

Area classification of flammable mists: summary of joint-industry project findings

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This paper presents the findings from a programme of research on mists produced from flammable or combustible fluids at temperatures below their flash points that was undertaken at the Health and Safety Laboratory and Cardiff University over the last four years. The purpose of the research was to improve our understanding of flammable mists and, in particular, to identify when leaks of high-flashpoint fluids may produce a flammable atmosphere and to help define the extent of the flammable cloud. The work was funded by a consortium of industry and regulatory sponsors.

The research programme consisted of five main elements:

1.) A detailed literature review (presented previously at the Hazards XXIII conference)

2.) Development of a classification system for releases of high-flashpoint fluids

3.) Experiments to determine the ignitable range of droplet size and concentration for different classes of spray release

4.) Computational Fluid Dynamics (CFD) modelling of the experiments and other releases relevant for area classification

5.) A final stage of analysis and comparison to area classification guidelines

This paper concentrates on the final four elements. The experiments and CFD modelling considered three fluids: Jet A1 (kerosene, flashpoint = 38 °C), a hydraulic oil (flashpoint = 223 °C) and a light fuel oil (flashpoint = 81 °C). These were chosen as representative of the range of high-flashpoint fluids used across industry. A single release geometry was studied that involved an orifice diameter of 1 mm and a downwards-directed spray. For pressures where the spray was fully atomised, it was found that the CFD model using the 'DNV Phase III JIP RR Primary Breakup Model' provided reasonably good predictions of the droplet size and concentration. Predictions from the validated CFD model were compared to hazard distances presented in the EI15 Model code of safe practice. The paper concludes with amendments to some of the existing guidelines for area classification of mists.

Keywords: flammable mists, high-flashpoint fluids, area classification, experiments, CFD

Introduction

It is well-known that mists of high-flashpoint fluids such as diesel, kerosene and lubricating oils can ignite and produce explosions at temperatures below their flashpoints (Bowen and Shirvill, 1994; Maragkos and Bowen, 2001). A review by Santon (2009) identified 37 historical ignition incidents involving flammable mists, including 20 explosions, of which nine were collectively responsible for a total of 29 fatalities. The potential hazard from mists is recognized in the European Explosive Atmospheres Directive (ATEX)[1], which is implemented in the UK under the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR)[2]. However, there is currently only limited guidance on methods to predict the extent of the hazard produced by mists of high-flashpoint fluids. The most recent version of the relevant IEC standard (IEC 60079-10-1; IEC 2015) contains two pages of qualitative guidance on flammable mists and the EI15 Model code of safe practice on area classification (Energy Institute, 2015) notes: "there is little knowledge on the formation of flammable mists and the appropriate extents of associated hazardous areas."

To address this issue, a project on the formation and mitigation of flammable mists was initiated by HSE in December 2011 that was jointly sponsored by 16 industry and regulatory partners (see Acknowledgements). The objective of the Joint Industry Project (JIP) was to develop practical criteria to define the likelihood of flammable mist formation that could be used as part of an area classification exercise. The scope of work included the formation of flammable mists, methods to predict the extent of the flammable cloud, protected equipment concepts and equipment selection. The JIP steering committee helped to narrow this broad scope to focus on specific topic areas.

The first stage in this project was an extensive literature review that examined three fundamental issues: mist flammability, mist generation and mitigation measures (Gant, 2013). A summary of the literature review was presented at the Hazards XXIII conference by Gant *et al*. (2013).

The fluids that were of interest to the JIP stakeholders included: lubricating oil, vegetable oil, hydraulic oil (both mineral and synthetic types), light/heavy fuel oil, heat transfer fluid, jet fuel (kerosene), transformer oils, process fluids (e.g. Solvesso), diesel, bio-diesel and white spirit. It was well beyond the means of the project to conduct experiments on each of these fluids to assess their propensity to produce flammable mists. A classification system was therefore developed to group together fluids with similar properties of relevance to mist formation and flammability.

[1] *http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31999L0092&from=EN (accessed 4 January 2016)*
[2] *http://www.legislation.gov.uk/uksi/2002/2776/contents/made (accessed 4 January 2016)*

A series of experiments were then conducted by the Gas Turbine Research Centre (GTRC) at Cardiff University to study the atomisation behaviour and flammability of three fluids: Jet A1, a hydraulic oil and a light fuel oil (LFO), which represented three distinct classes of fluids. The experiments were also simulated using Computational Fluid Dynamics (CFD) in order to develop a validated model that could be used to predict the extent of flammable mist clouds, and also to study a range of other releases. Results from the CFD model were compared to hazard radii presented in the EI15 Model code of safe practice. The findings from the project were then distilled into tentative guidelines on area classification of mists. Each of these work areas are described in more detail below.

Fluids Classification System

The purpose the fluids classification system was to categorise fluids according to their fluid properties and operating conditions into a small number of classes, analogous to the Gas Group and Temperature Class that is currently used for area classification of gases (IEC, 2015). The parameters that were likely to be most relevant for mist explosion hazards were reviewed and a classification system was developed based on the flashpoint and ease of atomisation (see Figure 1). The ease of atomisation was calculated as the ratio of the Ohnesorge number for a given fluid release (*Oh*) to the critical Ohnesorge number for atomization (Oh_c), where:

$$Oh = \frac{\mu_l}{\sqrt{\rho_l D \sigma_l}} \quad (1)$$

and

$$Oh_c = 745 \mathrm{Re}_l^{-1.22} \quad (2)$$

The terms in these equations are the fluid viscosity (μ_l), density (ρ_l), and surface tension (σ_l), the orifice diameter (D) and the Reynolds number, Re_l, which is defined as:

$$\mathrm{Re}_l = \frac{\rho_l U_l D}{\mu_l} \quad (3)$$

where U_l is the release velocity, which can be calculated from Bernoulli's equation. Equation (2) is taken from the empirical correlation of Ohnesorge (1936).

