

Liquid classification for flammable mists

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Many types of industrial equipment can potentially produce an explosive oil mist if a fault develops. However, information on the conditions in which a mist can be ignited and continue to burn is limited. To help address this, HSE and 14 industry sponsors co-funded a Joint Industry Project (JIP) on oil mist formation and ignition.

This report, produced for the JIP, addresses the contribution the fluid within a pressurised system makes to the risk of an ignitable mist forming if a leak develops.

Fluids were put into three groups, based on their flashpoint and ease of atomization: “volatile fuels” include fuels and solvents which have a low flashpoint and atomize easily; “lubricants” include many actual lubricants and also heat transfer fluids and other oils with a relatively high flashpoint and poor atomization; “fuel oils” which have a low flashpoint but poor atomization.

When heated, “fuel oils” should show similar behaviour to “volatile fuels”.

This work was used to select a representative fluid from each group for use in experimental tests.

This report and the work it describes were funded through a Joint Industry Project. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy or the views of the Joint Industry Project sponsors.

Liquid classification for flammable mists

Graham Burrell and Dr Simon Gant
Health and Safety Executive
Harpur Hill
Buxton
Derbyshire SK17 9JN

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EXECUTIVE SUMMARY

Objectives

The purpose of this report is to propose a classification system in order to group together the following liquids according to their potential to form flammable mists from pressurised releases:

- Lubricating Oil
- Hydraulic Oil
- Light Fuel Oil
- Heavy Fuel Oil
- Jet Fuel/Kerosene
- Diesel
- Bio-diesel
- Vegetable Oil
- Heat Transfer Fluid
- Transformer Oil
- Process Fluids (Solvesso)
- White Spirit

Main Findings

A classification system has been developed based on the flashpoint and estimated ease of atomisation, and the above liquids have been separated into three groups. Group one, “volatile fuels and solvents” atomise easily and have a relatively low flashpoint, a typical example being diesel. Group two, “lubricants” consists of heat transfer fluids and various application oils that have both a high flashpoint and a high resistance to atomisation. Group three “fuel oils” consists of petroleum fractions that have a low flashpoint and high resistance to atomisation at ambient temperature. It is believed that at elevated temperatures (i.e. once pre-heated) the properties of “fuel oils” should be similar to that of diesel. The limited data that were found for the properties of bio-diesel indicate that its behaviour lies between groups one and two.

Recommendations

To investigate a range of different fluid properties, it is recommended to conduct mist flammability tests using the following five liquids:

1. Lubricating oil (group 1 exemplar)
2. Kerosene (group 2 exemplar)
3. Light Fuel Oil at ambient temperature (group 3 exemplar)
4. Light Fuel Oil pre-heated before release
5. Bio-diesel

1 INTRODUCTION

A Joint Industry Project (JIP) is currently in progress to assess the risks resulting from flammable mists produced by pressurised releases of high flashpoint liquids through small orifices [1]. A number of liquids have been suggested for experimental investigation:

- Lubricating Oil
- Hydraulic Oil
- Light Fuel Oil
- Heavy Fuel Oil
- Jet Fuel/Kerosene
- Diesel
- Bio-diesel
- Vegetable Oil
- Heat Transfer Fluid
- Transformer Oil
- Process Fluids (Solvesso)
- White Spirit

Experimental measurements of the flammable mist properties of each of these liquids would be costly, time-consuming and have limited benefits, since many of the liquids are variable in terms of their composition and material properties.

To rationalise the selection of liquids for testing in the future JIP experiments, the present report presents a flammable mist classification system. This system uses two parameters to estimate the propensity for a liquid to form a flammable mist: the ignitability of the liquid (represented here by the flashpoint) and the tendency for a liquid jet to atomise into droplets when released through an orifice. For this latter measure, the atomisation behaviour is assessed using two different empirical correlations: the primary atomisation correlation from Ohnesorge [2] and the secondary atomisation correlation of Brodkey [3].

