ASSESSMENT OF FLAMMABLE GAS INGESTION AND MIXING IN OFFSHORE HVAC DUCTS: IMPLICATIONS FOR GAS DETECTION STRATEGIES

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An assessment of flammable gas ingestion and mixing in offshore HVAC ducts is presented as a basis for a set of initial recommendations on gas detection strategies. These recommendations are based on the findings of a literature review and Computational Fluid Dynamics modelling of gas releases, supported by a scoping study which examined technologies for the detection of hydrocarbons on offshore platforms.

The circumstances by which a non-uniform distribution of gas could be present immediately inside or outside of an HVAC inlet are of particular interest: if an HVAC inlet ingests a non-uniform distribution of gas then there is the possibility that this could be 'missed' by the detection system.

The overall aim is to provide a basis for advice to HSE inspectors and industry on the effectiveness of flammable gas detection strategies for offshore HVAC ducts. This paper concludes with a number of initial recommendations on such strategies.

1. INTRODUCTION

The accidental release of flammable gas on offshore installations can potentially lead to the build-up of an explosive mixture. Natural or forced ventilation can help to mitigate such incidents and gas detection systems play a key role in reducing the risks from releases by enabling early detection and subsequent interventions. The provision and siting of gas detectors for open areas and gas turbine enclosures has been studied over a number of years and is comparatively well documented. However, there is much less information available on the provision and siting of gas detection systems for HVAC (Heating, Ventilation and Air Conditioning) ducts supplying air to accommodation modules, temporary refuges or process areas on an installation.

This paper presents research funded by the UK Health and Safety Executive (HSE) to examine the ingestion of flammable gas releases into offshore HVAC inlets and the subsequent mixing of gas inside HVAC ducts. Full details can be found in Lea & Deevy

(2007). The circumstances by which a non-uniform distribution of gas could be present immediately inside or outside of an HVAC inlet are of particular interest: if an HVAC inlet ingests a non-uniform distribution of gas then there is the possibility that this could be 'missed' by the detection system. The overall aim of the research was to provide a basis for advice to HSE inspectors and industry on the effectiveness of flammable gas detection strategies for offshore HVAC ducts. A summary of gas detection technologies used on offshore platforms is provided in Section 2.

The research is based on a review of the literature and Computational Fluid Dynamics (CFD) modelling. It has, in part, been prompted by an incident on the Brae Alpha platform in 2004 when there was a delay in confirmed detection and shutdown of the HVAC system despite gas being ingested into the HVAC inlets. There is no suggestion that the detectors were not operating correctly at the time of this incident.

The literature review has been very wide-ranging. It draws heavily on relevant research from the nuclear industry on the sampling of gas distributions in exhaust stacks. The key findings are summarised in Section 3. CFD simulations of a high and low pressure gas release have been undertaken for idealised representations of an offshore platform, as well as a high pressure release for a more realistic geometry based loosely on the Brae Alpha incident. These CFD results are post-processed to gain insights into the likely effectiveness of a range of detector systems for HVAC ducts. A representative sample of the CFD simulations which have been undertaken in this research are described in Section 4. A discussion of the main findings and a set of initial recommendations on flammable gas detection strategies for offshore HVAC ducts are given in Section 5. Although the study is focused on offshore HVAC ducts, the findings are also likely to be relevant to onshore installations in which gas detection is required for HVAC ducts.

2. GAS DETECTION TECHNOLOGIES FOR OFFSHORE PLATFORMS

Walsh *et al*. (2005) divide technologies for detecting hydrocarbons on offshore platforms into three main categories (excluding acoustic systems which do not measure gas concentration):

- Catalytic (also known as pellistor) point detectors.
- Infrared point detectors, which are based on the absorption of infrared light at different wavelengths by flammable (and other) gases.
- Infrared open path (beam) detectors, which use the same measurement principle as the infrared point detectors but the beam traverses a long open path and absorption in the beam is detected as a gas concentration in the same way as for the infrared point detector.

A recent development in HVAC detection technology is the extended closed path point infrared detector, which measures an average concentration over a path length of typically around 1 m. Such systems have quoted minimum alarm levels of 5% of the Lower Explosive Limit (LEL), which is significantly lower than typical alarm levels of 20% LEL.

Detectors for offshore HVAC ducts are usually located immediately outside, or just inside, the HVAC inlet. For monitoring inside ducts, point detectors can be employed in two ways: in the duct itself or on the end of a sampling system which extracts gas from the duct (known as aspirated systems).

3. FLOW AND DISPERSION OF GAS IN A DUCT

The flow in offshore HVAC ducts will generally have a Reynolds number in the range 10^5 to 10^6, based on a typical duct velocity of 5 m/s (BS EN ISO 15138) and a range of duct hydraulic diameters from 0.5 to 5 m. Whilst this is high enough to ensure fully turbulent flow some distance downstream from the entrance to a duct, such conditions may not exist immediately inside the entrance. Usually there is a development region over which turbulent boundary layers on the walls of a duct grow and eventually merge, ultimately leading to a local equilibrium in which the flow no longer changes. It is then said to be fully-developed. As a rule of thumb, Hinze (1975) recommended that fully developed turbulent flow can be assumed to occur in straight pipes with a rounded inlet after a minimum development length of 40 pipe diameters. The flow in a straight square or rectangular duct behaves in a broadly similar manner, in that the distance to fully-developed conditions is not short. Melling & Whitelaw (1976) present data which show that fully-developed turbulent flow in a square duct is reached at about 25 duct widths from the inlet.