Figure 1 compares the flashpoint and Ohnesorge ratio for different fluids for just one set of conditions: a pressure of 10 barg and hole size of 1 mm. These values were chosen to match the conditions tested in the later experiments, and also match a release scenario considered in the EI15 Model code of safe practice.

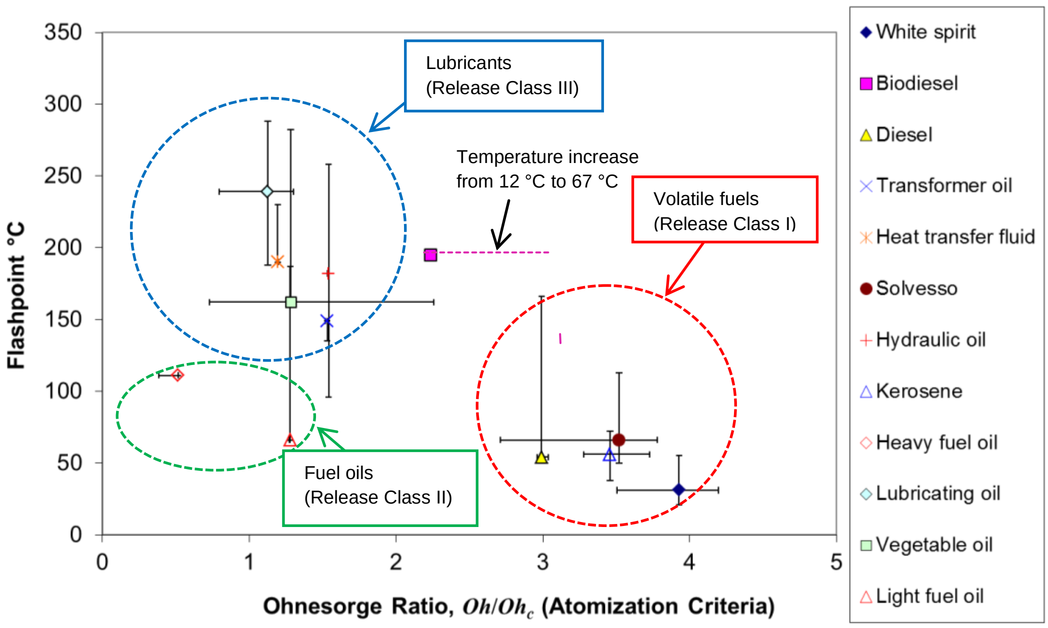

Figure 1 Classification of stakeholder fluids by flashpoint and atomisation criteria for a 10 barg release through a 1 mm diameter orifice

Using this classification system, the fluids of interest were separated into three groups:

- **Volatile fuels or solvents**: fluids that atomise easily and have a relatively low flashpoint, a typical example being diesel
- **Lubricants**: fluids that include heat transfer fluids and various application oils that have both a high flashpoint and a high resistance to atomisation at ambient temperature
- **Fuel oils**: fluids that include petroleum fractions that have a relatively low flashpoint and high resistance to atomisation at ambient temperature

Some releases may change categorization with heating, due primarily to the influence of temperature on viscosity. For example, if a fuel oil is heated it will move to the right in Figure 1 to become classified as a "volatile fuel or solvent". By rearranging Equations 1, 2 and 3, it can be shown that the Ohnesorge ratio, Oh/Oh_c, is proportional to $\mu^{-0.22}$.

To generalise this classification system to all fluids, the graph of flashpoint versus ease of atomisation (Figure 1) was split into quadrants to define four "Release Classes" (see Table 1). The specific values used to bound the four Release Classes were selected based on the best judgement at the present time and it should be noted that this judgement is based on limited evidence. As new evidence becomes available, these bounds may need to be revised.

Table 1 Boundary conditions used for determining Release Class

	Ohnesorge Ratio < 2	**Ohnesorge Ratio ≥ 2**
Flashpoint ≥ 125°C	Release Class III	Release Class IV
125 °C > Flashpoint > 32 °C	Release Class II	Release Class I

The lower bound in flashpoint of 32 °C in Table 1 was chosen since substances with a flashpoint below this level are classified as "highly flammable" and therefore they will create a hazardous area irrespective of any mist explosion hazard. The upper flashpoint bound of 125 °C and the "left" and "right" bounds of the Ohnesorge ratio of two were chosen subjectively based on the grouping of substances shown in Figure 1.

The four categories of Release Class that are produced using this system for a pressure of 10 barg and hole diameter of 1 mm comprise:

- **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.

In assigning a Release Class for a given situation, the fluid properties at the worst-case conditions (typically the highest operating temperature of the fluid) should be used.

To limit the number of fluids required for testing in the experimental work for the joint-industry project, the following substances were selected as exemplars for three of the release classes at typical ambient temperatures, a pressure of 10 barg and hole size of 1 mm:

1. **Release Class I**: Jet A1 (kerosene), flashpoint = 38 °C
2. **Release Class II**: Light Fuel Oil (LFO) conforming to BS2869 Class E at ambient temperature, flashpoint = 81 °C
3. **Release Class III**: Hydraulic oil (Mobil DTE Heavy-Medium VG68), flashpoint = 223 °C

Table 2 Summary of physical properties for the fluids tested

Substance	*Density (kg/m^3)*	*Kinematic Viscosity (mm^2/s)*	*Surface Tension (kg/s^2)*	*Flashpoint (°C)*
Jet A1	800	3.5	0.026	38
Hydraulic Oil	870	111	0.033	223
LFO at ambient temperature	930	170	0.033	81
LFO at 70 °C	880	18	0.031	81

The particular hydraulic oil was chosen in order to have similar fluid properties to the LFO but with a much higher flashpoint. In addition, an example of a release that changed from Release Class II to a Release Class I at high temperatures was chosen as LFO preheated to 70 °C. A summary of the material properties of the substances tested is given in Table 2. No attempt was made to identify and test a fluid that was typical of Release Class IV at ambient temperature, as no such fluids appeared on the JIP sponsors 'fluids of interest' list.

