

Impact of Water Content in Hydrocarbons using Consequence Modelling

Emoshoriamhe Erua, Process Safety Engineer

The hazards that high water content hydrocarbon mixtures pose may be underestimated in terms of its flammability potential and the effects of the fire. Water content is naturally found in most oil and gas fields and its percentage is increased in most ageing fields through water injection recovery methods used to boost production. Different stages exist in getting the oil/ gas separated from the water, the additional equipment required for this process increases the number of potential leak sources.

The impact of the water in the hydrocarbon mixtures is assessed in terms of pool fire and jet fire effects using consequence modelling. The main aspects considered by Safety Engineers in terms of protection of personnel and assets are the emissive power of potential fires and the hazard range to which they extend. The investigation is to assess the jet fires with water contents above 55%, an inventory considered by an earlier study to be incapable of sustaining a jet flame.

Four different hydrocarbon mixtures representing samples that can be found in oil and gas facilities were used in the investigation and the water content increased in them from 0% to 95%. The PHAST software tool was used to simulate the effects using these mixtures, alongside empirical calculation methods.

The results from the two methods showed similar trends in the behaviour/ effects of the fires resulting from these mixtures. Although a value was not specified at which the water content in hydrocarbon mixtures can be disregarded, the consequence modelling showed that fluids with 80-90% water content still have considerable impact in terms of emissive power and hazard ranges from jet fires and pool fires. This investigation also showed some areas in which further investigations will be needed, especially with the behaviour of water-hydrocarbon mixtures.

Keywords: Water Content, Hydrocarbons, Consequence Modelling, Hazard Range, Emissive Power, PHAST, Jet fire, Pool Fire

Scope of study

Intention of Study and Relevance to Industry

As oil fields age and depressurise, additional processes are required to increase pressure and hence increase hydrocarbon production. One method that is used in the oil industry is water injection (flooding). This involves injecting water to support the pressure of the reservoir, to displace and drive oil towards the well. Due to these operations, the water content in most crude oil being processed is high (some getting up to approximately 80%). Also many new wells being explored have naturally high water content in the crude and this will also need to be managed. This water content must be controlled to ensure quality control, enhance process optimisation and to manage corrosion issues.

The design of new installations and modifications to existing facilities require accurate modelling of the oil/water mixtures as part of fire and explosion studies. This study is intended to explore the flammability potential of the oil produced from wells with high water content (as it comes from the manifolds before the processing systems and also potential leaks from the separation systems). At present, there is limited experimental data in this area on the flammability of crude oil/ hydrocarbons with high water contents. The impact of this study will influence Fire and Explosion Risk Analysis (FERA), Escape and Evacuation Rescue Analysis (EERA) studies and Passive Fire Protection (PFP) requirements where there is the potential for crude oil fires with high water content. This will provide some investigation into the flammability potential of typical hydrocarbon compositions with high water content to ascertain the level at which it can be considered non-flammable and also investigate the impact of water content on:

- Burning Rates,
- Hazard Range (Flame Height and Flame Length)
- Flame Emissive Power

Review of existing knowledge

A number of studies, papers and experiments are available in the research area regarding the flammability of hydrocarbons and consequence modelling. Different types of fires from hydrocarbons have been studied to understand the effects that they have under certain conditions. This section will be describing the research done so far to estimate and evaluate the effects of pool fires and jet fires from the release of high water content mixtures.

According to the Oil and Gas UK Guidance 2014,

"The effect of increased water cut of the hydrocarbon reservoir on fire hazards should be considered carefully to avoid over-conservation in the fire risk analysis. For example, some researchers consider that water cuts above 60% make the oil very difficult to ignite."

Flammability of Hydrocarbon/ Water Mixtures

Hydrocarbons are known to be flammable depending on the individual components and the flammability characteristics like the flash point, LFL and UFL are usually estimated using the mixing rules such as Le Chatelier's principle. The impact of water on the flammability of these compounds have been investigated in studies over the years, one of such study (Chatterjee, et al., 2007) showed that the water content in a hydraulic fluid provides fire resistance. Based on experiments conducted and correlations developed to determine the flammability characteristics of pure hydrocarbons and mixtures, the same principle could be applied to hydrocarbon/ crude oil and water mixtures. Although most components in crude oil are of distinct properties some of which are not readily found from literature data, a basic estimation of the flammability using the Le Chatelier's principle can be used. When a fuel contains water which is an inert material, based on the principle of mixing, one would expect that the flammability characteristics of the overall mixture should be reduced.