In the offshore environment the entrance to an HVAC duct will typically be sharp-edged. In addition, there are usually obstructions present just inside and at the entrance to ducts comprising louvres, grilles and fire dampers to provide isolation from fire and gas in the event of an incident. All of these features will generate turbulence in the entrance region of a duct. Furthermore, the flow conditions immediately outside of an HVAC duct may also be turbulent due to wind flow over obstructions on an offshore platform. However, whilst the flow may well be turbulent at the inlet to an HVAC duct, and certainly will be turbulent across its full cross-section some distance downstream from the inlet, it would be wrong to simply assume that mixing will, as a consequence, be so rapid that any non-uniformity in the distribution of gas at an HVAC inlet will very quickly be dispersed to give well-mixed uniform conditions. This has a significant impact on the siting of gas detectors in HVAC ducts.

There is a significant body of literature on the mixing of a tracer gas in circular, square and rectangular ducts. In the presence or absence of bends and mixing elements it shows that the distance before well-mixed conditions are obtained can be very long and comparable to the length of the development region for fully-developed turbulent flow. This literature stems from research on the sampling of exhaust duct stacks in the nuclear industry undertaken to support the improvement and updating of American standards on gaseous radionuclide emissions (Hampl *et al.* 1986, McFarland *et al.* 1999, Anand *et al.* 2003 and Seo *et al.* 2006). In most of this research a passive tracer was released from a single location on the axis of a duct. Note that at low gas concentrations in the flammable range and for the velocities typically encountered in offshore HVAC ducts, a natural gas mixture can be regarded as a passive contaminant since the Richardson number (Simpson, 1997) is likely to be at least an order of magnitude too low for any turbulence-modifying effects of a slightly buoyant gas to dominate over shear-induced turbulence. In these tracer releases, multiple point concentration measurements were made across the entire cross-section of the duct at a number of axial locations downstream from the release. To characterise the degree of mixing, a parameter known as the Coefficient of Variation (COV) was introduced. This is defined as:

$$COV = \frac{1}{C_{mean}}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(C_i - C_{mean}\right)^2} \tag{1}$$

where N is the number of samples at a particular downstream location, C_i is the concentration of the ith sample and C_{mean} is the mean concentration over all samples at that location, defined as:

$$C_{mean} = \frac{1}{N}\sum_{i=1}^{N} C_i \tag{2}$$

The COV is simply the sample standard deviation divided by the sample mean. As an example, if the concentration distribution is such that across one half of a duct the concentration is a uniform 30% LEL whilst across the other half the concentration is a uniform 10% LEL, then the COV obtained from a large number of samples would be 0.5 (the sample mean is 20% LEL and the sample standard deviation is 10% LEL). The updated American standards (ANSI/HPS N13.1-1999) on the sampling of radioactive materials in stacks allow for single point sampling of gaseous contaminants in a duct if the COV for both velocity and concentration of a tracer gas are less than 0.2 over the central two-thirds of a duct. We do not suggest or comment on the practicality or appropriateness of these criteria for offshore HVAC ducts. However, the notion of a COV is helpful in quantifying the uniformity of mixing in a duct and it is readily computed from CFD results.

This body of research on stack sampling provides much useful data on how the COV is affected by a range of configurations. Anand *et al*. (2003) show that the distance from a point release of a tracer in a straight pipe to the position at which the COV is less than 0.2 depends on the upstream turbulence intensity. For a low turbulence intensity of 1.5%, the COV falls very slowly with distance and is still greater than unity at 30 duct diameters downstream from the point of release. Even with a high turbulence intensity of 10%, generated by passing the flow through an array of thick rods, a COV of 0.2 was still not reached after 25 duct diameters downstream.

McFarland *et al*. (1999) investigated the effect of bends and static mixing elements on the COV. They show that a single smooth 90° bend in a circular duct still requires a distance of nine diameters downstream from the bend before the 0.2 COV criterion is met. The performance of the static mixing elements was very variable; they all resulted in the 0.2 COV criterion being met within nine diameters downstream, but the most effective mixers were able to meet the criterion within three duct diameters of the mixing element. The most simple and effective mixing elements consisted of two large flow deflectors attached to opposite walls of a duct, giving a slot-like opening in the centre of the duct. Two or more of these mixing elements were used in series. The common characteristic of the most effective mixing elements appears to be the generation of large turbulent eddies which promote mixing across a duct (Seo *et al*., 2006). Mixing elements which only introduced flow swirl were less effective. One disadvantage of these simple deflector mixing elements is a relatively large non-dimensional pressure coefficient (5.0, for two elements in series).

