Flammability Testing for Heavy Oil Mists

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High flash point liquids are used widely throughout industry for various purposes such as heating, lubrication and hydraulics. In many cases these high flash point liquids are handled at temperatures below their flash point, but even at these temperatures, a pressurised release has the potential to result in the formation of a flammable mist. This introduces a requirement to consider these materials as part of an assessment under the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR). The Energy Institute Model code of safe practice Part 15 (Energy Institue, 2015) provides an approach to determine the extent of the hazardous zones resulting from a pressurised release of a high flash point liquid. Recent studies have indicated that these zones may be over-conservative in some instances, placing a requirement on operators to implement potentially unnecessary risk reduction measures.

Gexcon have been working together with a large client in the UK energy sector to perform further research into the atomisation of heavy oils (Class G in BS 2869). A series of experiments have been performed to determine whether a release of these liquids will form an ignitable flammable cloud. The experiments have been conducted across a set of pressures and temperatures considering both an impinging jet and a free spray.

This paper outlines the findings of the experiments and discusses their potential implication on hazardous area classifications.

Keywords: Flammability, Heavy Oil, Mist, DSEAR, HAC, Hazardous Area Classification

Introduction

High flash point liquids are used widely throughout industry for a variety of purposes such as heating, power generation, lubrication and hydraulics. So long as the high flash point liquid is stored and used at a temperature below its flash point and at atmospheric pressure, it can be regarded as non-hazardous with respect to DSEAR (Statutory Instrument 2776, 2002) and hazardous areas are not commonly designated. However, in practice, applications will often require the high flash point liquid to be held under pressure for the purpose of distribution, dispensing and sealing. In such cases, a release may result in atomisation and the formation of a flammable mist, which could be ignited by an effective source of ignition and behaves in a similar fashion to a flammable gas cloud. The likelihood of a formation of a flammable mist upon release of a high flash point liquid under pressure is dependent on many factors such as the release conditions (mainly pressure and temperature), the material properties including the flash point and viscosity, as well as the size and shape of the release orifice. Compared to the release of a flammable gas, the number of influencing factors for the generation of a flammable mist leads to a greater uncertainty when classifying hazardous areas as part of a DSEAR assessment. The EI15 model code of safe practice Part 15 '*Area classification for installations handling flammable fluids'* (Energy Institue, 2015) divides flammable and combustible liquids into different fluid categories and uses the release pressure and expected release hole diameter to provide guidance with respect to the required hazardous area classification for this type of event. However, the guidance within EI15 is based on limited research and only offers a broad approach to determine hazardous distances because various fluids with wide ranging properties are grouped in the same fluid category. With regards to the minimum pressure sufficient to generate a flammable mist EI15 Section A 1.2 refers to a paper by P.J. Bowen and L.C. Shirvill (P.J. Bowen, n.d.) in which it is concluded that "a few bar" of pressure are sufficient to atomise commonly encountered liquids. In practice, this simple guidance often leads to conservative hazardous area classifications, which may impose unnecessary costs on the operator of a facility with regards to risk reduction and the avoidance of sources of ignition in these hazardous areas.

Additional guidance to determine whether a pressurised release of a liquid may lead to the generation of a flammable mist is provided in the final report of report RR1107 *'Area classification for oil mists – final report of a Joint Industry Project*' (Health and Safety Executive, 2017) which introduces four different Release-classes depending on how easily the fluid can be atomised as well as the flash point of the fluid. Based on these Release-classes, recommendations regarding the Hazardous Area Classification are made. Though this research allows certain liquids under specific release conditions to be regarded as 'non-hazardous', the report refers the reader back to the guidance provided in EI15 for release conditions that are often encountered when assessing common applications using combustible liquids.

Gexcon have been working together with a large energy sector client based in the UK to further investigate the likelihood of generating a flammable mist upon release of heavy oils (Class G in BS 2869) when held under pressure, either by impingement or as a free spray. The experimental testing carried out as part of this project investigated the likelihood of generating a flammable mist following the pressurised release of heavy fuel oil as a free spray. Additionally, the influence of impingement was investigated. The aim of the work was either to verify the current hazardous area classification for this process, which is based on guidance from EI15 and report RR1107, or to provide experimental evidence that the formation of a flammable mist is unlikely for the specific grade of heavy oil and potential release conditions relevant for this specific application.