Jet fires

In the case of jet fires resulting from high water content hydrocarbons, there has been a paper based on the experiment carried out on jet fire scenarios from the release of crude oil with different water content levels conducted by a Joint Industry Project involving Advantica and Shell Global Solutions. This paper by (Hankinson, et al., 2007) states that a flame is extinguished if the water content by mass gets to about 55% and this is what is used in most risk assessments and assumption sheets in fire and explosion consequence analyses. The test was mainly to address the potential effects of crude oil fires with water content with regards over estimation of the effects of the release and unnecessary expense.

A jet fire will occur from either a flammable gas/ liquid/ liquid-gas mixture (two-phase) if the pipe or vessel operates at a pressure ≥2bar. At these pressures, a choked flow occurs and the flow of the material reaches sonic velocity (Bradley, 2012). All fuels have the potential to generate a jet fire, however not all releases of fuel would be able to stabilize a jet flame and this statement is made in reference to experiments carried out on flame stability in underexpanded natural gas jets by Birch et al, 1988 showing that certain release pressures will not sustain a jet flame.

The software PHAST used in consequence modelling, predicts that releases of crude oil mixtures with water contents up to 70% by mass result in jet fires. However, a risk analysis judgement is made depending on the emissive power of the jet flame and the velocity of the release with respect to effect on personnel, assets and equipment. The HSE gives an estimate of the heat flux tolerability from fires as shown in Table 1

Table 1: Effects of Thermal Radiation (HSE)

Thermal Radiation (kW/m2)	Effect
1.2	Received from the sun at noon in summer
2	Minimum to cause pain after 1 minute
Less than 6	Will cause pain in 15-20 seconds and injury after 30 seconds exposure
Greater than 6	Pain within approximately 10 seconds rapid escape only is possible
12.5	Significant chance of fatality for medium duration exposure. * Thin steel with insulation on the side away from the fire may reach thermal stress level high enough to cause structural failure.
25	* Likely fatality for extended exposure and significant chance of fatality for instantaneous exposure. * Spontaneous ignition of wood after long exposure. * Unprotected steel will reach thermal stress temperatures that can cause failure.
35	* Cellulosic material will pilot ignite within one minute's exposure. * Significant chance of fatality for people exposed instantaneously.

Some regulations and standards specify acceptability for the thermal radiation:

- EN-1473 specifies a criterion of 1.5kW/m^2 (Melhem, et al., 2007)
- Us Department of Housing and Urban Development (1.4kW/m^2) (Melhem, et al., 2007)
- The Society of fire protection engineers recommends 2.5kW/m^2 as public tolerance limit (Melhem et al, 2007) (Melhem, et al., 2007)

Pool Fires

The impact of water content of mixture resulting in pool fires has not been extensively researched so far; however there have been studies on the impact of water on burning of oil-water emulsions where there is water mixed in oil as in the case of in-situ burning. Pool fires burn when a flammable material spills or rains-out on a surface (land or water) so the studies done could be used as a guide on what could be expected for crude-oil water mixture releases on onshore and offshore installations.

An experiment of emulsion spill on water by (Kulkarni & Walavalkar , 2000) showed that a mixture of crude oil and water on water has the potential to burn with some higher heat flux. The experiment produced results for increase in the required heat flux as the water content increased. Further investigations would be required with respect to risk of ignition of crude-oil water mixture release on land in onshore/ offshore installations. The results from the tests also showed that it was non-realistic to sustain stability of the emulsion on water (in this case, the stability is characterized by the ability of the emulsion to hold without breaking into the oil and water phase) when spilled.

The consequence modelling

This paper focuses on jet and pool fire scenarios resulting from hydrocarbon releases containing water. Such scenarios can occur from a location on a crude oil facility where there is still high water content in the sample as it is extracted before the water is separated, processed and then transported.

The flammability of a crude oil sample containing water depends on the concentration of water in the mixture. Reasonably, a mixture having high water content is expected to not be flammable, but there is no clear cut value or range to support this claim so far. This work would provide an attempt on evaluating the flammability of different hydrocarbon samples with varying water contents based on the knowledge of hydrocarbon components and their flammability properties by carrying out consequence modelling of jet fires and pool fires. Jet fires and pool fires are the predominant fire types for most upstream producing/ processing facilities and so these are the two that are modelled for this investigation.