Seo *et al.* (2006) examined the behaviour of the COV in square and rectangular ducts (aspect ratio of 3:1) with and without bends. They report that the COV is similar for circular and square-section ducts at large distances downstream from the tracer release point both with and without bends. This implies that the main findings of the above work on circular-section ducts are largely likely to carry over to square-section ducts. However, a significant difference was found when the COV for the square and rectangular-section ducts were compared; typically the COV was much higher for the rectangular duct at any given distance downstream from the point of release, by about a factor of four. The COV for rectangular ducts with bends are also consistently higher than the same flow configuration in a square duct. Seo *et al*. (2006) speculate that this is because turbulent eddies in a wide duct have less opportunity to effectively transfer mass and momentum from one side of a duct to another.

Much of the above research on stack sampling is based on a flow which is well-controlled at the inlet to a duct, for example by use of a rounded entrance or other flow control devices. As already discussed, this will not be the case for offshore HVAC installations. Turbulence can be generated by large-scale flow separation at the sharp-edged entrance to a duct or may already be present in the ambient flow outside of the duct. McFarland *et al*. (1999) note that the work of Hampl *et al*. (1986) was based on a sharp-edged inlet and in comparison to their later research using a well-controlled approach flow the COV are found to be reduced by between a factor of two to three: flow separation at the inlet enhances mixing inside a duct. Nevertheless, Hampl *et al*. (1986) still suggest that up to 50 duct diameters may be needed for near-uniform mixing of a passive tracer in a straight pipe, even with a sharp-edged inlet.

The effect of grilles on the turbulence in a duct is relatively well understood. Laws & Livesey (1978) explain that the effect is either to suppress or enhance turbulence dependent on the geometry of the grille. Thus a very fine grille, or mesh, will tend to suppress turbulence and any turbulence which is introduced by the mesh decays quickly due to its small scale. A grid of relatively large diameter rods will enhance turbulence, although Laws & Livesey (1978) state that it is difficult to achieve a turbulence intensity of much higher than 10%. It is not clear whether grilles typically used to cover HVAC inlets will suppress or enhance turbulence. However, even if turbulence is significantly enhanced, Anand *et al*. (2003) show that the COV will remain high for long distances downstream. For an inlet turbulence intensity of 10% created by an array of thick rods, they found that the COV was still over 0.5 at 15 duct diameters downstream from the rod array. The reason for the relative ineffectiveness of such devices on mixing is that they introduce turbulence on too small a length-scale.

It is also significant that both Anand *et al*. (2003) and Seo *et al*. (2006) note that the COV is little-affected by the Reynolds number. Seo *et al.* (2006) state that for a square duct the Reynolds number over the range 25,000 to 150,000 has only a small effect on COV, whereas for a rectangular duct with a 3:1 aspect ratio the COV shows a significant dependence on Reynolds number below 50,000 but relatively little dependence at higher Reynolds number. Anand *et al*. (2003) and Seo *et al*. (2006) conclude that for fully turbulent flow, mixing is primarily dependent on geometry.

4. CFD MODELLING OF GAS INGESTION AND DISTRIBUTION INSIDE HVAC DUCTS

The distribution of gas concentration over the cross-section of a free jet or plume varies continuously with radius (Rodi, 1982). For a very high pressure release the pseudo-source approach of Ewan and Moodie (1986) can be used in conjunction with empirical data from Rodi (1982) to give a good indication of this concentration distribution. Thus for a release of pure methane at a stagnation pressure of 100 bar from a hole of 12 mm diameter, the concentration at approximately 10 m downstream from the release would be 100% LEL on the jet centreline but just 10% LEL at a radius of 1.9 m. This distance, over which concentration varies by a factor of ten, is broadly comparable to the dimensions of typical offshore HVAC inlets. If such a release were ingested into an HVAC inlet then significant non-uniformity in gas concentration could be expected outside and inside the HVAC duct.

Two idealised scenarios have been modelled: firstly a 2.5 kg/s high pressure release of pure methane across the underside of a platform for conditions similar to those described above and secondly a 0.55 kg/s low pressure release of pure methane in the wake of a platform. In each case the platform was modelled as a rough-walled cube of side 30 m located 25 m above sea level. Wind speeds of 1.5 to 2 m/s were simulated by imposing a neutral atmospheric boundary layer profile upstream of the platform. A large region of the atmosphere around the platform 120 m wide by 115 m high and 240 m long was modelled. Figure 1 shows the idealised platform. Only the low pressure release is presented in this paper. The initial trajectory of the release is indicated, being at the rear of a partially-obstructed module. Also shown is a high level horizontal HVAC duct of internal dimensions 23 m × 2.8 m × 1.8 m. Figure 2 shows the modelled geometry and mesh at the inlet to the duct comprising a set of 24 louvres and rectangular obstructions having a blockage equivalent to that of a set of open fire dampers with their supporting structure. A mass flow rate is imposed at the interior end of the duct equivalent to a uniform velocity of 6 m/s. The flow around the platform and inside the duct was simulated using the k-ε turbulence model. A total of 564,000 nodes (control volumes) are used.