Spray Release Experiments

There are many variables that influence the formation of a flammable mist from a pressurized spray release. These include: the material properties of the fluid, the size and shape of the orifice, the release velocity (or pressure) and release direction, the characteristics of the surrounding air flow and the nature of any nearby surfaces upon which the spray may impinge (Maragkos, 2002). In addition, the location and characteristics of the ignition source can affect whether a given mist will ignite. Quiescent mists ignited from below with a strong ignition source have been found to ignite at particularly low concentrations (see Gant, 2013).

Given all of these complexities, the focus of the spray release experiments was to conduct a series of practical tests on the selected fluids at a range of pressures to assess the conditions needed to produce a flammable mist. It was recognised from the outset that aerosols from accidental leaks would differ from those produced by engineered spray nozzles. The tests were therefore all conducted using a 1 mm diameter, smooth-bore, cylindrical plain orifice with length to diameter ratio of two, and the spray was directed downwards within a 1.2 metre square, 2.5 metre tall test chamber (Figure 2). Other configurations could have been tested, but these conditions provided a good starting point using a simple arrangement that should be repeatable. One advantage of selecting the 1 mm hole size is that it is the smallest hole given in the EI15 Model code of safe practice (Category "C" fluids in Table C4 of Energy Institute, 2015) and it therefore provides a direct reference point to EI15. In addition to the unobstructed spray tests, a limited set of experiments was also performed using an impingement plate close to the release point.

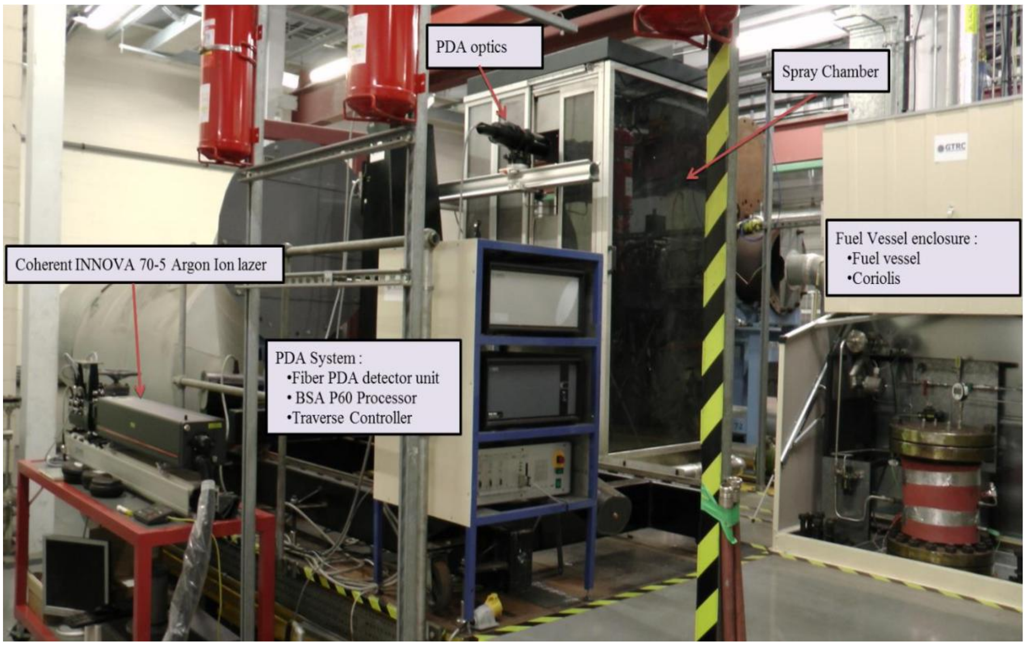

Figure 2 Photograph of test apparatus at GTRC configured for the PDA measurements

Ignition System

In order to assess the mist flammability, ignition tests were performed using a 1 Joule electric spark igniter. The Chentronics Smartspark ignition system was used, which operates reliably in high moisture environments and is insensitive to surface wetting. Prior to the start of experimental work, there was considerable discussion within the JIP 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 sources (sparks 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.

It is worth noting that area classification for gases does not consider the ease of ignition (although this is a factor in determining the required ignition protection of equipment within the hazardous area). Instead, for gases, the extent of the zone is defined in terms of the distance to the Lower Explosive Limit (LEL) (or in some cases the 50% LEL), where the LEL is determined experimentally using very powerful ignition sources (chemical igniters in excess of 1 kJ). The approach taken in this project is, therefore, inherently less conservative than that used for area classification of gases.

In each ignition experiment, the spray was released for ten seconds or until the spray ignited, whichever was sooner. Since the igniter frequency was 15 Hz, the maximum release duration corresponded to 150 ignition attempts. If no ignition was observed, the test was repeated up to a total of three times. The ignition result was classed as negative if no ignition of the spray was observed in all three tests.

Measurements were taken at multiple locations in the spray, both on the jet axis and at different radial locations, in order to characterise the spray flammability. Since the main interest was to determine limiting conditions where the mist was "just" flammable (to help define the LEL), a number of measurements were taken at the spray periphery, where there was considerable air entrainment.

Droplet Size and Concentration Measurement System

Measurements of the droplet size spectrum and droplet concentration were made using a laser-based Phase Doppler Anemometer (PDA) at the locations where ignition measurements were taken. PDA was chosen since it is non-intrusive and it requires no assumptions to be made of the droplet size distributions or velocities.

However, as with all droplet size measurement techniques, PDA has potential sources of error. One of these is that droplets must be close to spherical in shape in order to obtain accurate size measurements. To assess the sphericity of the droplets, the PDA system used three photo-detectors which were grouped into two pairs that allowed validation checks to be performed on the measured phase differences. For a perfectly spherical droplet, the pairs of phase differences would indicate exactly the same droplet diameter. A maximum sphericity error of 20% was allowed in the present work and droplets with a larger error were rejected by the processor and did not influence the results.

