Ignitability of diesel fuel mists over a vertical distance.

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Mists and sprays of high-flashpoint fluids can cause jet fires, flash fires or explosions. However, guidance by industry on hazardous area classification to address these risks is limited. This paper presents a summary of recent work under Work Package 3 of the MISTS2 Shared Research Project, investigating the ignitable extent of a vertical diesel mist spray. The work undertaken shows that the diesel mist generated at 5 bar g through a 1mm orifice is ignitable over a long jet length equal to or greater than 4.75 m axially for a vertical downwards facing release.

When compared to existing guidance and standards such as EI 15 (Energy Institute, 2015), which shows a circular radius for zoning considerations with a radius, R_1 of 2.0 metres and R_2 of 2.5 metres for a pressurised of 5 bar gauge at high level; There is a significant difference in the scale and type of zone that could be required for a vertically oriented mist release. This work shows that the zoning for diesel fuels requires consideration. It may not be unreasonable for an elevated diesel transfer line in a facility to be zoned to include a larger distance below the line rather than simply a uniform radius around it.

Further work could be undertaken to improve our understanding of the consequence of mist ignitions where a sustained but initially unignited release leads to mist accumulation. The effect of reduced ignition source energy could also be investigated to further understand the likelihood of ignition of the mist with commonly encountered ignition energies.

Introduction

In the UK, the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR) require employers and duty holders to classify areas into zones where fire and explosion hazards may occur. As these regulations originally implemented the European Union ATEX and Chemical Agents Directives, the same requirements also exist throughout the EU. The assessment methodology and protection measures required are well established for flammable gas hazards. However, guidance for high flashpoint fluid mists is relatively sparse. Combustible fluids formed into an aerosol of fine droplets can create a flammable atmosphere that can be ignited, even at temperatures below the fuel’s flash point. Such aerosol mists can be formed by, for example, pressurised leaks from damaged pipelines used to transfer or deliver fuel to machinery. Leaks are commonly caused by material corrosion, fatigue crack mechanisms or inadequate sealing of fittings

In 2009, HSE reviewed serious incidents involving the ignition of flammable mists of high-flashpoint fluids. The review identified 37 incidents which together were responsible for 29 fatalities (Santon, 2009). This was followed by an initial Joint Industry Project led by HSE, “MISTS, area classification for oil mists” (Gant et al., 2016; Bettis et al., 2017).

One outcome of the MISTS programme was a finding that kerosene mists were readily ignitable, even when released at low pressures. Previously, it was often assumed that low pressure systems would not produce ignitable mists. Typical estimates for the onset of mists hazards were at pressures above 5 bar g or even 10 bar g.

Following the MISTS project, HSE set up a new Shared Research Project to further develop understanding in this area. This project, MISTS2, focused on situations where empirical results can be used to give the greatest improvement in understanding of mist explosion safety. It had three work packages (WP1 to WP3) whose aims were to:

- Assess the characteristics of diesel fuel mists, using the same test apparatus as used in the previous MISTS project (WP1).
- Assess the effect of different orifices on the mist formed (WP2).
- Measure the maximum extent of the flammable mist (WP3)

Diesel fuel is a mixture of hydrocarbons with small additions of additives such as dispersants. Diesel supplied in the UK can contain up to 7% volume/volume of fatty acid methyl ester (FAME), which can result in a range of properties (Burrell and Gant, 2017).

The work covered in this report addresses the third of the MISTS2 work packages (WP3), i.e., assessment of the maximum distance from a leak at which the mist remains ignitable.

Aims

The aims of this experimental work package (WP3) within the MISTS2 project were:

- To create a vertically oriented diesel mist.
- To establish the flammable extent of a diesel mist over a test distance of up to 8 metres.
- To test the extent of the flammable mist at the lowest target test pressure where ignitions readily occur, between 5 and 20 bar gauge.
- To then determine the flame progression and consequences of ignition of a diesel mist.
- To validate and extend the experimental data set for diesel undertaken by the Gas Turbines Research Centre (GTRC) Cardiff University, which will be reported separately.

