Effectiveness of oil mist detectors in relation to oil mist droplet size and concentration

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Flammable oil mists are usually produced by one of two mechanisms: a) the pressurised escape of oil, for example from a pinhole or split in a hose of a hydraulic system resulting in droplets ranging from tens to hundreds of microns in diameter or b) where oil is vaporised by contact with a hot surface and then forms droplets typically <1µm in diameter as it condenses in the cooler surrounding air. Either mechanism can result in a sustained mist or cloud that forms a flammable mixture potentially resulting in a fire and explosion if ignited. Mists will ignite at a lower temperature than most gaseous hydrocarbon vapours and once ignited the combustion can be very destructive. The early detection of such emissions is therefore important since it can significantly reduce the likelihood of a hazardous situation arising or mitigate its effect.

A number of methods have been utilised to detect mists released into enclosed spaces, such as gas turbine enclosures and ship engine rooms, with varying degrees of effectiveness in controlling the risk of fire or explosion. Oil mist detectors (OMDs), as they are commonly known, are based on various detection technologies and standards.

The most common type of OMD activates and alarms above a pre-programmed threshold concentration of mist. It is generally set to the lowest level at which it gives an unambiguous indication of the presence of an oil mist.

The second type of OMD quantifies the amount of mist present in the air and is usually calibrated against a known concentration of oil mist. This can create problems for both types if the measured mist has different characteristics to the mist with which the instrument was initially calibrated.

Any OMD usually interacts with airborne oil droplets by either of two methods: the instrument draws air into a detection volume from which a measurement is made, or it measures across a chosen area of interest. These are commonly known respectively as “point” or “line” detectors.

Most OMDs determine the concentration or presence of airborne droplets by measuring the intensity of light produced by a solid state laser or LEDs that is scattered or absorbed by the droplets. A recently developed OMD detects oil mist by measuring an increase in air pressure that develops across a steel mesh filter as it becomes loaded with oil.

During this study, experiments were carried out using four distinct types of detectors namely:

1. Light scattering, point reading.
2. Light scattering, point alarm.
3. Light obscuration, line alarm.
4. Pressure drop, point alarm.

Experiments to determine the response and sensitivity of OMDs were carried out inside a modified dust tunnel facility that allows control of ventilation flow rate. Commercially available mist generators were used to generate oil mists inside the tunnel with varying droplet size and concentration so that the detector response could be measured.

Two droplet size ranges were generated and measurements made with mists containing droplets of <1 µm and ~20 µm in size. The experiments with droplets <1 µm showed that most types of detector detected oil mist at concentrations well below potential explosion limits. The exception was the pressure drop type which was unable to detect the smaller droplets even at the highest concentration achievable (~ 2000 mg m-3). The detectors were much less sensitive to larger droplets with the exception of the pressure drop type which alarmed at levels below the minimum concentration that could be reliably generated inside the dust tunnel (< 38 mg m-3).

Key words: Oil mist detectors, OMDs, mists, sprays, lower explosion limit, atmospheric aerosols, pressurised leaks, condensation aerosols, droplet size, test facility.

Introduction

There are numerous situations that can lead to the generation of a flammable mist which may, under certain conditions of use, result in a significant fire and explosion hazard. Early detection of such emissions is important since it can significantly reduce the likelihood of a hazardous situation arising or mitigate its effect.

A flammable oil mist is usually produced by two mechanisms: a) the pressurised escape of oil, for example from a hole or split in a hose of a hydraulic system; or b) where oil is vaporised by contact with a hot surface and then forms small droplets as it condenses in the cooler, surrounding air. It will ignite at a lower temperature than most gaseous hydrocarbon vapours and once ignited, the combustion can be very destructive.

Of particular concern are the flammable mists of fuel and lubricating oils that can occur in offshore locations such as gas turbine (GT) enclosures, diesel/ship engine rooms and platform legs. Most offshore rigs now contain one or more gas turbine based plants. The complex nature of high-pressure fuel pipework to the turbines and the associated fittings is the most common source of fuel leaks that can result in mists, which can reach flammable and potentially explosive levels if left unattended.

The lower explosive limit (LEL) for mists and sprays is dependent on droplet size. Gant (2013) explains that the minimum ignition energy of sprays (droplets > 50 µm) generated from high flashpoint fluids is much higher than mists (droplets 1 – 10 µm) but the LEL by mass is lower for droplets larger than about 20 µm than for a fine mist containing much smaller droplets. Therefore, with a sufficiently energetic ignition source, it is possible for a flame to propagate through a spray at lower mass concentrations than with a fine mist. For very small droplets, (less than 10 µm in diameter) experimental results show that the LEL for many hydrocarbons tends towards a value of around 48 g m^{-3}. While generally agreed figures cannot be ascribed to the LEL for sprays containing larger droplets, the presence of spray in the atmosphere must be treated with caution since it must at least be regarded as a potential fire hazard.

The Health and Safety Executive (HSE) recognises the use of oil mist detectors (OMDs) as a potential means of risk mitigation in safety systems (HSE, 2003). However, it also accepts that current oil mist detection systems may not give reliable measurements and/or detection. Influencing factors such as droplet size, oil type, air flow, humid and dusty environments, maintenance and location of the instrument can significantly affect the accuracy and reliability of measurements. This appears to be corroborated by the occurrence of four significant offshore fires in the UK in GT enclosures since 2006 and 42 identified oil mist leaks, of which 41 were initially not detected by installed instruments in the period 1991 – 2004 (Santon, 2005). It is clear then, that the effects of influencing factors on OMD performance need to be investigated and better defined.

The aim of this work was to produce a test method capable of assessing the effectiveness of oil mist detection under conditions typical of those found in practice and to use this method to test the performance of OMDs. The requirements of any test method are that it should at least be able to:

- Generate a range of droplet sizes representative of those produced in a real workplace situation ranging from sub-micron (where aerosols are produced from condensation of hot vapours) up to tens or hundreds of microns (where sprays or mists are produced by leaks of flammable liquids from holes or defects in pressurised systems). Most existing test methods (BS ISO 16437 [2012], IACS [2005], IMO [2003]) challenge OMDs with aerosols consisting of droplets smaller than 5 µm in diameter.
- Investigate the response of OMDs to mists produced from different flammable liquids.
- Investigate the response of OMDs to changes in the surrounding air velocity. In practice, oil mist detectors are often deliberately placed in locations where there is a moving air stream, e.g. in the exhaust of gas turbine enclosures. Many of the existing test methods are carried out in low air movements or “still air” and therefore the OMDs are not tested in “real” conditions.
- Investigate how interfering aerosols such as water sprays and dust (e.g. salt mists) affect OMD response.

Most OMDs determine the concentration or presence of airborne droplets by measuring the intensity of light produced by a solid state laser or LEDs that is scattered or absorbed by the droplets. It is well known that the response of light scattering instruments is highly dependent on the mean droplet size (PD CEN/TR 16013-3, 2012) and this is likely to be the biggest influencing factor. Therefore, this work concentrated on investigating the effects of droplet size and concentration on instrument performance and sensitivity.

Types of oil mist detectors

Instruments for detecting oil mist have historically been confined to a small number of target markets. These are most notably engine crankcases, engine rooms for marine diesel engines and gas turbine enclosures. The most common type of OMD activates and alarms above a pre-programmed threshold concentration of mist. It is generally set to the lowest level at which it should give an unambiguous indication of the presence of an oil mist.

Another type of OMD quantifies the amount of mist present in the air and is usually calibrated against a known concentration of mist. This can create problems for both types if the measured mist has different characteristics to the mist with which the instrument was calibrated. They are usually set to alarm at a level within the instruments’ measuring range.

An OMD usually interacts with the airborne oil droplets by either of two methods: the instrument draws air into a detection volume from which a measurement is made, or it measures across a chosen area of interest intersected by a light beam. These are known respectively as “point” or “line” detectors. The main disadvantage of point detectors is that they will only see a mist in their immediate area and so if the detector is located away from where an oil mist is generated then the mist may go undetected. Therefore detector positioning is critical, which can be partly resolved by strategically placing several detectors to cover the area at risk. Line detectors can be used to cover a much larger area because they respond to mist present anywhere along their path. Their main disadvantage is that they cannot distinguish between a localised high concentration and a more diffuse mist of lower concentration; consequently their reading depends on how much of the beam path length passes through the mist.