A more realistic scenario has also been modelled which draws upon some elements of an incident on Brae Alpha in 2004 where a high pressure gas riser failed resulting in gas

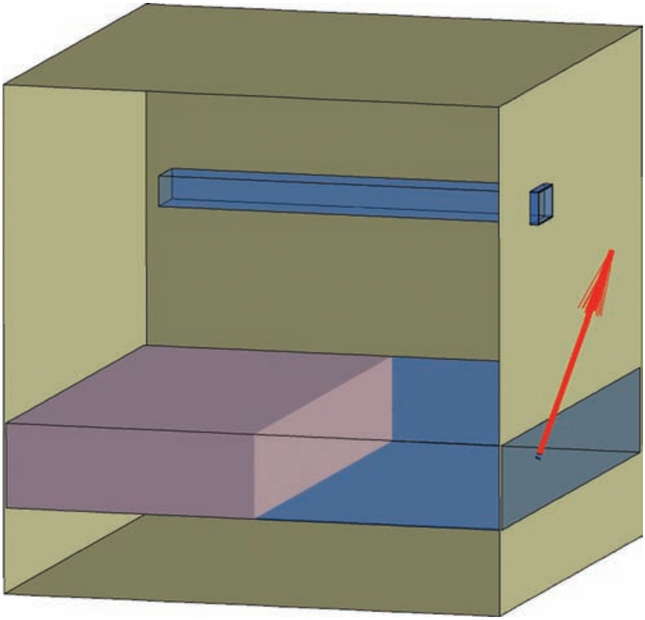

Figure 1. Idealised modelled geometry for an offshore platform, showing the location and orientation of a gas release from a partially-obstructed module. A HVAC duct is also shown

ingestion into Hazardous Modules via the Hazardous HVAC inlet duct. The intention has not been to replicate this incident but instead to devise a more realistic scenario than the idealised configurations outlined above so enabling more general conclusions to be drawn on the interaction between gas and HVAC inlets and ducts. A very simplified representation of the Brae Alpha platform has been modelled, see Figure 3. A large region of the atmosphere surrounding the platform has again been modelled. A wind speed of 12.3 m/s was imposed, with a wind direction chosen so as to direct the release towards the HVAC inlets located on the downwind side of the platform. The wind speed and direction is broadly consistent with that on the day of the incident. A high pressure gas release of pure methane at approximately 2 kg/s was modelled using the Ewan and Moodie (1986) approach. The release is initially directed vertically, but impinges on a horizontal pipe before being deflected by the wind. Credible flow rates are imposed through the three HVAC inlets shown in Figure 3. The geometry was meshed using a total of 665,000 nodes (control volumes).

All simulations have been undertaken using ANSYS CFX 10 software, in time-dependent mode.

The computed gas distribution for the low pressure idealised release scenario is shown in Figure 4. The location of the gas plume outside the HVAC duct is seen as a region

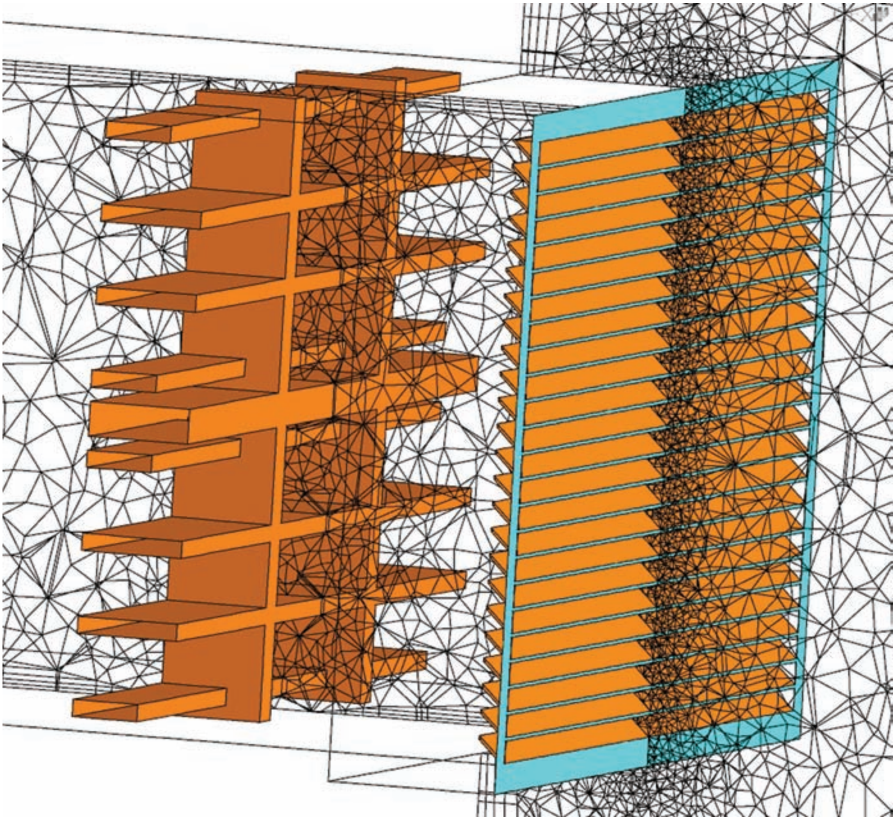

Figure 2. Geometry and meshing of louvres and open fire dampers at the inlet to an HVAC duct.