Existing Guidance and Experimental Research

A common approach for hazardous area classifications for applications which include the storage or use of flammable liquids is to follow the guidance outlined in the Model code of safe practice Part 15 – Area classification for installations handling flammable fluids (Energy Institue, 2015). The guidance requires categorisation of substances according to their properties in order to determine the most appropriate approach for a hazardous area classification. Table A1 within the guidance designates Petroleum classes 0 – III with increasing flash points, liquids with a flash point above 100°C are "unclassified". For high flash point liquids Section A 1.4 of EI15 provides guidance that if the temperature of the liquid cannot be raised to its flashpoint nor is it held under pressure sufficient to cause the formation of a flammable mist upon release, then applying a hazardous zone for this application is not required. Section A 1.2 suggests that for commonly encountered liquids “a few bar” of pressure is sufficient to cause atomisation upon release through a small hole and potentially generate a flammable mist. Additional reference is made to tests conducted as part of a Joint Industry Project (JIP) which indicate that for a kerosene release, pressures in the region of 1 barg are sufficient to support the formation of a flammable mist. Guidance for the extent of hazardous areas is given within EI15 in Table C4.

In practice this relatively vague threshold for the minimum pressure regarded as capable of resulting in the formation of flammable mists may cause uncertainty when applying the guidance, potentially leading to areas incorrectly being considered to be ‘non-hazardous’. In other cases, the uncertainty may result in overly conservative hazardous area classifications, including the designation of hazardous zones around potential points of release, which in practice may not pose the risk of a formation of a flammable mist.

Since the publication of the latest edition of EI15 (Energy Institue, 2015) in June 2015 the Joint Industry Project ‘Area classification for oil mists’ has been concluded and the final report has been prepared by the Health and Safety Executive as Report RR1107 (Health and Safety Executive, 2017). The report suggests that fluid applications can be classified in four Release-classes based on the flash point of the liquid held under pressure as well as the Ohnesorge ratio, which is dependent on extensive and intensive properties of the fuel. Most fuel applications fall into either Release-class I or Release-class II, with Release-class II applying to more viscous fuels such as fuel oils. Based on the classification into Release-classes, the test report provides recommendations with regards to the required hazardous area classification. Specifically, for Release-class III (less volatile and less atomising liquids such as hydraulic oils) report RR1107 suggests that for release hole diameters of 1mm and above and a release pressure below 20 barg, the generation of a flammable mist upon release is unlikely and no hazardous area is required to be classified.

On-site application & Testing Background

The heavy oil (Class G according to BS 2869) is used on-site as a fuel oil for boilers. The fuel is delivered by the supplier with varying properties. The flash point of the fuel is declared to be 66 °C, however in reality the flash point varies from batch to batch and can be as high as 125 °C. Following delivery of the fuel, the oil is stored at ambient temperature and only a few metres of head pressure. The report *‘Area classification for oil mists – final report of a Joint Industry Project’* RR1107 (Health and Safety Executive, 2017) suggests that these conditions would fall under Release-class II. Based on the conclusions within this report no hazardous area is required for this Release-class if the release hole size is 1 mm or greater, the release pressure is less than 20 barg and there is no possibility of impingement.

From the bulk storage the fuel oil is distributed to the pumphouse. Downstream from the pumphouse the fuel pressure is increased to around 40 barg and the temperature is increased to between 90°C and 130°C. For this type of application RR1107 (Health and Safety Executive, 2017) recommends that the fuel should be classed as a Category C fluid according to EI15 and the relevant guidance given within EI15 Table C4 should be followed with regards to the extent of hazardous areas. Based on an assumed 1 mm release hole diameter, this results in hazardous zones with an extent of up to 3 m.

The objective of the testing was to gather more conclusive information and practical examples of how this class of fluid behaves in controlled conditions providing more accurate input information for the hazardous area classification for equipment handling heavy oils in this specific application.