Any suspension of airborne particles/droplets will absorb and scatter a fraction of the light that passes through it and most OMDs make use of this property to detect its presence.

Commercial oil mist detector systems

Table 1 shows the most widely available and commonly used ambient OMDs at the time this paper was written. The following information has been taken from the literature supplied by the manufacturers of the instruments and so the authors make no claims as to its accuracy. All of the monitors have been developed for use in environments such as GT enclosures, enclosed oil rig well head areas, generator rooms, gas compressor stations, marine battery rooms, marine engine rooms.

The OMD manufacturers listed in Table 1 were contacted to enquire whether they would be willing to take part in the study. Most were willing to provide an OMD for testing purposes. As a result, OMDs that were regarded as representative of the most common types available and widely used were chosen for testing.

Net Safety Ltd - Millennium APM: A point-type monitor based on optical light scattering. It is certified explosion proof for use in hazardous areas and can monitor ambient air for smoke, oil mist, carbon, dust and ash. It features a single-beam IR lamp with no mirrors to become contaminated, field adjustable zero level of obscuration and three sensitivity settings (low, medium and high) that allow for fine tuning within specific application conditions to optimise performance and eliminate false alarms. Built-in relays are activated when the alarm limit is reached (depending on the sensitivity setting) which can be connected to visual or audible alarm systems. The sensor is connected to a separate control unit that has an 8-digit scrolling display and status LEDs that provide instructions and status alerts. Due to its open path design, the monitor is able to detect and monitor smoke and particulate matter moving at velocities up to 20 m s^{-1}.

QMI - Triplex: A point-type detector that uses separate light scattering detector heads to monitor oil mist in up to three locations. Oil mist concentration measured by each detector is transmitted to a central monitor. The detectors incorporate a small fan to ensure a flow of air through the sensing system. Three sensors inside the detector measure the backscatter of light from sampled particles/droplets and dirt on the lenses. An articulated mounting bracket allows the detector to be positioned facing the flow of air (usually downstream of the equipment being monitored). The manufacturers recommend that the alarm level should be set initially to the minimum setting of 0.05 mg l^{-1} (50 mg m^{-3}; 0.1% LEL) for use as an atmospheric detection system so that the main alarm activates as soon as any oil mist is sensed in the atmosphere. In areas where there may be high background levels of airborne particles the alarm level should be increased to prevent false alarms. An early warning relay is activated when the OMD detects 80% of the set alarm level. A main alarm warning relay is activated when the OMD detects 100% of the set alarm level. The relays can be connected to visual or audible alarm systems. Usually the early warning and main alarms will activate almost simultaneously as atmospheric oil mist levels tend to increase rapidly during a release. If the optics of the instrument become contaminated with oil or dust a fault is indicated. They can be accessed quickly and easily for cleaning.

Sigrist - VisGuard: A point-type detector also based on optical light scattering. Filtered air is fed through the detector flow cell, so that the measured mist sample is surrounded by a protective shroud of clean air which helps to keep the optics clean. The instrument complies with the IMO code of practice (IMO, 2003) for atmospheric oil mist detectors. Oil mist concentration measured by the detector is transmitted to a central monitor, where the concentration is displayed. The measuring range can be configured from 0 – 0.1 mg m^{-3} up to 0 – 100 mg m^{-3} and the instrument is calibrated at the factory using polystyrene latex aerosol (PLA). A single point check of factory calibration can be carried out using a supplied calibration rod. The control unit can be programmed so that a relay is activated when the OMD reaches an upper threshold limit and remains so until the reading drops below a lower threshold limit. The relays can be connected to visual or audible alarm systems. The zero point is checked by attaching a zero-air filter or placing the detector in clean air. The manufacturers recommend that the detector is mounted in the vertical position and away from any high air flows.

Tyco Ltd - IR6003/7: This is a line-type detector where a beam of infrared light is projected from the transceiver to a reflector and back again. It is designed to be highly sensitive to the presence of oil and kerosene mists or smoke particles in the path of the detector beam. Two levels of alarm status are provided: a low level and a high level that trigger relays when they are reached. The relays can be connected to visual or audible alarm systems. The instrument automatically compensates for contamination of the detector lenses and indicates when the lenses require cleaning. The lenses can be cleaned quickly and easily. It will also indicate if the beam becomes blocked or interrupted and will operate over a distance of 2-50 m.

Daspos - LAS10: This is a relatively new point-type OMD that detects oil mist by measuring the differential pressure that develops over a period of time across a removable, custom-made filter mesh located within the instrument. The filter is reusable and should be cleaned typically every 4-8 weeks, depending on the cleanliness of the surrounding air. A high flow rate of 10,000 l min^{-1} is maintained through the detector enabling it to respond rapidly to low levels of oil mist. The detector is connected to a remote control and relay unit. The presence of airborne oil mist will increase the differential pressure and if the reading exceeds predetermined values in the alarm settings, the system will activate an alarm relay which can be connected to visual or audible alarm systems. The oil filter limit is set to activate the alarm relay at 5% above the actual level of the differential pressure across the filter and is automatically adjusted every hour.

The Daspos is suitable for detecting heavy fuel, diesel oil, hydraulic oil and lubricating oil. The monitor also simultaneously measures hazardous hydrocarbons and certain other toxic gases using a built-in gas sensor.

Oil mist detector test methods and standards

Current test methods

A test method for assessing the performance of OMDs under changing conditions such as mist concentration, mist composition, air velocity and droplet diameter has been devised previously by the Science Division of the Health and Safety

Executive (HSE). Here, OMD measurements were compared with those obtained using standard isokinetic gravimetric sampling methods. A variety of spray/mist generating techniques were employed to generate droplets in the 1 – 50 µm size range. A revised OMD test protocol was subsequently proposed with the following recommendations:

- Tests should be carried out inside a test chamber to investigate the effects of oil mist concentration, oil type and droplet size on OMD performance. The dimensions should be such that line-type instruments can be tested through windows in either side of the chamber.
- Test using two sizes of oil mist i.e. an aerosol containing small droplets generated using a smoke machine and a mist of droplets produced using an atomising spray system that will have a mean droplet size 1 to 2 orders of magnitude larger.
- Test for response to different mist types – various lubricating oils and water are suggested as test materials.
- Investigate OMD response to changes in ventilation rate (air velocity) by carrying out tests in moving air inside a duct. Line-type detectors should be placed to operate across the width of the duct. Testing is proposed at three air velocities (2, 4, and 8 m s^{-1}).
- Determine the response of the instrument under test for all test conditions, by comparing it to a reference measurement of concentration, for a number of concentrations to give a “response curve”.

The International Association of Classification Societies (IACS, 2005), which contributes towards maritime safety and regulation, has developed a type test procedure to assess OMDs fitted to engine crankcases that are used to prevent fires and mechanical breakdown.

BS ISO 16437 (2012) describes a test method based on information given in International Maritime Organisation document “Code of Practice for Atmospheric Oil Mist Detectors” (IMO {2003}). However, the actual test procedure is based on IACS (2005), which has been modified or expanded for use with atmospheric OMDs. It specifies requirements, test methods and performance criteria for OMDs installed on marine vessels. However, since it is designed for assessing atmospheric OMDs, much of the content applies to their use in other atmospheric environments such as GT enclosures.

The standard specifies the requirements for testing aspirating single point-type detectors and detectors whereby the sampling point is separated from the sensing unit(s) and uses a pipe network to carry the sampling air to the sensing unit(s). It states that it should be used as guidance only for the testing of other types of detectors that operate using different detection principles.

Limitations of current test methods

The above methods have their limitations, which will need to be considered when designing any test method, namely:

- IACS (2005) and BS ISO 16437 (2012) specify a cuboid test system with no facility to alter the air velocity. Tests are therefore essentially carried out in still air conditions only.
- IACS (2005) and BS ISO 16437 (2012) specify the generation of an aerosol of micron-sized droplets (with a maximum droplet size of 5 µm). This does not allow the effects of droplet size on OMD performance to be investigated. In practice, droplets in the size range <1 to >100 µm could be produced and ideally any OMD should be tested over the range of droplet sizes to which it is likely to be exposed.
- BS ISO 16437 (2012) is designed to test point type detectors. It does not specify the testing of line-type OMDs, although the test method could be adapted to do so.

