MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

23rd Annual Process Safety International Symposium
October 20-21, 2020 | College Station, Texas

Flammable mist hazards involving high-flashpoint fluids

Simon Gant[1]*, Anthony Giles[2], Richard Bettis[1], Philip Bowen[2]
[1] Health and Safety Executive (HSE), Harpur Hill, Buxton, UK
[2] Gas Turbine Research Centre (GTRC), Cardiff University, Wales, UK
*Presenter E-mail: simon.gant@hse.gov.uk

Abstract

In 2009, the UK Health and Safety Executive (HSE) published a review of serious incidents involving ignition of flammable mists of high-flashpoint fluids, i.e. fluids whose vapours cannot be ignited and sustain a flame at normal room temperature (e.g. kerosene, diesel, lubrication oils and hydraulic oils). The review identified 37 incidents which together were responsible for 29 fatalities. In response to the findings, HSE and a consortium of other regulatory and industrial sponsors funded a Joint Industry Project (JIP) on the subject, which ran from 2011 to 2015. The work included a detailed literature review and a series of experiments at Cardiff University on a mist release configuration consisting of a downwards-pointing spray from a 1 mm diameter circular orifice. Test pressures ranged from 1.7 bar to 130 bar and three fluids were tested: Jet A1 (kerosene), a light fuel oil and a hydraulic oil. Computational Fluid Dynamics (CFD) simulations were also performed, and results were compared to existing hazardous area classification guidelines. The work was used to devise a preliminary classification scheme for mist flammability, based on a fluid's flashpoint and ease-of-atomization.

Several important questions remained unanswered following the first JIP relating to the effect of the orifice shape, size and release configuration, and the ignition characteristics of other common fluids, notably diesel. In 2018, HSE launched a follow-on JIP (currently ongoing) which aims to address these issues. The work started with an updated review of flammable mist incidents, published in 2019. Experiments on diesel have started in 2020 at Cardiff University and further, larger-scale experiments are planned for 2020-2021 at the HSE Science and Research Centre, Buxton.

This paper and presentation at the MKOPSC International Symposium 2020 provides an overview of the work led by HSE on flammable mists over the last decade, and a summary of the preliminary results from the ongoing experiments.

Keywords: flammable mist, high-flashpoint fluid, spray, ignition

Introduction

Combustible liquids are typically classified by their flashpoint temperature and are often regarded as being relatively non-hazardous if they are handled at temperatures well below their flashpoint (EI, 2015). However, if a high flashpoint liquid is atomised to produce a mist of fine droplets, it can be ignited below its flashpoint and produce a fire or explosion. These flammable mists hazards are mainly a concern for leaks from pressurized systems (e.g. pumps, pipework, valves) as a result of corrosion, mechanical damage, cracks, seal failures or loosening of screwed fittings (Eckhoff, 1995). Flammable mists can also be produced by condensation of vapour, such as that produced by an overheated bearing in a marine diesel engine (Freeston *et al*., 1956).

In Europe, there are regulations controlling flammable atmospheres, namely the ATEX 'Workplace' Directive (1999/92/EC)[1] across the EU and the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR)[2] in Great Britain. DSEAR was introduced to implement the ATEX Directive and has been retained within the UK following its departure from the EU. These regulations require the identification of any zones where a flammable atmosphere could form, either as part of normal operations or in the event of a reasonably-foreseeable equipment failure. Within such zones, all ignition sources must be controlled by using appropriate equipment rated for use within hazardous areas. Both ATEX and DSEAR cover flammable atmospheres produced by gases, dusts and/or mists.

There is established guidance available on the extent of hazardous areas for flammable gases (e.g. BSI, 2016; EI, 2015), but relatively few guidance documents or standards are available to assess equivalent hazardous areas for flammable mists, or to help select safe equipment for use in flammable mist atmospheres. The relevant British and European standard, BS EN 60079-10-1 (BSI, 2016) contains limited guidance in Annex G, but this is qualitative rather than quantitative. The Energy Institute model code of safe practice EI15 (EI, 2015) provides guidance on area classification for installations handling flammable fluids, which includes tabulated hazard distances for higher flashpoint fluids leaking at different pressures through various specified hole sizes. However, the document acknowledges that "there is little knowledge on the formation of flammable mists and the appropriate extents of associated hazardous areas". The release conditions given in EI15 are also tailored towards relatively large-scale equipment, with hole sizes ranging from 1 mm to 10 mm.

Many areas of concern exist in plant rooms and other enclosed areas. Here, the lack of definitive guidance often leads to the whole plant room being considered as a hazardous area. Many assessments assume that leaks do not form a mist at lower pressures (perhaps below 5 or 10 bar gauge), and it is not clear that all potential mist hazards are fully recognised.

Is there a need for oil mist zoning?

Common items of industrial equipment may have the potential to produce oil mists. For example, hydraulic equipment, lubricating oil systems and delivery lines for high-flashpoint fuels (diesel,

---

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31999L0092 (accessed 10 September 2020).
[2] https://www.hse.gov.uk/fireandexplosion/dsear.htm (accessed 10 September 2020).

kerosene etc.) could create aerosols if they failed under pressurised conditions. Such equipment is in widespread use, but the creation and ignition of flammable mists does not seem to be a frequent occurrence. The apparent lack of mist explosion events suggests that there are often mitigating factors preventing flammable mists being created or ignited. Understanding these factors could allow more accurate assessment of when control measures are unnecessary and when they are essential.

It should be noted that the perception of oil mists seems quite different on board ships. Following several incidents involving loss of life, the Safety of Life At Sea (SOLAS) regulations require unattended engine crankcases to be fitted with oil mist detectors and automatic shutdown (IMO, 1974). The International Maritime Organisation (IMO) notes that the majority of engine room fires are the result of oil mist formation and has guidance on the fitting of oil mist detectors in these more open areas.

In 2009, the UK Government's safety regulator, the Health and Safety Executive (HSE), published a review of serious incidents involving ignition of flammable mists of high-flashpoint fluids (Santon, 2009). HSE also recently worked in collaboration with the French national laboratory INERIS[3] and the Université de Lorraine in France (Lees *et al*., 2019) to produce a systematic study of three European national incident databases: the UK's Offshore Hydrocarbon Release Database, the French ARIA database and the German ZEMA databases. These 2009 and 2019 incident reviews both showed that while oil mist explosions were relatively infrequent events, they happen sufficiently often that the possibility of one occurring should not be ignored. For example, the latter study showed that over a 30 month period from 2016 to 2018, there was approximately one incident per month that involved fluid mists or sprays on offshore oil and gas installations operating on the UK continental shelf. Oil mist explosions have led to deaths, injuries and significant property loss.