This results in a classification system separating the selected liquids into distinctive categories based on modelled behaviour. A number of exemplar liquids have been suggested including a representative liquid from each category.

2 LIQUID BREAK-UP

2.1 PRIMARY BREAK-UP

In 1936, Ohnesorge [2] published the results from a series of experiments that examined the primary break-up of pressurised liquid jets through an orifice (Figure 1). The experiments were undertaken with various oils, glycerine, aniline, and water using orifice diameters of between 0.5 mm and 4.0 mm. Liquid jet break-up was characterised into three regimes: Rayleigh, wind-induced and atomisation, based on the Reynolds and Ohnesorge numbers. The mean diameters of the droplet distribution become progressively smaller from each of these regimes.

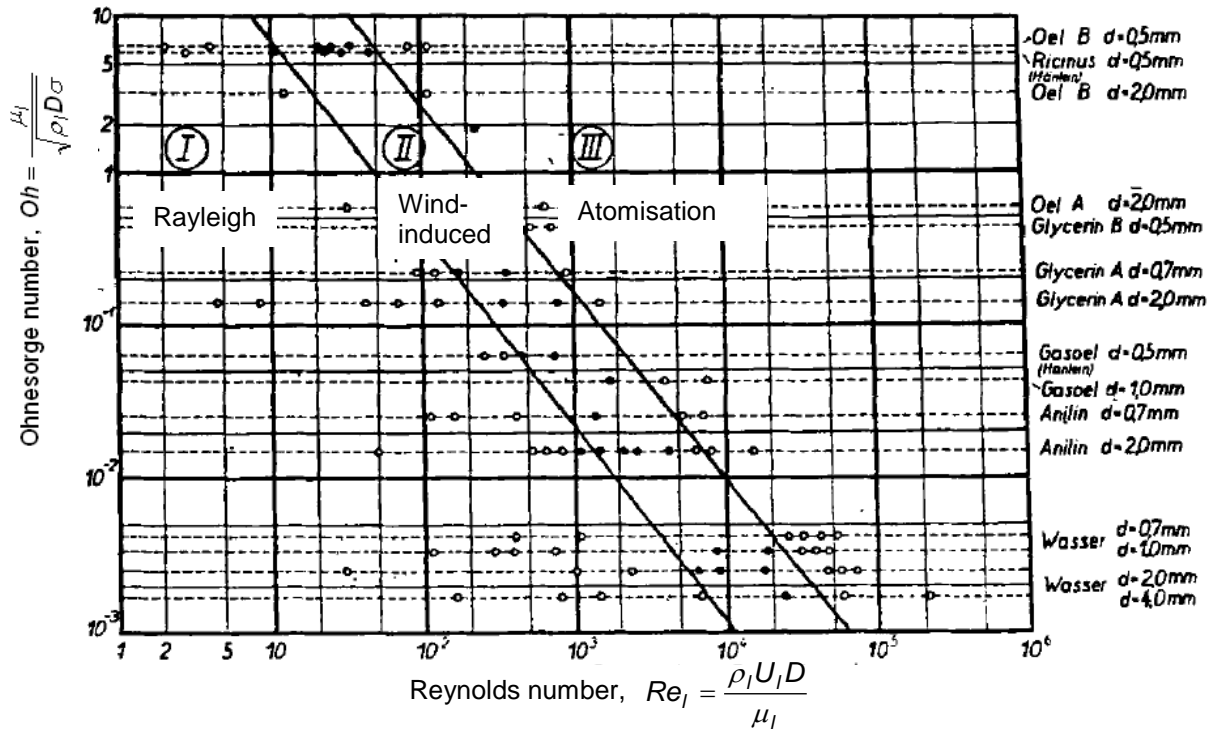


Figure 1 – Spray breakup regimes, from Ohnesorge [2]

The Reynolds number was determined by Ohnesorge [2] from:

$$Re_l = \frac{\rho_l U_o d_o}{\mu_l} \quad (1)$$

where:

ρ_l = Density of liquid (kgm^{-3});

d_o = Diameter of orifice (m);

μ_l = Dynamic viscosity of liquid ($\text{kgm}^{-1}\text{s}^{-1}$); and

U_o = Velocity of liquid at the orifice (ms^{-1}).