Oil mist detector tests

Dust tunnel

Based on previous work and the procedure described in BS 16437 (2012), a method was devised suitable for the testing of OMDs. It has been developed to overcome some of the problems and limitations of previous test systems.

The test method utilised an existing dust tunnel test facility that is normally used for assessing the performance of personal dust samplers and direct-reading dust monitors. It was modified to make it suitable for the generation of oil mists and testing of OMDs. It is shown schematically in Figure 1. The tunnel comprises a 12 m long straight rectangular section with a width of 1.5 m and a height of 1 m. This is large enough to avoid problems that can occur caused by tunnel blockage created by the presence of the OMD. It is also wide enough to allow for the testing of line-type detectors. Air is blown down the tunnel using a centrifugal fan with speed controller to produce variable air velocities. A series of metal mixing grids just downstream of the fan are used to produce a uniform air flow across the width of the tunnel. Oil mist was generated and transported through the tunnel to the sampling region where the OMD and reference samplers were located. Transparent viewing windows either side of the tunnel at the measurement position allowed line-type OMDs to be tested, but were also used as windows for non-intrusive measurement of the droplet size. The air was exhausted through an array of pleated filters to remove the airborne particles/droplets before being recirculated back into the surrounding building. The filtration system was augmented by adding a sheet of high efficiency filter material on the upstream side of the filters. This acted as a pre-filter to extend the life of the main filters but also provided an additional level of filtration for removing smaller droplets (< 1µm in diameter).

The floor of the tunnel was lined with oil absorbent material to soak up any oil that settled there. This was attached using magnets so that it could be replaced quickly and easily.

Spray/mist generation

Atomiser and spray generation technology is a vast subject area covering many different applications such as paint spraying, crop protection, perfume sprays, metered dose nebulisers etc. The aim of this work was to choose methods of generation that produced droplets ranging from sub-micron (typically produced from condensation of hot gases) up to tens or hundreds of microns (typically produced by leaks from holes or defects in pressurised systems). The aerosols also needed to be produced in sufficiently large quantities so as to test the OMDs at the concentrations they would detect and/or trigger an alarm. After careful consideration of the many types of commercially available spray/mist generators, two were considered as suitable for the testing of OMDs.

Small droplets (<1 µm diameter): Concept oil mist generator

Concept Engineering Ltd manufactures an oil mist generator (OMG) that is used by many of the world's specialists in oil mist detection (see Figure 2). A mixture of oil and inert gas passes through a precision heat exchanger chamber. Here, the oil is vaporised, and the resulting vapour condenses on exiting the heat exchanger to form a dense, controllable oil mist/fog. It has a high, continuous output of 0 – 850 mg s^{-1} and can be programmed to allow for various oil types. It produces droplets from 0.2 µm mass median diameter. The oil mist concentration is increased by adjusting the OMG oil/gas mixing valve thereby changing the ratio of oil and gas being heated. The advantage of the Concept OMG is that it produces the oil droplets in the same way as they would be generated in practice, i.e. by vaporising oil on a hot surface and then allowing this to condense out in cooler air and is a similar but much safer method than that described in BS ISO 16437 (BSI, 2012). The Concept OMG came ready to use with Ondina "smoke oil" which is a highly refined, aromatic-free paraffinic white mineral oil. It is often used in pharmaceutical, food packaging, food machinery lubrication, cosmetics and other applications, where high purity is required.

The oil mist was injected into the tunnel using an air mover (Brauer Ltd) towards a large baffle plate which acted to produce a localised region of highly turbulent mixing (see Figure 1). The large eddies produced were then broken up into much smaller eddies by a turbulence grid positioned further downstream of the plate. To aid mixing further, a series of 3 axial fans were attached to the turbulence grid with their air flow directed against the tunnel flow. This resulted in a very uniform concentration of oil mist across the tunnel at the position of the OMDs. A scanning mobility particle sizer (SMPS, Grimm Inc) was used to measure the droplets generated by the Concept OMG. This measures droplets in the size range 5 – 1110 nm in near real-time.

Large droplets (~20 µm diameter): The Newland rotary atomiser

Rotary atomisers utilise centrifugal forces to generate sprays from liquid fed into the device. Newland Design Ltd manufacture an electrically-driven rotary atomiser that generates a cloud of near-equally sized droplets. Liquid is fed through a spray tip into a rapidly rotating porous spray head. As the Liquid reaches the outer surface of the spray head, it is atomised due to the shearing action of the air. Droplet size can be varied by changing the speed of rotation or liquid feed rate. Droplet size is also dependent on the surface tension of the liquid. The size range is largely governed by the maximum speed of rotation and the maximum liquid feed rate. It is capable of generating large quantities of spray, making it ideal for testing OMDs. As with the Concept OMG, the atomiser was also used with Ondina oil so that the physical properties of the oil remained the same. A peristaltic pump (Watson-Marlow model 120s/DV) was used to supply the oil. Two atomisers and two peristaltic pumps were used in an attempt create a uniform and sufficiently high mist concentration in the region where the OMDs were located. The atomisers were fastened onto a steel grid located across the tunnel as shown in Figure 3 and the x-y positions of the atomisers were adjusted until the spray concentration was sufficiently uniform at the position where the OMDs were tested.

A laser diffraction droplet size analyser (Spraytec, Malvern Instruments Ltd) was used to measure the size of the droplets generated by the Newland rotary atomiser. The Spraytec comprises a transmitter and detector unit which were located either side of the tunnel just downstream of the OMD under test. The instrument works by measuring the angular intensity of light scattered from a spray as it passes through a laser beam produced by the transmitter. The recorded scattering pattern is then analysed by the detector to determine the droplet size distribution with a size range typically from 0.5 – 600 µm. The size distribution is determined almost instantaneously (usually within 100 µs) enabling the instrument to measure rapidly changing sprays.

Oil mist detector test procedure

All of the OMDs were wired and set up according to the manufacturers supplied instruction manuals. Where possible the OMDs were zeroed and, in the case of the Sigrist Visguard, a single point span calibration check was carried out using the supplied calibration rod.

Gravimetric isokinetic samplers were used to determine the oil mist concentrations that the OMDs were exposed to. During isokinetic sampling, air is pulled through a sharp-edged inlet probe designed so that air velocity into the probe matches that of the surrounding air ensuring that a representative sample of airborne contaminant is collected. Personal sampling pumps or area sampling pumps (SKC Universal PCXR4 or Flite 3) were used to regulate the sampler flow rate. The isokinetic samplers therefore gave a measure of the "true" concentration of airborne oil mist present. The sampler flow rate was adjusted and checked before and after each test using a primary flow calibrator (TSI 4046). The sampled oil mist was collected onto 25 mm diameter GF/F glass fibre filters fitted inside the samplers. These were acclimatised inside a temperature and humidity controlled balance room before and after exposure before being weighed. The airborne oil mist concentration was then calculated from the amount of oil collected on the filter, the average sampler flow rate and the duration of sampling. As the oil mist concentrations generated inside the tunnel during testing were high, the isokinetic samplers were only required to run for a few minutes in order to collect a weighable oil deposit onto the filter.

For point-type OMDs, the detector was placed centrally across the tunnel and at a height of 40 cm from the tunnel floor. An isokinetic sampler was placed 30 cm either side of the OMD (see Figures 1 and 4). This separation was regarded as adequate such that the OMD did not interfere with the sampling characteristics of the isokinetic probes and vice versa. It also ensured that the samplers and the OMD were in a region of aerosol uniformity. BS ISO 16437 (2012) states that the reference samplers should give readings within 10% of each other.