of high concentration close to one side of the inlet. A portion of this release is ingested into the duct. It is clear that the gas concentration is far from uniform at the inlet to the duct. It remains non-uniform immediately downstream from the louvres and fire dampers. This non-uniformity persists along the full length of the duct. Thus, the COV just outside of the duct is 1.27, immediately downstream from the fire dampers it is 0.97, whilst at the end of the duct it is still 0.67. Figure 5 shows more detail of the concentration distribution just inside the inlet. Although the average concentration in the duct is 21% LEL, in many locations the gas concentration is well below 10% LEL and often below 5% LEL. If point detectors were located on only one side of the duct then this release could potentially be missed by the detection system. Post-processing of these results shows that, in contrast, a

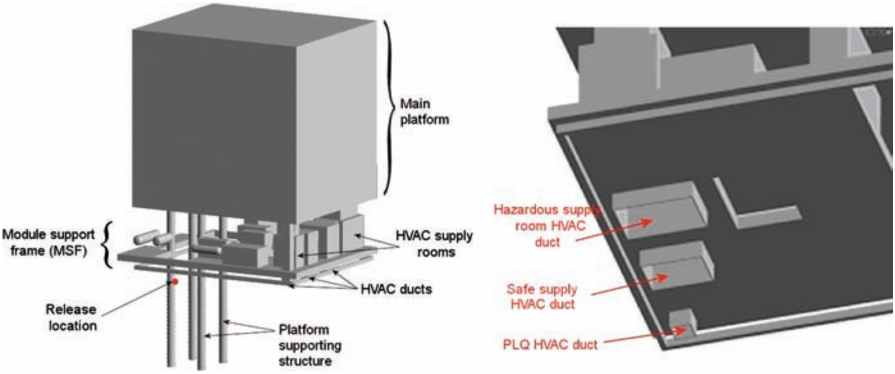

Figure 3. Geometry and location of HVAC inlets for the more realistic scenario

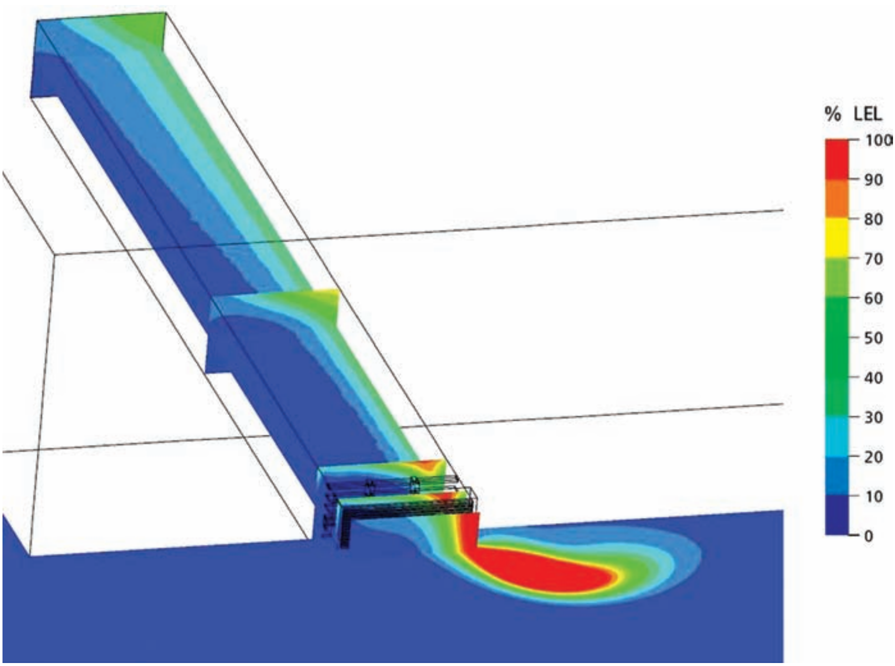

Figure 4. Gas concentration distribution inside and outside of an HVAC duct for a low pressure release, shown on a horizontal mid-plane of the duct

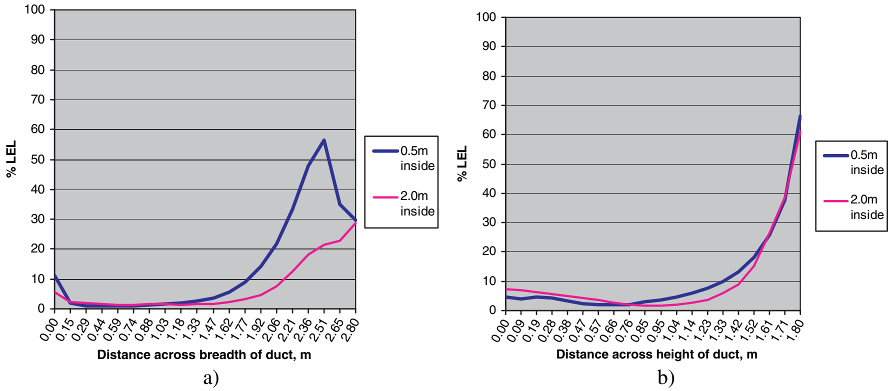

Figure 5. Computed gas distribution inside an HVAC duct. The location '0.5 m inside' is immediately downstream from the modelled louvres, the location '2.0 m inside' is immediately downstream from the modelled fire dampers. Also see Figure 2. a) Across the breadth of the duct b) Across the height of the duct