Flammability Tests

Two series of tests were carried out to investigate the flammability of heavy oil mists through impingement or as a free spray. The release temperature and pressure were adopted from the application on-site, in order to produce test results which give an indication of the likelihood of generating a flammable mist for the specific process parameters encountered on-site. Table-1 and Table-2 below highlight the release conditions considered for this set of tests. Experiments for the free spray tests were carried out with different hole diameters ranging from 1 mm to 2 mm. Experiments for the impingement test conditions were carried out using a 0.5mm nozzle. In both series of tests, the generation of mist clouds and their ignitability was monitored.

Table-1 Oil Mist Flammability Testing Conditions (free spray)

Pressure (bar) Max	Temperature (°C) Max
1.2	60
20	145
50	145

Table-2 Oil Mist Flammability Testing Conditions (impingement)

Pressure (bar) Max	Temperature (°C) Max
1	145
4	145
7	145

Test Series One: Flammable Mist Formation through Impingement

Testing of the likelihood of generating a flammable mist when the fuel oil is released under pressure into a small, confined area, resulting in impingement, was carried out in a closed but vented combustion chamber. A schematic of the test arrangement is illustrated in Figure 1 below. A sample of the heavy fuel oil (Class G in BS2869) is kept in a high-pressure reservoir at up to 150 bar and heated to the required release temperature. To simulate the release of the heavy oil under pressure the actuated valve (4) is opened, and the oil sample is released into the combustion chamber through a nozzle. For the first series of tests, an oscillating electric arc was used as ignition source. The generation and ignition of the mist cloud was monitored through a transparent wall of the combustion chamber. Photographs of the test arrangement are provided in Figure 2 and Figure 3.