For the Tyco line-type OMD, the combined transmitter/detector head was positioned outside the tunnel and the beam of light was shone through a glass window located in the side of the tunnel. The light beam passed through the tunnel and was reflected from the rear wall using a reflective sheet and back to the detector. For small droplets, a concentration uniformity check across the tunnel using three isokinetic sampling probes at a height of 40 cm and at distances of 29, 75 and 121 cm from the tunnel wall revealed that the oil mist was well mixed and dispersed, giving a coefficient of variation in the tunnel concentration of 3.4%. Therefore, a single isokinetic probe was used to determine the average concentration across the tunnel. For tests using larger droplets, the spray was less uniform and so an average measurement of tunnel concentration was determined immediately after the OMD alarmed using five equally-spaced isokinetic samplers located at the height of the OMD light beam.

The test procedure depended on the type of OMD and the droplet size. For OMDs that give a reading of mist concentration, the average value (taken over the gravimetric sampling period) reported by the OMD was compared to the average gravimetric measurement. A graph of OMD concentration versus gravimetric reference concentration was then produced. For OMDs used to indicate an alarm situation, the concentration was slowly increased until the OMD alarm activated and then the concentration was immediately determined using the gravimetric method. This was repeated at least 3 times.

For small droplets, the tunnel concentration was monitored using a direct-reading dust monitor (Microdust Pro Cel-712, Casella Ltd) positioned centrally inside the tunnel and approximately 1 m upstream of the OMD. This is capable of measuring aerosol concentrations between 0.001 and 250,000 mg m^{-3}. It was used to give an indication of tunnel concentration so that the test duration required to give a weighable deposit of oil on the filter could be estimated from the isokinetic sampler flow rate. The response of the Microdust Pro drops significantly with increasing droplet size and so, for the larger droplets the tunnel concentration was estimated from the oil feed rate of the Watson-Marlow- peristaltic pumps. The feed rate in g min^{-1} was determined for a range of pump settings by feeding the oil into a container located on a top pan 2-figure balance (Sartorius model MP8-2, resolution 0.01g). The increase in container weight over set time intervals was used to determine the feed rate. Knowing the air velocity through the tunnel and hence the volume flow rate, it was possible to estimate the maximum spray concentration at any pump setting. In reality the concentration would be different due to settling of the larger droplets and/or insufficient mixing. However, from this it was possible to estimate roughly the test duration required to give a weighable deposit of oil on the filter.

The tunnel was operated at an air velocity of 0.25 m s^{-1} for the small droplets using isokinetic probes of 1 cm internal diameter and operating at a flow rate of 2.36 l min^{-1} to give a matching velocity at the probe inlet. The tunnel was operated at an air velocity of 0.5 m s^{-1} for the large droplets to minimise settling of the droplets between the point of generation and the location of the OMDs. In this case, isokinetic probes of 2.1 cm internal diameter were used and operated at a flow rate of 5.2 l min^{-1} to give a matching velocity at the probe inlet.

The Millennium and Tyco OMDs indicate a low and high oil mist level alarm and so they were tested at each setting. The Daspos OMD has no sensitivity setting and so it was just tested until it reached an alarm state. The Sigrist OMD has various range settings and was set to the highest measurement range (0 – 100 PLA). The QMI OMD was set to various alarm limit values and the oil mist concentration was increased until the percentage output displayed on the instrument was close to 100% of the set limit value. The average percentage reading during a test multiplied by the alarm limit value was taken as the measured concentration. For both the Sigrist and QMI OMDs the instrument output display was noted at set intervals (usually every 10-15 seconds) for the duration of the test.

Ideally the droplet size should have been measured for each test. However, this was beyond the scope of this project and so the size distribution of the droplets generated by the Concept OMG and the Newland rotary atomiser was measured at low and high concentrations to see if there was any variation in droplet size with increased concentration.

Results and discussion

The results of the droplet size measurements are shown in Figures 5 and 6. Figure 5 shows the size distribution for the small droplets generated using the Concept OMG. It can be seen that the volume median diameter increased from around 0.25 µm to 0.30 µm as the concentration increased from around 24 – 217 mg m^{-3} (measured inside the tunnel with the Microdust Pro). This is consistent with the manufacturer’s instruction manual that quotes a typical droplet size of > 0.20 µm and which describes an increase in droplet size with increasing concentration. Figure 6 shows the size distribution for the larger droplets generated with the Newland atomiser. It can be seen that there was a minor increase in volume median diameter from 16.9 to 20.4 µm as the tunnel concentration increased from 299 to 1811 mg m^{-3}. This small increase is somewhat surprising since the manufacturer states that the droplet size increases with increasing liquid feed rate. What is also notable, however, is the increase in spread of the size distribution with increasing concentration.

The following discussion is based on an assumed LEL of 48 g m^{-3} that is often quoted in the literature although, as discussed earlier, this will likely change with droplet size and is likely to fall for droplets > 20 µm (Gant, 2013). Therefore, this value should not be regarded as absolute and is just used as an indicator of detector performance.

VisGuard (Sigrist)

The response of the VisGuard OMD to concentration and droplet size is shown in Figure 7. It can be seen that there is a very good fit to the data with a coefficient of correlation close to 1 for both droplet sizes. The best curve fit to the data for the smaller droplets was found to be a power fit and the best curve fit to the data for the larger droplets was found to be a 2-power polynomial fit. For both droplet sizes, the OMD underestimated the true concentration of oil mist measured by the gravimetric samplers as shown by comparing the curves with the 1:1 relationship in Figure 7. The reason for the highly non-linear response of the smaller droplets is not certain, but it may be a result of the increase in droplet size with increasing concentration as shown in Figure 5. The response was much lower for the droplets generated with the Newland rotary atomiser which were approximately two orders of magnitude larger. These findings are not surprising since the response of most light scattering instruments is highly dependent on particle/droplet size. Clearly, in order to set the instrument to alarm accurately at any given concentration then the detector calibration curve for the droplet size of interest would be required. Droplet size will vary depending on how the spray/mist is generated and so it would be very difficult to set an absolute alarm limit. Best practice would be to set the alarm to a very low value such that even for a spray/mist containing larger droplets the OMD would still alarm at a "safe" concentration. For example, if the OMD was set to alarm at 10 mg m^{-3} (calibrated using PLA), from Figure 7 the actual concentration of oil mist for the small and large droplets would be approximately 100 and 400 mg m^{-3} respectively i.e. very unlikely to represent a risk of explosion.

QMI Triplex

The response of the QMI OMD with concentration for the smaller droplets is shown in Figure 8. The best fit to the data was a linear fit which gave a coefficient of correlation of 0.9794. The linearity of response would tend to suggest that the instrument is not as sensitive to changes in droplet size. The QMI OMD in general overestimated the true concentration measured by the gravimetric samplers by a factor of 2 – 4.

For the larger droplets it was not possible to assess the detector over a wide range of concentrations since it would only just detect droplets when set to the lowest alarm setting (50 mg m^{-3}) at the highest concentration of mist that could be generated inside the tunnel. Therefore, with the instrument set at an alarm level of 50 mg m^{-3} the liquid feed rate was increased until the instrument read 50 – 150% of the alarm level. Three repeat tests were carried out and the results are shown in Table 2. It can be seen that there is some variation in the response of the OMD given by the ratio of reference concentration to OMD concentration with a coefficient of variation (COV) of 33%. This is likely because the OMD was at its limit of detection and the instrument display varied considerably during the test even though the concentration inside the tunnel was relatively constant. However, what can be clearly seen is that the OMD underestimated the "true" concentration by a factor of about 10 to 20.

Best practice would therefore be to set the OMD to the lowest alarm setting (50 mg m^{-3}) since even for the larger droplets the OMD would alarm at an actual concentration of around 800 mg m^{-3} which is unlikely to represent an explosion risk (1.7% of the LEL assuming a LEL of 48,000 mg m^{-3}).

It should be noted that the optics of the OMD rapidly became contaminated at these levels of oil mist (900 – 1700 mg m^{-3}) such that near the end of a 2 min test a dirty optics error was displayed. No such error was observed for the smaller droplets. This may also have had an effect on the response of the instrument during use.