Method

Outline

To undertake the flammability trial, a vertical mist jet of diesel mist was required. A pressurised release of diesel was created with a vertical drop in free space of 8 metres (Figure 1). The release was undertaken indoors, in the Burn Hall facility at HSE's Science and Research Centre in Buxton, Derbyshire.

This facility is a realistic environment for a mist release indoors and provided shelter from weather effects. The Burn Hall allowed for the installation of a 10-metre-tall scaffold tower with an 8-metre-high release point.

The ignition point was set vertically below the release point and could be varied in height and position within the mist spray as shown in

Figure **1**. The point of ignition was then moved vertically downwards upon ignition of the mist until the ignitions stopped or the flame started to interact with a fuel catch tray which was placed at the base of the tower.

A catch tray was used at the bottom of the scaffold tower to allow for safe collection and disposal of the diesel fuel. The tray with integrated safety devices outlined below, ensured that a pool fire would not escalate if the ignited fuel interacted with the caught diesel.

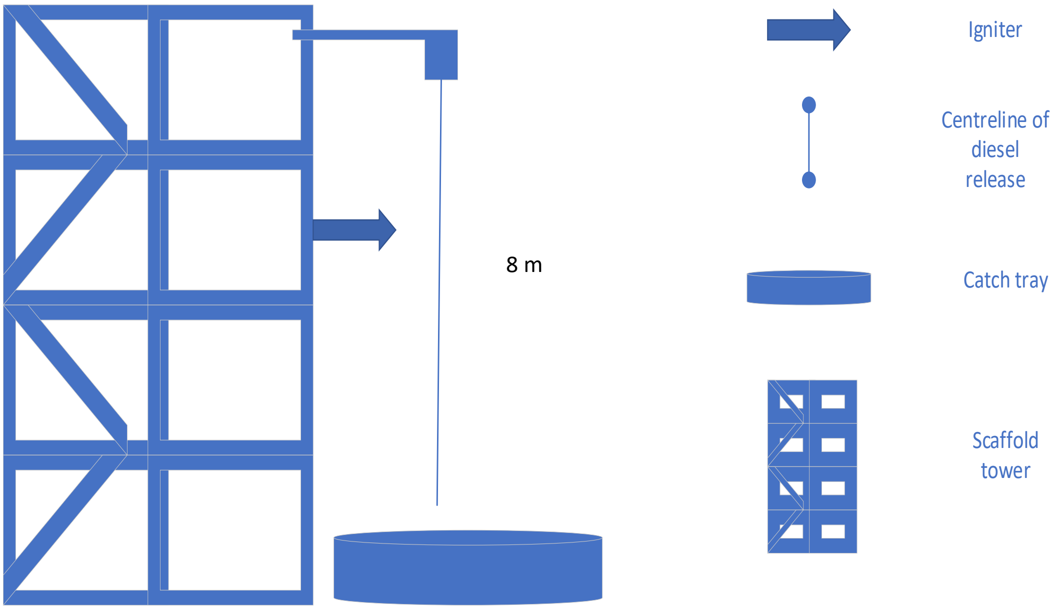

Figure 1: Rig schematic

Test method

This project focused on situations where empirical results could be used to give the greatest improvement in understanding of mist explosion safety. It addressed the maximum distance that a mist can travel before the diesel had dissipated in air to the point where it could no longer be ignited.

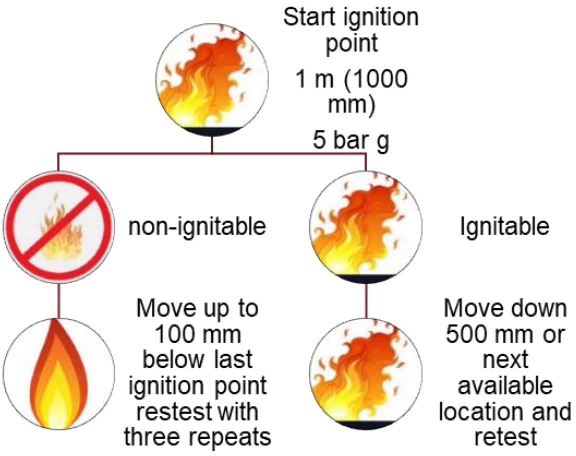

Figure 2: Test methodology for 5 bar tests

If ignitions had not been seen at 5 bar g, the pressure of the release would have then been increased in increments of 5 bar until readily ignitable mass clouds of mist were being created, up to a maximum of 20 bar g. This aspect of the method is shown pictorially in Figure 3 below. In practice, such pressure increases were not necessary.