Consequence modelling will be used to determine the effects of the fires that could occur from the release of a mixture of crude oil with different mass compositions of water. Three different hole sizes (25mm, 50mm and 100mm) were used in the original study to simulate a scenario that can occur on an offshore or onshore installation, however for this paper the results of the pressurised leak from a 50mm hole size is shown.

The releases will also be modelled assuming land surfaces and assuming a prevalent wind speed of 5m/s. Releases on water also occur on most facilities and these are mostly considered when modelling pool fires. However, the modelling of pool fire on water is still estimated using the correlations for a pool fire on land. For hydrocarbon fires on water, the Dutch yellow book explains that there are differences in the burning flux for the pools on water and on land. However, for crude oil and gasoline, the difference is not so distinct (Bosch & Weterings , 2005) for this reason; the pool fires on water were not considered separately for this.

Within this study, calculations performed using equations from literature will be compared with the results given in PHAST. The samples will vary in composition, phase (gas and liquid) and water content.

Four sample models are used in this study to investigate the impact of water content when released under a specific temperature and pressure which was chosen based on a typical heat and material balance data for a production platform. The samples were picked to model and investigate impact of water with varying compositions in different samples; Samples 1, 2 and 3 are mixtures representative of possible hydrocarbon releases that occur in the industry while the Sample 4 was picked from the composition of a crude oil sample of an oil platform in the UK.

The first two mixtures were used to investigate the impact of water content with respect to both light and heavy ends separately, also sample one which is made of natural gas composition can be found on a typical production platform.

Also these two mixtures are typical compositions that are well modelled by PHAST as they are of similar hydrocarbons; the software is known sometimes to give ‘unrealistic’ evaluation of the properties of a mixture with distinct compositions.

SAMPLE 1:

C1: Methane (CH_4), C2: Ethane (C_2H_6), C3: Propane (C_3H_8), C4: Butane (C_4H_{10}) and Water

This sample is a mix of the light end hydrocarbons with water and likened to a natural gas well composition. The composition used is based on a Natural Gas website (Natural Gas.org, 2013) which shows that a typical composition of natural gas consists of 70% Methane.

SAMPLE 2:

This sample is a mix of a typical heavy end of a crude oil sample and it consists of:

C7: Heptane (C_7H_{16}), C8: Octane (C_8H_{18}), C10: Decane ($C_{10}H_{22}$), C12: Dodecane ($C_{12}H_{26}$) and Water

SAMPLE 3:

This sample is a simple mix of light and heavy end hydrocarbons with water, its composition was based on the FABIG Technical note (FABIG, 2013) and consists of:

C3: Propane (C_3H_8), C4: Butane (C_4H_{10}), C5: Pentane (C_5H_{12}), C6: Hexane (C_6H_{14}), C7: Heptane (C_7H_{16}), C10: Decane ($C_{10}H_{22}$) and Water

SAMPLE 4:

This sample is taken from the heat and material balance of a crude oil sample of an oil platform in the UK and consists of:

H2: Hydrogen, H2S: Hydrogen Sulphide, N2: Nitrogen, CO2: Carbon dioxide, C1: Methane (CH_4), C2: Ethane (C_2H_6), C3: Propane (C_3H_8), C4: Butane (C_4H_{10}), C5: Pentane (C_5H_{12}), C6: Hexane (C_6H_{14}), C7: Heptane (C_7H_{16}), C8: Octane (C_8H_{18}), C9: Nonane (C_9H_{20}), C10: Decane ($C_{10}H_{22}$), C12: Dodecane ($C_{12}H_{26}$) and Water.

The composition as well as the water contents added to the sample are based on mass fractions. In deciding on the pattern of variation of the water content, a test sample was first used in PHAST at 0, 20, 40, 60 and 80% by mass. It was observed that at the 80% water cut level the mixture was still flammable based on its simulation. It then became necessary to add lesser amounts of water by mass (90%, 91%, 92 %....) after the 80% water content to observe the level at which the mixture would be non-flammable. Therefore for each sample, 11 cases of water content levels (**0, 20, 40, 60, 80%, 90%, 91%, 92%, 93%, 94% and 95%)** are considered.