Millennium APM

Table 3 shows the concentration of oil mist at which the detector alarmed for the two droplets sizes. It can be seen that for the smaller droplets and with the detectors set to the highest and lowest sensitivities the detector alarmed at very low concentrations i.e. 66 and 164 mg m^{-3} respectively. This translates to 0.14 and 0.34% of the LEL. These were the averages of three repeat measurements. The COV of the 3 readings at both sensitivities was very low (3.4 and 4.8% for the highest and lowest sensitivities respectively) indicating good repeatability of the measurements. For the larger droplets, and with the detectors set to the highest and lowest sensitivities, the detector alarmed at considerably higher concentrations i.e. 272 and 606 mg m^{-3} respectively. This relates to 0.6 and 1.3% of the LEL. The COV was very low (4%) for the 4 tests carried out at the lowest sensitivity indicating very good repeatability of the measurements. The repeatability was not as good with the detector set to the highest sensitivity with a COV of 17% for 3 tests.

Best practice would therefore be to set the OMD to the highest sensitivity so that if exposed to larger droplets it would alarm at a concentration less likely to represent an explosion risk.

Tyco

Table 4 shows the concentration of oil mist at which the detector alarmed for the two droplets sizes. The instrument has a low and high level alarm that relates to the highest and lowest sensitivity settings on the Millennium OMD. It can be seen that for smaller droplets at the low and high oil mist alarm levels the detector alarmed at very low concentrations i.e. 94.3 and 149.6 mg m^{-3} respectively. This relates to 0.16 and 0.31% of the LEL. These are very similar values to those obtained with the Millennium OMD. These were the averages of five repeat measurements and the COV at both alarm limits was low (4.3 and 10.3 % at the high and low alarm levels respectively) indicating good repeatability of the measurements. For the larger droplets and with the detectors set to the low and high oil mist alarm levels the detector alarmed at considerably higher concentrations of 448 and 1242 mg m^{-3} respectively. This relates to 0.9 and 2.6 % of the LEL. These were the averages of seven and five repeat measurements at the low and high alarm limits respectively. The COV at both sensitivities was very low i.e. 7.8 and 2.4% for the low and high oil mist alarm levels respectively, indicating good repeatability of the measurements.

Best practice would therefore be to set the OMD to the lowest alarm level so that if exposed to larger droplets it would alarm at a concentration less likely to represent an explosion hazard.

Daspos (LAS10)

For the small droplets (0.25 – 0.3 µm), the Daspos OMD detector failed to alarm at the highest concentration of oil mist that the Concept OMG could produce inside the tunnel, i.e. > 2000 mg m^{-3} (4.2% LEL) measured using the Microdust pro dust monitor. This is assumed to be because the droplets were too small to be captured by the steel mesh filter resulting in no detectable increase in pressure drop across the filter. Contrary to this, for the larger droplets (~20 µm), the Daspos alarmed at the lowest concentration of droplets that could be generated using the Newland rotary atomiser, i.e. at a speed setting of 1 on the peristaltic pump. This equated to a concentration of ~ 38 mg m^{-3} (0.08% LEL) measured using the gravimetric isokinetic samplers. Clearly, the response of the Daspos OMD is very sensitive to the presence of larger droplets. The Daspos repeatedly alarmed at the lowest pump setting and so all that can be concluded is that it will detect concentrations < 38 mg m^{-3} of Ondina oil mist containing droplets of approximately 20 µm in diameter.

Conclusions

The following conclusions can be drawn:

- A dust tunnel facility has been modified to allow the response of commercially available OMDs (both point and line detectors) to be investigated as a function of droplet size, concentration and ambient air velocity.
- All OMDs that detect airborne droplets by light scattering or light obscuration were very sensitive to oil droplets smaller than 1 µm and measured concentrations or alarmed at concentrations much lower than potential explosive levels.
- All OMDs that detect airborne droplets by light scattering or light obscuration were much less sensitive to droplets ~ 20 µm in diameter but still measured concentrations or alarmed at concentrations significantly lower than levels likely to cause an explosion.
- The Daspos LAS10 OMD that detects airborne droplets by measuring the increase in differential pressure across a removable filter mesh located within the instrument did not detect oil droplets ~ 0.3µm in diameter at the highest concentration that the oil mist generator could produce inside the tunnel (~2000 mg m^{-3}).
- Contrary to this, for the larger droplets the Daspos LAS10 alarmed at the lowest concentration of droplets that the oil mist generator could produce inside the tunnel (~ 38 mg m^{-3}).
- Some OMDs appear to be more prone to contamination than others. The optics of the QMI OMD quickly became coated with oil at the high concentrations required to obtain a response for the larger droplets, giving a dirty optics error. However, the optics can be cleaned easily and quickly. No such problem was apparent for the smaller droplets and none of the other OMDs indicated contamination of the optics for either droplet size throughout the tests.

Implications

It has been shown that the sensitivity of light scattering oil mist detectors decreased significantly with increasing droplet size and it may be that as the droplet size increases even further they will be less likely to detect or alarm effectively at safe levels. Contrary to this the sensitivity of the pressure drop oil mist detector increased with increasing droplet size. Therefore, in a scenario where a mist is produced that contains small droplets, such as when oil comes into contact with a hot surface, light scattering detectors could be a very effective detection method. Where the mist/spray contains larger droplets such as when oil is released from a pinhole or split in a hose of a hydraulic system, the pressure type could be the most effective detection method. In reality, the likely release mechanism and resultant droplet size may not be known in which case the best strategy may be to use a combination of the two detection methods. Other operational factors would also need to be considered when deploying OMDs such as reliability, ease and frequency of maintenance, cost-benefit analysis.

Since this work is based on just two droplet sizes and it is clear that detector response depends critically on droplet size, further investigations are required into detector response with increasing droplet size.

The aim in future will be to engage with the British Standards Committee making them aware of this research and to help set out a more robust test methodology that accounts for these findings.

Disclaimer

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Table 1. Various commercially available OMDs

Manufacturer	Model	Detection Method	Scan distance (m)	Measurement range	Response time (seconds)	Performance Certification	Typical applications	Manufacturers quoted features
Millennium (www.net-safety.com)	APM	Single point	N/A	Low, medium and high sensitivities	N/A	N/A	Gas compressor stations, engine rooms, gas turbine enclosures, marine battery rooms, duct monitoring, HVAC systems	No mirrors to become contaminated Not affected by high air velocities Multiple sensitivity settings Certified for use in hazardous areas
QMI (www.oilmist.com)	Triplex	Single point	N/A	0 - 1.3 mg l^{-1} 0 - 2 mg l^{-1}	0.05	N/A	Engine rooms, generator rooms, hydraulic chambers, purifier rooms, steering gear, bow thrusters	No false alarms Fast response Detectors located > 100m from monitor Minimal maintenance
Specsvision www.specsvision.com)	Vision IIIA	Single point	N/A	0 - 5 mg l^{-1} Alarm setting 2.5 mg l^{-1}	N/A	Tested to IACS M67	Engine rooms, purifier rooms, pump rooms, generator rooms	Instantaneous response to an alarm Less contamination sensor design Superior accuracy verified
Valcom (www.valcom.it)	DSOMD01	Single point	N/A	0 - 2 mg l^{-1} (alarms at 1.2 mg l^{-1})	N/A	Complies with IMO code of practice	Marine and industrial applications Pump rooms, engine rooms	Detectable particle diameter: 0.4 - 10um Advanced diagnostic and control system
Sigrist www.photometer.com)	Visguard	Single point	N/A	0 - 100 mg m^{-3} PLA (1 µm polystyrene latex aerosol)	N/A	Complies with IMO code of practice	No information given	1 - 40 sampling positions can be monitored Easy calibration check with calibration rod High sensitivity, stability and accuracy Easy to install and service
Green Instruments www.greeninstruments .com)	G2000	Line of sight	3 - 9 1 - 3 (optional)	0 - 100% opacity level	0.1 to 10	N/A	Typically used to monitor pump rooms and ship engine rooms	Covers and protects over a large area Multiple alarm levels Durable and robust design East cleaning of contaminated lenses
Wormald (www.wormald.com)	6003/1 6003/2 6003/3 6003/4	Line of sight	2 - 50	0 - 100% opacity level	5 - 6 10 - 12 5 - 6 10 - 12	N/A	Used to detect oil mist Used to detect oil mist Used to detect smoke Used to detect smoke	Automatic Self Calibration Dual automatic compensation Indication of dirty optics. Configured by software Functions up to 90% lens contamination
Daspos (www.daspos.com)		Pressure drop across a steel mesh	N/A	>0.002 mg l^{-1}	5 - 10	N/A	Typically used to monitor ship engine rooms and off-shore oil rigs.	Detects oil mist and hydrocarbon gas simultaneously. Suitable for heavy fuel, diesel oil, hydraulic oil and lubricating oil No optics contamination