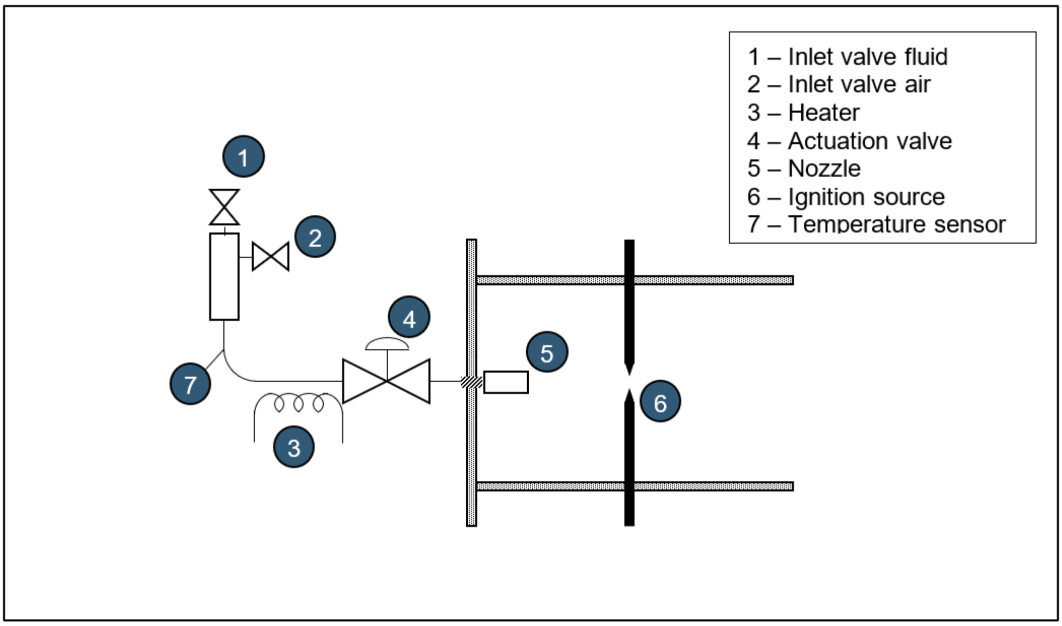

Figure 1- Mist Flammability Test Setup Schematic

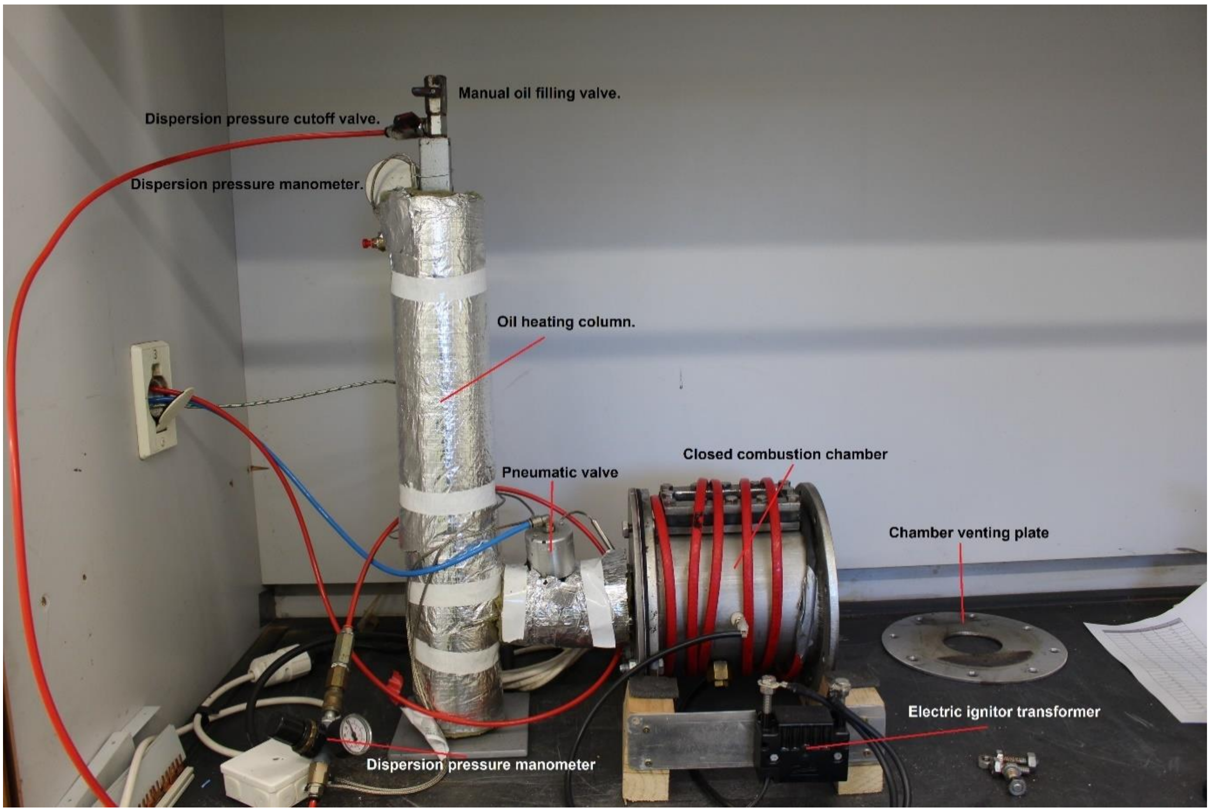

Figure 2 - Oil Mist Flammability Test Setup - Closed Vessel

Figure 3 - Oil Mist Flammability Test Setup - Closed Vessel (Internal)

Test Series Two: Flammable Mist Formation as a Free Jet

The second series of tests was conducted to investigate the formation of flammable mists following a release of pressurised fuel oil as a free spray. For this purpose, the test arrangement illustrated in Figure 1 was modified. The closed combustion chamber was removed to allow a free development of the heavy oil jet following the pressurised release. The free spray testing rig consisted of an oil reservoir with a capacity of approximately 225 ml, a pneumatically activated valve system, a dispersion nozzle, an oil heating system, and a dispersion driving pressure system. The oil reservoir could be manually opened via a ball valve for oil filling. Similar to the first test series, an electric arc ignition source was employed for ignition of the oil mist generated during testing.

