).
χ is the portion of the total heat of combustion (Q_{tot}) emitted as radiation, which depend on pool size and obscuring smoke. Sjöström et al (2013) have investigated the effect of pool diameter (D, m) and fuel on χ. It was found that at large pool fire sizes, χ is far greater for ethanol fires than hydrocarbon fires. The correlation they found is plotted in Figure 2. From this correlation, the following relations are derived for hydrocarbon and ethanol fires, respectively.

$$\chi_{Hydrocarbons} = 0.576D^{-0,679} \tag{7}$$

$$\chi_{Ethanol} = 0.593D^{-0,235} \tag{8}$$

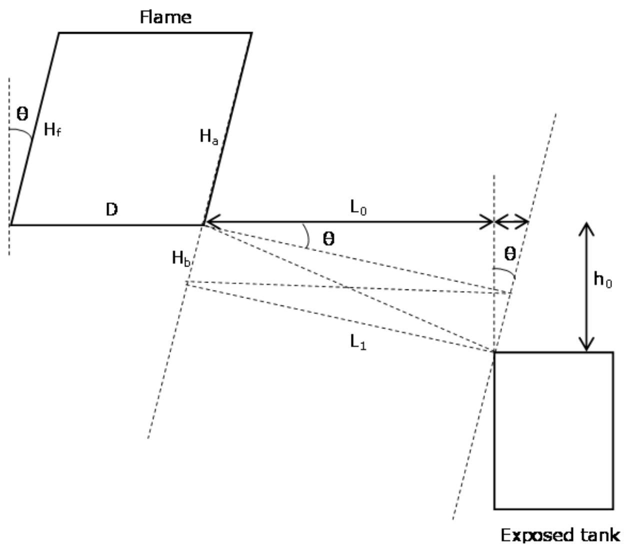

Figure 1: Effects of flame tilt and site topography on view factor.

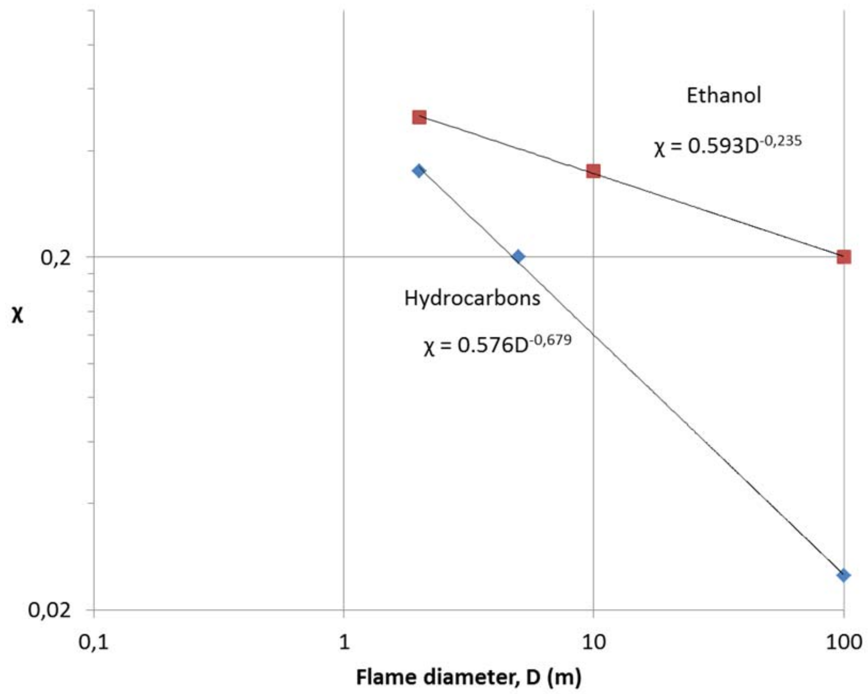

Figure 2: Effects of pool (flame) diameter on the portion of combustion energy released as radiation (χ) for hydrocarbons and ethanol, respectively.

