An Experimental Investigation on Fire Extinguishing Powder Efficiency

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A series of large-scale tests were carried out to evaluate the effectiveness of using extinguishing powder (Purple K) to supress propane or petrol fire or to reduce emitted radiative heat flux. Three sets of different fire were carried out: a petrol leakage fire, a petrol pool fire and a liquid propane jet fire impinging a horizontal cylinder. In these tests, the powder was not able to extinguish the liquid hydrocarbons fire, but in some cases was able to extinguish the propane jet fire. In all cases, powder spray had excellent properties to reduce radiative heat flux.

1. Introduction

Gas and hydrocarbons fires pose a serious hazard to oil and gas installations with the potential for escalation to a major accident. Hence it is important to have a good understanding of fire hazards and best practices for fire control. There are many ways to control fire, among them using water, foam, carbon dioxide and chemical inhibiting agents. Chemical inhibiting agents may be discharged from an extinguisher, a hose reel nozzle, a fire truck monitor, or a fixed system of nozzles as a free flowing cloud. They are frequently used to supress hydrocarbons fires, but have also demonstrated excellent properties to reduce vapour cloud explosion hazards (Van Wingerden et al., 2013, 2019).
Purple K is a commercial solid extinguisher, it is an effective dry chemical in fighting class B (flammable liquid) and has about 4–5 times more effectiveness against class B fires than carbon dioxide. However, little experimental data can be found at large scale to study the effectiveness of purple K to suppress hydrocarbons or propane fires. This work was intended to provide knowledge on how purple K interacts with fire when sprayed by a firefighter using a commercial extinguisher.

1.1 Pool and jet fire hazards

Thermal radiation from a flame is a result of emission, absorption and scattering of radiation by gases and particles within the flame. The gases produced by combustion are mainly carbon dioxide and water. Depending on the fuel, combustion will also create more or less soot of unburnt species. Premixed flames or light hydrocarbons flames entail little soot because of complete combustion, but more soot is produced in fires involving higher hydrocarbons (eg heptane). Soot particles are often important contributors to the radiative heat transfer. Radiation emitted by soot depends on the temperature and concentration of the particles. (Mehta et al., 2010) investigated soot radiation in turbulent jet flames and concluded that incandescent soot could contribute with 70% of the emitted radiation by the flames. The fraction of heat radiated to the surroundings is defined by the fraction of heat that is emitted by radiation on the total heat of combustion of the fuel. For natural gas fire jet this value starts at 0.05 and reaches 0.13 for large flames (>30 meters); for liquid propane jet fire a value of 0.24 is recommended, for higher hydrocarbons a value of 0.45 should be taken (Koseki and Yumoto, 1988). According to these points, liquid propane and hydrocarbons fires are serious concern for fire safety because of the intense radiated heat. When hydrocarbons and liquid propane flames are thick, they behave as a black body with an emission spectrum mostly located in the infrared range (Figure 1). In addition, carbon dioxide in the flame emits a double peak wavelength (2.8 µm; 4.3 µm) and

water a single peak (2.9 µm) that add up to the infrared radiation. As a result, most flame spectrum is emitted in the range [0.4 – 6] µm. The intensity of radiative heat transferred to the surroundings depends on the properties of the flame but also on the absorption properties of the media between fire and the target. The simplest model for predicting the radiative heat flux emitted by a flame is based on the solid flame model and Stefan Boltzmann's law (Drysdale, 1990). This model takes into account the view factor and the transmittivity of intermediate media, and proposes to write the radiative heat flux received by a target from a fire as:

$$\Phi = F.\tau.\sigma.\varepsilon.T^4 \tag{1}$$

Where ϕ is the heat flux received by a target (per square meter, kW.m^{-2}), F is the view factor between flame and target (-), τ is the transmittivity (-), σ is Stefan-Boltzmann's constant, ε is the flame emissivity (-) and T is the flame temperature (K). This model is applicable for optically thick flames, emissivity can be assumed to be close to unity. Ambient humidity is known to absorb IR radiation and decrease τ factor.