Typically, small droplets will be close to perfect spheres, whilst larger droplets may be distorted. The system used here counted the distorted droplets but they did not influence the diameter measurements. Any "ligaments" of liquid significantly larger than the PDA measurement control volume were not measured. If more than one droplet passed through the measurement control volume at the same time, the system recognised it as a corrupted signal and a diameter measurement was not produced, although the measurement was still included in the droplet count. Very high droplet concentrations may have obscured the optical path of the laser beams, at least from time to time, which could have biased the measurements.

Alternative techniques were considered but rejected, including other laser-diagnostic techniques and iso-kinetic sampling, since there were concerns that it would be difficult to configure the system correctly within the spray, due to droplets of different size moving at different velocities.

Results from the Experiments

Initially, tests were performed for four pressures (5 barg, 10 barg, 15 barg and 20 barg) for each of the fluids. Once the results from these tests were obtained, further tests were performed with Jet A1 at pressures down to 1.7 barg and with the hydraulic oil at pressures of up to 150 barg.

Jet A1

In the Jet A1 experiments, the spray was ignitable at all of the pressures from 5 barg to 20 barg. A photograph showing the typical ignition behaviour is given in Figure 3. For the 5 barg and 10 barg cases, the radial extent of the flammable envelope was determined for distances up to 1.5 m from the release point. For the two higher pressures, the spray was ignited at all the positions that were tested. For the 5 barg leaks, the flame only propagated with the flow away from the release point, whereas at higher pressures the flame propagated back to the release point. Additional ignition tests were then performed at lower pressures of 4 barg, 3 barg, 2 barg and 1.7 barg. Again, the sprays ignited in each case.

In the past, it has often been considered that leaks from systems below 5 barg would not pose an ignition risk. These tests clearly showed that this is not always the case. Even the 1.7 barg pressure does not necessarily represent a lower limit: this pressure was just the lowest practical pressure possible with the test rig.

The droplet size measurements indicated that the sprays consisted of a dense core of large droplets moving at high speed, surrounded by a slower-moving mist of finer droplets. On the periphery of the spray, near the ignition boundary, the measured droplet concentrations were close to the LEL concentration of the equivalent vapour (approximately 50 g/m^3).

Hydraulic Oil

None of the hydraulic oil sprays ignited at pressures of 5 barg to 20 barg. Subsequently, the fluid delivery system was extensively modified to allow much higher pressures to be investigated. Further tests were then carried out at release pressures of 30 barg, 70 barg, 110 barg and 130 barg. Again, there was no sustained combustion, although very short lived "flashes" appeared occasionally around the ignition point. Either the flow velocity was too high or the turbulence level too intense for the flame kernel to grow.

The hydraulic oil results showed very clear differences to those for Jet A1, which indicates that at the very least there is merit in considering different Release Classes. The results imply that there is little or no ignition risk within the jet produced by a leak of hydraulic oil at near-ambient temperatures for a hole size of 1 mm and pressures up to 130 barg. However, the experimental rig was limited in length and it was not possible to take ignition measurements far downstream, where the velocity would be much lower. It was also not possible to assess whether the mist could be ignited if the spray was confined in a room with low ventilation rates that allowed concentrations of quiescent mist to build up.

The droplet size and concentration measurements proved to be very challenging in the hydraulic oil tests. Few droplets were measured except at the highest pressures. At lower pressures, the spray consisted of a continuous liquid stream or long string of fluid filaments that could not be reliably measured by the PDA.

Figure 3 Photograph showing ignition of Jet A1 at a nominal release pressure of 20 barg

Light Fuel Oil

In the LFO tests at ambient temperature, no ignitions were observed across the range of pressures up to 20 barg.

When the LFO was preheated to 70 °C, ignitions were seen at all of the test pressures from 5 barg to 20 barg. The 5 barg leak was only ignited close to the release point. The 10 barg and 15 barg releases were ignited at points along the whole length of the spray tested (up to 1.5 m from the release point). The 20 barg releases showed mixed results, with ignitions up to 0.9 m from the release point. In all of the cases, the flame failed to propagate back towards the release point. The results clearly demonstrated that it is important to consider the process conditions (particularly the fluid temperature) if an accurate assessment of ignition potential is to be made.

In these tests, the fluid close to the release point was near its flashpoint (for the LFO, the flashpoint was 81°C). However, the spray was expected to cool as ambient air was entrained so that further downstream the droplets would be at a similar temperature to those released at ambient temperature.

The PDA system could not reliably measure the droplet size and concentration for the ambient temperature LFO, since the sprays consisted mainly of a continuous liquid stream or long fluid ligaments. For the heated LFO, more small droplets were measured and the Sauter Mean Diameter (SMD) was found to be large compared to the equivalent Jet A1 sprays.

Impinging Spray Experiments

The impingement tests were only carried out for the fluids that did not ignite in the previous series of free-spray experiments. The impingement structure consisted of a flat mild steel plate arranged at 90° to the spray axis. For the hydraulic oil, tests were carried out first with the plate located 0.4 m downstream from the release point. No ignitions were observed at any of the four leak pressures from 5 barg to 20 barg. The impingement plate was then moved closer, to only 0.145 m from the release point, and a single test carried out at 20 barg pressure. Again, no ignition was observed, and it was deemed unnecessary to carry out further testing at the lower pressures because ignitions were not expected.

For ambient temperature LFO with the impingement plate located at 0.15 m from the release point, no ignition was seen at the highest pressure of 20 barg. Again, it was deemed unnecessary to carry out further testing at lower pressures because ignitions were not expected. The impingement plate was moved further away, to 0.4 m from the release point, and an ignition was observed at 20 barg. No ignition was seen when the pressure was reduced to 15 barg.

Heated LFO had shown ignitions at all release pressures in the free-spray configuration, but combustion was limited to the region of the spray downstream of the ignition point. Impingement of LFO preheated to 70 °C onto a plate located at 0.4 m downstream from the release point resulted in the flame propagating throughout the release at all pressures from 5 barg to 20 barg.

