

## **PRESSURISED ATOMISATION OF HIGH FLASHPOINT LIQUIDS - IMPLICATIONS FOR HAZARDOUS AREA CLASSIFICATION \***

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High flashpoint liquids normally considered non-hazardous in the context of area classification can, if released under pressure, atomise to produce a flammable aerosol. Current understanding of the underlying science is reviewed and a simple method is presented for characterising liquid leaks in terms of their potential to atomise. It is concluded that the possibility of creating aerosols which may result in flammable atmospheres cannot be disregarded for commonly handled high-flashpoint liquids.

Atomisation, Flashpoint, Area Classification

### INTRODUCTION

Area classification of petroleum installations is carried out in accordance with the IP Model Code of Safe Practice (1). Areas in which a flammable atmosphere may be expected to be present at such frequencies as to require special precautions for the construction and use of electrical apparatus are classified as hazardous. All other areas are classified as non-hazardous in this context.

Commonly encountered installations and fluids are classified directly from typical examples, others are classified by consideration of each identifiable potential release as an individual point source.

The general classification of the fluid is based on its flashpoint. Class II(1) and Class III(1) petroleum fluids, with flashpoints 21-55°C and 55-100°C respectively, handled below their flashpoint do not give rise to a hazardous area. An additional proviso is that they cannot be released in the form of a flammable mist, spray or foam since it is known that in these forms a flammable liquid can be ignited when at temperatures far below its flashpoint.

This principle is also applied to the additional concept of fluid category used in the point source classification procedure. A category C fluid is a flammable liquid which can, on release, be at a temperature above its flashpoint or form a flammable mist.

High-flashpoint liquids that would normally result in a non-hazardous classification, can, when stored or handled under pressure, be potential sources of flammable mist. One example might be diesel fuel used for emergency drivers on offshore facilities. When stored at ambient temperature and atmospheric pressure, its flashpoint is sufficiently high, >55°C, not to give rise to a hazardous area. However, when pumped under pressure, a leak, for example from a flanged joint, might result in a flammable mist by atomisation and thereby require consideration as an individual point source.

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In Section 2, experimental studies of ignition energy and flammability of high-flashpoint liquids in aerosol form are reviewed to demonstrate the potential hazard. Section 3 reviews the basic understanding of droplet formation resulting from Newtonian liquid flow through simple circular orifices. Empirical relationships involving the dominant parameters in dimensionless groups are presented for the break-up of an unobstructed jet.

Jet impingement upon any obstacle is shown to be important but its further consideration is outside the scope of the present study. Predictions for the initial 'mean' droplet size and the volume fraction of droplets under a certain size in a spray resulting from an unobstructed pressurised release are quoted from the literature. Examples of pressurised liquid releases considered relevant are posed, and jet-break-up and 'mean' droplet-size predictions are quoted.

Section 4 reports a set of experiments and an incident to illustrate the concern, thereby giving more credence to the potential hazard.

Proceeding a general discussion regarding the present understanding of this problem in Section 5, the conclusions are drawn in Section 6.

It is not within the scope of this study to provide the important link between the creation of droplets and the evolution of a flammable cloud. This would involve consideration of effects, such as evaporation (although small in the case of these liquids), entrainment, coalescence and gravitational fall-out, which would require a much deeper analysis than has been possible in this short study.

In the spirit of hazard analysis, a conservative approach has been retained throughout this study. Since a complete analysis from droplet formation through to the creation and dispersion of a flammable cloud is as yet unavailable, it is assumed that if atomisation is predicted, a flammable aerosol, and therefore a hazard, will result.

### IGNITION AND FLAMMABILITY OF LIQUID AEROSOLS

Few studies have been conducted on ignition and flammability of liquid aerosol systems by comparison with the number considered for the vapour counterpart, and the HSE(2) consider this problem to be an important, outstanding area of research in need of investigation.