1.2 Inhibition of combustion reactions by dry chemicals

The fire suppression potential of dry chemicals is only activated when they evaporate or decompose by the time that they reach the flame. The following 4 main steps are relevant to suppression by an aerosol of solid particles: 1/ aerosol heating; 2/aerosol evaporation and/or decomposition; 3/production of inhibitor radical specie and 4/inhibition of the combustion process. The efficiency of a powder is therefore mainly linked with the particle size (thermal process, steps 1&2) and the inhibition efficiency (chemical process, steps 3&4).

(Babushok and Tsang, 2000) and (Babushok et al., 2017) indicate that potassium compounds are very effective flame inhibitors. According to (Ewing et al., 1989), heptane pool fire was extinguished at lab scale with potassium bicarbonate ($KHCO_3$) concentrations in the range [64-225g.m^{-3}]. (Hoorelbeke, 2011) collected velocities of laminar propane flames and showed a clear decrease in flame velocity with $KHCO_3$ mixtures. They noted that for a bicarbonate concentration of 100 g.m^{-3}, the laminar velocity decreased by almost 10% and decreased by 50% when bicarbonate concentration was 500 g.m^{-3}. These data correspond to premixed gas mixtures tests, no data was collected with liquid flashing propane fire.

Purple K is mainly composed by potassium bicarbonate particles treated with flow promoting and moisture repellent additives, aiming at avoiding clogs if powder is humid. For high quality commercial grades, the average size is 20 µm. Chemical effect on fire suppression is most pronounced at low concentrations. When the concentration powder is increased, a chemical saturation effect occurs (Babushok and Tsang, 2000). Near extinction, contributions from heat capacity and dilution effect become much more important. Thus, it is not possible to linearly extrapolate the results from experiments conducted at low concentrations of suppressant loading to high concentrations.

1.3 Radiative heat absorption

When suppressant powder is sprayed to fire, emitted heat flux will interact with the aerosol by three phenomena: absorption, reflection and diffraction. The contribution of each phenomenon depends on the particles surface material properties and diameter. $KHCO_3$ presents several absorption peaks in the infrared spectrum (Figure 2) and will absorb heat since infrared is the main radiation spectrum of hydrocarbon flames.
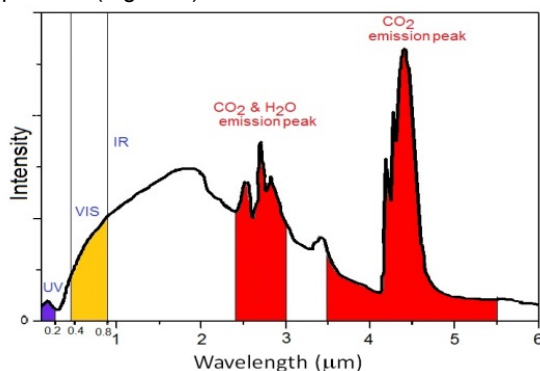

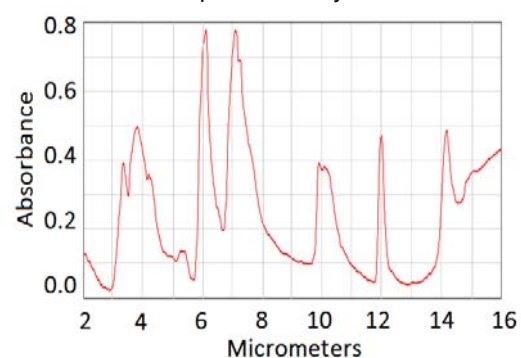*Figure 1: Typical hydrocarbons fire emission spectrum*

Figure 2: $KHCO_3$ absorbance spectrum

Moreover, like all aerosols, the cloud will also reduce heat flux by diffraction and reflection of radiation. Since the particle sizes are greater than the wavelength range of emitted radiation from flames, the extinction type will be Geometric and Mie scattering will occur. An extinction efficiency factor of two is expected. Both points let expecting that purple K will absorb much radiation and transmit little between fire and a target.