The velocity here can be calculated from Bernoulli's equation.

$$\Delta P = \frac{1}{2} \rho_l U_o^2 \quad (2)$$

where ΔP is the difference in pressure across the orifice (Pa).

The Ohnesorge number was determined from:

$$Oh = \frac{\mu_l}{\sqrt{\rho_l d_o \sigma_l}} \quad (3)$$

where σ_l is the surface tension (kgs^{-2}).

By digitally scanning the graph presented by Ohnesorge [2] (Figure 1), the transition from wind-induced to atomisation break-up was determined by Gant [4] to occur at or above the critical Ohnesorge number, given by:

$$Oh_{Cr} = 745 \text{Re}_l^{-1.22} \quad (4)$$

In the present work, to classify different liquids according to their propensity to atomise, the following parameter has been determined for each liquid:

$$\frac{Oh}{Oh_{Cr}} = \frac{\mu_l / \rho_l d_o \sigma_l}{745 (\rho_l U_o d_o / \mu_l)^{-1.22}} \quad (5)$$

based on reference conditions of a 10 bar pressure drop ($\Delta P = 10^6$ Pa) and 1 mm orifice diameter ($d_o = 10^{-3}$ m).

2.2 SECONDARY BREAK-UP

Droplets formed by the primary break-up of the liquid jet will continue to move under momentum and are subject to both internal and aerodynamic forces. If the droplet is above a critical size, the aerodynamic resistance will induce internal instabilities, which will lead to droplet deformation and break-up. These forces are characterised by the Weber number:

$$We = \frac{\rho_l U_D^2 d_D}{\sigma_l} \quad (6)$$

where:

d_D = Diameter of droplet (m), and

U_D = The relative velocity between the droplet and the surrounding air (ms^{-1}), assumed to be equal to the initial liquid velocity at the orifice, U_o .

Above a characteristic value of We , the droplet is unstable aerodynamically and will break up. This “upper limit” for stability is called the critical Weber number (We_{cr}).

Brodkey [3] derived the following empirical correlation for the critical Weber number as a function of the droplet Ohnesorge number:

$$We_{cr} = 12 \left(1 + 1.077 Oh_D^{1.6} \right) \quad (7)$$

where:

$$Oh_D = \frac{\mu_l}{\sqrt{\rho_l d_D \sigma_l}} \quad (8)$$

In the present work, to classify different liquids according to their propensity to atomise, the following parameter has been determined for each liquid:

$$\frac{We}{We_{cr}} = \frac{\rho_l U_D^2 d_D / \sigma_l}{12 \left[1 + 1.077 \left(\mu_l / \sqrt{\rho_l d_D \sigma_l} \right)^{1.6} \right]} \quad (9)$$

based on reference conditions of a 10 bar pressure drop ($\Delta P = 10^6$ Pa) and an atomised droplet diameter of 30 μm ($d_D = 3 \times 10^{-6}$ m).

3 DATA SOURCES FOR LIQUIDS

None of the listed liquids are pure chemical compounds but refer to either a mixture of chemicals whose composition may vary from source to source (e.g. diesel), or any liquid mixture used for a specific application (e.g. lubricating oil). Material property data for each of the liquids has been sourced from a number of references [5 –24]. Since the liquid name could refer to separate blends or chemicals, different sources state different properties for the same liquid name. Therefore, wherever possible the same source has been used to quote the experimental value for all parameters.

Material properties are temperature dependent so for simplicity, data has been obtained for typical ambient temperatures (15 – 20 °C). Where data is not available at ambient temperatures, estimations have been made from data quoted for elevated temperatures using a linear or single term polynomial trend line for surface tension and viscosity respectively.