Most studies consider ignition by a low-energy spark, and usually present results in terms of probability of ignition over a fixed number of attempts. A typical test is outlined in Danis et al.(3), where the number of positive ignitions from a series of 100 successive tests are counted. The spark energy - under predefined conditions for spark gap, ignition criterion, etc. - which ignites a fixed fuel mixture 50 times is defined as the minimum ignition energy. The same criterion is adopted for the pre-vaporised states in order to provide a meaningful comparison between the single and two-phase systems.

A typical graphical representation of results is reproduced in Figure 1, from Singh and Polymeropolous(4), who considered tetralin which has a flashpoint (Fp.) of 77°C. The figure shows that aerosol ignition is critically dependent upon droplet size for fixed fuel/air ratio. 60% ignition frequency was achieved for spark energies less than 5 milli-joules for monodisperse aerosols of

droplet sizes between about 20-30  $\mu\text{m}$ . To put this in context, the HSE consider equipment to be "intrinsically safe" if it is incapable of producing energies in excess of 0.2 milli-joules, and normal electrical equipment is capable of discharging a spectrum of energies ranging up to the order of Joules. It is worth noting that droplets within this size range will be relatively stable in suspension, i.e. they will not rain-out rapidly.

Ballal and Lefebvre(5) produced a validated model for spark ignition of aerosol/vapour systems. Notably, the model was validated against heavy fuel oil, diesel oil and gas oil. All these fuels are predicted to have minimum ignition energies of a few milli-joules for systems with SMDs of about 30  $\mu\text{m}$ , over a wide range of equivalence ratios. The model takes the generalised form:

$$E_{\min} = c_{pa} \Delta T (\pi/6) \rho_a d_q^3$$

where  $d_q$  is the quenching distance. Expressions for  $d_q$  are derived for various characteristics of the mixture, including the heterogeneity, polydispersity, turbulence-intensity, fuel properties, etc. As an example, under simplified conditions of infinitely fast chemical reaction times, for a non-turbulent monodisperse system,  $d_q$  takes the form:

$$d_q = D[\rho_f(1-\Omega)/\rho_a \phi \log(1+B)]^{0.5}$$

This implies that  $E_{\min}$  is dominated by a cubic dependence upon droplet diameter.

Hayashi et al.(6) considered propagation of flames in two-phase decane (Fp. 46°C)/air and dodecane(Fp. 71°C)/air mixtures. It was found that, for monodisperse systems in the droplet size range 40  $\mu\text{m} < D < 160 \mu\text{m}$ , the critical fuel concentration governing flame propagation decreased with increase in droplet size. The critical fuel concentration was found to be less than half the lower flammability limit of the pre-vaporised system.

In response to an aerosol explosion incident (see Section 4), the HSE(7) showed that a mist of high-flashpoint liquid could ignite when atomised at 11°C, some 60°C below its flashpoint. No details regarding the ignition source are included in the report.

In summary, it has been shown that high-flashpoint liquids, when in dispersed states, can exhibit ignition and flammability characteristics comparable to those associated with the same fuel but in a pre-vaporised state. Moreover, under certain conditions, the aerosol may be considered more hazardous than the pre-vaporised fuel. The likelihood of attaining these conditions from a plausible release scenario has yet to be determined.

### LIQUID JET BREAKUP

The previous section highlights why fuels in aerosol form should be considered hazardous if the fuel concentration and droplet sizes are within particular ranges. The question now arises of how to relate liquid flowing under pressure through small orifices to the efficiency of atomisation.

Relevant Parameters, Dimensionless Groups and Ranges of Applicability

For the objectives of this review, it has been assumed that the gas is atmospheric air, and that its properties will not vary during atomisation. Also, the fluid properties will be fixed for all flowrates in each scenario. The characteristics of the aperture have been shown to be influential parameters, but their effects are likely to confuse the conclusions of this simple study at this stage. A simple, smooth, circular orifice has been presumed.

Furthermore, it is postulated that any non-Newtonian effects(8) are likely to inhibit droplet formation, and thus, consistent with our conservative approach, these have not been considered. To quantify or completely validate this hypothesis would require considerable research effort again beyond the remit of this investigation.