MISTS – a Joint Industry Project

Following the review of mist incidents in 2009, HSE set up a joint industry project to help improve our understanding of flammable mists. The four-year project started in December 2011 and was jointly sponsored by 16 industry and regulatory partners (HSE, ONR, RIVM, GE, Siemens, EDF/British Energy, RWE, Maersk Oil, Statoil, BP, ConocoPhilips, Nexen, Syngenta, Aero Engine Controls, Atkins, Frazer Nash and the Energy Institute).

Literature review

The first stage of the project was an extensive literature review that examined three fundamental issues: mist flammability, mist generation and mitigation measures (Gant *et al.*, 2012; Gant, 2013). Data on mist flammability were reviewed that included measurements of the Lower Explosive Limit (LEL), Minimum Ignition Energy (MIE), Minimum Igniting Current (MIC), Maximum Experimental Safe Gap (MESG) and Minimum Host Surface Ignition Temperature (MHSIT). One of the significant findings was that the LEL for mists could fall to as low as 10% of the LEL for the vapour of the same substance (i.e. to around 5 g/m^3). Mists were found

[3] Institut National de l'Environnement Industriel et des Risques, http://www.ineris.fr (accessed 10 September 2020).

generally to be more difficult to ignite than the equivalent vapour, due to the energy needed to vaporise droplets prior to ignition.

Regarding releases from pressurized systems, the literature review noted that one of the challenges in conducting tests with mists (as compared to gases and dusts) is the complexity introduced by droplet breakup and agglomeration, impact with surfaces and evaporation. Correlations for primary atomisation, secondary droplet breakup, and droplet impingement were reviewed. Much of the historical work on sprays was found to be motivated by the development of internal combustion engines and gas turbines. The study noted that there was uncertainty in applying correlations developed for those applications to the very different scales and operating pressures typical of industrial equipment requiring hazardous area classification (e.g. pumps and pressurized pipework).

Release classification

Following the literature review, a method to classify releases was developed to group together similar fluids and release scenarios (Burrell and Gant, 2017). This was deemed necessary because of the large number of high-flashpoint fluids in use across a range of industries, which would make detailed case-by-case assessments impractical. The classification method was based on two factors that were considered to be significant for flammable mist formation from leaks of fluids under pressure, namely the flashpoint of the fluid and the propensity for releases to atomize into droplets. The chosen atomization criteria were calculated based on the Ohnesorge number, Oh, which is a dimensionless parameter that depends on the fluid viscosity (μ), density (ρ) and surface tension (σ) and the equivalent diameter of the leak (D):

$$Oh = \frac{\mu}{\sqrt{\rho D \sigma}} \tag{1}$$

Ohnesorge (1936) provided an empirical correlation for atomization breakup that depends on the Reynolds number of the fluid released through the orifice, Re:

$$Oh_c = 745 Re^{-1.22} \tag{2}$$

To characterise the propensity of a given release to atomize, it was proposed to use the ratio of Oh to Oh_c. The greater the value of this ratio (Oh/Oh_c) was taken to indicate a greater propensity for the release to atomize into small, more easily ignitable droplets.

Figure 1 shows the flashpoint plotted against this ratio for a range of different fluids released through a 1 mm diameter hole at 10 bar gauge pressure. These values were chosen to represent a credible accident scenario and it is one of the conditions considered in EI15. It is also readily achievable in experimental studies. The fluids assessed were chosen because they were of particular interest to the organisations sponsoring the JIP. The vertical and horizontal error bars in Figure 1 show the range in flashpoint and (Oh/Oh_c) values resulting from the range in fluid properties, which were taken from various data sources in the literature (see Burrell and Gant, 2017 for details). For biodiesel, the effect of changing the release temperature (which alters the fluid properties) is also shown in the Figure.

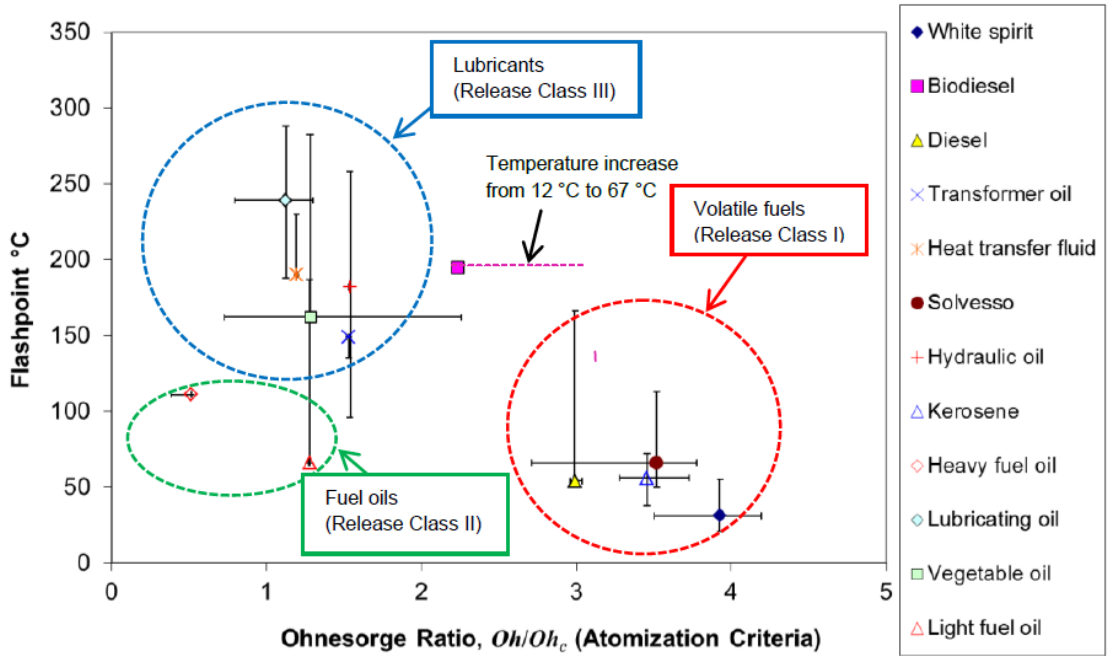

Figure 1. Mist classification by flashpoint and atomisation criteria for a 10 bar release through a 1 mm hole

The fluids appeared to fall naturally into three groups in Figure 1. To generalise this classification system to all fluids, the figure was split into quadrants defining four "Release Classes" (see Figure 2), which can be summarised as:

- **Release Class I**: More volatile fluids that are more prone to atomisation, such as many commercial fuels.
- **Release Class II**: More volatile fluids that are less prone to atomisation, such as viscous fuel oils at ambient temperatures.
- **Release Class III**: Less volatile fluids that are also less prone to atomisation, such as many lubricants and hydraulic fluids at cool (near ambient) temperatures.
- **Release Class IV**: Less volatile fluids that are more prone to atomisation, such as many lubricants and hydraulic fluids at high temperatures that may arise during use.