Methodologies used

The model was run assuming a wind speed of 5m/s, ambient temperature of 25^0C in D-Neutral Pasquill Stability (little sun and high wind/ overcast night). The operating conditions of the mixture released are: Pressure of 20 bar (g), Temperature of 105^0C and mass inventory of 1000kg.

The version 7.1 of the PHAST software which has been validated over time was used to generate the results for the effects of the jet fires and pool fires for the varying mixtures. The Soave-Redlich-Kwong (SRK) thermodynamic template was used, this Equation of State model is suitable for accurately modelling liquid and vapour-phase and it uses the simple mixing rules for its other properties.

The empirical calculations were done based on TNO (The Netherlands Organisation) methodologies of calculations, CCPS (Centre for Chemical Process Safety) Guidelines for Fire Protection and the SFPE (Society of Fire Protection Engineers) Handbook of Fire Protection. For jet fires and pool fires, calculations were carried out to obtain values of surface emissive power of the flames, flame length and burn rate using the properties of the varying mixtures. The properties of the components of these mixtures were obtained and evaluated from literature/ experimental data available and then for the overall mixtures.

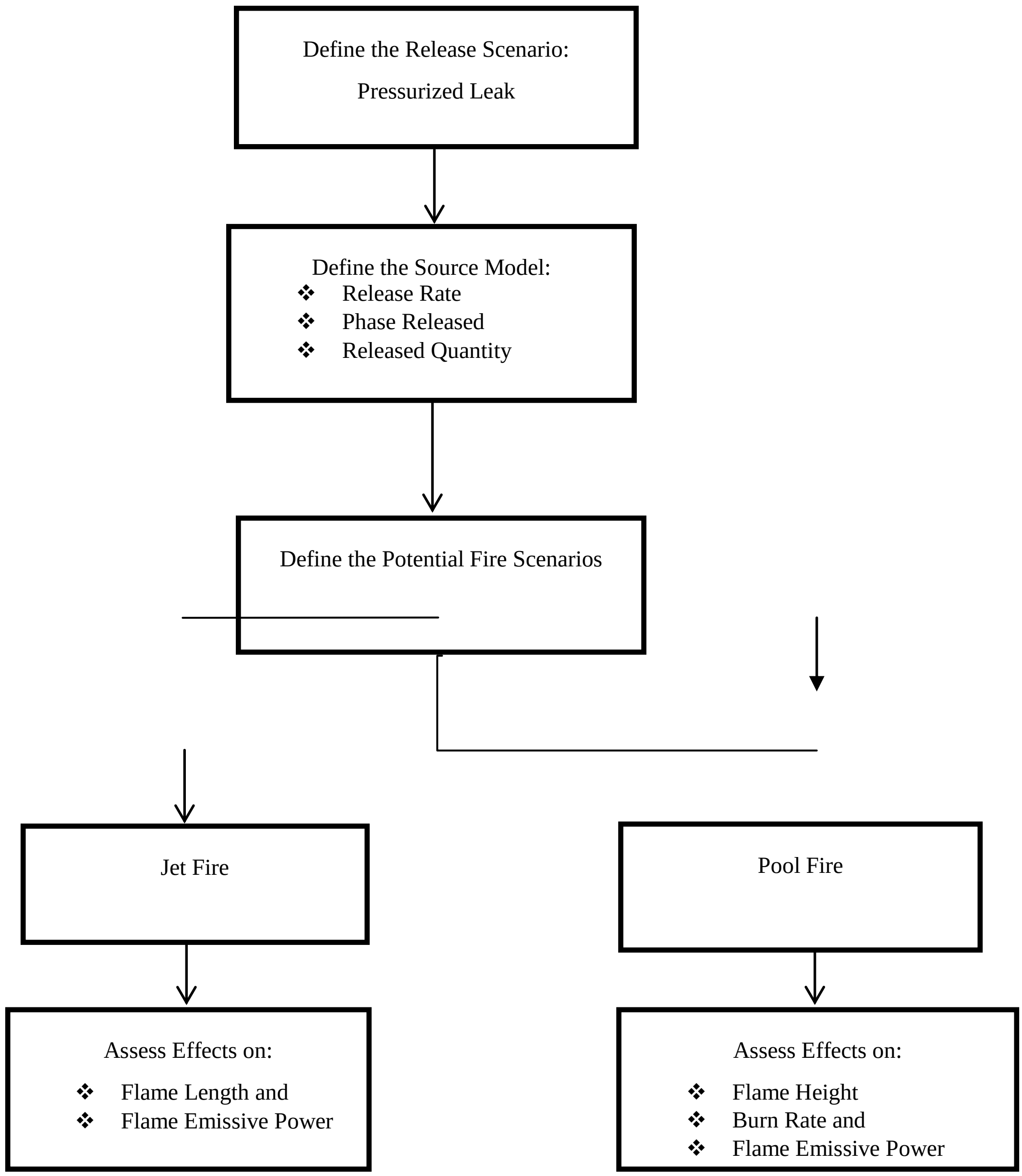

Figure 1: Process of Consequence Modelling used in this Study

Results of sample modelling

In the original study, the results from the PHAST models and empirical calculations showed similar trends in the impact of water content. For this paper, the results shown here were from the PHAST model. The values were plotted in excel and some graphs are shown here and for the jet and pool fire effects, the results are in a table (The columns without values show that PHAST did not generate results for the fire effects with the composition of the sample)

From PHAST the results of the Lower and Upper Flammability Limits of the samples were plotted against the varying water contents and the impact of this is shown in the graphs below.