The practical variables characterising the release conditions for a particular liquid are considered to be the containment pressure of the liquid,  $P_L$ , and the hole or orifice diameter,  $d_o$ . In order to interpret relevant studies to date, the containment pressure is related to the liquid exit velocity using the simplistic, 1-dimensional relationship:

$$U = K_v (2\Delta P/\rho_L)^{0.5}$$

where  $\Delta P = P_L - P_A$ . Throughout the remainder of this review, it is accepted that expressions involving liquid exit velocity can be rewritten in terms of containment pressure via this relationship.

Several non-dimensional groups are commonly used to relate influential parameters for this problem(9,10). The Reynolds number ( $Re_L = Ud_o/\nu$ ) is a measure of the ratio of inertial force to viscous force. The Weber number ( $We = \rho U^2 d_o / \sigma_L$ ) has proved a useful grouping in this area, as it represents the ratio of inertial force to surface tension force. Ohnsorge(9) introduced the Ohnsorge or stability number ( $Z = \mu_L (\sigma_L \rho_L d_o)^{-0.5}$ ), which determines the ratio of viscosity force to the square root of the product, surface tension force x inertial force. All these groups have been shown to be useful, dependent upon which characteristics are being investigated.

For ease of interpretation, we require two non-dimensional groups that represent orifice size and the liquid exit velocity independently when all liquid-characteristic properties are set. The Ohnsorge number is proportional to the inverse root of the orifice diameter and independent of liquid velocity. If we introduce another group, referred to as the Capillarity number ( $Ca = We/Re_L = \mu_L U \sigma_L^{-1}$ ), then this is directly proportional to the liquid exit velocity and independent of orifice diameter. This grouping represents the ratio of the viscous to surface-tension forces. Hence, the non-dimensionalised domain chosen for liquid-jet break-up presentation is the (Z, Ca) plane.

The hole size range where results appear to be valid for jet-break-up prediction, covers two orders of magnitude: between 0.1 mm and 10 mm. Pressure differentials applicable are considered to be between 0.1 bar and 60 bar; liquid densities, 700-1000 kg/m<sup>3</sup>; liquid zero-shear viscosity,  $5 \times 10^{-4}$  -  $5 \times 10^{-1}$  kg/ms; liquid surface tension,  $20 \times 10^{-3}$  -  $73 \times 10^{-3}$  N/m. These ranges should cover a large proportion of the cases likely to be encountered in the industrial environment, but should not be considered absolute; they are included as guidelines only.

### Regimes of Droplet Break-up

Liquid jet break-up is usually described in terms of four main regimes(11-16): drip, Rayleigh break-up, wind-induced break-up - sometimes sub-divided to give "first-wind" and "second-wind" regimes - and finally atomisation (see Figure 2, reproduced from Faeth(13)).

The drip regime involves slow formation of large drops immediately at the jet exit, which then fall as a single stream. Flowrates are very small for the smaller orifices and orifices in the order of 10 mm produce very large droplets in this regime.

Rayleigh break-up is a surface tension effect; it occurs many jet diameters from the exit point and yields a stream of drops but again of sizes greater than the orifice diameter. The drip and Rayleigh break-up regimes do not present an increased hazard in the context of this study.

Wind-induced break-up is because of instabilities caused by the relative motion of gas and liquid, moderated to some extent by surface tension. Characteristic of this regime is a finite length along which insignificant atomisation occurs, followed by a diverging jet region containing droplets ranging from the size of the orifice diameter (first-wind) to approximately one order of magnitude smaller (second-wind).

The atomisation regime is considered to be potentially the most hazardous situation. High flowrate jets start breaking up immediately at the orifice exit producing a conical jet (cone angle  $5^\circ < \alpha < 15^\circ$ ) of finely atomised spray some distance from the orifice exit.

### Hazardous Regimes and Empirical Formulae

Only the second-wind induced and atomisation regimes are considered to be capable of producing potentially hazardous aerosols. There may be a case for refining this rather broad domain as further evidence becomes available, but at this time, it is considered necessary to remain within a conservative boundary.

This stance is consolidated by noting that impingement-induced atomisation and more efficient atomisation, caused by uneven orifice edges, are two important, realistic considerations that have been excluded from this study. One could argue that an accidentally exposed aperture will almost certainly not be smooth, and atomisation due to impingement is known to have contributed significantly to at least one fatal accident in the process industries(7).