The specific values used to bound the four Release Classes (i.e. flashpoint of 125 ºC and Ohnesorge ratio of 2) were selected based on the best judgement at the time. As and when new evidence becomes available it is possible (and even likely) that these bounds may need to be revised.

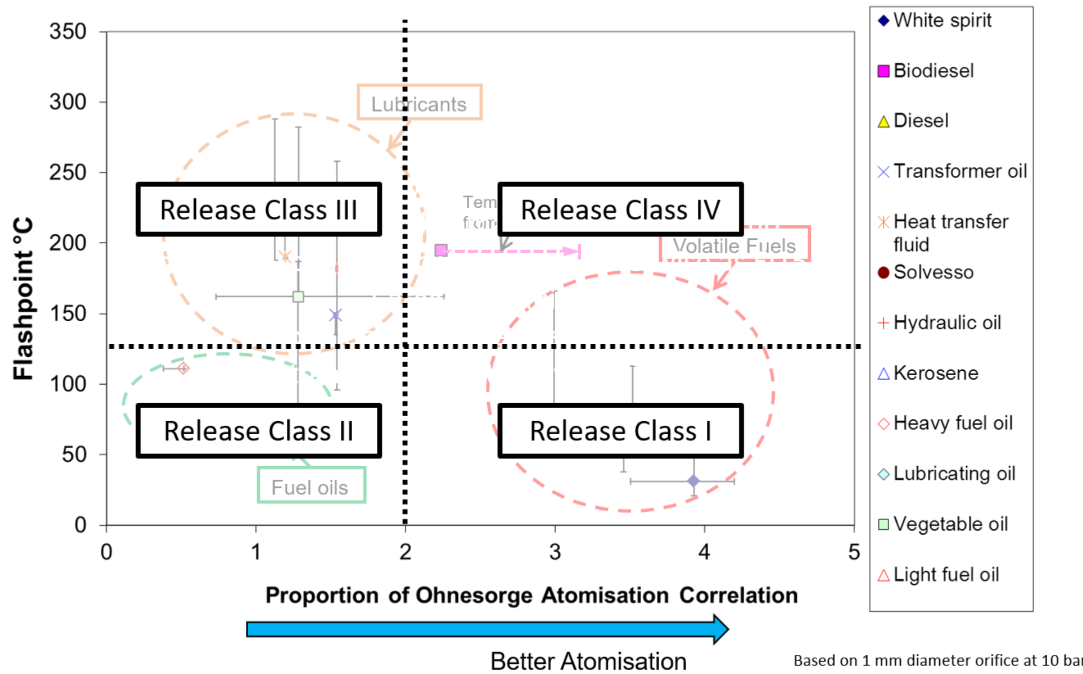

Figure 2. Mist classification diagram overlaid with the four release classes

Experimental studies

To investigate the flammability of mists, experiments were conducted at Cardiff University's Gas Turbine Research Centre (GTRC) using three exemplar fluids: one each from the Release Classes I, II and III (Mouzakitis *et al.*, 2017a; 2017b). These experiments were designed to produce a mist from a pressurised leak through a small hole. The aim was to determine whether the mists produced by the three fluids could be ignited and, if so, to use a spark igniter to map the extent of the flammable cloud. Following this, the aim was to measure droplet size distributions and concentrations at the edge of the flammable cloud, to investigate the LEL.

The tests were all conducted using a 1 mm diameter, smooth-bore, cylindrical plain orifice with length-to-diameter ratio of 2. The releases were all directed downwards to prevent asymmetric effects, and the experiments were conducted within a 1.2 m square, 2.5 m tall test chamber (shown in Figure 3). This configuration provided a good starting point using a simple arrangement that is well defined and readily repeatable. The 1 mm hole size is the smallest hole tabulated in the EI15 model code of safe practice and it therefore allowed for direct comparison to the existing guidance.

The ignition tests all used a 1 Joule electric spark (Chentronic's Smartspark[4]). Prior to the start of experimental work, there was considerable discussion within the project's Steering Committee regarding the ignition source. The intention was for the source to represent a credible upper limit for most situations where area classification would be considered. While most commonly occurring electrical sparks are significantly lower in energy, the consensus view was that 1 J represented a reasonable upper limit. Situations with the potential for higher-energy ignition

[4] https://www.chentronics.com/products/smart-spark (accessed 10 September 2020).

sources (or even naked flames) may exist in a few cases, but these were considered to be sufficiently unusual that they would be outside the scope of normal guidance.

During a series of releases, the igniter was placed at a set axial distance from the release point and then tracked across a radius of the jet to locate points just inside and outside of the ignitable envelope. Similar radial tracks were tested at several different distances along the axis of the expanding jet.

Droplet sizes and concentrations were measured using a non-intrusive laser Phase Doppler Anemometer (PDA) system (Dantec Dynamics coherent Innova 70-5 Series argon-ion laser with BSA P60 flow and particle processor[5]). PDA measurements were made following the ignition tests at locations inside and outside of the ignitable envelope at the same locations as those tested for ignition.