The impinging spray experiments demonstrated that there is the potential for impingement to make a spray release easier to ignite, but that impingement does not always produce ignitable sprays.

Summary of the Experimental Findings

Table 3 provides a summary of all the ignition test results. Overall, the results suggest that material properties influencing spray break-up may be more significant than other factors, such as the release pressure. For instance, the Jet A1 results showed that ignition was possible even at very low pressure, where the spray was only just atomizing according to the Ohnesorge correlation given by Equation 2 (see Figure 4). In contrast, the hydraulic oil was difficult to ignite even at high pressures (well within the atomisation regime, according to Figure 4).

Table 3 Summary of ignition test results

Spray Geometry	*Fluid*	*Pressure (barg)*	*Temperature*	*Ignited?*
Free spray	Jet A1	1.7, 2, 3, 4, 5, 10, 15, 20	Ambient	At all pressures
Free spray	Hydraulic oil	5, 10, 15, 20, 30, 70, 110, 130	Ambient	No, but some "flashes" at highest pressures
Free spray	Light fuel oil	5, 10, 15, 20	Ambient	No
Free spray	Light fuel oil	5, 10, 15, 20	70 °C	At all pressures
Impinging	Hydraulic oil	5, 10, 15, 20	Ambient	No
Impinging	Light fuel oil	15, 20	Ambient	At 20 barg only
Impinging	Light fuel oil	5, 10, 15, 20	70°C	At all pressures

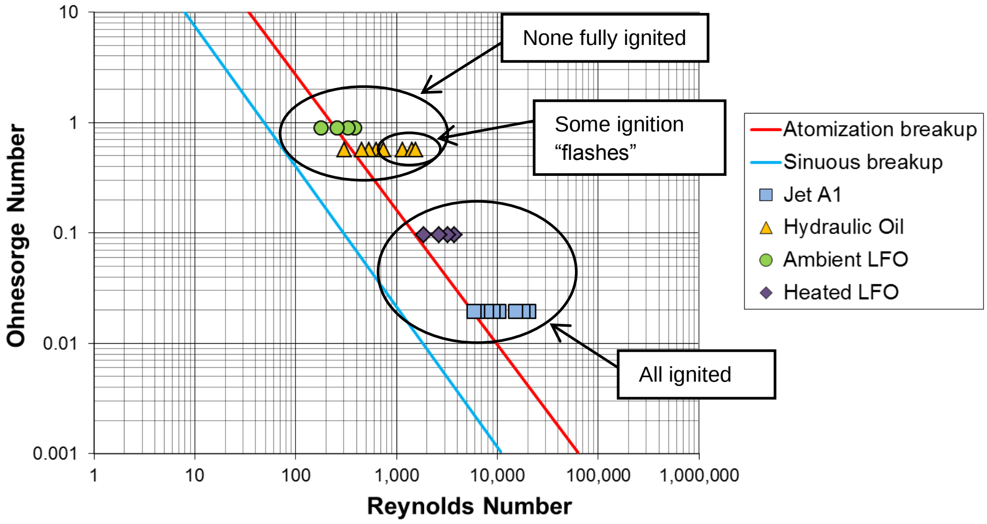

Figure 4 Summary of conditions tested in the GTRC free spray experiments. The Reynolds number was calculated using the velocity from Bernoulli's equation without taking into account the discharge coefficient of the orifice. The atomisation and sinuous breakup correlations were taken from Ohnesorge (1936).

The complex behaviour exhibited by the results may at first sight appear to be strongly influenced by the flashpoint. All of the Jet A1 releases ignited, and its flashpoint of 38 °C was low in comparison to the other fluids tested. However, the heated LFO was ignited in all of the free-spray tests whilst the ambient temperature LFO was not ignited (despite the flashpoint being the same in both cases). One possible explanation is that the difference in temperature between the droplets and their flashpoint is an important criteria, i.e. the heated LFO was easier to ignite because only a small increase in temperature was needed to raise the droplets to the flashpoint. The temperature of the heated LFO droplets decreased with distance downwind from the release point, but at the furthest downstream ignition point the CFD results indicated that droplet temperatures ranged from 30 °C to 50 °C. Another important factor is the influence of temperature upon atomization. When the LFO was heated, the reduction in fluid viscosity produced smaller (more flammable) droplets. The spray impingement tests with ambient temperature LFO also demonstrated that if a sufficiently high concentration of small droplets were produced, the mist could be ignited.

Analysis of the data identified some limitations in the experiments. In the current test rig, it was not possible to create a high-pressure release and allow the velocity to decay with distance downstream, due to the limited height of the enclosure. In the Jet A1 tests, the spray was ignited at all positions in the enclosure and it was not possible to measure the maximum vertical extent of the flammable cloud. It would be beneficial to conduct further tests in larger spaces and/or with smaller orifices.

Computational Fluid Dynamics (CFD)

Methodology

The purpose of the CFD modelling was to develop a validated model that could be used to reliably predict the extent of flammable mist clouds and to study a range of other releases that could not be tested experimentally.

The model was constructed in the commercial CFD software ANSYS-CFX version 15 (ANSYS, 2013a) using an Eulerian-Lagrangian approach in which the GTRC spray booth was represented by a fixed computational mesh and the spray was represented by individual particles that were tracked through the flow. Particles were injected at the nozzle location and 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. To model the effects of turbulence, the industry-standard SST model of Menter (1994) was used. 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.

The three main uncertainties in the configuration of the CFD model concerned the outflow, primary spray breakup and secondary breakup conditions. To specify the outflow conditions, tests were performed using the Schmidt and Corradini (1997) model that determines an effective orifice area based on the state of the flow through the orifice (cavitating or non-cavitating). However, it was found that the model overpredicted the mass flow rates measured in the GTRC experiments by a significant amount, particularly for Jet A1. The velocity predictions from this model were very similar to that obtained using Bernoulli's equation. Due to the potential for errors in the mass flow rate to propagate throughout the simulations and affect the results, it was decided to use the measured mass flow rates from the GTRC experiments as inputs for the CFD model, but to specify the initial droplet velocity using the Schmidt and Corradini (1997) model.