Low flowrates and large droplet sizes will ensure that a flammable mixture will not result from the other jet-break-up regimes. Therefore, the transition curve between hazardous and non-hazardous scenarios is chosen to be the division between first-wind and second-wind induced regimes.

It should be emphasised that predictive criteria governing transition from one regime to another still have not been uniquely defined. Reitz(17) and Faeth(13) quote a correlation dependent upon gas Weber number, and Faeth presents a transition graph indicating where he considers the 'grey areas' lie (Figure 3). However, in this exposition, the Miesse(10) transition curves are plotted in the Capillarity/Ohnsorge plane (Figure 4), to highlight effects of varying orifice diameter (horizontal lines), and liquid pressure (vertical lines) independently. The curve governing transition between the

atomisation and second-wind induced regions is given explicitly in Lefebvre(16) and transforms to give

$$Ca = (149.2)Z^{0.91}$$

Both this condition for transition and the gas Weber number correlation agree qualitatively that to assist progression to the atomisation regime, the orifice diameter and liquid exit velocity should be maximised.

From diagrams presented in Zanelli(15) and Lefebvre(16), the transition between the first and second-wind induced regimes has been estimated thus:

$$Ca = (17.8)Z^{0.91}$$

Points lying above this curve in Figure 4, where  $Ca > (17.8)Z^{0.91}$ , are considered to represent potentially hazardous conditions. Examples of the liquids, diesel ( $Fp. > 55^{\circ}C$ ) and aviation kerosine ( $Fp. 38-44^{\circ}C$ ), flowing through various sized orifices under different pressure differentials are indicated on the plot and tabulated in Table 1.  $K_v$  has been set to 0.8. Predictions for other liquids of interest can be obtained if the relevant liquid parameters of density, viscosity and surface tension, are known or can be estimated. Note the counter-intuitive result mentioned earlier, that increasing the orifice size while keeping the pressure differential constant aids transition to the hazardous regime. Lefebvre explains this effect as being because of increased liquid turbulence in the liquid jet for the higher Reynolds' number flow, which induces instabilities and so enhances disintegration. For example, the three regimes are traversed by the horizontal dashed line, which represents diesel fuel at a fixed pressure differential of 2 bar while varying the orifice size. Alternatively, the vertical lines can be used to indicate the effect of containment pressure for a fixed fuel and orifice size. The vertical dotted line represents a kerosine jet forced through a 3 mm orifice at different containment pressures. It is evident that, for orifice sizes within the realistic range stated in Section 3.1 and the containment pressure differential fixed at 2 bar, a hole size can be chosen to satisfy the hazardous condition for each of the three liquids considered. This conclusion still holds even if the hazardous transition condition is relaxed and redefined as the curve separating the atomisation and the second wind-induced regimes. Furthermore, all the examples given in Table 1 are predicted to be potentially hazardous when assessed by the alternative correlations given in Faeth(13).

#### Droplet-size predictions after jet-break-up

As illustrated in Section 2, fuel concentration and fineness of atomisation are two properties of an aerosol system which will affect the flammability characteristics significantly. Prediction of these two parameters at points in space and time is necessary to determine the flammability of an aerosol system.

Several authors have attempted to correlate typical droplet sizes from atomised jets with the fluid and dynamic properties of the system. Unlike the controlled aerosol ignition studies reported in Section 2, accidentally created aerosols will not be monodisperse. The aerosol will contain a distribution of droplet sizes, usually presented as a number or mass distribution. To characterise a droplet-size distribution with one parameter, averages of these distributions have been defined. In

combustion studies, the Sauter Mean Diameter (SMD) is the most common average, as it relates the mass and surface area of the droplet distribution - it is the size of droplet that has the same mass/surface area ratio as that for the entire aerosol system.

Measurement of distributions of droplet sizes is notoriously difficult, with most droplet-sizing techniques having their own characteristic inadequacies. Therefore, across data comparison is unlikely to be accurate. Furthermore, it is not obvious how quantitatively to relate data from studies on mono- to poly-disperse systems.