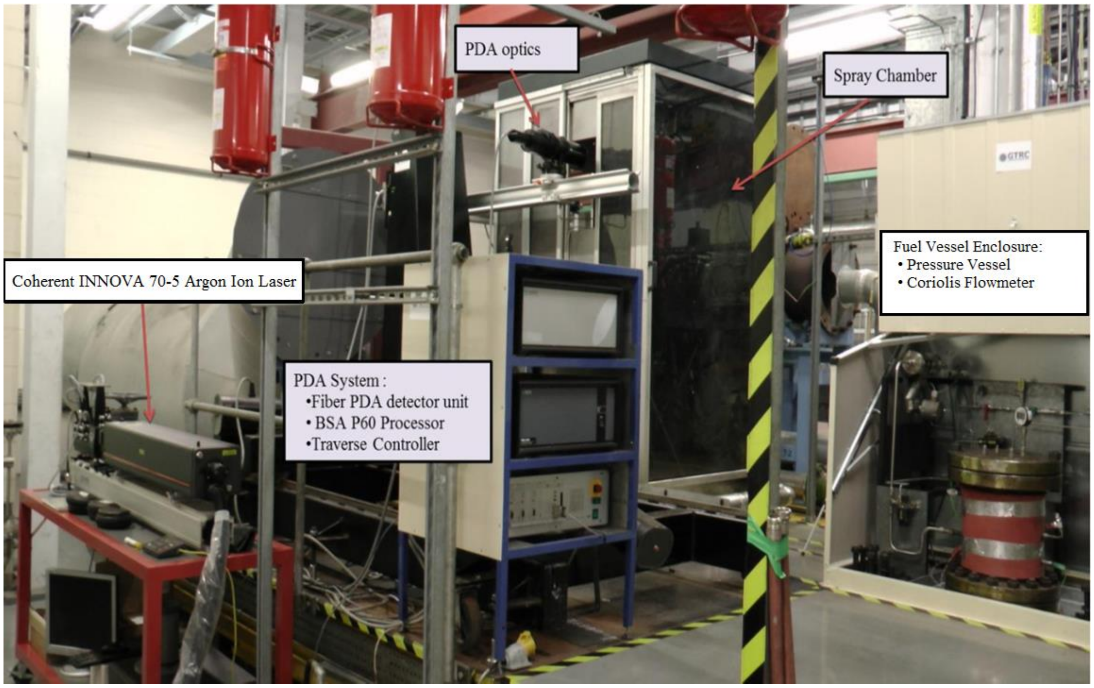

Figure 3. GTRC test apparatus configured for PDA measurements

The three fluids tested were:

- **For Release Class I**: Kerosene (Jet A1), low viscosity, flashpoint = 38 °C)
- **For Release Class II**: Light Fuel Oil (LFO), higher viscosity, flashpoint = 81 °C.
- **For Release Class III**: Hydraulic oil, higher viscosity, flashpoint = 223 °C.

[5] https://www.dantecdynamics.com/ (accessed 10 September 2020).

Tests were also carried out with the same LFO heated to 70 °C. This temperature was still below the flashpoint, but the increase in temperature changed the physical properties sufficiently that the heated LFO was moved from Release Class II into Release Class I.

For each fluid, tests were first carried out at release pressures of 5, 10, 15 and 20 bar gauge. Following these test pressures, further tests were carried out for kerosene and the hydraulic oil at lower and higher pressures (respectively) to determine the limiting pressures were the mist could be ignited.

The tests described above were all carried out for a “free jet” configuration, with the unobstructed spray directed downwards from the top of the enclosure. Following these tests, a further set of results were obtained for LFO and hydraulic oil with a flat mild steel impingement plate located at either 150 mm or 400 mm below the orifice. In both cases, the igniter was located 25 mm above the plate. The aim of these impingement tests was to see whether mists that could not be ignited in the free jet configuration could be ignited after they had impinged at high-velocity onto a solid surface and broken up to produce a finer mist.

Experimental results

Figure 4 shows some example photos of the ignition tests. The tests showed significant differences between the three fluids from the different Release Classes (see Table 1). In the free jet tests, kerosene was found to ignite at all of the test pressures from 5 to 20 bar. The pressure was then reduced in steps of 1 bar to the lowest test pressure possible on the apparatus (1.7 bar gauge) and the kerosene mist ignited in each case. The hydraulic oil showed the opposite behaviour and could not be ignited at any of the pressures between 5 and 20 bar. The pressure was then increased in stages up to 130 bar and the hydraulic oil mist still did not ignite fully, although there were occasional localised flashes near the spark igniter but the flame did not propagate through the mist. LFO did not ignite at ambient temperature across the range of pressures from 5 to 20 bar, but when it was heated to 70 °C it ignited at all of the pressures.

In the impingement tests, the hydraulic oil again did not ignite at any of the pressures. The LFO at ambient temperature did not ignite at a pressure of 15 bar but did ignite at the higher pressure of 20 bar. When the LFO was heated to 70 °C, it behaved in the impingement tests as it had done previously in the free jet tests and ignited at all of the pressures from 5 to 20 bar.

In addition to these ignition test results, it was noted that there were significant differences in the visible appearance of releases with the different fluids. At one extreme, the hydraulic oil released at lower pressures remained largely concentrated in a dense, almost unbroken core of liquid with very few small droplets being formed. At the other extreme, a significant proportion of kerosene was well atomised even at very low pressures.

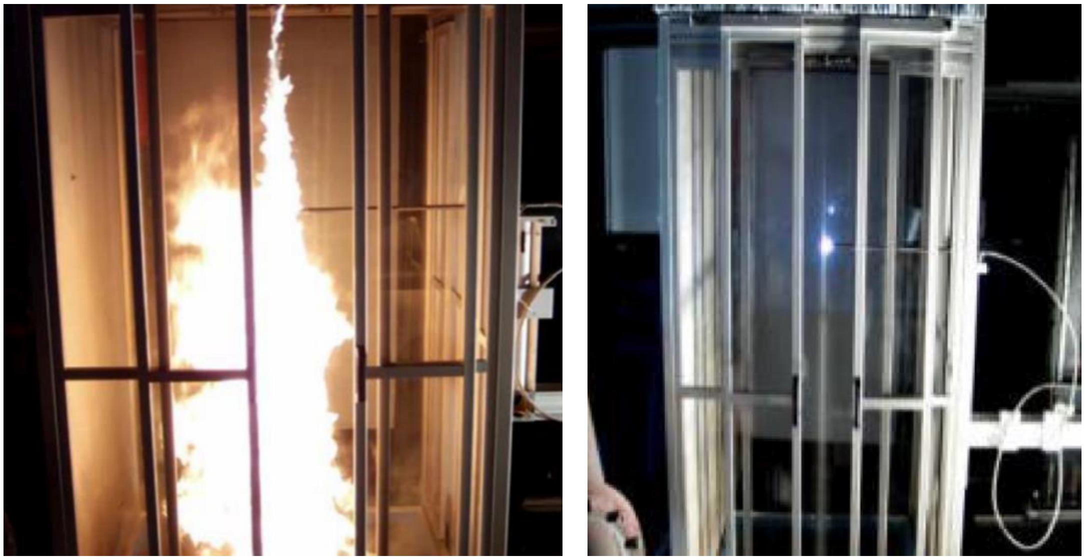

Figure 4. Ignition tests with kerosene (left) and hydraulic oil (right)

Table 1. Ignition Test results

Spray Geometry	Fluid (Flashpoint)	Temperature	Release Pressure (barg)	Ignition
Free spray	Kerosene (FP = 38 ºC)	Ambient	1.7, 2, 3, 4, 5, 10, 15, 20	At all pressures
Free spray	Hydraulic oil (FP = 223 ºC)	Ambient	5, 10, 15, 20, 30, 70, 110, 130	No, but some “flashes” at highest pressures
Free spray	Light fuel oil (FP = 81 ºC)	Ambient	5, 10, 15, 20	No
Free spray	Light fuel oil (FP = 81 ºC)	70 °C	5, 10, 15, 20	At all pressures
Impinging	Hydraulic oil (FP = 223 ºC)	Ambient	5, 10, 15, 20	No
Impinging	Light fuel oil (FP = 81 ºC)	Ambient	15, 20	At 20 barg only
Impinging	Light fuel oil (FP = 81 ºC)	70°C	5, 10, 15, 20	At all pressures

Figure 5 shows an example map of the ignition test results through the kerosene free jet release at 5 bar showing both ignition locations and positions where PDA droplet size and concentration measurements were made. The PDA system worked from direct measurements of individual droplets, collecting many thousands of measurements to obtain a statistical analysis of the aerosol within a small measuring volume. The lack of small droplets in the releases with hydraulic oil and LFO meant that the measurements were of low quality for those fluids. Some good PDA measurements were obtained, but those only corresponded to areas where ignitions were certain. There was little or no good quality data from locations outside the ignition envelope or even on the borderline.