The dispersion driving pressure was verified and monitored with an IKM Instrutek DMT-1 digital manometer, while the temperature was verified and regulated by a Shimaden SRS1 temperature controller using a K-type thermocouple and a braided cord style heating element. The heating element was tightly wrapped around the bottom section of the oil reservoir as depicted in Figure 4, as well as being wrapped just above the oil dispersion nozzle, which is not depicted. The heating of the area just above the nozzle was added to avoid potential blockage caused by cooler oil thickening in the small chamber just below the pneumatic valve.

In addition to the electric arc, a pilot flame was used as an ignition source for one of the test series. The tests were repeated with varying distances between the nozzle and the source of ignition to investigate the maximum distance between nozzle and ignition source which results in an ignition.

Pictures of the test arrangement are illustrated in Figure 4 and Figure 5 below.

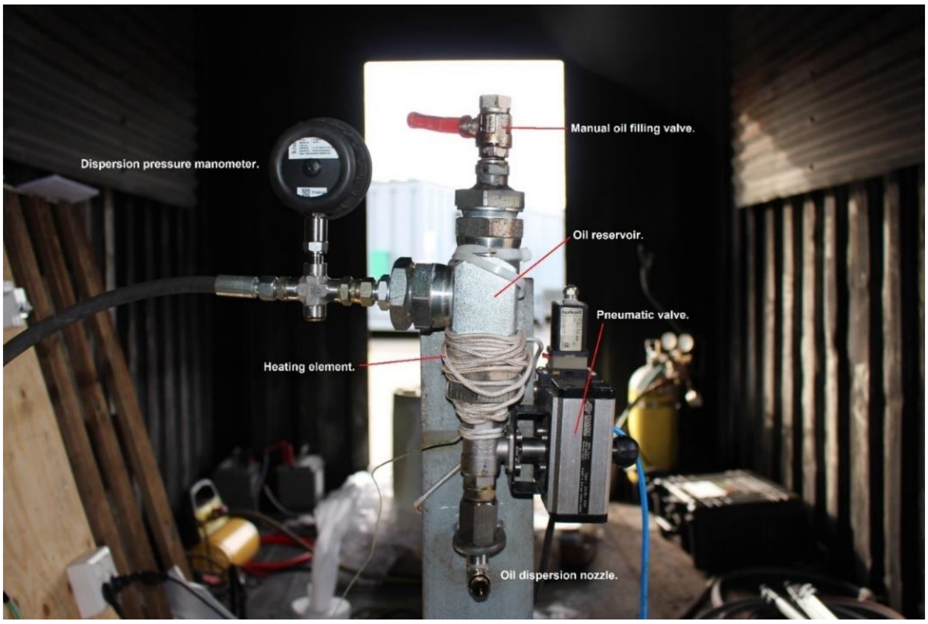

Figure 4 - Oil Mist Flammability Test Setup – Open Jet

Figure 5 - Oil Mist Flammability Test Setup - Open Jet - side view

Test Results

Closed Chamber Experiments

A total of 9 full value tests were conducted with closed chamber conditions. A full value test is defined as a test that was given a test number, with full result notation taken.

The closed chamber experiments were performed with a 0.5 mm nozzle only; the larger nozzles resulted in high flow rates causing flooding of the interior of the chamber with oil. This resulted in large inconsistencies in the results during exploratory testing.

All tests were performed with a dispersion time of 1.5 seconds. The combination of pressures and temperatures tested is shown in Table-3. In every case except for 1.0 barg at 65°C, the oil was dispersed and subsequently ignited. In the case of the test at 1.0 barg and 65°C, no oil dispersion was noted at all. The inside of the vessel was checked, and with the exception of 2-3 drops of oil, no dispersion was observed even after multiple dispersion attempts.

A secondary explosion could be observed during several of the closed chamber experiments. This is likely due to an increase in ambient temperature from the initial ignition which then causes accelerated vaporisation of the contained oil droplets, leading to an oil vapor cloud which is more susceptible to ignition than the mist cloud itself.

A collection of the results can be seen in table 3 below.

Table-3 Results for the closed chamber tests.