However, we can draw qualitative conclusions from droplet distribution predictions. For most systems, for example, the smaller the initial 'average' droplet size, the easier it will be to ignite at a fixed fuel concentration. Thus, it is considered relevant to draw upon the various formulae quoted in the literature to give a guide to the initial quality or fineness of atomisation in the case of an unobstructed jet.

Two formulae are suggested for this purpose:

$$\text{SMD} = 3330 d_o^{0.3} \mu_L^{0.07} \rho_L^{-0.648} \sigma_L^{-0.15} U_L^{-0.55} \mu_G^{0.78} \rho_G^{-0.052}$$

from Harmon (18), and

$$\text{SMD} = 3.08 (v_L)^{0.385} (\sigma \rho_L)^{0.737} \rho_A^{0.06} \Delta P^{-0.54}$$

from Elktob (19), derived when investigating the performance of diesel-type injectors.

Owing to the conditions under which these formulae were derived, it is considered only valid to quote these formulae when full atomisation has been predicted. Even then, for the cases of large orifices or small pressure differentials, correlations are being extrapolated away from the base data sets considerably. However, SMD predictions are presented for jets that are predicted to atomise fully in Table 1.

Large droplets (100s of micrometres) rain out of suspension rapidly, and are less susceptible to ignition compared with small droplets (10s of micrometres). Quantification of the volume percentage of small droplets in an aerosol is useful as a source parameter in assessing the likelihood, nature, and severity, of a combustion hazard. Elktob(19) attempted to generalise the droplet-size distributions for small pressure atomisers - essentially, the simple, circular orifices of interest here. His correlation shows reasonable agreement across several high-flashpoint fuels relevant to this study, but understandably, owing to the objectives of that study, he considered high pressure (70 bar min.), small orifice (of order 1mm) conditions only. Although not one of the best correlations for the data, the Rosin-Rammler distribution function exhibits the correct trends, is easy to analyse and, considering the accuracy required here, is considered sufficient. For Elktob's data, it is represented thus:

$$1-v(D) = e^{-0.422(D/SMD)^{5.32}}$$

Interesting indicators can be drawn from this correlation. For example, a negligible number of droplets are predicted to have diameters less than 10% of the SMD. Furthermore, it emphasises the misleading nature of droplet number distributions; although about 40% of the total number of droplets are less than 60% of the SMD, together they contain less than 3% of the total volume of fuel. If this is related to spark ignition discussed in Section 2, where droplets less than 30  $\mu\text{m}$  were shown to be the most hazardous, then it is concluded that for sprays with SMD 300  $\mu\text{m}$ , no droplets less than 30  $\mu\text{m}$  exist, and less than 3% volume of the total spray is contained in droplets of diameter less than 180  $\mu\text{m}$ . If correlations of this nature could be extrapolated, or modified, to ensure validity over a broader domain, then they would be extremely useful as tools to determine source terms for hazard assessment. Combining this information with the flowrate prediction, and the Ballal and Lefebvre(5) relationships for minimum spark ignition energy could form the basis of a modelling approach.

*In practice, small droplets may accumulate if separated from larger ones and, until such effects can also be accounted for, the conservative assumption must be that if atomisation is predicted, a flammable aerosol will result.*

### PRACTICAL ILLUSTRATIONS

A large-scale study and a real-life incident serve to illustrate the problem posed by aerosol fuel systems.

Kopyt et al.(20) considered ignition of large unconfined clouds of fuels that are relevant to this investigation: diesel, kerosine, fuel oil and gasoline. Admittedly, ignition was from a high-energy source and initial turbulence due to the method of atomisation would undoubtedly have played a dominant role. The publication refers to "apparent flamespeeds" of in excess 100 m/s for the high-flashpoint fuels tested. This data would be very impressive, and cause for concern, if the authors are referring to flamespeed in the traditional sense, i.e. the speed of the flame relative to the stationary observer. However, this is not apparent from the formula quoted in their publication, and further confusion is caused by reference to "visible flamespeeds" of the same order for similar experiments in other publications by the same authors. Fuel oil F5 ( $\rho_L = 965 \text{ kg/m}^3$ ,  $\mu_L = 43.8 \times 10^{-3} \text{ kg/m s}$ ,  $\sigma_L = 38 \times 10^{-3} \text{ N/m}$ , Bp. 723 K) proved to be the most violent. Note that the fuel with the **highest** flashpoint resulted in the most severe explosion.