In the kerosene tests, the minimum calculated concentration from the PDA measurements for a successful ignition point was 3 g/m^3. However, the average concentration of the ignition positions near the edge of the flammable envelope was 69 g/m^3. The average concentration of the unsuccessful ignition points from the PDA measurements was 21 g/m^3. In comparison, the LEL for kerosene vapour is approximately 48 g/m^3 (Zabetakis, 1965).

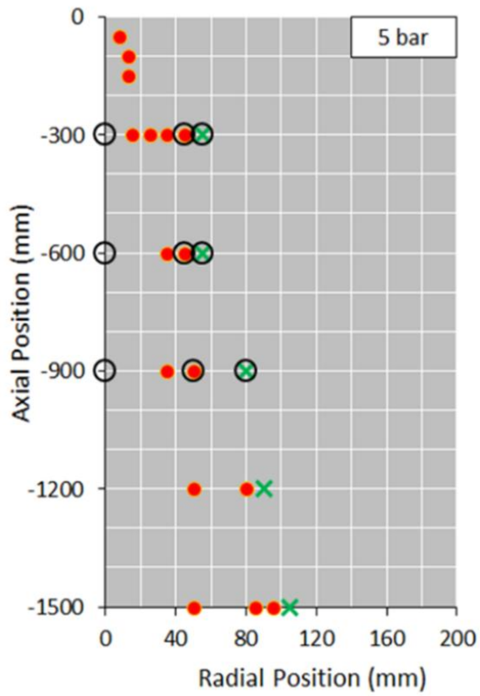

Figure 5. Cross-section through the 5 bar kerosene mist showing the igniter positions as either red dots (where ignition was successful) or green crosses (where ignition was attempted but the mist did not ignite). The locations where PDA droplet size and concentration measurements were made are shown as black circles. The release point is at zero on the axial and radial axes.

CFD modelling

Alongside the experimental studies, a set of CFD simulations were performed using the ANSYS CFX-15 software[6] (Coldrick and Gant, 2017). The model used an Eulerian-Lagrangian approach in which the GTRC spray booth was represented by a fixed computational mesh and the spray was represented by individual computational particles (representing a statistical sample of droplets) that were tracked through the flow. Computational particles were released at the orifice location and droplets were allowed to break apart under aerodynamic forces. The model accounted for the transfer of mass, momentum and energy between the droplets and the surrounding air. Tests were performed to ensure that the results were insensitive to the grid cell size and particle count. For most of the simulations, a grid of 1.3 million nodes was used with 10,000 particles.

[6] http://www.ansys.com (accessed 10 September 2020)

At the orifice, the primary breakup of the liquid into droplets was defined in the model by specifying the initial spray cone angle and initial droplet size. Seven different cone angle models and nine different droplet size models were tested. Two secondary breakup models were also tested to account for aerodynamic forces on droplets. Details of these models are given in the report by Coldrick and Gant (2017). Sensitivity tests with different combinations of models were undertaken and results compared to the data from the GTRC experiments on kerosene at 20 bar. The best performing combination of models was then used to model all of the other tests (i.e. the kerosene tests at different pressures and the hydraulic oil and LFO free jets for pressures between 5 and 20 bar). The best performing primary breakup model was found to be the DNV Phase III JIP Rosin-Rammler correlation (DNV, 2006), which gave predictions within a factor of 2 for the measured droplet concentration and droplet diameter for the kerosene releases. Predictions for the hydraulic oil and LFO were in worse agreement with the measurement data. The main issue there was that the CFD model assumed that the release atomized whereas in the experiments only a small fraction of the liquid was actually atomised. The model therefore predicted flammable concentrations to occur when in practice the mist could not be ignited. Examples of the CFD results are given in Figure 6.