An ignited test was defined as an ignition kernel that then propagated in any direction. A non-ignited test was defined as having no ignition kernel or a short-lived kernel that then did not propagate into a flame.

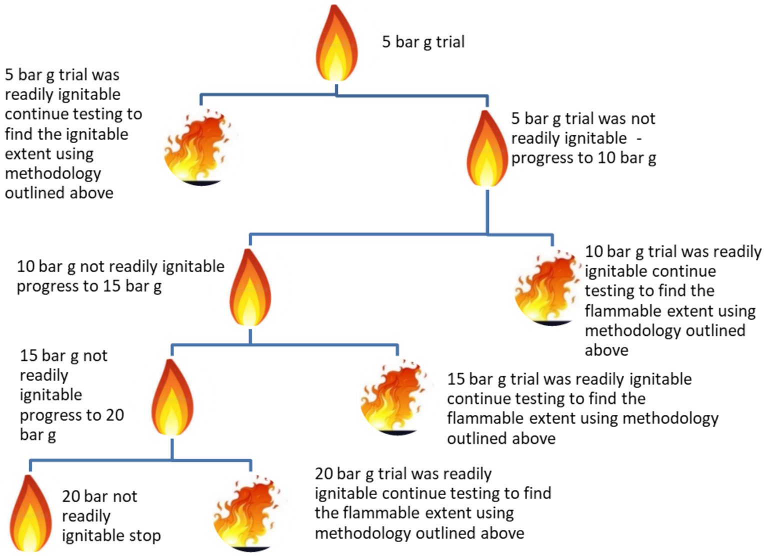

Figure 3: Test pressure selection

Igniter

The igniter used for the ignition trials at Buxton was a Chentronics SmartSpark system. This system was previously used by GTRC during their ignition trials. It creates a 1 J electrical spark with 15 Hz repetition. The spark was used for up to 10 s of release or until an ignition occurred.

Test orientation

The test orientation is shown below in Figure 4. The axial distance in meters (m) is the distance vertically between the release point and the ignition point. The radial distance in meters (m) is the distance horizontally from the centreline of the release. The diagram shown below assumes that the release is perfectly vertical. The radial distance was measured from the idealised position of the release by using a plumb line or laser level from the nozzle to indicate the nominal centreline of the vertical release.

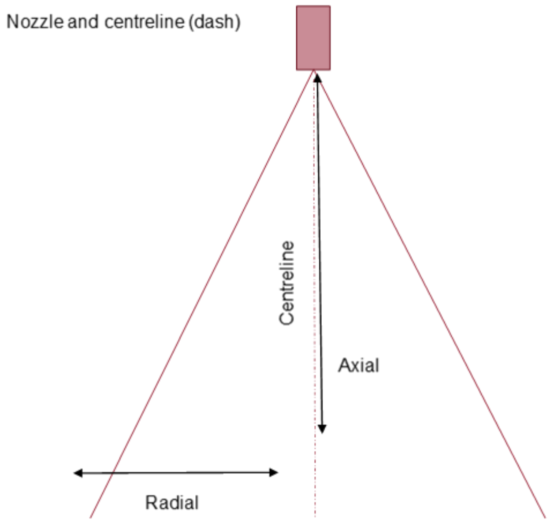

Figure 4: Release orientation schematic

Results

The tests show that the diesel mist generated by a pressurised release of 5 bar g through a 1 mm orifice, is ignitable over a long jet length. Results showing the ignitable extent of the mist with increasing axial and radial distance in meters are shown in Figure 5 below.

At increasing distances, the likelihood of ignition for any one spark reduced. With the sequential spark igniter, this meant that the average time until ignition was almost instantaneous at short distances and significantly longer as the distance from the release point increased.

The diesel fuel mist could be ignited to an axial distance of at least 4.75 m (see Figures 6 to 15).

Due to the delay in ignition of the mist increasing with axial distance, the downward propagating flame and the potential for a larger mist combustion event and/or a pool fire, it was deemed too dangerous to continue testing for ignitions at distances greater than 4.75 m.