An HSE report(7) refers to an incident where heated aviation kerosine was being sprayed from an ex-fire-service tender in an attempt to remove stubborn deposits from the interior of large, empty, fuel tanks. An explosion ensued which ripped apart one tank, and killed three men working in the vicinity. The ignition source was not confirmed, but an electrostatic discharge or hot surface ignition was identified as a plausible cause. Tests conducted by the HSE, following the accident, revealed that a fine spray was created when the jet from the nozzle, driven by a 10 bar supply, impinged on a vertical surface.



## DISCUSSION

*It appears that hazard assessments based only on the flashpoint of a leaking liquid may not be conservative. Unless a leak results in an unobstructed jet which does not break up, or breaks up insufficiently, a hazard may be present even though the liquid may have a high flashpoint.*

Furthermore, it appears that unobstructed liquid jets of practical interest are capable of producing potentially hazardous small droplets. In an industrial setting there must be a high likelihood of a leak impinging upon some obstacle in its vicinity, enhancing jet break up and thereby exacerbating the hazard.

Note in this study, spark ignition has been used as an example of ignition source, whereas in practice all sources need to be considered.

To provide more helpful guidance in hazard assessment, in addition to improvements in the formulae quoted herein, there are several areas in particular which require a greater understanding, together with quantifiable analyses. These include: the effect of impingement on spray characteristics; aerosol cloud development; ignition of aerosols from a variety of sources; more realistic release conditions, e.g. transient pressure differential, complex orifices, rheological influences, ambient influences.

In the context of hazardous area classification, there appears to be quite a simple solution to some problems of potentially hazardous aerosol leaks of high-flashpoint liquids. The potential hazard only exists because an aerosol spray can be released. If the spray leak can be changed into a dripping liquid leak then it would revert to a non-hazardous classification by virtue of the high flashpoint of the liquid.

Using the example, given in the Introduction, of pressurised diesel fuel leaking from a flange joint, a simple porous guard around the joint to catch the droplets and allow them to coalesce back to the original bulk liquid state and drip away would overcome the potential hazard. Proprietary spray guards based on this principle are available and could also be applied to other potential spray leak sources, for example, pump glands.

An accidental pipe failure, of course, cannot be protected in this way because it requires prior knowledge of where the leak will occur. It should be remembered however that it is not the aim of hazardous area classification to guard against the ignition of major releases resulting from catastrophic failure.

## CONCLUSIONS

1. When leaking under pressure, high-flashpoint liquids do have the potential to create a flammable mist and this needs to be considered when carrying out area classification. Pressure differentials of only a few bar are shown to be sufficient to atomise commonly encountered liquids.
2. The potential hazard is dominated by the size of the suspended droplets generated by the leak. A proposed correlation shows a cubic dependence of minimum spark ignition energy with droplet

size, which minimises for small droplets at about the energy associated with ignition in the vapour phase. The droplet size generated bears an inverse relationship to the pressure differential, thus the hazard can be minimised by operating systems at the minimum pressure practicable.

3. This study has highlighted a dearth of information relating directly to combustion hazards posed by pressurised atomisation of high-flashpoint liquids. Where information does exist, we have quoted correlations in this paper, but note that they all require exacting validation.
4. In the specific context of area classification, a simple solution to some potentially hazardous aerosol leaks is to contain the spray within a porous guard, thereby causing it to coalesce back to the original bulk liquid state and drip away.