Table 2. Response of the QMI OMD for large droplets

Oil mist Concentration (mg m^{-3})		Grav/OMD	% LEL
Gravimetric	OMD		
871	82.9	10.5	1.8
746	45.3	16.5	1.6
1706	81.3	21.0	3.6
	Average	**16.0**	
	StDev	**5.3**	
	COV	**32.9**	

Table 3. Concentration of oil mist at which the Millennium OMD alarm triggered for small and large droplet sizes

SMALL DROPLETS (Concept OMG)					LARGE DROPLETS (Newland rotary atomiser)		
	OMD alarm (mg m^{-3})		**OMD alarm (% LEL)***			**OMD alarm (peristaltic pump speed)**	
	Highest sensitivity	**Lowest sensitivity**	**Highest sensitivity**	**Lowest sensitivity**		**Highest** sensitivity**	**Lowest** sensitivity**
	63.4	158.7	0.13	0.33		10	26
	67.8	160.1	0.14	0.33		8	24
	66.3	172.9	0.14	0.36		7	25
						10	
Average conc	**65.8**	**163.9**	**0.14**	**0.34**	**Average pump speed**	**8.8**	**25.0**
StDev	**2.2**	**7.8**	**0.005**	**0.016**	**StDev pump speed**	**1.5**	**1.0**
COV	**3.4**	**4.8**	**3.4**	**4.8**	**COV**	**17.1**	**4.0**
					Average conc (mg m^{-3})	**272.8**	**605.8**
					%LEL	**0.6**	**1.3**

* for an assumed LEL of 48,000 mg m^{-3}
**liquid feed rate increased until detector alarmed then mist concentration measured

Table 4. Concentration of oil mist at which the Tyco OMD alarm triggered for small and large droplet sizes

SMALL DROPLETS					LARGE DROPLETS		
	OMD alarm (mg m^{-3})		**OMD alarm (% LEL)***			**OMD alarm (peristaltic pump feed)**	
	Low	**High**	**Low**	**High**		**Low****	**High****
	110.5	148.5	0.23	0.31		13	65
	91	160.4	0.19	0.33		13	62
	98.8	143.5	0.21	0.30		13	64
	102.7	148.3	0.21	0.31		14	66
	84.5	147.1	0.18	0.31		12	65
						11	
						12	
Average conc	**97.5**	**149.6**	**0.20**	**0.31**	**Average pump speed**	**12.6**	**64.4**
StDev	**10.1**	**6.4**	**0.021**	**0.013**	**StDev pump speed**	**1.0**	**1.5**
COV	**10.4**	**4.3**	**10.4**	**4.3**	**COV**	**7.8**	**2.4**
					Average conc (mg m^{-3})	**448.3**	**1242.4**
					%LEL	**0.9**	**2.6**

* for an assumed LEL of 48,000 mg m^{-3}
**liquid feed rate increased until detector alarmed then mist concentration measured