The primary breakup behaviour was defined in the CFD model by specifying the initial spray cone angle and initial droplet size. Seven different cone angle models and nine different droplet size models were investigated. For a 20 barg Jet A1 release three realistic cone angles were produced (some models gave non-physical results). The values were 2.3° for the Reitz and Bracco (1979) and Heywood (1988) models, 3.3° for the Ruiz and Chigier (1991) model and 7.4° for the Arai *et al*. (1984) and Abramovich (1963) models.

The various droplet size models are summarised in Table 4. Results are shown only for the independent primary breakup models and not for the in-built models in CFX that were tested (the Enhanced Blob and Turbulence Induced Atomization models). Two different variants of the DNV Phase III JIP model were tested, based on either a single Sauter Mean Diameter (SMD) or on a Rosin-Rammler (RR) size spectrum. The models predicted a wide range of diameters, from 1 mm for the CFX Blob model through to 0.029 mm for the Fluent model for a 20 barg release of Jet A1.

Table 4 Summary of droplet size models tested and values predicted for a 20 barg release of Jet A1

Model	*SMD (mm)*	*RR Size (mm)*	*RR Index*	*Reference*
TNO Yellow Book	0.0603	-	-	TNO (2005)
DNV Phase III JIP	0.423	0.671	2	DNV (2006)
Miesse	0.710	-	-	Miesse (1955)
Fluent	-	0.0290	1.5	Ansys (2013b)
CFX Blob	1	-	-	Ansys (2013a)
Maragkos	0.0841	-	-	Maragkos (2002)

For the secondary breakup behaviour, two different models were tested: the Schmehl and ETAB models, which are both described in detail in the CFX documentation (ANSYS, 2013a). The Schmehl model is based upon a characteristic timescale and breakup regimes classified according to Weber and Ohnesorge numbers. The ETAB model is based on the Taylor analogy, where droplet distortion from a spherical shape is modelled as a one-dimensional, forced, damped, harmonic oscillation.

It was not feasible to run all the possible combinations of models for all four test liquids at all four pressures. Therefore, an initial set of screening simulations was carried out to assess the performance of the various spray cone angle and primary/secondary breakup models using Jet A1 at a pressure of 20 barg. A total of 38 simulations were run, which covered most of the combinations of cone angle, primary breakup and secondary breakup models. Sample results are shown in Figure 5.

To determine the "best" model using only visual comparison with the experiments would have been time-consuming and would introduce a large subjective element. For these reasons, the visual comparison was supplemented with a procedural quantitative approach based on two Statistical Performance Measures (SPM): the mean relative bias and mean relative square error. Using this method, a subset of models that performed well in the 20 barg Jet A1 tests were selected and then used to simulate the remaining GTRC experiments. Model predictions were again compared to the experimental data using the SPM method to identify which models performed best.

Summary of CFD Findings

For Jet A1 at 20 bar, where the spray was well atomised, the CFD model was relatively insensitive to the prescribed spray cone angle and secondary droplet breakup model. The main effect on the results was from the prescribed initial droplet size. The best performing models for the spray centreline predictions of concentration and droplet size were the Miesse and DNV Phase III JIP RR models. The centreline predictions of concentration and Sauter Mean Diameter using these models were within a factor of two of the measurements. The predictions using these models also captured some of the nuances seen in the experiments, such as the mean droplet diameter increasing on the centreline with the smaller droplets drifting to the periphery.

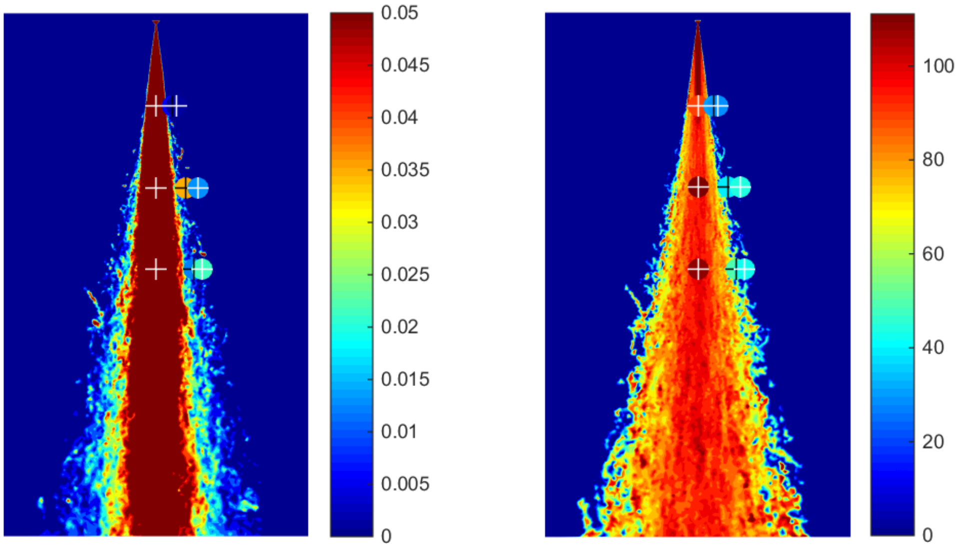

Figure 5 Contour plots showing CFD predictions of concentration in kg/m^3 (left) and Sauter Mean Diameter in μm (right) with the DNV Phase III JIP RR primary breakup model, cone angle of 7.4° and ETAB secondary breakup model for a 20 barg release of Jet A1. *Coloured circles show measured values with 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.*

However, a limitation of the Miesse model was that it predicted behaviour for the LFO which was qualitatively incorrect, in that it gave larger droplets for the heated LFO than for the ambient temperature LFO. The DNV Phase III JIP RR model also had problems for Jet A1 at pressures of 10 barg and below, and for LFO and hydraulic oil at pressures of 5 to 20 barg, where it predicted droplets that were much larger than the nozzle diameter. This is likely to reflect the fact that the model was developed for atomising sprays, whereas the sprays in these cases were not fully atomised.