The radius of the ignitable mist extended 0.30 m away from the centreline of the release at 1.0 m axial distance. By 1.50 m along the centreline, the observed ignitable radius had reduced markedly, to 0.05 m. At 2.9 m distance the ignitable radius was 0.12 m, and at 4.75 m distance it was 0.05 m.

Analysis of the CCTV and high-speed camera images showed that the mist did not form a uniform spray. The images showed that as the jet develops, the droplet concentration was greater near the centreline, and that vortices formed at the outside of the moving mist jet. These vortices entrained air into the edges of the jet. As a result, at any one point on the periphery of the jet, there were transient eddies of mist interspersed with pockets of entrained air. A region of mist with a large enough fuel density to allowed ignition to be sustained and a flame to propagate. Therefore, after the initial jet development length, the presence of ignitable mist became more intermittent away from the spray axis than it was close to the centreline.

At a distance of 4.75 m the mist was becoming more difficult to ignite even on the centreline. The number of ignition sparks required to produce a sustained ignition of the fuel increased significantly. However, the fuel was still ignited within 10 seconds after the release start. There was an accumulation of fuel in the area in which larger drops were seen close to the igniter before ignition. It is possible that the larger drops were simultaneously broken up and ignited in the intense and rapidly expanding plasma of the spark, leading to subsequent ignition of the mist cloud.

There were also noticeable changes in the growth of the flame with increasing axial ignition distance from the release point.