2. Experimental work and results

2.1 Description of experimental conditions

In order to study efficiency of Purple K powder in suppressing fire or reducing heat flux, a series of 3 different tests were carried out as GESIP facility, France (Figure 3). The first test involved a pump leak fuelled by class C petroleum (flowrate 50L.min^{-1}). The pump was placed in a retention basin (10x5m). The second test concerned a fire in a cylindrical pan (surface 5.4m^2) containing the same petroleum (100L). The petroleum in both tests was a mixture of paraffinic and cyclic hydrocarbons having carbon numbers predominantly in the C6-C7 range and boiling in the range of approximately between 60°C and 102°C (CAS 64742-73-0). The third test was a liquid propane jet fire impacting a horizontal cylindrical vessel. The propane outlet was located at 1 meter away from the 1.4m diameter cylinder. For all tests, two radiative heat flux sensors (0-100 kW.m^{-2}, CAPTEC) were placed at 3 and 6 meters from fire. A FLIR SC4000 infrared camera was used to characterize fire.
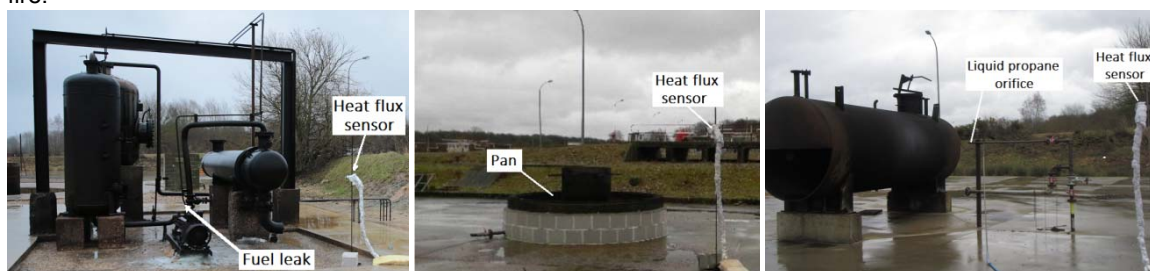

Figure 3: Experimental setups: pump leak (left); cylindrical pan (centre) and liquid propane jet fire (right)

The powder was propelled by a standard Desautel P50 fire extinguisher, filled with 50 kg purple K and using 90g of liquefied carbon dioxide as propellant. According to the manufacturer datasheet, the emptying time is 35 seconds which makes an average release of 1.4 kg.s^{-1}.The flow rate was probably significantly reduced at the end of the emptying. The powder jet can be divided in three zones: a first part [3-4m] with high velocity and a narrow cone angle of 15°, then an expansion zone [2-3 m] where turbulence mixes powder with air and a last zone where powder moves with ambient wind and settles to the ground (Figure 13). Powder was displayed by two operating modes: a direct jet to fire (Figure 4, left) and a dispersed jet resulting from large movements of the fire hose to make large powder clouds (Figure 4, right). An estimate of powder concentration reaching fire was done by mass balance (Eq. 2):

$$C = \frac{4Q}{S.\pi H^2}$$

(2)

Where C is the average mass concentration (g.m^{-3}), Q is the mass release flowrate of powder (g.s^{-1}), H is the height (m) and S is the speed (m.s^{-1}) of the powder cloud/jet reaching fire (Figure 4, centre). It can be expected that powder concentration depends on the operating mode and distance from fire. Estimates will be given in results parts.
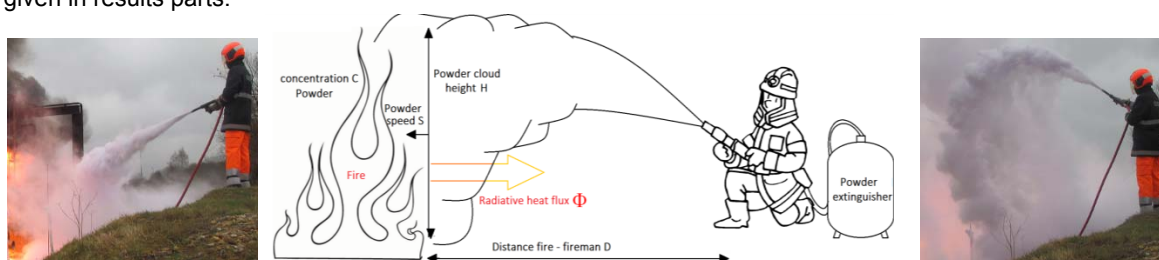