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### NOMENCLATURE

#### Symbols

B	Droplet mass transfer number
Bp.	Boiling point of liquid (K)
D	Diameter of a droplet (m) - usually from a monodisperse aerosol
E	Ignition energy
P	Stagnation pressure (N/m <sup>2</sup> )
c	Specific heat (Joules/(kg x K))
d	Diameter (m)
Fp.	Flash Point (°C)
g	Gravity at earth's surface = 9.8 m/s <sup>2</sup> approximately
K	Discharge coefficient
L	Perpendicular distance from the orifice plane (m)
SMD	Sauter Mean Diameter (m)
U	Jet exit velocity at orifice (m/s)
v(D)	Fraction of total volume of spray contained in droplets of size less than D.
α	Angle of spray cone in atomisation regime (°)
ΔP	Pressure differential across orifice (N/m <sup>2</sup> )
ΔT	Temperature rise due to combustion (K)
μm	10 <sup>-6</sup> metres
ν	Kinematic viscosity = μ/ρ (m <sup>2</sup> /s)
Ω	Fraction of total fuel in form of vapour
φ	Equivalence ratio
ρ	Density (kg/m <sup>3</sup> )
σ	Surface tension (N/m)
μ	Dynamic shear viscosity (kg/(ms))

**Subscripts**

A	Atmospheric
a	Air
B	Position of jet break-up
G or g	Gaseous
L or f	Liquid
min	Minimum
o	Orifice
p	At constant pressure
v	Velocity

**Dimensionless Groupings**

Ca	Capillarity number
Re	Reynolds number
We	Weber number
Z	Ohnsorge number

Table 1

No.	Fuel	Hole diameter mm	Pressure diff. bar	Breakup regime	SMD, $\mu\text{m}$ HARMON (1955)	SMD, $\mu\text{m}$ ELKOTB (1982)
1	Diesel	8	1.5	second wind		
2	Diesel	10	1.5	atomisation	541	500
3	Diesel	4	4	atomisation	314	295
4	Aviation kerosine	8	1	second wind		
5	Aviation kerosine	1	12	atomisation	149	90
6	Aviation kerosine	5	5	atomisation	306	145

Fuel	Surface tension, N/m	Shear viscosity, kg/ms	Density, kg/m <sup>3</sup>
Diesel	0.032	0.004	828
Aviation kerosine	0.026	0.0014	800

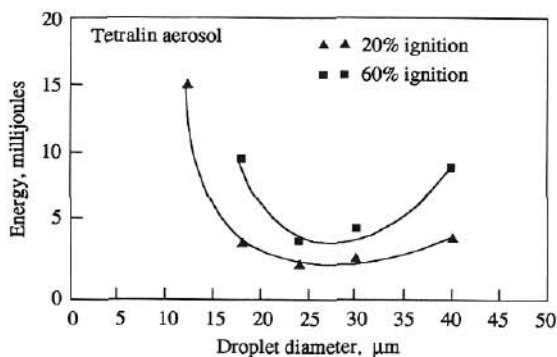


FIG. 1

Variation of minimum ignition energy with droplet sizes.  
(Reproduced from Singh and Polymeropolous(4))