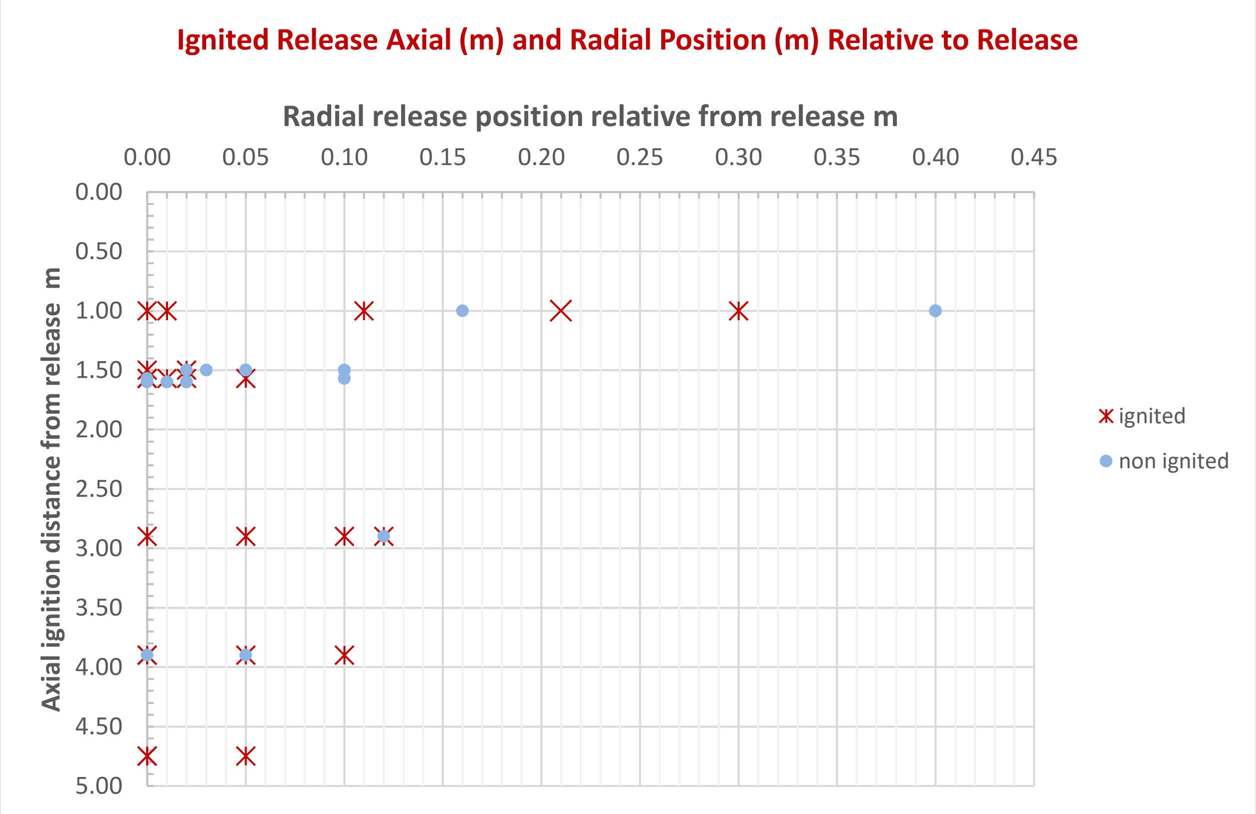

Figure 5: Ignited release locations relative to release location (m). Note that different scales are used on vertical and horizontal axes.

Ignited release flame behaviour

It was observed that the flame behaviour of the ignited mist jets varied with ignition location and the axial distance from the release. Mist ignited within a short axial distance from the release point exhibited flash-fire behaviour, with the flame burning back to the release point. The burn back to the release could, if allowed, escalate to a jet fire. Therefore, in practice, the consequences of ignition of a similar mist jet within around 2.9 metres of its release point could be significant fire damage within the surroundings of the release.

When the mist was ignited at an axial distance from the release point that was equal or greater than 2.9 metres, the mist ignited but did not burn back to the release point. A flash fire occurred which consumed the mist in the vicinity of the ignition point. In practice, this suggests that a mist ignited far below the release point may produce a localised flash fire rather than a sustained jet fire.

With increasing axial distance between the release and ignition point, the flash fires became less vigorous, and a much slower flame growth was observed. The flash fire was of short duration, partially due to the cessation of the mist jet release.

The consequences of ignitions appeared to decrease in severity with increasing axial distance between the ignition and release point, at least within the moving mist jet.

All releases tested were ceased upon ignition of the mist jet, therefore escalations of the ignition were limited by the mass of diesel released. If releases continued as they would in a leak scenario there could be potential escalations and changes in behaviour due to the accumulation of the mist (if confined).

Flame propagation sequence at 1.0 meters

Figure 6: CCTV image 2 - Test 5 Axial 1.0 m ignition position

Figure 7: CCTV image 5 - Test 5 Axial 1.0 m ignition position

Flame propagation sequence at 1.5 meters

Figure 8: CCTV image 3 - Test 57 Axial 1.5 m ignition position

Figure 9: CCTV image 5 - Test 57 Axial 1.5 m ignition position

Flame propagation sequence at 2.9 meters

Figure 10: CCTV image 2 - Test 64 Axial 2.9 m ignition position

Figure 11: CCTV image 5 - Test 64 Axial 2.9 m ignition position

Flame propagation sequence at 3.9 meters

Figure 12: CCTV image 1 - Test 74 Axial 3.9 m ignition position

Figure 13: CCTV image 4 - Test 74 Axial 3.9 m ignition position

Flame propagation sequence at 4.75 meters

Figure 14: CCTV image 1 - Test 79 Axial 4.75 m ignition position

Figure 15: CCTV image 5 - Test 79 Axial 4.75 m ignition position

Mist visualisation

Unignited releases were undertaken at ~ 5 bar g pressure to examine the visual composition of the mist in the regions that had been shown to contain ignitable mist. A high-speed camera at a frame rate of 3000 fps was focussed on areas of the mist where ignitions were seen in the ignited trials. Short sequences were captured during a 10 second release. Individual images from these video sequences showed the visual differences in droplet size and spread within the mist (see Figures 16 to 20).

The jet appeared to be non-uniform, with higher mist density close to the centreline and the mist becoming less dense at greater radial distances due to increased air entrainment and larger-scale shearing of the mist droplets as they fall through the air. This shearing created vortices that resulted in pockets of less dense mist with increased air entrainment occurring towards the periphery of the spray. The resulting intermittent concentration changes toward the outside of the spray accounted for the inconsistencies in ignitions as the radial distance of the igniter was increased. The radial positions tested may have encountered a pocket of air entrainment and therefore the density of the mist was not high enough to ignite. However, these pockets are transient and may not persist if the release was to continue as would occur in a real-life leak scenario.