beam detector located just upstream or downstream of the fire damper and oriented across the 2.8 m width of the duct would indicate a gas concentration of approximately 10% LEL per m.

Figure 6 shows an iso-surface of gas concentration at 10% LEL for the more realistic scenario. The gas can be seen to spread through and underneath the lowest parts of the platform and being ingested into the smaller of the three HVAC inlets. Inside the very large Hazardous HVAC inlet (~6 m × 4 m cross-section), the gas distribution is far from uniform, as shown in Figure 7. However, it is not just large ducts which can exhibit such non-uniformity in gas concentration. Figure 8 shows the gas distribution inside the smallest of the three ducts, with a 1.5 m square cross-section. The gas concentration is again very non-uniform; the COV is 0.43 at 2 m inside the duct. Although the average gas concentration in this smaller duct is approximately 16 % LEL, it falls below 10% over a significant part of the cross-section. Post-processing of these results shows that beam detectors located 2 m inside the duct and oriented across the width of the duct would indicate a gas concentration of approximately 16% LEL per m which is comparable to the average concentration.

5. DISCUSSION AND INITIAL RECOMMENDATIONS ON FLAMMABLE GAS DETECTION STRATEGIES FOR OFFSHORE HVAC DUCTS

The most significant finding is that in all of the CFD simulations the distribution of gas at HVAC inlets is non-uniform: large variations in gas concentration are present over the cross-section of the modelled HVAC inlets. This implies a potential for gas releases to be

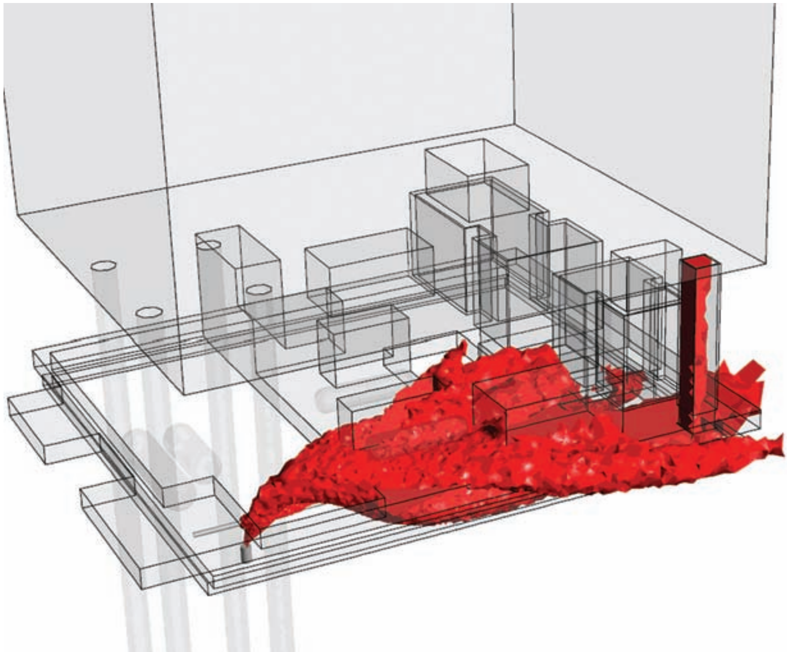

Figure 6. Iso-surface of gas at 10% LEL for the more realistic scenario

'missed' by detection systems unless this non-uniformity in gas concentration is anticipated in the selection and siting of gas detectors at HVAC inlets. The CFD results also show that a variation in gas concentration over a duct cross-section only reduces slowly with distance along a straight duct. These findings are consistent with theoretical considerations of the distribution of gas in a high pressure jet or low pressure buoyant plume, and the literature stemming from the sampling of gas distributions in the exhaust ducts of nuclear stacks.

The literature highlights that purpose-designed mixing elements and bends in a duct can be effective in creating well-mixed conditions but at the cost of increased pressure drop. It also suggests that relatively small-scale obstructions, such as louvres and fire dampers, are unlikely to significantly enhance mixing. This is borne out by CFD modelling of such obstructions in this study. The implications of the modelling work, substantiated by the literature, are that in the absence of purpose-designed mixing elements or a series of bends upstream from gas detectors, no significant benefit would be gained from siting detectors a significant distance downstream from an HVAC inlet. Also, no significant benefit can be expected to be gained from siting detectors inside an HVAC duct compared to locating them immediately outside the HVAC inlet.