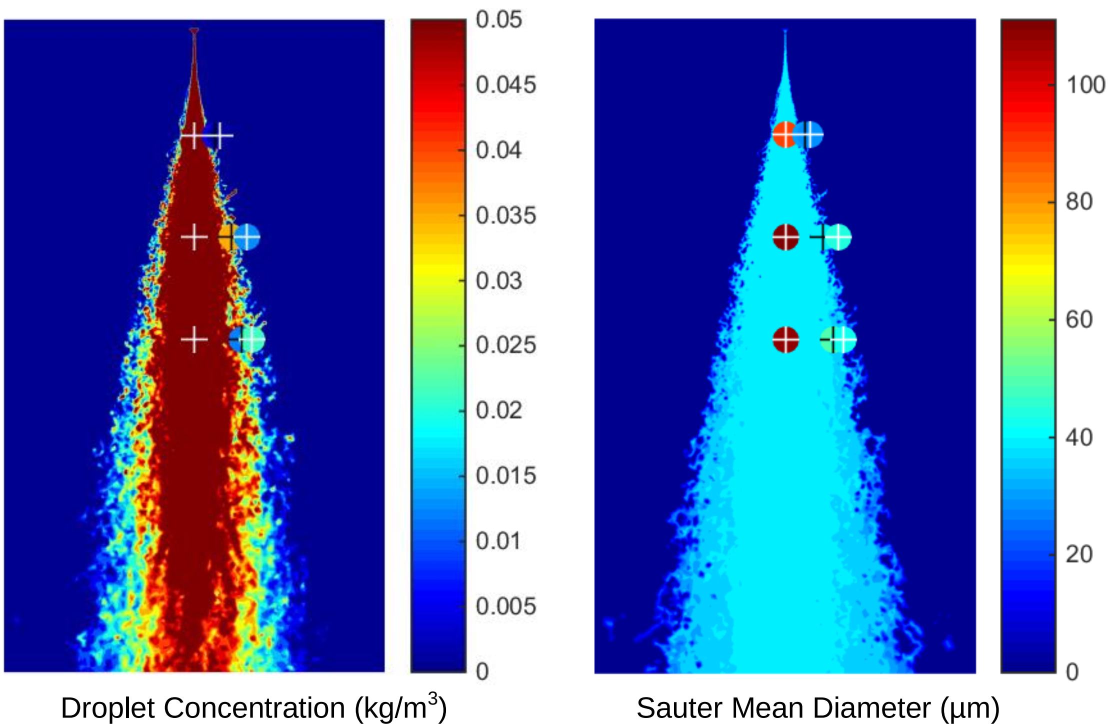

Figure 6. CFD predictions of droplet concentration and size for the kerosene release at 20 bar. Coloured circles show measured values with the same colour scale as the contours. Crosses indicate where ignition occurred (a black cross) or did not occur (a white cross). Ignitions were not attempted on the centreline and only droplet diameter and concentration were measured there (a white cross on the centreline is used to identify solely the measurement location). Note that the scales chosen are not the maximum levels: concentrations in excess of 50 g/m^3 are shown in the left-hand figure as red.

The kerosene CFD model was subsequently used to predict the extent of the flammable mist cloud for Category C fluids in Table C4 of the EI15 code of safe practice (EI, 2015). These EI15 values were originally determined using the consequence modelling software DNV-GL Phast[7] for spray releases directed horizontally in a 2 m/s wind, where the wind was blowing in the same direction as the release (i.e. co-flowing). The hazard range was defined in EI15 as the distance to the LEL, which was assumed to be a droplet concentration of 43 g/m^3. EI15 presents results for four different hole sizes of 1 mm, 2 mm, 5 mm and 10 mm and four pressures of 5 bar, 10 bar, 50 bar and 100 bar. The same set of conditions was modelled using CFD, although the pressures were modelled as gauge pressure whereas the EI15 values are for absolute pressure, i.e. the CFD results were for a 1 bar higher pressure in each case. The configuration of the CFD model was the same as that described earlier in the model validation study, with a vertical downwards spray in nil wind, using the DNV Phase III JIP primary droplet breakup model.

The results comparison (Table 2 and Figure 7) showed that the CFD model gave somewhat larger hazard distances than those given in EI15, particularly for lower pressure releases. The EI15 distances all increase with pressure, but the CFD results exhibit more complex behaviour. This was likely due to the EI15 hazard distance assuming a horizontal release, whereas the CFD value was for a vertically-downwards release.

Table 2. Predicted hazard distances from CFD model compared to EI15 values for Category C fluids

Release Pressure, bar	***Hazard Distance (m) for Release Hole Diameter of:***							
	1 mm		***2 mm***		***5 mm***		***10 mm***	
	EI15	***CFD***	***EI15***	***CFD***	***EI15***	***CFD***	***EI15***	***CFD***
5	2	4.3	4	7.1	8	16	14	28
10	2.5	3.4	4.5	5.7	9	13	17	23
50	2.5	2.8	5	5.4	11	13	21	27
100	2.5	3.0	5	6.0	12	13	22	27

The literature review of mists by Gant (2013) showed that the LEL in quiescent mists could be lower than the 43 g/m^3 value assumed by EI15, by as much as a factor of 10 (i.e. approximately 5 g/m^3). These lower concentration ignitions were observed in experiments with a strong ignition source at the base of a quiescent mist cloud. Given this finding and the longer hazard distances produced by the CFD model for downwards-directed releases, the results suggested that hazardous distances could extend over a spherical volume with a radius around the release point similar to that given in EI15, but with the hazardous zone extending over a greater distance downwards in a cylindrical region below the release point (potentially, to the floor).

[7] http://www.dnvgl.com/phast-and-safeti, accessed 10 September 2020.

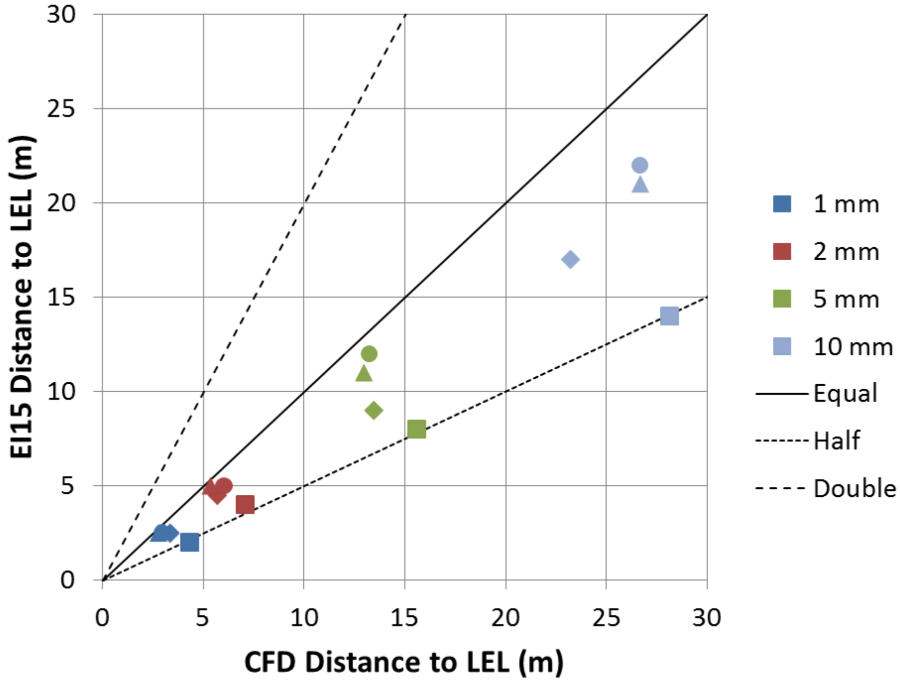

Figure 7. Comparison of CFD predictions to the guidance on hazard distances for mists produced by Category C fluids from Table C4 of EI15 (EI, 2015). Symbols are coloured according to the orifice diameter as shown in the key. Symbol shapes indicate the release pressure as follows: ■ 5 bar, ◆ 10 bar, ▲ 50 bar, ● 100 bar.

Additions to guidance

Based on the findings of the MISTS project, some tentative new guidance was developed (see Figure 8 and Bettis *et al.*, 2017). Whilst the MISTS experimental and modelling results confirmed that the EI15 guidance was broadly appropriate, the new results identified differences between fluids that fell within the broad class of EI15 Category C fluids. Where the MISTS experimental findings clearly showed that particular releases did not produce ignitable mists, the new guidance reflected the absence of a flammable zone. In the case of Release Class I, the ignition of kerosene at lower pressures than the lowest pressure of 5 bar in the relevant EI15 table was also highlighted.