Mist visualisation centre of video still 1.0 m axial from release point.

Figure 16: 1.0 m axially from release (pressure 5.05 bar g)

Mist visualisation centre of video still 1.35 m axial from release point.

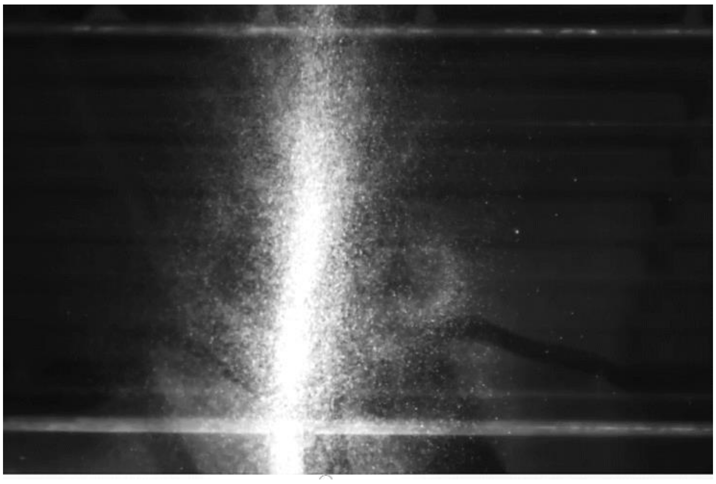

Figure 17: Test 3 shot b – 1.35 m from release (pressure 5.13 bar g)

Mist visualisation centre of video still 2.9 m axial from release point.

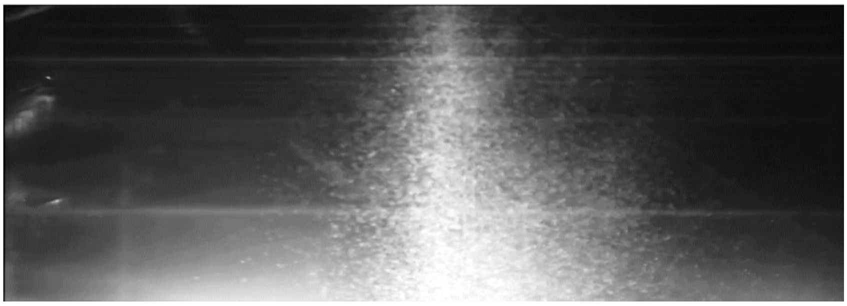

Figure 18: Test 4 shot b – 2.9 m from release (pressure 4.8 bar g)

Mist visualisation centre of video still 3.9 m axial from release point.

Figure 19: test 7 shot a - 3.9 m from release (pressure 5.00 bar g) * highlights are lights through the black background from lighting.

Mist visualisation centre of video still 4.75 m axial from release point.

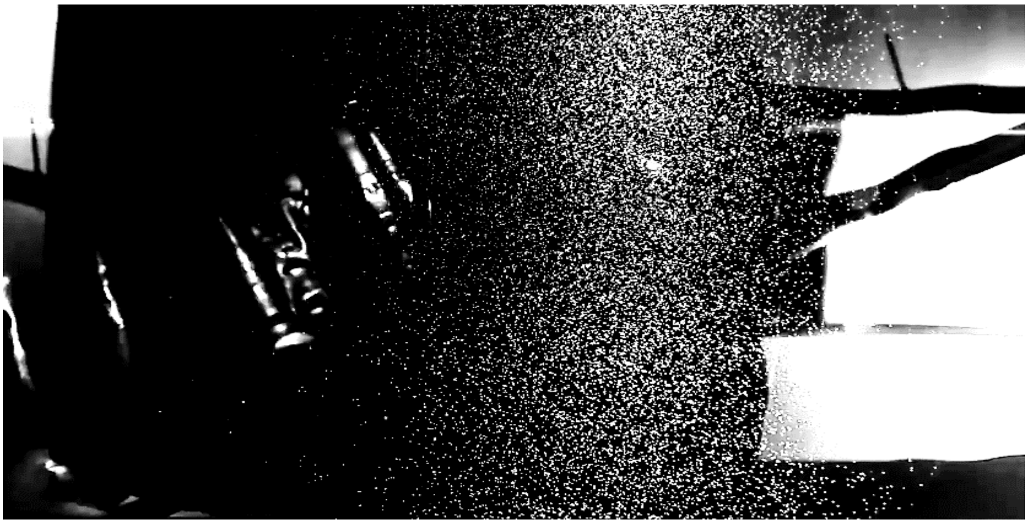

Figure 20: test 9 shot a – 4.75 m from release (pressure 4.90 bar g) * highlights are lights through the black background from lighting.