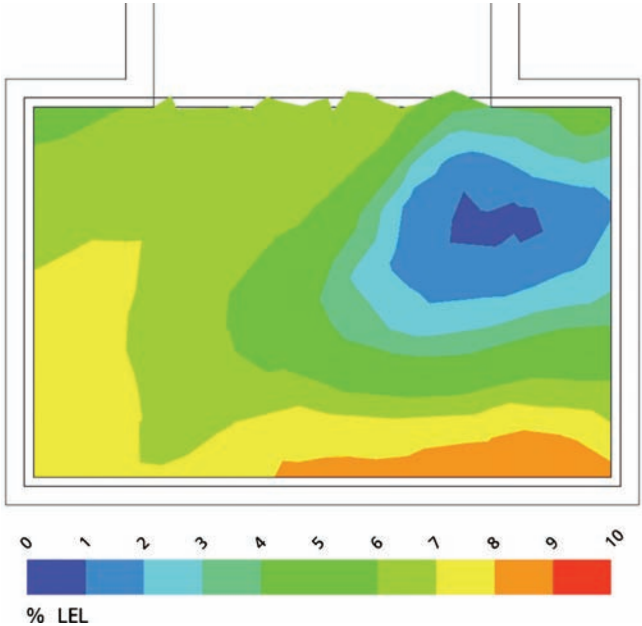

Figure 7. Gas concentration distribution 3.5 m inside the Hazardous HVAC inlet duct

Our initial recommendations on flammable gas detection strategies for offshore HVAC ducts are based on the outcomes of the research summarised in this paper and are listed below:

(a) Detector alarm levels should be set as low as reasonably practical: 10% LEL or less.

Justification: The possibility of significant non-uniformity in the distribution of gas which is ingested into an HVAC duct has been demonstrated by CFD modelling and is also indicated by theoretical considerations. The literature review has highlighted that, in the absence of purpose-designed mixing elements, an initial non-uniform distribution of gas in a duct requires a very long downstream distance before uniformity is approached. HVAC detectors are now available with a concentration range of 0 to 20% LEL and quoted minimum alarm levels of 5% LEL (Walsh *et al*., 2005). Hence, to reduce the likelihood that detectors will 'miss' a non-uniform distribution of gas ingested into an HVAC duct, it is recommended that alarm levels be set no greater than 10% LEL. HSE have already provided information which states that although it is common practice for gas detector alarm levels to be set at 20% LEL, duty holders should explore the feasibility of reducing this alarm level to ~10% LEL (HSE, 2006). The low alarm levels have to be balanced with the minimisation of false alarms which arise from detector drift and transient operational activities.

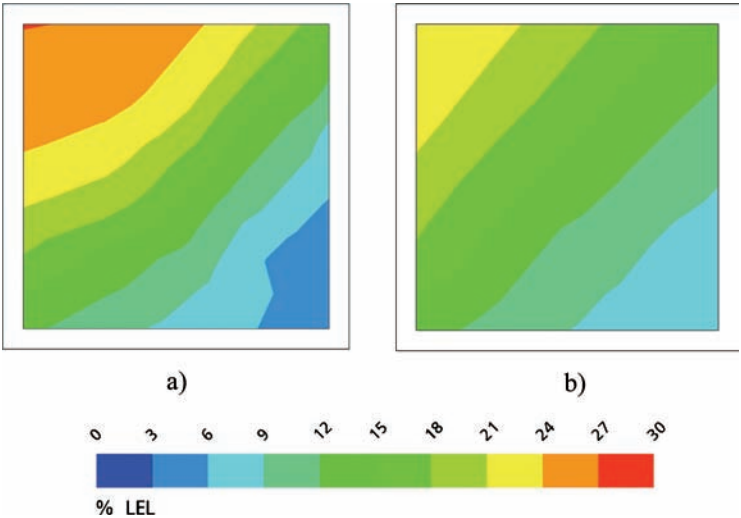

Figure 8. Gas concentration distribution inside the 1.5 m square ‘PLQ’ duct. a) 2 m inside the duct b) 6 m inside the duct

(b) Point catalytic, point infra-red, extended path point infra-red, cross-duct beam infra-red and aspirated point detector systems all have the potential to be effective in detecting non-uniform distributions of flammable gas in and around HVAC ducts provided that their sensitivity is sufficiently high (low detection limit) and that due regard is given to the possibility that gas will be distributed non-uniformly.
Justification: A range of detector types is available with high sensitivity, although there is some question as to whether all of the point and cross-duct beam infra-red systems have sufficiently-high sensitivity. Each detector type has its benefits and limitations, demanding differing siting requirements to ensure that non-uniform gas distributions are not ‘missed’.
(c) Extended path point infra-red detector systems currently appear to offer the greatest sensitivity, but multiple detectors should be used and sited so as to anticipate non-uniform mixing.
Justification: Extended path point infra-red detector systems are available with a concentration range of 0 to 20% LEL and quoted minimum alarm levels of 5% LEL. In addition, specially designed point catalytic detectors (e.g. for gas turbine enclosures) are available with a similar sensitivity although typical catalytic detectors are usually not as sensitive or as reliable as infra-red types. However, whether either type operates reliably in the field with minimum false alarms is currently uncertain. The CFD modelling demonstrates that there is a possibility of significant non-uniformity in the distribution of gas inside and

around an HVAC inlet. The literature review indicates that this non-uniformity will reduce slowly with distance downstream in a duct. It is difficult to provide firm guidance on how many point or extended path detectors should be used since this depends on the size and shape of a duct. However, there should be good coverage of the cross-section of the duct. For large ducts this may mean that four detectors would be needed for systems which alarm upon two positive detections.