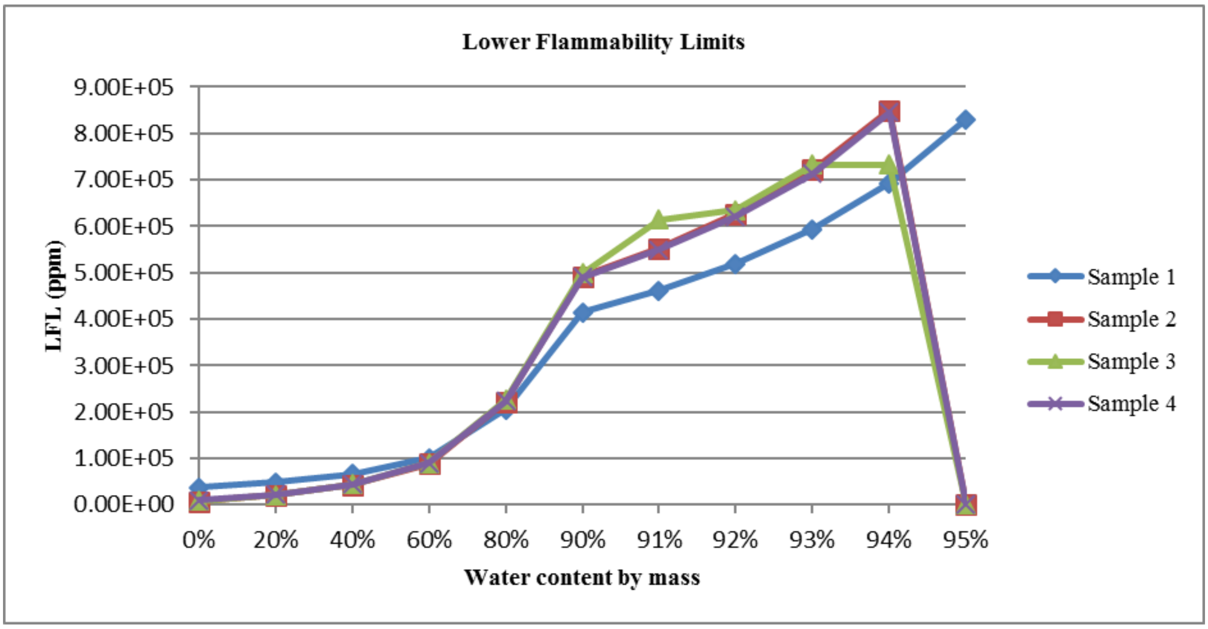

Figure 2: Lower Flammability Limits vs. the Water content in the Samples

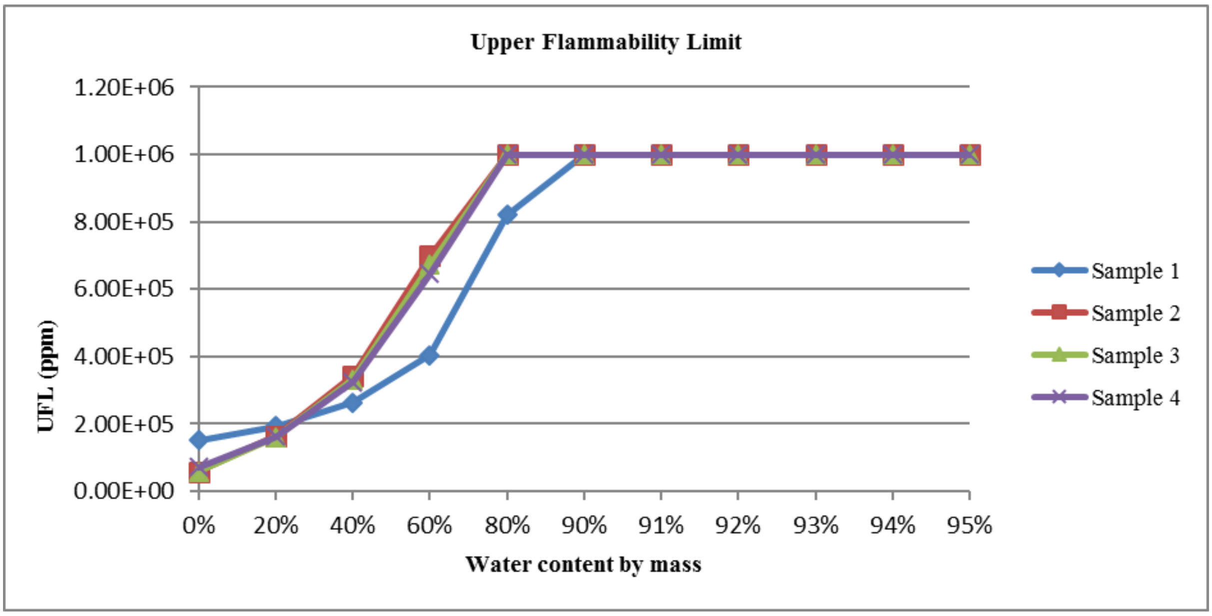

Figure 3: Upper Flammability Limits vs. the Water content in the Samples

The LFL which is the minimum concentration below which the vaporised mass in air will not burn or produce a flame when ignited is observed to increase with increasing water content, this depicts a lesser likelihood of ignition of the mixture as a higher concentration (ppm) is required to have the mixture to be combustible upon ignition.

The UFL on the other hand which is the maximum concentration, above which the vaporised mass in air will not burn or produce a flame when ignited tends to also increase and then stabilizes at a maximum (100%) as the water content in the mixture increased. This also shows a lesser likelihood of ignition of the material when released.

Impact in Jet Fires

Having run the first set of models in PHAST, the results showed that the water had major impact in more than just the flammability of the jet fire. It also affected the rainout, the release rate and significantly the jet flame length for some of the samples. For this reason, it became imperative to run standalone models in PHAST and investigate the impact of the water on the jet independent of the changes in release rate. The results for the jet