Pressure (barg)	Temperature (C)	Ignition? (yes/no)
1	65	No, and no dispersion of oil
4	65	Yes
7	65	Yes
1	100	Yes
4	100	Yes
7	100	Yes
1	145	Yes
4	145	Yes
7	145	Yes

Free jet experiments

A total of 72 full value tests were conducted with free jet conditions. In this section, only the full value tests will be discussed, although a number of other diagnostic and exploratory tests were conducted in parallel with the full value tests.

Experiments using 1.0 mm nozzle

Testing with the 1.0 mm nozzle is broken down into several sections defined by their parameters. The 1.0 mm nozzle was tested with 1.2 barg driving pressure at 65°C and 145°C, at 20 barg at 145°C and at 50 barg at 145°C. Please note that the temperatures reported are the temperatures of the oil, not the surrounding environment.

The tests at 1.2 barg provided no mist generation, and therefore no ignition at any distance.

The tests at 20 barg were performed with an oil temperature of 145°C. This led to consistent ignition of the mist cloud to a distance of 0.75 m. At 1.0 m ignition became less reliable, igniting only 6 times out of 10. No ignition was noted at distances of 1.25 m or 1.5 m.

The tests at 50 barg were performed with an oil temperature of 145°C. This led to consistent ignition of the mist cloud out to a distance of 1.75 m. At a distance of 2.0 m ignition became less reliable, igniting only 5 times out of 8. No ignition was noted at distances above 2.0 m.

A collection of the results can be seen in Table-4 below.

Table-4 Results for the 1.0 mm nozzle tests during the free jet experiments.

Pressure (barg)	Temperature (C)	Maximum Consistent Ignition Distance	Maximum Ignition Distance	Minimum No-Ignition Distance
1.2	65	No ignitions or mist generation.	No ignitions or mist generation.	No ignitions or mist generation.
1.2	145	No ignitions or mist generation.	No ignitions or mist generation.	No ignitions or mist generation.
20	145	0.75 meters.	1.0 meters. 6 ignitions out of 10.	1.25 meters.
50	145	1.75 meters.	2.0 meters. 5 ignitions out of 8.	2.25 meters.

Experiments using 1.65 mm nozzle

Testing with the 1.65 mm nozzle is broken down into several sections defined by their parameters. Experiments were performed at 1.2 barg driving pressure at 65°C, at 20 barg at 145°C and at 50 barg at 145°C. Again, the temperatures reported are the temperatures of the oil, not the surrounding environment.

As above, the tests at 1.2 barg did not result in any mist generation, and therefore no ignition at any distance.

The tests at 20 barg were performed with an oil temperature of 145°C. This led to consistent ignition of the mist cloud out to a distance of 2.0 m. At 2.25 m ignition became less reliable, igniting only 6 times out of 10. No ignition was noted at distances above 2.25 m, but it was noted that at this distance, gravity and drag began to heavily influence the mist cloud, which was unable to reliably reach the ignition source at distances beyond 2.5 m.

The tests at 50 barg were performed with an oil temperature of 145°C. This led to consistent ignition of the mist cloud at a distance of 1.25 m. At 1.5 m ignition became less reliable, igniting only 5 times out of 10. No ignition was noted at distances above 1.5 m. These results were noted as being curious, as the increased pressure reduced the distance at which the mist cloud would ignite, with the distance being even lower than when compared with the 1.0 mm nozzle. However, after many diagnostic and explorative tests, it was determined that the higher dispersion pressure resulted in an increased spraying angle, which seems to add volume to the mist cloud so that the drag forces overwhelm it, preventing it from traveling as far as anticipated.

A collection of the results can be seen in Table-5 below.

Table-5 Results for the 1.65 mm nozzle tests during the free jet experiments.

Pressure (barg)	Temperature (C)	Maximum Consistent Ignition Distance	Maximum Ignition Distance	Minimum No-Ignition Distance
1.2	65	No ignitions or mist generation.	No ignitions or mist generation.	No ignitions or mist generation.
20	145	2.0 meters.	2.25 meters. 6 ignitions out of 10.	2.5 meters.
50	145	1.25 meters.	1.5 meters. 5 ignitions out of 10.	1.75 meters.