(d) Cross-duct beam infra-red, extended path or aspirated point detector systems should be based on two approximately orthogonal beams or lines of aspirated point probes.

Justification: As stated above, the CFD modelling demonstrates that there is a possibility of significant non-uniformity in the distribution of gas inside and around an HVAC inlet whilst the literature review indicates that this non-uniformity will reduce slowly with distance downstream in a duct. For these reasons there should be good coverage of the cross-section of a duct. This can be achieved by two infra-red beams arranged approximately orthogonally, either as open-path cross duct or extended path point infra-red, or lines of aspirated point probes.

(e) No significant benefit can be expected to be gained from siting detectors inside an HVAC duct compared to locating them immediately outside the HVAC inlet.

Justification: The literature review indicates that effective mixing in a duct is only achieved if large-scale turbulent eddies are introduced via purpose-designed mixing elements or bends. The CFD modelling indicates that louvres at the inlet to a duct or fire/gas dampers inside a duct will not, in themselves, be sufficient to rapidly ensure that well-mixed conditions exist in a duct. The literature review also indicates that grilles at the entrance to HVAC ducts are unlikely to significantly enhance mixing.

(f) In the absence of purpose-designed mixing elements or a series of bends upstream from gas detectors no significant benefit is to be gained from siting detectors a significant distance downstream from an HVAC inlet.

Justification: The literature review and the CFD modelling strongly indicate that, for a straight duct, well-mixed conditions are only achieved a very long way downstream from an HVAC inlet.

(g) Mixing elements have the potential to reduce any non-uniformity in the distribution of gas in a duct but their effectiveness should be proven by physical tests.

Justification: This is supported by the literature review. It should also be noted that mixing elements will result in an additional resistance to flow in a duct and that the resulting pressure drop may be significant.

The above recommendations are based on evidence from CFD modelling and the published literature. However, CFD modelling has inherent uncertainties and it is not certain that the findings from the literature are always directly relevant. These initial recommendations could be further substantiated by physical trials using real detectors.

6. ACKNOWLEDGEMENTS

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REFERENCES

Anand N K, McFarland A R, Rajagopal K R, 2003, Gas mixing for achieving suitable conditions for single point aerosol sampling in a straight tube: experimental and numerical results, *Health Physics*, Vol. 84, No. 1, pp 82–91.

ANSI/HPS N13.1-1999, Guide to sampling airborne radioactive materials in stacks and ducts, American National Standards Institute/Health Physics Society.

BS EN 15138:2001, Offshore production installations – HVAC, British Standards Institute, London.

Ewan B C R, Moodie K, 1986, Structure and velocity measurements in under-expanded jets, *Combustion Science & Technology*, Vol. 45, pp 275–288.

Hampl V, Niemela R, Shulman S, Bartley D L, 1986, Use of tracer gas technique for industrial exhaust hood efficiency evaluation – where to sample? *American Industrial Hygiene Assoc J.*, Vol. 45, Part 5, pp 281–287.

Hinze J O, 1975, Turbulence, McGraw-Hill Book Company.

HSE, 2006, Testing regime for offshore TR-HVAC fire dampers & TR pressurisation requirements, Offshore Information Sheet No. 1/2006.

Laws E M, Livesey J L, 1978, Flow through screens, *Ann. Review of Fluid Mechanics*, Vol. 10, pp 247–266.

Lea C J, Deevy M, 2007, Assessment of gas detection strategies for offshore HVAC ducts based on CFD modelling, Health and Safety Executive Research Report RR602, http://www.hse.gov.uk/research/rrhtm/rr602.htm.

McFarland A R, Gupta R, Anand N K, 1999, Suitability of air sampling locations downstream of bends and static mixing elements, *Health Physics*, Vol. 77, No. 6, pp 703–712.

Melling A, Whitelaw J H, 1976, Turbulent flow in a rectangular duct, *J. Fluid Mechanics*, Vol. 78, Part 2, pp 289–315.

Rodi W, 1982, Turbulent buoyant jets and plumes, Pergamon Press.

Seo Y, McFarland A R, Ortiz C A, O'Neal D L, 2006, Mixing in a square and rectangular duct regarding selection of locations for extractive sampling of gaseous contaminants, *Health Physics*, Vol. 91, No. 1, pp 47–57.

Simpson J E, 1997, Gravity currents in the environment and the laboratory, 2nd edition, Cambridge University Press.

Walsh P, Johnson A, Ivings M, 2005, Effectiveness of gas detection in HVAC ducts: Scoping study, Health and Safety Laboratory Report FM/04/11.