flame length were then modelled using constant jet release rate, jet velocity and post-expansion jet temperature. The jet flame emissive power and the flame length against the varying water contents are shown in the Table 2 and Table 3.

Table 2: Jet Flame Emissive Power vs. the Water content in the Samples

Jet Fire Emissive Power (kW/m^2)											
	0%	20%	40%	60%	80%	90%	91%	92%	93%	94%	95%
Sample 1	215.16	171.51	53.54	36.26	15.38	6.16	5.31	4.44	2.56	2.03	1.55
Sample 2	400	175.83	68.11	28.88	9.93	4.3	3.82	3.36	2.9	2.46	
Sample 3	400	192.83	75.42	30.34	9.77	4.31	3.32	3.21	2.77	2.34	
Sample 4	286.84	267.36	88.8	39.06	12.4	5.05	4.43	3.84	3.29		

Emissive power is observed to be greatly reduced as the water content in the mixture is increased.

Table 3: Jet Flame Length vs. the Water content in the Samples

Jet Flame Length (m)											
	0%	20%	40%	60%	80%	90%	91%	92%	93%	94%	95%
Sample 1	28.24	28.33	56.86	86.27	106.27	122.49	125.22	128.99	57.54	52.2	46.69
Sample 2	53.03	73.92	78.59	83.19	86.68	88.24	88.39	88.54	88.69	88.84	
Sample 3	48.73	68.67	86.51	93.95	90.62	89.89	89.82	99.81	89.78	89.76	
Sample 4	91.18	59.7	82.26	97.08	116.92	116.35	113.29	110.31	107.4		

Here the jet flame length is observed to increase with increasing water content, the increasing water content has effect on the resulting density of the mixture which the flame length is dependent on.