To provide an estimate of the range of behaviour of each liquid, the highest or lowest reported value from any reference at ambient temperature has also been quoted.

Furthermore, some references quote a kinematic viscosity. This has been converted to an absolute viscosity using the density value quoted for the same liquid in the same source. However, since the density is known to change with temperature, this conversion is only accurate for values at the temperature for which the density is quoted.

3.1 LUBRICATING OIL

Lubricating oil can refer to any liquid used for the purposes of lubrication. It can also refer to a fraction of petroleum distillate with a boiling point in excess of 400 °C. Petroleum derived lubricating oils hold the largest market share but other synthetic oils are available. The essential parameters for the selection of lubricating oil are a high viscosity and high boiling point. The values used for analysis are quoted in Table 1.

Table 1 – Lubricating oil physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	872.4	1004.4	846.0
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.183	0.8569	0.10005
Surface tension (kgs^{-2})	0.03135*	0.0314	0.0313
Flashpoint (°C)	239	288	188

* Averaged new compressor and turbine oil at 15 °C

3.2 HYDRAULIC OIL

The primary purpose of hydraulic fluids is to transfer force from one location to another but most hydraulic fluids are based on a petroleum fraction, mineral oil. This base stock shows the required compressibility as well as having useful properties for lubricating machinery. Therefore hydraulic oil properties can be expected to be similar to lubricating oils. The values used for analysis are quoted in Table 2.

Table 2 – Hydraulic oil physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	872.7	882.1	837.5
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.102		
Surface tension (kgs^{-2})	0.0214		
Flashpoint ($^{\circ}\text{C}$)	182	258	96

Values for Esso XD3-10 at 15 °C

3.3 LIGHT FUEL OIL

Fuel oil is a petroleum fraction product that is used to make liquid petroleum fuels. The ASTM defines Fuel oil into 6 grades. Light Fuel oil covers grades 1-3, which are blends of distilled oil, and cover the boiling point range of kerosene and diesel. The values used for analysis are quoted in Table 3.

Table 3 – Light Fuel oil physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	930		900
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.172		
Surface tension (kgs^{-2})	0.025		
Flashpoint ($^{\circ}\text{C}$)	66	187	

Data for 15 °C

3.4 HEAVY FUEL OIL

Fuel oil grades 4-6 are blends of residual fractions of petroleum. Most are too viscous to be useable at ambient temperatures and must be pre-heated, prior to pumping or use in engines. The values used for analysis are quoted in Table 4.

Table 4 – Heavy Fuel oil physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	988.8	1014	953.7
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	12.45*	22.8	
Surface tension (kgs^{-2})	0.0238#	0.0329	
Flashpoint ($^{\circ}\text{C}$)	111		

* Extrapolation using single term polynomial function from Lefebvre [6] quoted values at 40, 93 and 127 to 15 °C

Extrapolation using linear function from Lefebvre [6] quoted values at 40, 93 and 127 to 15 °C

3.5 JET FUEL/KEROSENE

Kerosene is a product derived from distilling petroleum in the boiling range 150 – 275 °C. It is used in a range of applications from lamps to jet fuel and so has a range of specifications. The values used for analysis are quoted in Table 5.

Table 5 – Jet Fuel/Kerosene physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	800	848.3	766.8
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.0016		0.001
Surface tension (kgs^{-2})	0.026	0.032	0.0226
Flashpoint (°C)	56	38	72

Data for 20 °C

3.6 DIESEL

Diesel fuel can refer to any fuel used in a diesel engine but for the purposes of this report it refers to fuel derived from the distillation of petroleum in the boiling range 200 – 350 °C. The values used for analysis are quoted in Table 6.