The experimental results for the hydraulic oil and ambient temperature LFO tests showed an initially narrow jet with an almost continuous stream of liquid and no ignitions were observed at any of the locations. The model comparisons were made with these results on the centreline, due to the lack of reliable data on the spray periphery. The agreement between the model predictions and experiments was generally poorer in these tests. None of the models were clearly superior.

The overall conclusion from the validation exercise was that the CFD model using the DNV Phase III JIP RR primary breakup model could provide reasonably good predictions of the droplet sizes and concentrations for atomising sprays.

For non-atomising sprays or discharges that produced long breakup lengths, the results showed that CFD models were less reliable. In these cases, the CFD models predicted droplets to occur where in reality the liquid remained as a continuous liquid stream or long fluid ligaments.

The modelling work suggested that a possible way forward for area classification of high-flashpoint fluids may be to use a criterion based on Ohnesorge ratio to determine whether or not a release will atomise and pose a flammability risk. For releases that do atomise, such as Jet A1 under the release conditions tested in this programme, the study showed that CFD models provide reasonably good predictions of the droplet size and concentration.

Comparison of CFD to EI15 Model Code of Safe Practice

To provide a demonstration of how a CFD model could be used to predict the extent of a flammable mist cloud, CFD simulations were performed for the same set of releases presented for Category C fluids in Table C4 of the EI15 Model code of safe practice (Energy Institute, 2015). These EI15 values were determined using the consequence modelling software

DNV-GL Phast[3] 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 radii were defined as the distance to the LEL, which EI15 assumed to be a 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.

Table 5 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 CFD results (Table 5) showed that the droplet concentration reached a value of 0.043 kg/m^3 at a somewhat longer distance than that given by EI15. This was particularly the case for lower pressure releases. Indeed, the CFD model predicted the distance to the LEL to reduce as the pressure was increased, up to a release pressure of around 50 bar. The Phast model used to generate the EI15 hazard radii assumed a horizontal release, whereas the CFD modelled a downward vertical release. It may be that this change in geometry was responsible for some, if not all, of the difference in the results.

It should be noted that the literature review (Gant, 2013) showed that the LEL in quiescent mists could be much 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 the hazardous area 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 further downwards in a cylindrical region below the release point (potentially, to the floor).

Tentative New Guidelines for Area Classification of Mists

The aim of the current project was to produce new scientific information on the formation and mitigation of flammable mists that could be used by industry to develop evidence-based guidelines on area classification of mists. Although the project succeeded in producing a classification scheme for spray releases and relevant data from experiments and modelling, it should be recognized that this new information is limited in scope. Compared to the decades of research into flammable gas hazards, the work on flammable mists is still at an early stage. Because of the limited amount of data that has been produced in the current project, any extension of the results to generic guidance for all orifices, all pressures and all fluids is inappropriate. At best, the results presented in this paper should only be used as one input into a considered, professional examination of a given problem.

For those who need a straightforward recommendation on area classification of mists, there is already some limited information presented in EI15 (Energy Institute, 2015). The hazard radii given by EI15 are based upon model predictions of sprays where the hazard is defined as an average droplet concentration above an LEL of 43 g/m^3. This differs from the approach taken for gas releases, where the flammable envelope is typically taken to be an average concentration of ½ LEL. The use of ½ LEL instead of LEL is mainly to account for turbulence that causes instantaneous fluctuations in concentration above and below the average value (see Webber, 2002). It is currently unknown whether a similar criterion ought to be adopted for mists. There are also questions over the choice of 43 g/m^3 for the LEL – as discussed above.

The suggested guidelines given below for each of the Release Classes are based on the limited amount of data available from the current project and must be treated with caution. For consistency with EI15, it is assumed that any flammable volume is limited to the distance to an average LEL concentration – but this remains to be established with confidence. The Release Classes discussed here are those described in Table 1 in terms of the flashpoint and Ohnesorge ratio. The Release Class must be based on the worst-case operational conditions, i.e. the highest operating pressure and the fluid properties that are appropriate for the highest operating temperature.

1. **Release Class I**: Should be treated as EI15 Category C fluids. For pressures below 5 bar, the hazard radii given in EI15 for 5 bar should be used. Tests on Jet A1 showed that flammable mists were produced at a pressure of just 1.7 barg. A margin of conservatism is strongly recommended. It may be appropriate to consider any Release Class I with a pressure above 1 barg as capable of creating a hazardous zone.

2. **Release-class II**

[3] *http://www.dnvgl.com/phast-and-safeti, accessed 29 December 2015*

   a. **For hole sizes of 1 mm or above and pressure below 20 bar:** No flammable zone if there is no possibility of spray impingement, otherwise as EI15 Category C fluids.

   b. **For conditions outside this range:** Unknown – treat as EI15 Category C fluids.

3. **Release-class III**

   a. **For hole sizes of 1 mm or above and pressure below 20 bar:** No flammable zone created.

   b. **For conditions outside this range:** Unknown - treat as EI15 Category C fluids.

4. **Release-class IV**: Unknown – treat as EI15 Category C fluids.

These tentative guidelines are based on the findings of the JIP experiments and modelling. In other more complex spray release situations, where for example the spray may impinge upon hot surfaces, the assessment will need to take other factors into account. These guidelines should be reviewed as more information on flammable mists becomes available.

If a hazardous zone is identified, only suitably ignition protected equipment should be installed within that zone. Since there is currently no standard against which equipment may be certified as safe in a flammable mist, it is necessary to apply sound technical judgement. Conventionally, equipment with an Ingress Protection (IP) of 5 (or higher) against liquid ingress and a surface temperature rating below the auto-ignition temperature is often specified. Other protection concepts could also be used, such as intrinsic safety, encapsulation, or pressurisation.