Experiments using 2.0mm Nozzle

Testing with the 2.0 mm nozzle is broken down into several sections defined by their parameters. Experiments were performed at 1.2 barg driving pressure at 65°C, at 20 barg at 145°C and at 50 barg at 145°C. Please note that the temperatures noted are the temperatures of the oil, not the surrounding environment.

The tests at 1.2 barg provided no mist generation, and therefore no ignition at any distance. This is consistent with previous results.

The tests at 20 barg and 50 barg resulted in mist generation, but the mist did not ignite at any of the tested distances. This is assumed to be due to the larger mist droplet size that a larger nozzle generates. To verify the test results, a propane burner was used as a potential source of ignition for three of the tests, but this did not result in ignition of the mist either. The mist cloud was also observed to sink rapidly after dispersion, again assumed to be a product of the large droplet size, which yielded increased droplet rainout.

A collection of the results can be seen in Table-6 below.

Table-6 Results for the 2.0 mm nozzle tests during the free jet experiments.

Pressure (barg)	Temperature (C)	Maximum Consistent Ignition Distance	Maximum Ignition Distance	Minimum No-Ignition Distance
1.2	65	No ignitions or mist generation.	No ignitions or mist generation.	No ignitions or mist generation.
20	145	Mist generated, but no ignitions.	None found.	None found.
50	145	Mist generated, but no ignitions.	None found.	None found.

Comparison of test results with standard Hazardous Area Classification approach

Table 7 below provides a comparison between experimental test results and Hazardous Area Classification guidance as provided in EI15 Table C4 and RR1107 Section 6.2.3. When comparing the test results with relevant guidance, it is apparent that none of the experimental tests with combinations of release parameters which would lead to a 'non-hazardous' classification when following the above guidance indicated the formation of a flammable mist. Additionally, none of the experiments carried out led to an ignition at a greater distance than the relevant hazardous area extent as indicated in relevant guidance documents.

It should be noted that, generally, EI15 Table C4 indicates an increasing hazardous area extent with increasing pressure and release hole diameter. Specifically, test conditions 9 and 10 in the table below indicate that this general correlation may not always be applicable. However, it should be noted that whether an increased release hole diameter leads to an increased droplet size which reduces the likelihood of generating a flammable mist will likely depend on various other factors such as the viscosity and density of the released fluid.

The adverse effect of impingement which increases the likelihood of generating a flammable mist, as suggested in RR1107 and EI15, can be observed in the summary of the test results in Table 7.

Table 7 - Comparison between experimental test results and HAC guidance from EI15 and RR1107

#Ref Test Conditions	Test Conditions	Ignition	Maximum Ignition Distance [m]	Guidance HAC distance [m]	Comment
1	Free Jet – 1.2 barg / 65°C / 1mm nozzle	No	N/A	Non-hazardous	Based on RR1107, for Release-Class II
2	Free Jet – 1.2 barg / 145°C / 1mm nozzle	No	N/A	2	Based on EI15 Table C4 R_1 for Fluid Category C / 5 barA
3	Free Jet – 20 barg / 145°C / 1mm nozzle	Yes	1	2.5	Based on EI15 Table C4 R_1 for Fluid Category C / 50 barA
4	Free Jet – 50 barg / 145°C / 1mm nozzle	Yes	2	2.5	Based on EI15 Table C4 R_1 for Fluid Category C / 50 barA
5	Free Jet – 1.2 barg / 65°C / 1.65mm nozzle	No	N/A	Non-hazardous	Based on RR1107, for Release-Class II
6	Free Jet – 20 barg / 145°C / 1.65mm nozzle	Yes	2.25	5	Based on EI15 Table C4 R_1 for Fluid Category C / 50 barA and 2mm release hole diameter
7	Free Jet – 50 barg / 145°C / 1.65mm nozzle	Yes	1.5	5	Based on EI15 Table C4 R_1 for Fluid Category C / 50 barA and 2mm release hole diameter
8	Free Jet – 1.2 barg / 65°C / 2mm nozzle	No	N/A	Non-hazardous	Based on RR1107, for Release-Class II
9	Free Jet – 20 barg / 145°C / 2mm nozzle	No	N/A	5	Based on EI15 Table C4 R_1 for Fluid Category C / 50