Table 6 – Diesel physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	831	950	
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.00276		
Surface tension (kgs^{-2})	0.0275	0.028039*	
Flashpoint (°C)	54	166	52

* Extrapolation using linear function from Kyriakides et al at 2 and 157 to 15 °C

3.7 BIO-DIESEL

This is a mixture of fatty acid methyl esters manufactured by the reaction of an alcohol with a vegetable oil. Since the composition of the bio-diesel depends on the type of vegetable oil and the conditions of processing there is a large variation in properties. The commonality is that they are all intended as fuels in diesel engines and therefore share similar properties. Bio-diesels are commonly blended with each other and petroleum diesel. The values used for analysis are quoted in Table 7.

Table 7 – Bio-Diesel physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	895		
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.008055		
Surface tension (kgs^{-2})	0.0312		
Flashpoint ($^{\circ}\text{C}$)	195		

Data for 12 $^{\circ}\text{C}$

3.8 VEGETABLE OIL

Vegetable oils are usually derived from seeds and vary from species to species. They can be processed into bio-diesel or used directly in some engines. Vegetable oils show a particularly wide range of properties. For example, castor oil is particularly viscous. The values used for analysis are quoted in Table 8.

Table 8 – Vegetable oil physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	918*	960#	
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.084*	0.986#	0.007@
Surface tension (kgs^{-2})	0.034£	0.0355\$	0.0331*
Flashpoint ($^{\circ}\text{C}$)	162	282	

* olive oil, # castor oil, @ cottonseed oil, \$ peanut oil, £ average corn, peanut, olive oil
Data for 20 $^{\circ}\text{C}$

3.9 HEAT TRANSFER FLUID

This name describes the function of the liquid and may refer to range of liquids. Mineral oil, castor oil, lubricating oil or silicone oil can all be used as heat transfer fluids. The following properties refer to commercial cooling fluids. The values used for analysis are quoted in Table 9.

Table 9 – Heat Transfer Fluid physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	857	877.2	
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.174185*		
Surface tension (kgs^{-2})	0.02805#		
Flashpoint ($^{\circ}\text{C}$)	206	230	190

* Average single term polynomial extrapolation from trendlines of MobilTherm43 and 605 values at 40 and 100 to 15 $^{\circ}\text{C}$

Linear extrapolation from Coolanol 45R values at 40 and 100 to 15 $^{\circ}\text{C}$

3.10 TRANSFORMER OIL

This is a specialised heat transfer fluid and electrical insulating oil used for high voltage electrical transformers. The values used for analysis are quoted in Table 10.

Table 10 – Transformer oil physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	950		889
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.019201*		
Surface tension (kgs^{-2})	0.046		
Flashpoint ($^{\circ}\text{C}$)	149		135

* Power extrapolation for Univolt N61B from 40 and 100 to 25 $^{\circ}\text{C}$

3.11 PROCESS FLUIDS (SOLVESSO)

Solvesso is the trade name of a range of industrial solvents composed principally of aromatic hydrocarbons with differing distillation ranges. The values used for analysis are quoted in Table 11.

Table 11 – Solvesso physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	896	994	879
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.00108416	0.00351876	0.00082626
Surface tension (kgs^{-2})	0.0305		
Flashpoint ($^{\circ}\text{C}$)	66	113	50

Data for Solvesso150 at 25 $^{\circ}\text{C}$

3.12 WHITE SPIRIT

This is a commonly used solvent derived from paraffin. Three grades of white spirit have been quoted. The values used for analysis are quoted in Table 12.

Table 12 – White Spirit physical properties

	Value	Maximum	Minimum
Density (kgm^{-3})	793	795	765
Viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)	0.001	0.00165	0.00074
Surface tension (kgs^{-2})	0.0247		
Flashpoint ($^{\circ}\text{C}$)	31	55	21

Data for 15 $^{\circ}\text{C}$

4 RESULTS

The Ohnesorge correlation has been used to predict the propensity for each of the liquids to atomise if released under pressure, using Equation (5). Table 13 and Figure 2 provide the resulting values and the flashpoints for each of the liquids.

In a similar manner, the “Brodkey parameter” has been calculated for each of the liquids from Equation (9) and the results are summarised in Table 14 and Figure 3.