Conclusions and Future Research

The findings from a four-year project on flammable mist formation and mitigation have been briefly summarised. Progress has been made in addressing the difficult problem of area classification for mist-forming fluids released below their flashpoint. The work has shown that some situations require more care with zoning than may previously have been appreciated, particularly for Release Class I fluids such as kerosene at pressures below 5 bar. In other cases, the work has indicated that hazardous zones may not be needed; for example, for Release Class III fluids such as lubricating or hydraulic oils in some specific circumstances at ambient temperatures and pressures up to 20 bar. Despite these useful findings and tentative guidelines, the work presented here represents just a starting point. Only a single nozzle size of 1 mm has been examined and the results are based on just three fluids in one particular configuration involving a downward-directed spray. The guidelines derived from these results should be treated with caution and used as only one input into a considered, professional examination of a given area classification problem.

There remain many unknowns, including:

- Do the guidelines apply equally well for other holes, not just for 1 mm diameter circular holes?
- What criteria should be used for defining the flammable zone? Is a single LEL criterion appropriate?
- In quiescent mists that are ignited from below with a strong ignition source, a very low LEL value of 5 g/m^3 has been measured experimentally. How should this finding be addressed by industry codes of practice?
- Can the build-up of mist in enclosures with/without ventilation be modelled reliably?
- Can a minimum size of mist cloud be defined, below which the consequences of an ignition are insignificant?
- What is the influence of spray impingement more generally on mist formation?

It is hoped that these questions, and others, can be addressed in future collaborative research programmes.

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References

Abramovich, G. N., 1963, Theory of turbulent jets, MIT Press, Cambridge, Massachusetts, USA.

ANSYS, 2013a, ANSYS CFX-15 User Guide, ANSYS, Inc., Canonsburg, Pennsylvania, USA.

ANSYS, 2013b, ANSYS Fluent Theory Guide, ANSYS, Inc., Canonsburg, Pennsylvania, USA.

Arai, M., Tabata, M., Hiroyasu, H., and Shimizu, M., 1984, Disintegrating process and spray characterization of fuel jet injected by a diesel nozzle, Society of Automotive Engineers (SAE) Technical Paper 840275.

Bowen, P.J., and Shirvill, L.C., 1994, Combustion hazards posed by the pressurised atomisation of high-flashpoint liquids, Journal of Loss Prevention in the Process Industries, 7(3): 233-241.

DNV, 2006, Droplet size theory document, Det Norske Veritas (DNV) Software, London, UK.

Energy Institute, 2015, Model code of safe practice: Area classification code for installations handling flammable fluids, Fourth Edition, Energy Institute, London, UK. (Available from: https://www.energyinst.org/technical/safety/ei-15-hazardous-area-classification, accessed 8 December 2015).

Gant S.E., Bettis R., Santon R., Buckland I., Bowen P. and Kay P., 2012, Generation of flammable mists from high flashpoint fluids: Literature Review" IChemE Hazards XXIII Conference, Southport, UK, 12-15 November 2012. Available from: http://www.icheme.org/~/media/Documents/Subject%20Groups/Safety_Loss_Prevention/Hazards%20Archive/XXIII/XXIII-Paper-43.pdf, accessed 8 December 2015.

Heywood J., 1988, Internal combustion engine fundamentals, McGraw-Hill.

IEC, 2015, Explosive atmospheres – Part 10-1: Classification of areas – explosive gas atmospheres, IEC 60079-10-1:2015, International Electrotechnical Commission (IEC), Geneva, Switzerland. (Available from: https://webstore.iec.ch/publication/23265, accessed 28 December 2015).

Maragkos, A., 2002, Combustion hazard quantification of accidental releases of high-flashpoint liquid fuels, PhD thesis, University of Wales, Cardiff.

Maragkos, A., and Bowen, P.J., 2002, Combustion hazards due to impingement of pressurised releases of high flashpoint liquid fuels, Proceedings of the Combustion Institute, 29(1): 305-311.

Menter, F. R., 1994, Two-equation eddy-viscosity turbulence models for engineering applications, AIAA Journal 32: 1598-1605.

Miesse, C. C., 1955, Correlation of experimental data on the disintegration of liquid jets, Ind. Eng. Chem., 47:1690-1701.

Ohnesorge, W.V., 1936, Die Bildung von Tropfen an Düsen und die Auflösung flüssiger Strahlen, Z. angew. Math. Mech., 16: 355–358. DOI: 10.1002/zamm.19360160611.

Reitz, R.D. and Bracco, F.V., 1979, On the dependence of the spray angle and other spray parameters on nozzle design and operating conditions, Society of Automotive Engineers (SAE) Technical Paper 790494.

Ruiz, F. and Chigier, N. A., 1991, Parametric experiments on liquid jet atomization, Atomization and Sprays, 1(1): 23-45.

Santon, R.C., 2009, Mist fires and explosions - an incident survey. Proc. IChemE Hazards XXI Symposium & Workshop, Manchester, UK. (Available from: https://www.icheme.org/~/media/Documents/Subject%20Groups/Safety_Loss_Prevention/Hazards%20Archive/XXI/XXI-Paper-054.pdf, accessed 29 December 2015).

Schmidt D. P. and Corradini M. L., 1997, Analytical prediction of the exit flow of cavitating orifices, Atomization and Sprays. 7(6): 603-616.

TNO, 2005, Methods for the calculation of physical effects due to releases of hazardous materials (liquids and gases) - Third edition Second revised print. (Available from: https://www.tno.nl/en/focus-area/urbanisation/environment-sustainability/public-safety/the-coloured-books-yellow-green-purple-red/, accessed 29 December 2015).

Webber, D.M., 2002, On defining a safety criterion for flammable clouds, Report HSL/2007/30, Health and Safety Laboratory, Buxton, UK. (Available from: www.hse.gov.uk/research/hsl_pdf/2007/hsl0730.pdf, accessed 29 December 2015).