Figure 4: Powder spraying modes: direct (left) and dispersed (right)

2.2 Gasoline pump fire

The petrol fire was very intense with [3-4m] high flames. The emitted heat flux was distributed around an average flux of 77 kW.m^{-2} (Figure 5 and Figure 7). These data are consistent with the results of (Koseki, 2000). The firefighter never managed to put out the fire, but heat fluxes measured by sensors were sharply decreased (Figure 6). According to the operating mode, a dense (Figure 8), or dispersed (Figure 9) powder cloud was sprayed to fire. The best efficiency was obtained with the dense cloud when the firefighter was close to fire: only 2.8% of emitted heat flux reached the sensor. For other tests, between 13% and 50% of heat flux was transferred to the sensor.

Table 1: Remaining heat flux with powder

Configuration (related to Figure 6)	Firefighter location	Concentration estimate	Remaining heat flux
Mark 1: firefighter close to fire and direct jet to fire	6m	300-400 g.m^{-3}	2.9%[a] 2.8%[b]
Mark 2: firefighter close to fire and dispersed jet to fire	6m	50-100 g.m^{-3}	35%[a] / 31%[b]
Mark 3: firefighter far from fire and direct jet to fire	12m	80-150 g.m^{-3}	22%[a] / 13%[b]
Mark 4: firefighter far from fire and dispersed jet to fire	12m	30-80 g.m^{-3}	50%[a] / 24%[b]

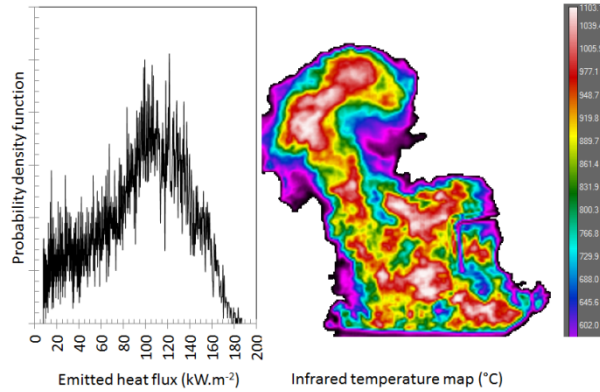[a] data measured at 3m; [b] data measured at 6m

Figure 5: Emitted radiant heat flux distribution and infrared temperature map
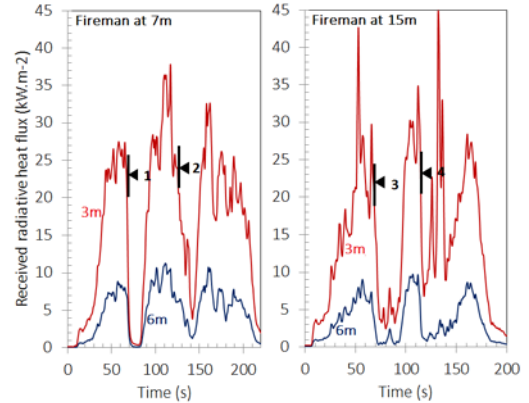

Figure 6: Incident heat flux on sensors

Figure 7: Petrol leak fire

Figure 8: Dense cloud

Figure 9: Dispersed cloud

2.3 Gasoline pool fire

The petrol fire was less intense with [2-3m] high flames. The emitted heat flux was distributed around an average flux of 84 kW.m^{-2} (Figure 10 and Figure 12).
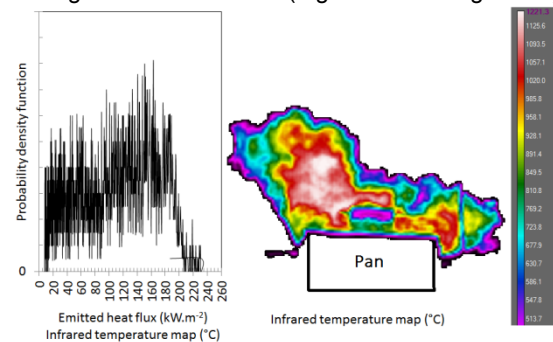