Table 13 – Ohnesorge atomisation correlation vs. Flashpoint of Liquids

Liquid	Ohnesorge atomisation parameter			Flashpoint (°C)		
	Value	Max	Min	Value	Max	Min
White spirit	3.9268	4.2	3.5	31	55	21
Biodiesel	2.2375	2.24	2.24	195	195	195
Diesel	2.992	3.04	2.96	54	166	52
Transformer oil	1.5322	1.53	1.52	149	149	135
Heat transfer fluid	1.1943	1.2	1.19	206	230	190
Solvesso	3.5185	3.78	2.71	66	113	50
Hydraulic oil	1.5412	1.54	1.53	182	258	96
Kerosene	3.4548	4.14	3.1	56	72	38
Heavy fuel oil	0.5149	0.52	0.38	111	111	111
Lubricating oil	1.1197	1.3	0.79	239	288	188
Vegetable oil	1.2832	2.26	0.73	162	282	162
Light fuel oil	1.28	1.28	1.28	66	187	66

Calculated from Ohnesorge parameter using an orifice diameter of 1mm and a pressure difference of 1,000,000 Pa

Table 14 – Brodkey atomisation correlation vs. Flashpoint of Liquids

Liquid	Weber atomisation parameter			Flashpoint (°C)		
	Value	Max	Min	Value	Max	Min
White spirit	201.11	202	199	31	55	21
Biodiesel	140.68	140.68	140.68	195	195	195
Diesel	176.62	177	173	54	166	52
Transformer oil	78.179	78.2	77	149	149	135
Heat transfer fluid	7.9404	8.08	7.94	190	230	190
Solvesso	163	163	158	66	113	50
Hydraulic oil	19.231	19.4	18.7	182	258	96
Kerosene	189.79	220	154	56	72	38
Heavy fuel oil	0.0104	0.01	0	111	111	111
Lubricating oil	7.2709	19.7	0.63	239	288	188
Vegetable oil	22.91	137	0.52	162	282	162
Light fuel oil	8.854	8.85	8.63	66	187	66

Calculated from Brodkey parameter using a droplet diameter of 30µm and a pressure difference of 1,000,000 Pa