2.2 Thermal Response Model

The thermal response model of the exposed tank summarizes the effect of received radiation from the fire ($Q_{rad,fire,\ recieved}$) from eq. 3, convection from the exposed hot side of the tank ($Q_{conv,wall,1}$), radiation inside the tank ($Q_{rad,wall,1\text{-}2}$), and convection from the tank side opposite to the exposed ($Q_{conv,wall,2}$). Heat conduction in the tank shell into the liquid is not considered significant, based on the simulations by Rebec (2014). Basically, the tank is modelled as two infinitive parallel plates, with vacuum inside and air at ambient temperature on the outside giving the following basic heat transfer models which can be found textbooks on thermodynamics, e.g. Ekroth et al (1991):

$$Q_{\text{conv,wall}} = \alpha(T_1 - T_0) \tag{9}$$

$$\alpha = \frac{\text{Nu}\times\text{L}}{\delta} \tag{10}$$

$$\text{Nu} = 0{,}13\ (Gr \times Pr)^{1/3} \tag{11}$$

$$Gr = \frac{g\beta\Delta T H^3}{v^2} \tag{12}$$

$$Q_{\text{rad,wall,1}-2} = \sigma F_{12}(T_1^4 - T_2^4) \tag{13}$$

Given the heat capacity (C_p), tank thickness (l) and density (ρ), each of the tank wall temperatures (T_x) will rise as a cause of the resulting heat transfer:

$$\frac{dT_x}{dt} = \frac{\Delta Q_x}{l\rho C_p} \tag{14}$$

This expression can be numerically solved in a spreadsheet using Eulers method:

$$T_x(t_0) = T_0 \tag{15}$$

$$T_x(t_{n+1}) = T_{1\ldots4}(t_n) + \Delta t\ \frac{\Delta Q_x(T_x(t_0))}{l_x \rho_x C_{p,x}} \tag{16}$$

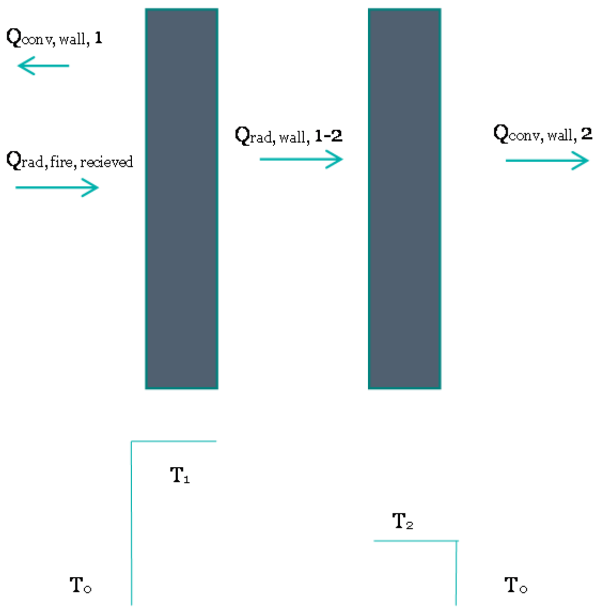

Figure 3: Heat flow mechanisms and temperature gradient through exposed tank.

3. Result

In Figur 4 and 5 the output of the spreadsheet model for the thermal response of a tank exposed to ethanol and gasoline fire are shown, respectively. The input and output data is summarised in Table 1.

Table 1: Input data, steel tank, 1 cm thickness

Model input									Model output		
Burning fuel	Burning rate (kg/m^{2}s)	Heat of combustion (kJ/kg)	Pool fire (D, m)	Wind speed (m/s)	Flame length (H_f, m)	Flame tilt (θ, °)	Horizontal distance to burning pool edge (L_0, m)	Vertical distance to pool base (h_0, m)	χ	Received radiation (kW/m^2)	Maximum tank temperature (°C)
Gasoline	0.055	44 000	22	5	35	48	20	-20	0.06	3.7	271
Ethanol	0.074	27 000	22	5	35	48	20	-20	0.27	11.2	553

In Table 2 the results of proposed model is compared to simulations by Rebet et al (2014).

Table 2: Input data, aluminum dome, thickness 1.27 mm

Input data				Rebec et al 2014		Current Model	
Burning fuel	Horizontal distance to burning pool edge (L_0, m)	Pool fire (D, m)	Wind speed (m/s)	Maximum tank temperature (°C)	Time to 200°C (s)	Maximum tank temperature (°C)	Time to maximum temperature (s)
Fuel oil	20	60	5	325	190	490	80 s
Fuel oil	20	60	3	100	-	130	-