Figure 10: Emitted radiant heat flux distribution and infrared temperature map
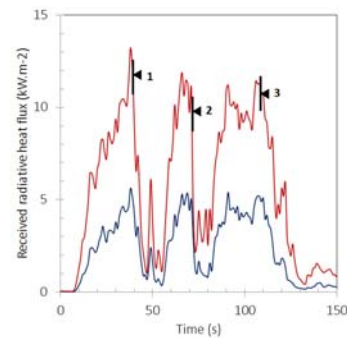

Figure 11: Incident heat flux from pool fire

The firefighter sprayed powder on a dispersed mode and never managed to put out the fire (Figure 14). The best efficiency was obtained when the firefighter was close to the pan: only 31% of emitted heat flux reached the sensor. For other operating modes, between 50% and 73% of heat flux was transferred to the sensor.

Table 2: Heat transmittivity (petrol pool fire)

Configuration (related to Figure 11)	Firefighter location	Concentration estimate	Remaining heat flux
Mark 1: firefighter close to fire and dispersed jet to fire	7m	100-150 g.m^{-3}	31%[a] 33%[b]
Mark 2: firefighter close to fire and dispersed jet to fire	7m	100-150 g.m^{-3}	73%[a] / 51%[b]
Mark 3: firefighter far from fire and dispersed jet to fire	12m	80-120 g.m^{-3}	55%[a] / 50%[b]

[a] data measured at 3m; [b] data measured at 6m

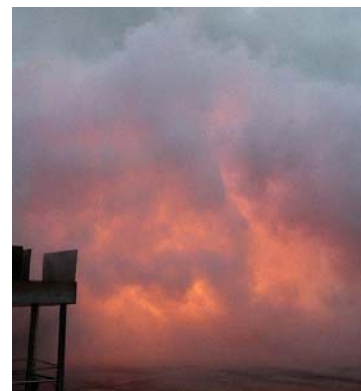Figure 12: Pool fire

Figure 13: Powder spraying

Figure 14: Masked fire

2.4 Flashing propane jet fire

The last test considered a propane jet fire impinging a cylindrical vessel. This scenario is likely to happen in LPG installations (Heymes et al., 2014). The flashing liquid jet interacts in a complex way with the cylindrical obstacle. The central area of the point of impact is a stagnation zone from which the jet is diverted radially. This point is not conducive to combustion (cold mixture, little contact with air). In the lateral areas the fuel ignites and gradually heats up. As the more radiative part of the flame is usually closer to the tail of the jet fire, this can result in the highest overall heat fluxes being experienced on the rear surface of the cylindrical obstacle which may seem counter-intuitive (Lowesmith et al., 2004) (Figure 15).
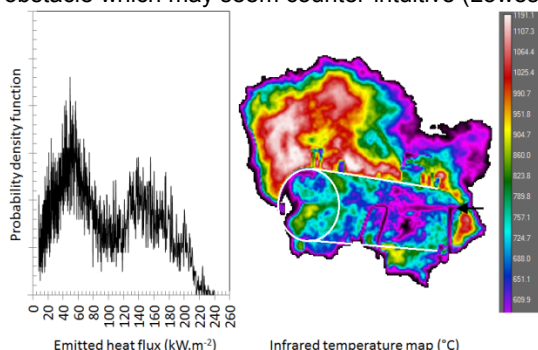

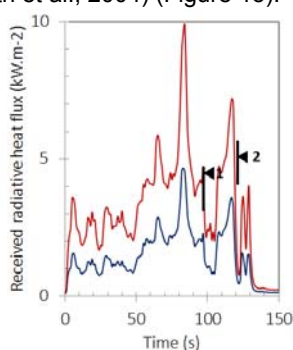Figure 15: Infrared picture of gasoline pump fire

Figure 16: Incident heat from propane jet fire

Figure 17: frozen stain

The cold zone due to flashing jet impact can be seen on IR picture and resulted in a frozen stain containing purple K (Figure 17). 9 tests were performed. The most intense radiation was emitted at the tail of the fire jet, the average heat flux was 76 kW.m^{-2} (Figure 15). Two different strategies were tested: covering the entire fire by a distant powder spraying, or trying to extinguish fire by injecting powder directly at the jet location.