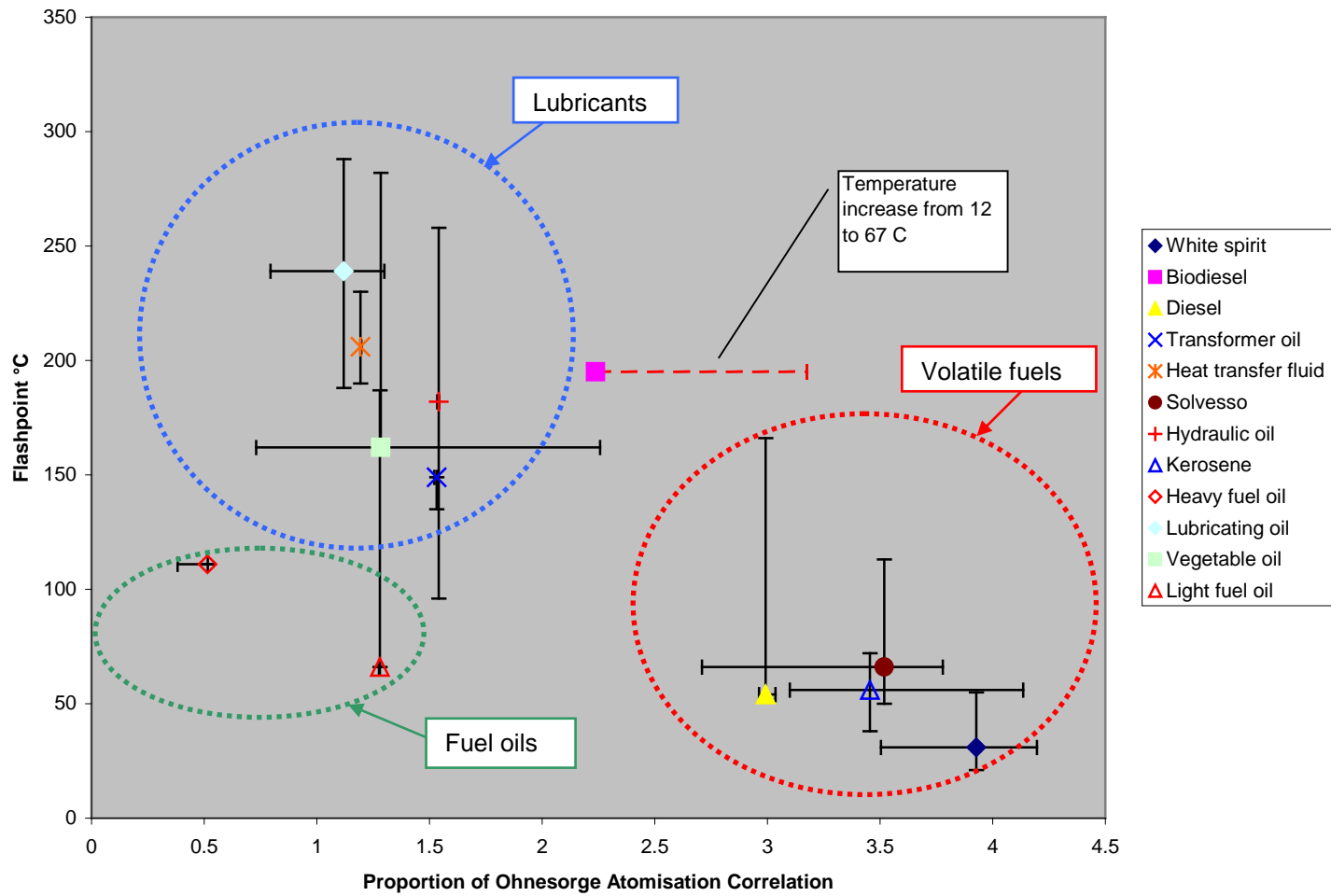


Figure 2 – Ohnesorge atomisation correlation vs. flashpoint

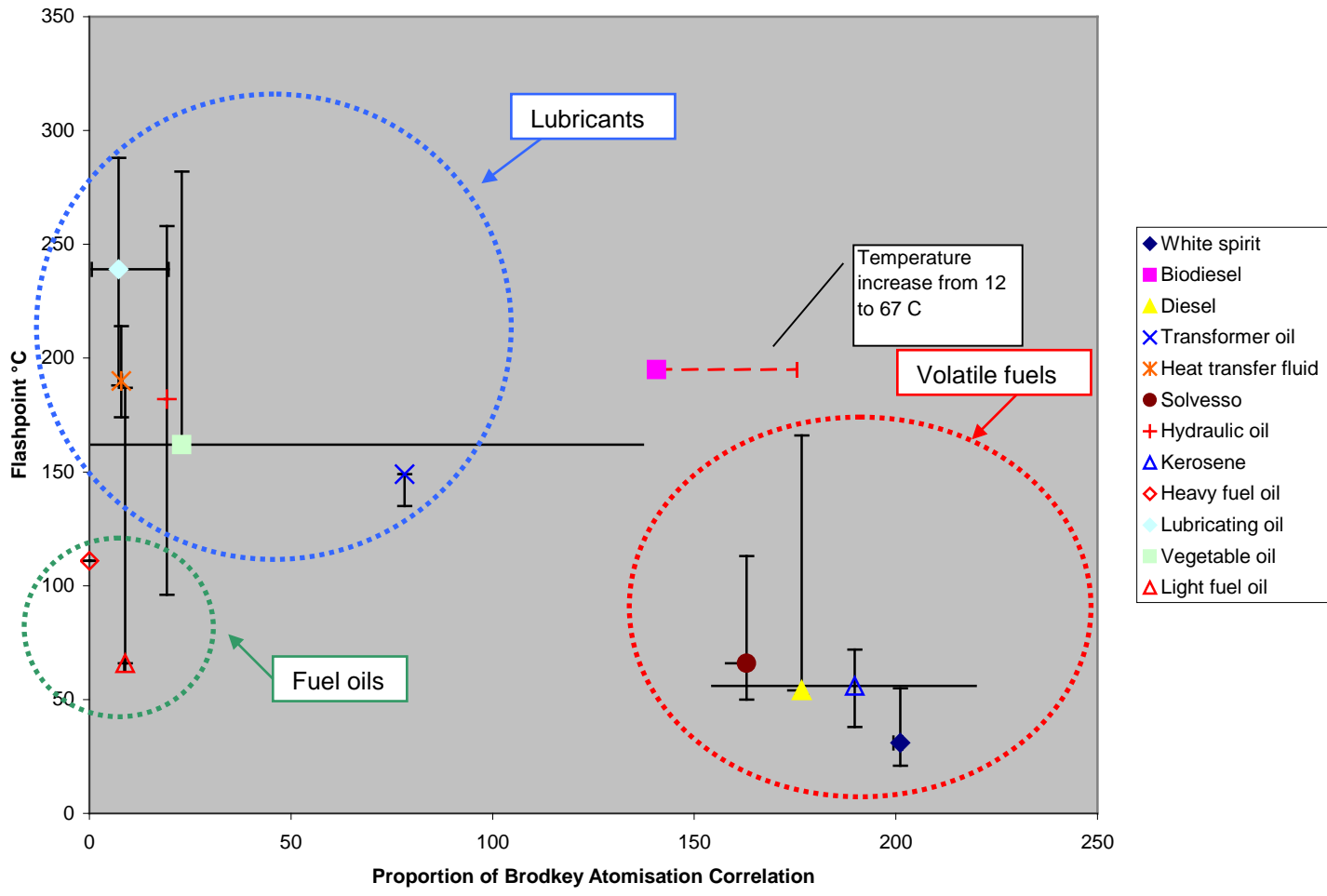


Figure 3 – Brodkey atomisation correlation vs. flashpoint

5 CONCLUSIONS

The results presented in Section 4 show that the liquids can be classified into three groups: group one, “volatile fuels and solvents”, that readily atomise and have a relatively low flashpoint; group two, “lubricants”, that are more difficult to atomise and have a higher flashpoint; and group three, “fuel oils”, that are difficult to atomise but have a low flashpoint.

The first category, group one “volatile fuels and solvents” includes:

- Diesel
- Kerosene
- Solvesso
- White spirit

The second category, group two “lubricants” includes:

- Lubricating oil
- Heat transfer fluid
- Hydraulic oil
- Transformer oil
- Vegetable oil

The third category, group three “fuel oils” includes:

- Light fuel oil
- Heavy fuel oil

Fuel oils are usually pre-heated before they are atomised in engines, to reduce their viscosity and improve the atomisation behaviour. This change in their material properties has the effect of shifting their behaviour to the right in Figures 2 and 3, producing similar performance under operating temperatures to diesel at ambient temperature.

The behaviour of bio-diesel is predicted to fall between the group one “lubricants” and the group two “volatile fuels and solvents” categories, but this is based on very limited data, identified in the literature. Considering the potential range of chemical composition, pre-cursor and production process encompassed by the name bio-diesel, further investigation may be necessary.

To investigate a range of different liquid properties in the JIP experiments, it is recommended to conduct tests using the following five liquids:

1. Lubricating oil
2. Kerosene
3. Light Fuel Oil (ambient temperature)
4. Light Fuel Oil (pre-heated before release)
5. Bio-diesel

This list includes one liquid for each of the three groups, a pre-heated fuel oil to study the effects of liquid temperature on mist generation, and a final test on bio-diesel to examine whether it exhibits similar behaviour to standard diesel.

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