Discussion

Mist ignition experiments were conducted on vertically-orientated mist of diesel produced from a 1 millimetre drilled circular orifice with a test pressure of 5 bar g. The diesel mist jet was found to be ignitable by a repeating 1 Joule spark. Ignitions occurred within the 10 second test window and over an axial distance (below the leak point) of at least 4.75 metres. Beyond this point, no further tests were carried out due to the potential to produce a large mist combustion event and/or pool fire.

The test pressure of 5 bar g was sufficient to obtain ignitions of the mist jet across the full available vertical extent of the mist. Therefore, higher pressures were not tested.

The ignitable mist only persisted for a short distance out from the centreline of the mist jet with the largest radial ignition distance of 0.30 metres being observed close to the release point. The maximum radial ignition distance reduced with increasing axial distance. This differs from the results seen in the work undertaken at GTRC, where radial ignition distance increased consistently with axial ignition distance from the release point up to their maximum axial distance of 0.9 m and radial distance of 0.06 m. The difference in radial ignition behaviour may be due to the difference in scale between the two rigs, the lack of confinement in the HSE tests as compared to the GTRC ignition spray booth, and the way in which air was entrained into the jets.

Analysis of CCTV and high-speed imagery showed that the mist was non-uniform in the HSE tests. Entrainment of air into the periphery of the jet created transient air pockets of less dense mist. The mist jet was also shown to shear and break up when falling through the air. The jet became visibly less dense and spread radially outwards from the centreline. Radial ignitions of the mist were more variable than that at the centre of the mist.

There was a significant change in the flame behaviour of the ignited mist with increasing axial distance between the release and ignition point. It is important to note that the releases were ceased upon ignition of the diesel fuel. Therefore, significant accumulations of diesel did not occur. Accumulations of mist have not been considered in this work.

At axial distances of 1.0 metres and 1.5 metres from the release point, ignitions gave rise to a rapid flash fire which engulfed the area of the mist and burnt back to the release point. The release was ceased upon ignition of the fuel. However, in reality if the release had continued it is likely that it would have led to a jet fire, with the potential for severe consequences for the facility and persons contained within it.

By the time the ignition distance reached 2.9 metres and beyond, the flame speed and intensity were reduced. Relatively slow flame propagation consumed the mist in the vicinity of the ignition point, moving downward with the mist as it burned. However, this kernel failed to propagate upward through the full extent of the mist and extinguished itself before all of the remaining mist was consumed.

At an axial distance of 4.75 metres, it was observed that larger droplets were being created where the mist coalesced on the body of the igniter at the ignition point. It was not possible to prevent these larger drops forming, attempts to shield the igniter simply moved the source of larger drips to the shield. However, when one of these larger droplets was ignited, the ignition propagated out into the mist. Several small, short-lived flame kernels were observed before a kernel finally propagated more widely and the localised mist was consumed with a lazy flash fire flame.

Conclusions

Guidance and standards such as EI 15 (Energy Institute, 2015), show a circular radius for zoning considerations with a radius, R_1 of 2.0 metres and R_2 of 2.5 metres for a pressurised of 5 bar gauge at high level; There is a significant difference in the scale and type of zone that could be required for a vertically oriented mist release.

This work shows that the zoning for diesel fuels requires consideration. It may not be unreasonable for an elevated diesel transfer line in a facility to be zoned to include a larger distance below the line rather than simply a uniform radius around it.

Further work could be undertaken to improve our understanding of the consequence of mist ignitions where a sustained but initially unignited release leads to mist accumulation. The effect of reduced ignition source energy could also be investigated to further understand the likelihood of ignition of the mist with commonly encountered ignition sources.

Disclaimer

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