Impact in Pool Fire

The Impact of the varying water contents on the pool fire emissive power, burn rates and the flame height are shown here. The early pool fire depicts the steady state where the rate of release into the pool is equal to the burn rate, while the late pool fire assumes a maximum pool diameter. Both scenarios were shown in the PHAST results as modelled using the appropriate correlations.

Table 4: Flame Emissive Power vs. the Water content in the Samples (Early Pool Fire)

Early Pool Fire Emissive Power (kW/m^2)											
	0%	20%	40%	60%	80%	90%	91%	92%	93%	94%	95%
Sample 1						20.24	18.22	16.2	14.18	12.16	10.15
Sample 2	29.84	20.61	20	56.01	28.06	14.01	12.61	11.21	9.81	8.42	
Sample 3	111.71	36.83	20.02	56.29	28.25	14.09	11.62	11.27	9.86	8.46	
Sample 4		42.58	31.89	14.96	6.9	2.22	1.86	1.52	1.21		

Table 5: Flame Emissive Power vs. the Water content in the Samples (Late Pool Fire)

Late Pool Fire Emissive Power (kW/m^2)											
	0%	20%	40%	60%	80%	90%	91%	92%	93%	94%	95%
Sample 1						20.24	18.22	16.2	14.18	12.16	10.15
Sample 2	21.3	20.13	20	56.01	28.06	14.01	12.61	11.21	9.81	8.42	
Sample 3	94.61	31	20.02	56.29	28.25	14.09	11.62	11.27	9.86	8.46	
Sample 4		42.58	31.89	14.96	6.9	2.22	1.86	1.52	1.21		

Table 6: Burn Rate vs the Water Content in the Samples (Early Pool Fire)

Early Pool Fire Burn Rate (kg/s)											
	0%	20%	40%	60%	80%	90%	91%	92%	93%	94%	95%
Sample 1						22.01	26	31.13	58.17	59.06	59.86
Sample 2	22.98	31.74	35.12	18.01	7.18	3.22	2.87	2.53	2.19	1.86	0
Sample 3	0.32	3.51	21.76	15.16	6.6	3.02	2.45	2.37	2.06	1.75	
Sample 4		0.82	2.01	0.23	3.46	2.83	2.65	2.44	1.21		

Table 7: Burn Rate vs the Water Content in the Samples (Late Pool Fire)

Late Pool Fire Burn Rate (kg/s)											
	0%	20%	40%	60%	80%	90%	91%	92%	93%	94%	95%
Sample 1						387.78	450.34	526.25	774.28	682.18	676.53
Sample 2	75.17	53.79	35.12	18.01	7.18	3.22	2.87	2.53	2.19	1.86	
Sample 3	0.98	5.47	21.76	15.16	6.6	3.02	2.45	2.37	2.06	1.75	
Sample 4		0.82	2.01	0.23	3.46	2.83	2.65	2.44	2.21		

Table 8: Flame Height vs the Water Content in the Samples (Early Pool Fire)

Early Pool Fire Flame Length (m)											
	0%	20%	40%	60%	80%	90%	91%	92%	93%	94%	95%
Sample 1						35.86	37.99	40.45	50.26	50.53	50.77
Sample 2	30.23	28.71	25.17	16.73	9.6	5.91	5.51	5.1	4.67	4.23	
Sample 3	7.15	13.31	21.1	15.57	9.2	5.7	5.02	4.92	4.51	4.08	
Sample 4		5.68	7.38	3.21	7.22	5.72	5.47	5.16	4.83		

Table 9: Flame Height vs the Water Content in the Samples (Late Pool Fire)

Late Pool Fire Flame Length (m)											
	0%	20%	40%	60%	80%	90%	91%	92%	93%	94%	95%
Sample 1						97.18	102.36	108.06	123.57	118.25	117.91
Sample 2	45.63	34.48	25.17	16.73	9.6	5.91	5.51	5.1	4.67	4.23	
Sample 3	10.55	15.54	21.1	15.57	9.2	5.7	5.02	4.92	4.51	4.08	
Sample 4		5.68	7.38	3.21	7.22	5.72	5.47	5.16	4.83		

Conclusions from results

This section contains a summary of the findings from this study and also highlights some areas of research identified while carrying out this study that would need more investigations.