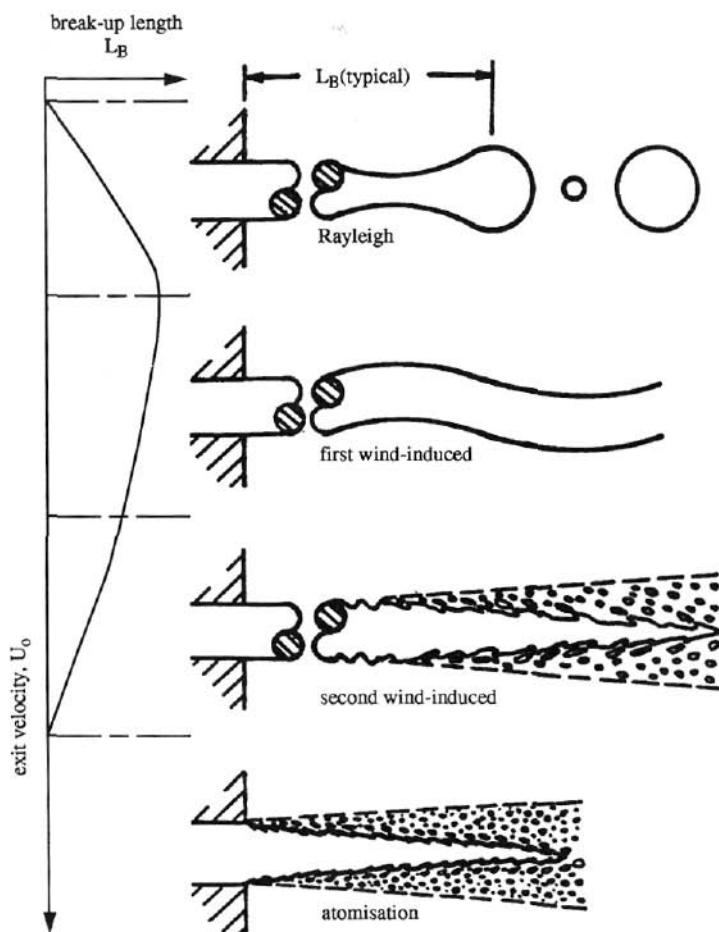


FIG. 2

Change in jet break-up regime and length of solid liquid core with exit velocity.  
(Reproduced from Faeth(13))

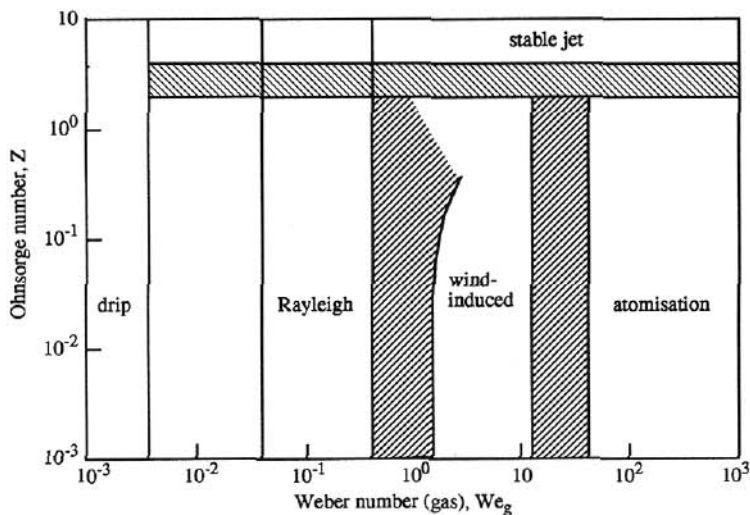


FIG. 3

Jet break-up regimes. (Reproduced from Faeth(13))

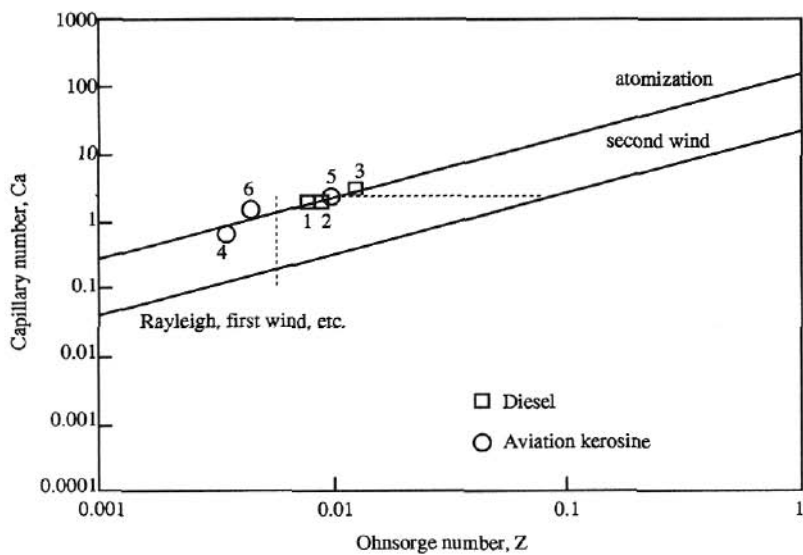


FIG. 4

Transition curves for jet break-up