#Ref Test Conditions	Test Conditions	Ignition	Maximum Ignition Distance [m]	Guidance HAC distance [m]	Comment
					barA and 2mm release hole diameter
10	Free Jet – 50 barg / 145°C / 2mm nozzle	No	N/A	5	Based on EI15 Table C4 R_1 for Fluid Category C / 50 barA and 2mm release hole diameter
11	Closed Chamber – 1 barg / 65°C / 0.5mm nozzle	No	N/A	2	Based on EI15 Table C4 R_1 for Fluid Category C / 5 barA and 1mm release hole diameter
12	Closed Chamber – 4 barg / 65°C / 0.5mm nozzle	Yes	N/A	2	Based on EI15 Table C4 R_1 for Fluid Category C / 5 barA and 1mm release hole diameter
13	Closed Chamber – 1 barg / 100°C / 0.5mm nozzle	Yes	N/A	2	Based on EI15 Table C4 R_1 for Fluid Category C / 5 barA and 1mm release hole diameter
14	Closed Chamber – 1 barg / 145°C / 0.5mm nozzle	Yes	N/A	2	Based on EI15 Table C4 R_1 for Fluid Category C / 5 barA and 1mm release hole diameter

Conclusion

A series of oil-mist dispersion and ignition tests have been performed, in both free-air and confined/vented test volumes, using fuel oil (Class G according to BS 2869). The oil temperature and dispersion pressure has been varied along with the location of the ignition source in order to map or characterise the sensitivity of the system to dispersion extent and ignitability. This paper describes the conditions under which the experiments were performed and compares the test results with existing guidance on conducting a Hazardous Area Classification as provided in EI15 and RR1107.

During the free jet tests, it was found that a driving pressure of 1.2 barg was insufficient to generate an oil mist at all, and no ignition was observed. Driving pressures of 20 barg and 50 barg generated ignitable oil mists with the 1.0 mm and 1.65 mm nozzles, while the 2.0 mm nozzle was unable to generate an ignitable oil mist at any of the tested driving pressures.

For the closed chamber tests, it was found that 1 barg driving pressure was sufficient to generate a combustible environment so long as the oil temperature was high enough to allow for dispersion to take place. The testing found that a flammable mist was generated with all other driving pressures at the minimum tested oil temperature of 65°C and above.

Based upon the observations from the experiments performed, it is shown that the tested fuel oil is very likely to generate oil misting under various operating conditions, and that said oil mist clouds were found to be ignitable up to certain distances depending on various dispersion conditions.

When comparing the test results with relevant HAC guidance from EI15 and RR1107 it can be observed that for experiments which generated a flammable mist, the maximum distance to ignition was consistently below the hazardous area extent as indicated in the above-mentioned guidance. It should however be noted that the guidance as provided in EI15 and RR1107 applies to a range of fluids, some of which are likely to be more susceptible to a generation of flammable mists when released under pressure. It is therefore difficult to make a general judgement on the conservatism of existing guidance such as presented in EI15 and RR1107 based on the limited scope of experiments carried out in this project. Additional experiments reviewing a wide range of fluids and release characteristics should be carried out to further investigate the likelihood and extent of flammable mists generated when releasing fluids under pressure.

Although the experimental tests carried out in this project indicate that, for this specific application the distance at which a flammable mist may be ignited is below the hazardous area extent derived from guidance provided in EI15 and RR1107, the hazardous area classification on-site was not changed. This is mainly because the difference between applied hazardous distances and test results were not sufficiently large to warrant a reduction of hazardous areas on-site. Additionally, it would be considered appropriate to apply a safety factor when basing hazardous distances on experiment results to account for varying conditions on-site. This would further reduce the difference between the current hazardous area classification based on guidance from EI15 and RR1107 and hazardous area extents based on the outcome of the experiments.

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