Summary

The empirical calculations were used not to validate the results from PHAST but to check that basic calculation methods will also give similar results of the effects of the fires with the water content mixtures. The software also makes use of empirical calculations, but there are other aspects such as the thermodynamics of the mixture, the release conditions and specific details of mass, volume, etc. which are not taken into consideration when using the basic calculations.

The results from both models of PHAST and empirical calculation methods (manual) showed similar trend in the behaviour of the samples for the jet and pool fire results. Although the calculation methods used did not necessarily define the levels at which a jet/pool fire could or could not occur, the effects calculated were valid for this study. It is established that the water content in the hydrocarbon mixtures will reduce the emissive power of the flames when there is a fire.

In consequence modelling, the major areas of interest to fire protection engineers are the amount of heat generated and its hazard range. The emissive power of the jet fires from the samples decreased and this was observed to have a noticeable decline at the 80% water content level. The stability of a jet fire might not be easily observed from this method but the credibility of the effects of the jet fire in terms of the emissive power potential can be seen. Table 1 showed the threshold values adopted by HSE in terms of the effects of thermal radiation. Radiation of < 6 kW/m^2 will cause pain in 15-20 seconds and injury after 30 seconds exposure.

The jet fire from the light hydrocarbon mixture sample produced the greatest emissive power while the Sample 3 showed lesser emissive powers from the flames when compared to the other samples. These results established that jet fires can still be considered in terms of the maximum emissive powers that can be produced from the flame even at 80-90% water content. Jet fires are considered credible as long as the composition is flammable and release conditions occur above pressures of 2 barg and as seen from this, the water content will only reduce the effects of the jet but not necessarily cause the jet fires to be discredited in consequence modelling. The water content in the mixtures was also observed to cause an increase in jet flame length which was dependent on the release rate and from the empirical calculations it showed dependency on the molecular weight and density of the mixture. However, with the approach of consequence modelling, an increased flame length with low emissive power might not necessarily cause harm to personnel, except in terms of the velocity at which the jet will be released. As the flame lengths also increase, it is important to also consider the effects of this element for water content levels between 20% and 80% where the emissive powers can be considered high enough to cause harm.

For the pool fires, early and late pool fires were considered, though in theory the late pool fires resulting from the mixtures with high water content can be considered to be the burning of the liquid hydrocarbon mixture at the top layer and the water content settled at the bottom. For Sample 1 (light end hydrocarbons) in which the mixture results in a pool fire at high water contents of 90%, the flammability of the gases can be seen to influence the burning of the pool formed as the liquid is spilled on the surface. The emissive power of the pool fires also tend to reduce as the water content in the mixture is reduced; this is also similar for all samples. However, the burn rate and flame height tend to increase for Sample 1 as the water content is increased but the results from empirical calculations show a decrease in burn rate and flame height for all the samples.

The impact of water content in heavy and light crude can be seen in Samples 1 (light end), 2 (heavy ends) and 3 (mixture of light and heavy crude). The potential and impact of jet fires in the light crude is seen to be higher in terms of emissive power and flame lengths compared to sample 2.

For pool fires, the likelihood with light end crude (Sample 1) is lower however with high water content the emissive power and burn rate of the pool fire formed is observed to be higher than that from the heavy end (Sample 2).

For the assessment of crude oil fires, the impact of water content in the resulting effects of the fires that occur is explained and shown using different samples. Water content reduces the effects of the fires at different levels to some extent. Taking a release of sample 4 for example, water content of 80% reduced the jet fire emissive power to 12.4 kWm-2 from 39.06 kWm-2 at the 60% water cut with a flame length of 116.92m increased from 97m at the 60% water cut. The emissive power was greatly reduced but the hazard range to which this will affect has been increased. A qualitative risk assessment will be required to evaluate this effect with respect to the persons or assets within the hazard range. For pool fires the hazards are reduced in terms of emissive power and flame height with high water contents for heavy ends and the mixed hydrocarbon mixtures (Samples 2, 3 and 4).

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