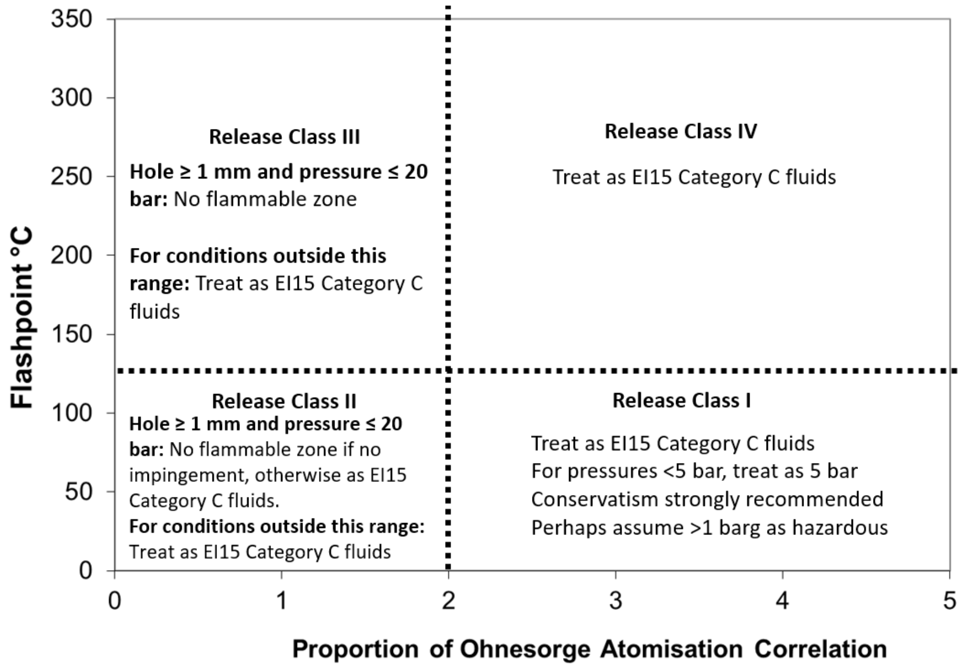

Figure 8. Tentative mists hazardous area classification guidance produced by the MISTS project

MISTS2 project

Following the end of the MISTS project, HSE led a workshop involving other regulatory agencies, industry groups and consultancies to discuss the findings and possible future work. Based on information gathered in that consultation exercise, HSE proposed a second project under its “Shared Research” programme and invited other organisations to contribute time and funding to increase the amount of work that could be undertaken. The new MISTS2 project began in 2018 and it was planned to finish at the end of 2020. However, due to the COVID-19 pandemic, the project is now likely to extend into 2021. In addition to HSE, the project is being supported by Shell, Électricité de France (EDF), the Office for Nuclear Regulation (ONR), the Energy Institute and INERIS. The scope of work for this ongoing MISTS2 project are described below.

Diesel fuel

The somewhat unexpected ignitions of kerosene at very low pressures in the MISTS project raised questions about diesel. It is very widely used and has similar fluid properties to kerosene with a flashpoint around 20 °C higher. Understanding the potential for diesel to create flammable mists, particularly at low operating pressures, is a priority task in the MISTS2 project.

The diesel tests are using the same experimental test procedures as those used in the previous MISTS programme, to allow like-for-like comparison of results. Two different diesel fuels are being tested: the first is an ‘ultra-low sulphur’ diesel that is typical of the UK vehicle ‘pump’ diesel (available from petrol stations, or US gas stations), which is largely composed of mineral-oil derived fuel, and the second fuel is a 100% biodiesel. The biodiesel has a flashpoint of 145 °C, significantly higher than the 58 °C flashpoint of the standard ‘pump’ diesel blend.

At the time of writing (September 2020), the GTRC test rig had been redesigned and rebuilt to allow the duplicate testing in a more robust and safe test environment (see Figure 9) and the ignition tests have been completed. The 'pump' diesel was found to ignite at all the pre-defined pressures of 5, 10, 15 and 20 bar gauge. A test at a lower pressure of 3 bar gauge did not ignite. The biodiesel could be ignited at a release pressure of 20 bar gauge but did not ignite at the lower test pressures of 5 to 15 bar gauge. Work is currently underway to visualise the spray and measure the droplet sizes and concentrations.

Figure 9. GTRC test rig rebuilt for MISTS2 studies

Hole shape

All of the experimental work to date has used a 1 mm diameter drilled circular orifice with a length-to-diameter ratio of two. In practice, accidental releases of fluids will involve a variety of situations where the leak path has a more complex geometry. Examples might include:

- Holes created by corrosion, where leaks are likely to have very short path lengths through thinned material, with rough edges;
- Loosened screwed fittings, where the leak is along the threads;
- Cracked pipes or fittings, where the leak is through a relatively long and narrow opening;
- Damaged or missing seals and gaskets, where the leak is through an arc of the fitting.

To better understand whether the range of possible release paths will alter the likelihood of a flammable mist being created, a series of tests will be carried out with more complex orifices. Additive manufacturing (i.e. 3D printing) will be used to create orifices with different geometries. For each geometry, a range of small size variations will be produced and tested to select ones that closely match the discharge rates of the circular nozzle. In this way, differences in the mists will only be due to changes in the leak shape rather than flow rate.

Ignitable extent

The MISTS experiments were conducted in a relatively small-scale test chamber that did not provide data on the maximum extent of the flammable cloud on the flow centreline. In the kerosene tests, the mist could be ignited all the way to the floor of the chamber. Since the maximum extent of the flammable cloud is such an important parameter for hazardous area classification, it is proposed in the MISTS2 project to duplicate the GTRC releases in a much larger indoor facility at the HSE Science and Research Centre in Buxton, England (see Figure 10).

The pressurised releases in the HSE Burn Hall will be directed vertically downwards from a boom offset from a 10 m high scaffold. To minimise differences from the MISTS releases and the MISTS2 trials, the same GTRC orifices will be used. The ignition trials will also use the same spark igniter, which GTRC have agreed to loan to HSE for these tests. It is currently proposed to use diesel for these experiments. The HSE test rig will allow the igniter to be placed on the centreline, or slightly offset from it if there is a dense liquid stream in the centre. Ignition locations will extend out to axial distances (below the orifice) in excess of 8 metres, which is well beyond the flammable cloud extent predicted by current models. It is anticipated that these tests will provide evidence to support current guidance and future predictive modelling.