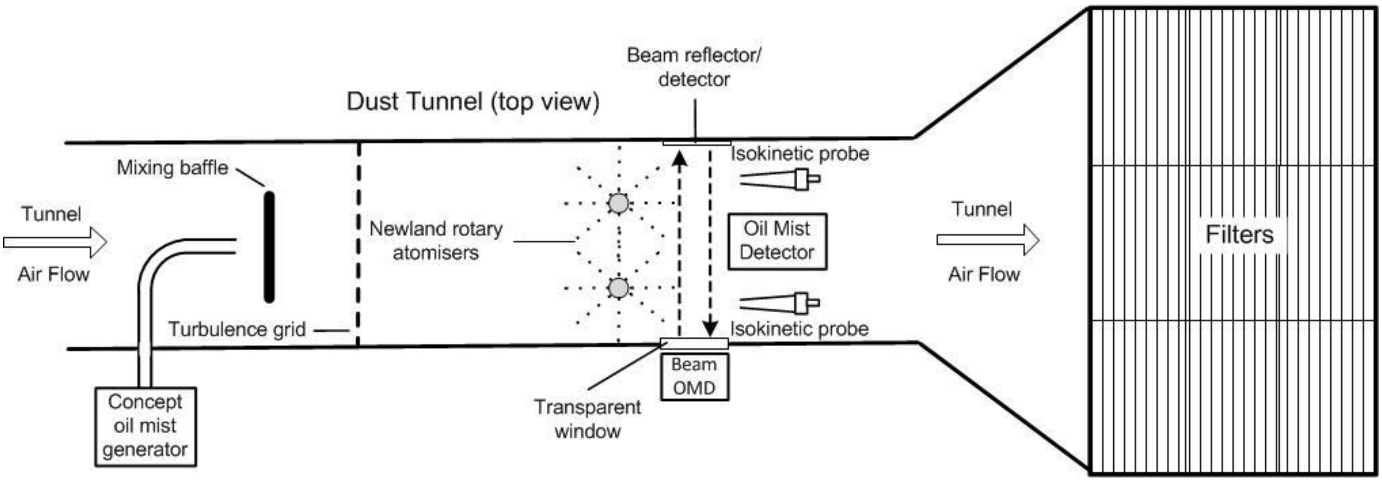


Figure 1 Schematic of tunnel used to test oil mist detectors

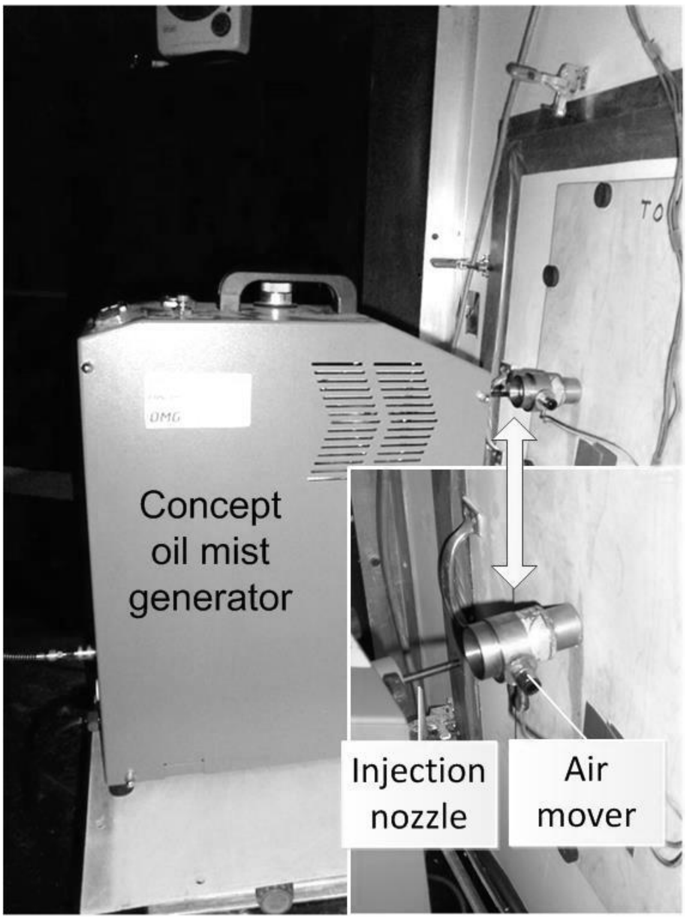


Figure 2 Generation of small droplets using the Concept oil mist generator

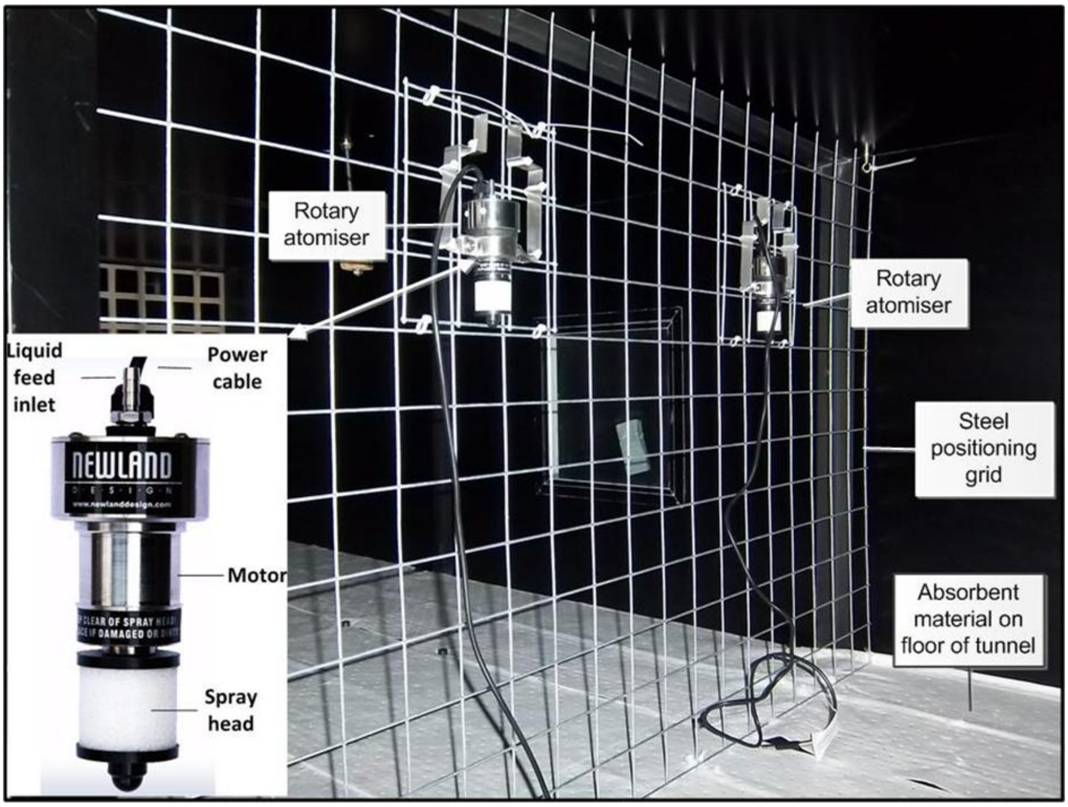


Figure 3 Generation of large droplets using the Newland rotary atomisers

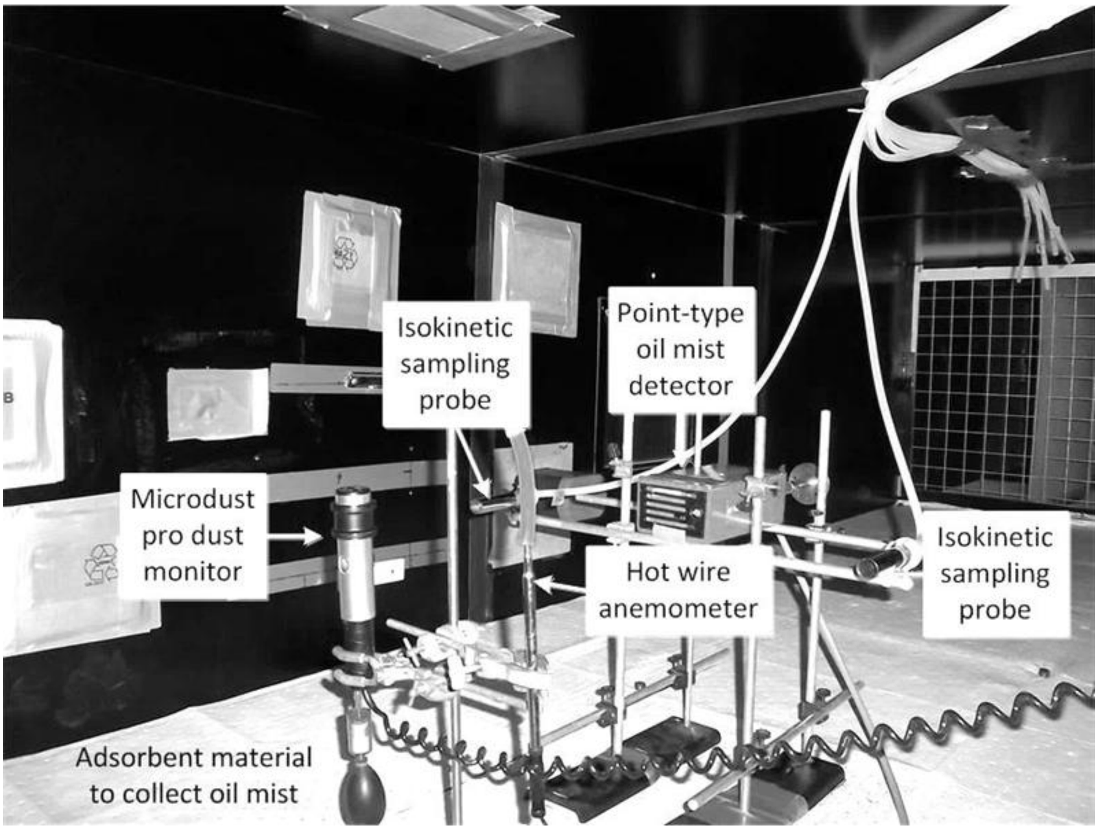
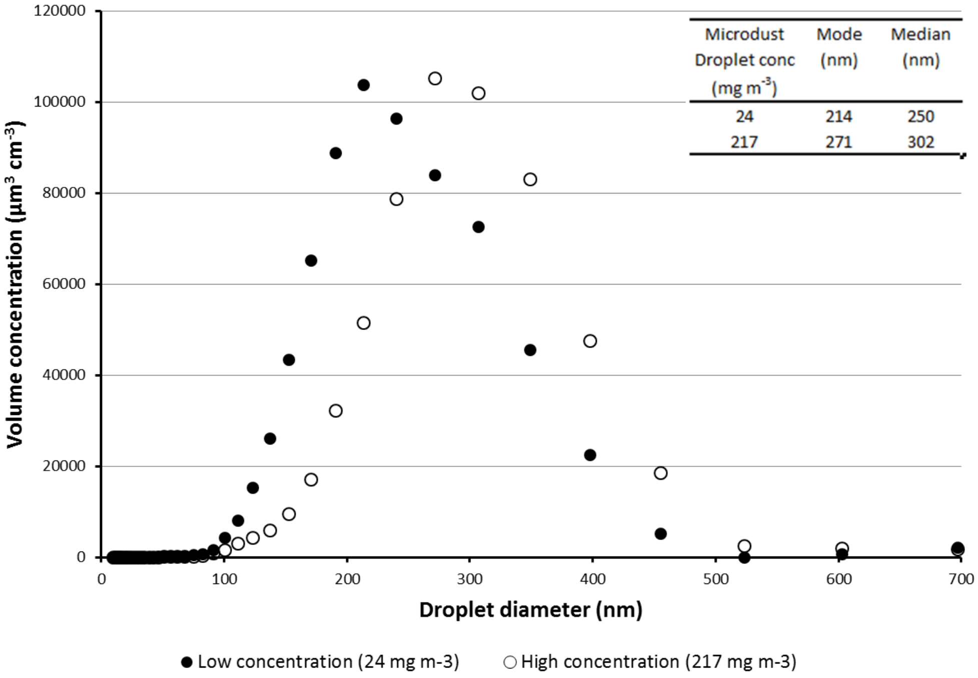
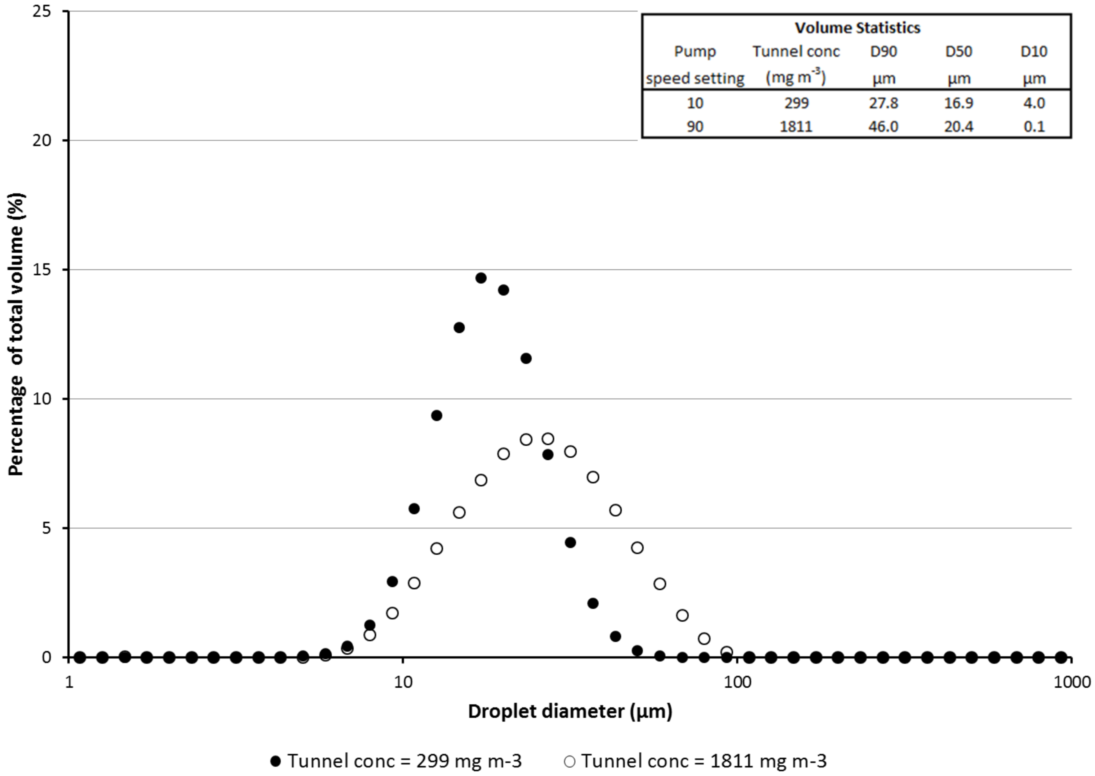