- For dispersed powder jet (Figure 18-A, concentration [50-100g.m^{-3}]) fire was not extinguished, but heat flux was reduced and a remaining heat flux of 60% was observed. When the powder was directly and densely sprayed on fire (Figure 18-B, concentration [100-150g.m^{-3}]), heat flux dropped to 39% and eventually fire stopped.
- When injecting powder directly into the flashing jet, most tests ended in extinction after several seconds. The powder jet created an extremely concentrated area in the central part of the front face, which succeeded in stopping the fire (Figure 18-C). This was however dependent of the fire intensity. For one very intense fire (Figure 18-D), the firefighter never succeeded in extinguishing fire.

Figure 18: Infrared picture of gasoline pump fire

3. Conclusions

Tests showed that purple K powder spraying is an excellent method to decrease radiative heat transfer. This efficiency is linked with combustion rate decrease but also with screen effect of the powder: the opaque cloud absorbs a significant part of the radiation. The way powder is sprayed is critical; in some cases up to 97% of the heat flux has been stopped. In this work it was not possible to estimate the contribution weight of inhibition and screen effect. However, the best efficiency was observed when powder was directly injected into fire.

The extinguishment efficiency was not very good. The authors think that the success was quite low because most of the powder did not interact with fire and simply passed by the fire. A better efficiency could be expected if powder would be directly sprayed into fire.

Acknowledgments

References

Babushok, V., Linteris, G.L., Hoorelbeke, P., Roosendans, D., Van Wingerden, K., 2017. Flame Inhibition by Potassium-Containing Compounds. Combust. Sci. Technol. 189, 2039–2055.

Babushok, V., Tsang, W., 2000. Inhibitor rankings for alkane combustion. Combust. Flame 123, 488–506.

Drysdale, D.D., 1990. An introduction to fire dynamics. John Wiley and Sons, New York.

Ewing, C.T., Faith, F.R., Hughes, J., Carhart, H.W., 1989. Flame extinguishment properties of dry chemicals : extinction concentrations for small diffusion pan fires. Fire Tech 134–149.

Heymes, F., Aprin, L., Slangen, P., Lapébie, E., Osmont, A., Dusserre, G., 2014. On the effects of a triple aggression (fragment, blast, fireball) on an LPG storage. Chem. Eng. Trans. 36.

Hoorelbeke, L., 2011. Numerical and Experimental Study of Vapour Cloud Explosions – Mitigation by Inhibitors. University of Brussel.

Koseki, H., Yumoto, T., 1988. Air entrainment and thermal radiation from heptane pool fires. Fire Technol. 24, 33–47.

Lowesmith, B.J., Hankinson, G., Acton, M.R., Chamberlain, G., 2004. An overview of the nature of hydrocarbons jet fire hazards in the oil and gas industry and a simplified approach to assessing the hazards. Process Saf. Environ. Prot. 85, 207–220.

Mehta, R.S., Modest, M.F., Haworth, D.C., 2010. Radiation characteristics and turbulence–radiation interactions in sooting turbulent jet flames. Combust. Theory Model. 14, 105–124.

Van Wingerden, K., Holme, M., Olsen, K., Roosendans, D., 2019. Explosion Mitigation using Aqueous Solutions of Water and Flame Inhibitors. Chem. Eng. Trans. 77, 967–972.

Van Wingerden, K., Middha, P., Hoorelbeke, P., 2013. Modelling of Mitigation of Vapour Cloud Explosions Using Flame Inhibitors. Chem. Eng. Trans. 31, 721–726.