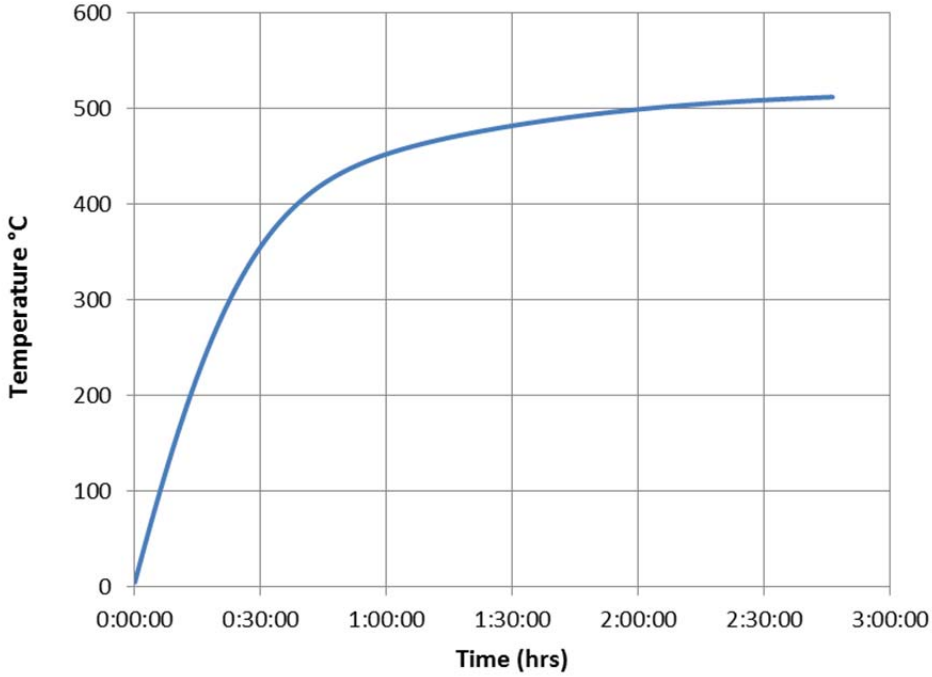

Figure 4: Tank wall temperature, exposed to the radiation from an ethanol fire for conditions given in Table 1.

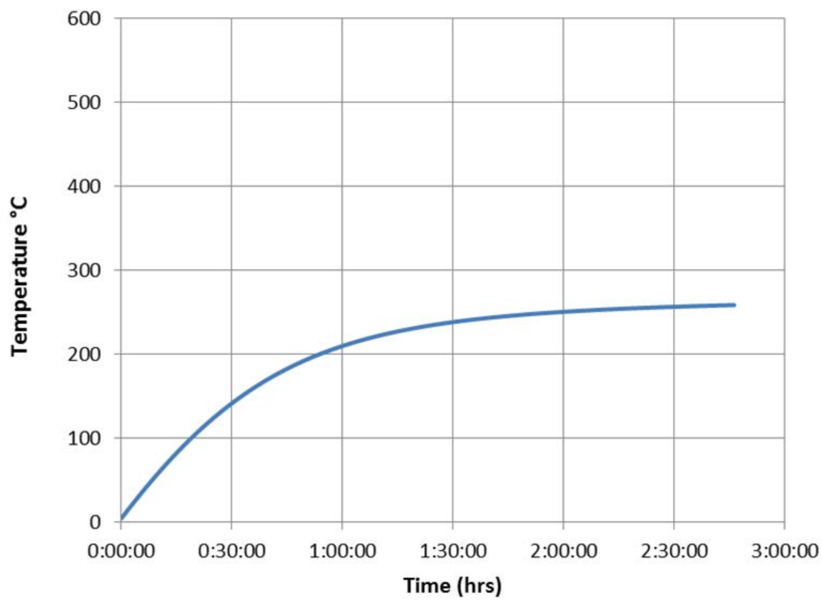

Figure 5: Tank wall temperature, exposed to the radiation from a gasoline pool fire for conditions given in Table 1.

4. Conclusions

The conclusion of this paper is that the proposed spreadsheet model gives useful data, and that they can be considered as conservative in relation to more sophisticated simulation models as shown in Table 2.
The results in Figure 4 and 5 show the great difference between the effects of a ethanol and gasoline fire. The difference is attributed to fact that for a large ethanol fire a greater portion of the released combustion energy contributes to heat radiation. This fact has serious implications on the recommended layout and installations on a fuel depot for ethanol-based fuels.
In this spreadsheet model, the exposed tank wall temperature is calculated. This temperature can be compared to the auto ignition of the fuel in the exposed tank, to assess the risk of fire spread. This criteria for fire spreading is however too conservative in comparison to real fires, Mansouri (2012). Future studies on simplified criteria for fire spreading are thus recommended. More large scale testing of ethanol fires and different topographies are also recommended to validate the model, and the view factor calculations.

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