Figure 4 Photograph showing oil mist detector and reference isokinetic sampling probes either side



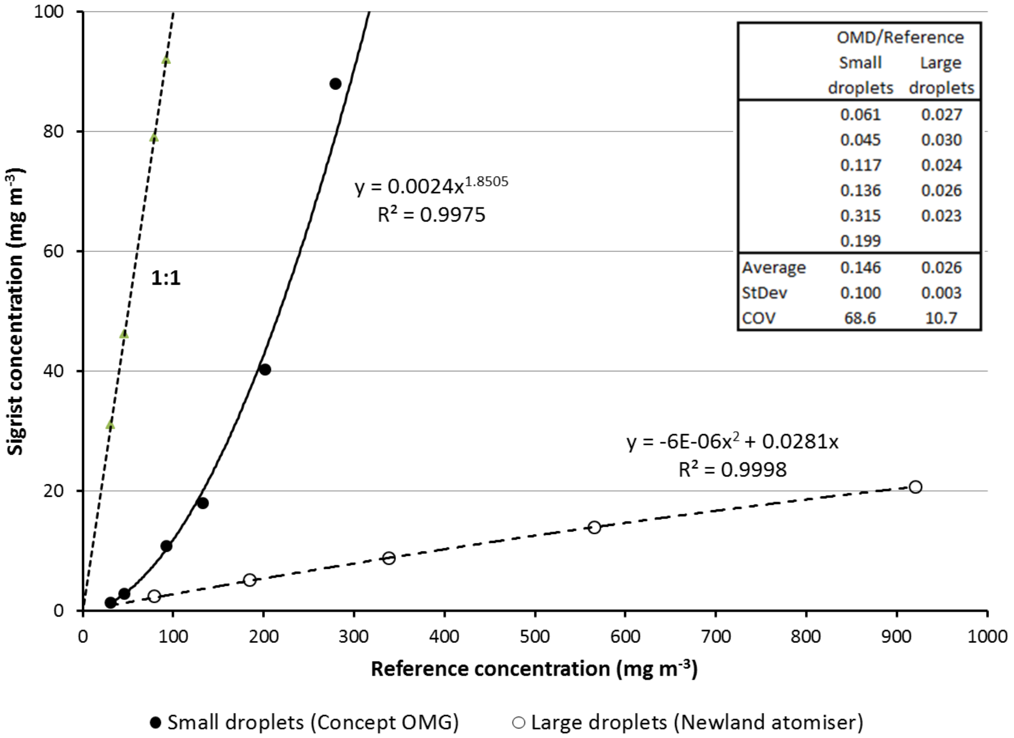
Microdust Droplet conc (mg m^{-3})	Mode (nm)	Median (nm)
24	214	250
217	271	302

Figure 5 Size distribution of small droplets generated using the Concept OMG and measured using the GRIMM SMPS



Volume Statistics				
Pump speed setting	Tunnel conc (mg m^{-3})	D90 µm	D50 µm	D10 µm
10	299	27.8	16.9	4.0
90	1811	46.0	20.4	0.1

Figure 6 Size distribution of large droplets generated using the Newland rotary atomiser and measured using the Malvern Spraytec *(Note: D50 represents the cumulative 50% point of diameter, i.e. the median)*



	OMD/Reference Small droplets	 Large droplets
	0.061	0.027
	0.045	0.030
	0.117	0.024
	0.136	0.026
	0.315	0.023
	0.199	
Average	0.146	0.026
StDev	0.100	0.003
COV	68.6	10.7

Figure 7 Response of the Sigrist Visguard OMD to changing oil mist concentration and droplet size

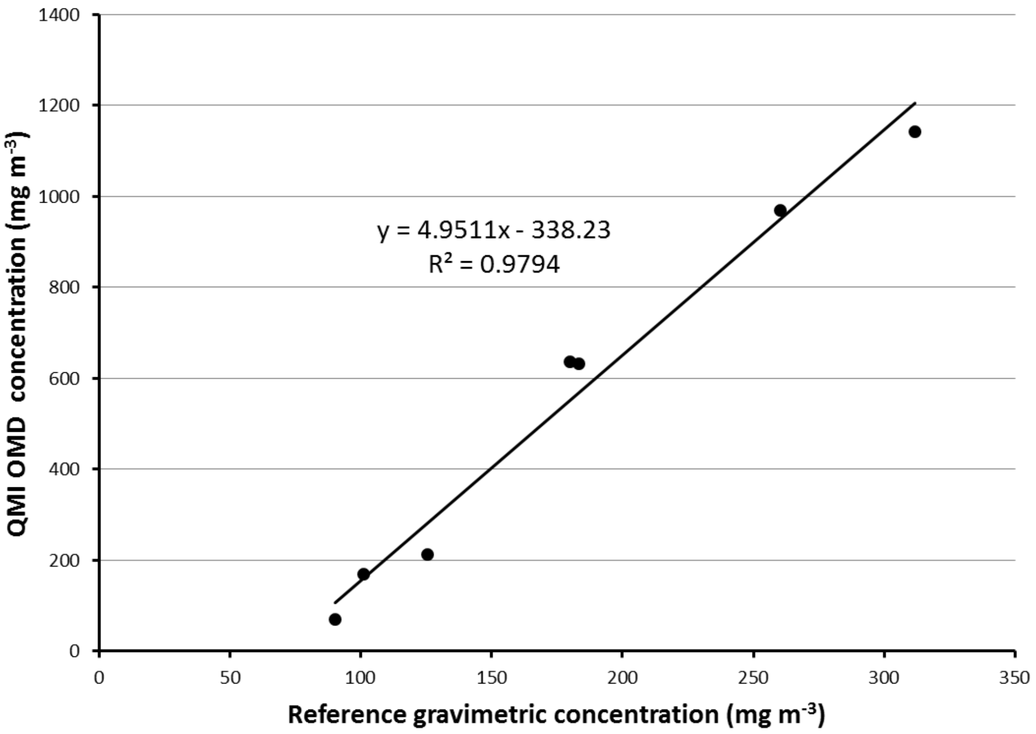


Figure 8 Response of the QMI Triplex OMD to changing concentration of oil mist, for smaller droplets