Figure 10. The indoor Burn Hall at HSE Science and Research Centre

Summary

In 2009, the UK Health and Safety Executive (HSE) published a review of serious incidents involving the ignition of flammable mists of high-flashpoint fluids, which identified 37 incidents which together were responsible for 29 fatalities. In response to the findings, HSE and a consortium of other regulatory and industrial sponsors funded the MISTS Joint Industry Project, which ran from 2011 to 2015. The project involved a detailed literature review and a series of experiments at Cardiff University on a mist release configuration consisting of a downwards-pointing spray from a 1 mm diameter circular orifice. Test pressures ranged from 1.7 bar to 130 bar and three fluids were tested: kerosene, a light fuel oil and a hydraulic oil. CFD simulations were also performed, and results were compared to existing hazardous area classification guidelines. One of the notable results from the experimental work was that mists of kerosene (with a flashpoint of 38 ºC) could be ignited with release pressures as low as 1.7 bar. The findings from the MISTS project were used to develop a tentative classification scheme for mist flammability, based on the fluid's flashpoint and ease-of-atomization.

Several important questions remained unanswered following the MISTS project, relating to the effect of the orifice shape, size and release configuration, and the ignition characteristics of other common fluids, notably diesel. In 2018, HSE launched a follow-on project, MISTS2, which is currently ongoing. This new project is conducting tests on diesel, on different orifice shapes and taking measurements of the maximum extent of the flammable mist. Preliminary results have shown that standard 'pump' diesel can be ignited at pressures from 5 to 20 bar gauge, but not at 3 bar gauge. Tests with a higher flashpoint 100% bio-diesel found that it can be ignited at 20 bar gauge but not at lower pressures. Further work is ongoing at GTRC Cardiff University and at the HSE Science and Research Centre in Buxton.

The flammability of mists is a complex subject and there are many unknowns that need to be addressed to develop proportionate, reliable and scientifically-robust hazardous area classification guidance. Compared to the decades of research on flammable gases, the work on mists is still at an early stage. HSE is keen to collaborate with other organisations that share an interest in this topic going forward.

Acknowledgements

The authors would like to thank the organisations responsible for supporting the work described here on flammable mists, including: HSE, ONR, RIVM, GE, Siemens, EDF/British Energy, RWE, Maersk Oil, Statoil, Shell, BP, ConocoPhilips, Nexen, Syngenta, Aero Engine Controls, Atkins, Frazer Nash, the Energy Institute and INERIS.

The contributions of HSE staff to producing this conference paper were funded by HSE. The contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

References

BSI (2016), “Explosive atmospheres Part 10-1: Classification of areas — Explosive gas atmospheres (incorporating corrigendum December 2016)”, BS EN 60079-10-1:2015, British Standards Institute, https://shop.bsigroup.com/ProductDetail?pid=000000000030353978, (accessed 10 September 2020).

Bettis R., Burrell G., Gant S., Coldrick S., Mouzakitis K. and Giles A. (2017) “Area classification for oil mists - final report of a Joint Industry Project”, HSE Research Report RR1107, http://www.hse.gov.uk/research/rrhtm/rr1107.htm (accessed 10 September 2020).

Burrell G. and Gant S. (2017) “Liquid classification for explosive oil mists”, HSE Research Report RR1108, http://www.hse.gov.uk/research/rrhtm/rr1108.htm (accessed 10 September 2020).

Coldrick S. and Gant S. (2017) “CFD modelling of explosive oil mists”, HSE Research Report RR1111, http://www.hse.gov.uk/research/rrhtm/rr1111.htm (accessed 10 September 2020).

DNV (2006) “Phast droplet size theory document”, Det Norske Veritas (DNV) Software, London, UK.

Eckhoff R.K. (1995) “Generation, ignition, combustion and explosion of sprays and mists of flammable liquids in air: a literature survey”. Offshore Technology Report - OTN 95 260, Health and Safety Executive, Bootle, UK.

EI (2015) “Model Code of Safe Practice – Part 15: Area Classification Code for Installations Handling Flammable Fluids (EI15)”, 4th Edition, Energy Institute (EI), https://publishing.energyinst.org/topics/asset-integrity/ei-model-code-of-safe-practice-part-15-area-classification-for-installations-handling-flammable-fluids (accessed 10 September 2020).

Freeston H.G., Roberts J.D. and Thomas A. (1956) “Crankcase explosions: an investigation into some factors governing the selection of protective devices”. Proc. Institution of Mechanical Engineers (IMechE), 170, p811-824.

Gant S., Bettis R., Santon S., Buckland I., Bowen P. and Kay P. (2012) “Generation of Flammable Mists from High Flashpoint Fluids: Literature Review”, IChemE Hazards XXIII conference, 12-15 November 2012, https://www.icheme.org/media/9045/xxiii-paper-43.pdf (accessed 10 September 2020).

Gant S. (2013) “Generation of Flammable Mists from High Flashpoint Fluids: Literature Review”, HSE Research Report RR980, http://www.hse.gov.uk/research/rrhtm/rr980.htm (accessed 10 September 2020).

IMO (2020) "International Convention for the Safety of Life at Sea (SOLAS), 1974", last amended 2020, International Maritime Organisation, http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx (accessed 10 September 2020).

Lees P., Gant S., Bettis R., Vignes A., Lacome J.-M. and Dufaud O. (2019) "Review of recent incidents involving flammable mists". IChemE Hazards 29, 22-24 May 2019, https://www.icheme.org/media/12613/hazards-29-paper-31-review-of-recent-incidents-involving-flammable-mists.pdf (accessed 10 September 2020).

Mouzakitis K., Giles A., Morris S. and Bowen P. (2017a) "Experimental Investigation of Oil Mist Explosion Hazards (Phase 1)", HSE Research Report RR1109, http://www.hse.gov.uk/research/rrhtm/rr1109.htm (accessed 10 September 2020).

Mouzakitis K., Giles A., Morris S. and Bowen P. (2017b) "Experimental Investigation of Oil Mist Explosion Hazards (Phase 2)", HSE Research Report RR1110, http://www.hse.gov.uk/research/rrhtm/rr1110.htm (accessed 10 September 2020).

Ohnesorge W.V. (1936) "Die Bildung von Tropfen an Düsen und die Auflösung flüssiger Strahlen". Z. angew. Math. Mech., 16: 355–358, http://dx.doi.org/10.1002/zamm.19360160611 (accessed 10 September 2020).

Santon R.C. (2009) "Mist Fires and Explosions – An Incident Survey", IChemE Hazards XXI Conference, Manchester, UK, https://www.icheme.org/media/9551/xxi-paper-054.pdf (accessed 10 September 2020).

Zabetakis M.G. (1965) "Flammability characteristics of combustible gases and vapors", Bulletin 627, Bureau of Mines, U.S. Government Printing Office, https://apps.dtic.mil/dtic/tr/fulltext/u2/701576.pdf (accessed 10 September 2020).