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TITLE:

A review of application of integral atmospheric jet dispersion model to flammable hazards – is hazard distance at 0.5 LFL conservative?

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ABSTRACT

Integral atmospheric dispersion models are used widely for flammable hazard and its risk analysis. There is a widespread belief that flammable distances from these models are conservative when flammable ranges are calculated using the 0.5 lower flammability limits (LFL) concentration threshold. This is erroneous. This paper traces through the development of these models and the research that led to the Birch Guidance. It shows that the 0.5 LFL is a necessary factor to transform the results of dispersion models designed for environmental assessment to applications to flammable hazard assessment in quiescent conditions. Current applications do not take account of turbulence due to wind, large and small obstructions, etc. A set of simple guidance is given in the paper to manage flammable hazards based on results from atmospheric dispersion models, including topics for future research.

KEYWORDS

Atmospheric Dispersion, Integral Model, Flammable Hazards, Flammable distances

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1 Introduction

In early 2010, a routine cargo venting from a tank containing flammable products was ignited, this had the potential to cause a major hazard accident. During the same period, a discharge of cold methane vapour from a vent stack set off gas alarms in the process plant some distance away, leading to a major incident response. These are just a small sample of similar incidents in that period. None of these incidents should have happened according to assessments carried out during the design of these facilities. Hazard distances of these scenarios were assessed by integral atmospheric dispersion models which predicted extents of flammable hazards to be well short of any potential ignition sources and process areas nearby. This paper examines the issue relating to the industries' understanding and application of the model used.

Integral atmospheric jet dispersion models are widely used to estimate flammable hazard distances, for design (e.g. zoning of hazard zones, in the design of cold vents to define vent heights required for safe dispersal, etc.) and for risk assessment (e.g. small to large leaks in hydrocarbon process areas).

To be conservative, flammable hazard distances are often defined by the distances to gas concentration at half of the lower flammability limits (LFL) of the released gas mixtures, and they are often calculated accordingly. In some studies, distances to LFL were used to eliminate unnecessary conservatism.

1.1 The over-conservatism rationale

It is encountered often, reports by hazard and risk analysts that their results are conservative. Among the many reasons, a key one is that the dispersion distances are calculated to a lower concentration than needed; half the lower flammability limit (LFL) instead of LFL. As a gas mixture is only flammable at concentration above LFL and the half LFL distance is longer than the LFL distance, sometimes substantially longer, the rationale is that conservatism is built into the methodology.

The use of 0.5 LFL distances increase calculated risks and could lead to more costly designs. From a design point of view, the exclusion zone is made larger by using a 0.5 LFL distance. For example, a non-rated administration building is sited further than it needs be from flammable hazards (such as blast or gas ingress) as defined by the LFL contours, hence built in margin of safety at a cost of increasing the site footprint, additional cabling, roads and paving. From a risk assessment perspective, a larger flammable area as defined by the 0.5 LFL envelope than that by the LFL envelope leads to higher resultant risk figure results.

Hence, as the above argument goes, the 0.5 LFL criterion leads to conservatism. In some studies, this conservatism is removed.

1.2 Does this match up with reality?

However, despite this conservative approach, regular incidents occur which in theory they should not have. For example, flammable clouds were ignited when there were no ignition sources within the calculated flammable cloud, as in the case of ignition of a cold vent (Gant et al., 2016). One study on an incident investigation that the authors conducted on an emergency gas release from a cold vent, showed that flammable gas did migrate to an area way outside the calculated flammable zone and triggered the gas detector alarms. These are not isolated incidents.

The UK Health and Safety Laboratory found that over 65% of ignited hydrocarbon releases had no identifiable ignition sources (Astbury and Hawksworth, 2007). While some of these could be due to new ignition mechanism such as spontaneous ignition (Xu et al., 2008), it is possible that some of these unidentified ignition sources could be due to flammable cloud "strayed" beyond the calculated flammable zone. A re-examination of data from these incidents would clarify this.

One common factor in the responses to these events is one of surprise. This is due to the understanding from past analysis during design and subsequent to the accident using conventional well-established tool, that these incidents could not have happened.

1.3 Cause of this perception error

The authors content that this mismatch of theory and practice is due to lack of understanding of dispersion modelling by practitioners and misplaced confidence i.e. confidence in accuracy and reliability of integral dispersion models and the interpretations of results from them. This phenomenon was observed previously in relation to the modelling of flammable gas cloud for gas explosion (Tam et al., 2008). Before this issue is elucidated in detailed and on the ways forward, the source of the dispersion model and how this problem come about shall be discussed below.

2 Integral Jet Dispersion Models Development

Lets begin with an examination of the origin of integral jet dispersion models. Current integral jet dispersion models are based on the elevated dispersion model developed in the early 70s to assess effects of pollutants from tall stacks for environmental impact assessment. Coal fired power stations were common then. Many of them were located close to or within heavily populated cities (e.g. the Battersea power station in London). The prime application of the model was the assessment of the impact of the pollutant, particularly sulphur, on air quality on communities immediate downwind of the chimney.

A jet dispersion model (also called high momentum dispersion model, or elevated plume model) describes the dispersion of a gas discharged at velocities, significantly higher than ambient wind velocities.

The dense gas dispersion model was developed later. Although it was specifically developed for safety assessment, the basic mathematical modelling concept for flammability is similar (more in the Discussion section later).

Integral atmospheric jet dispersion models are usually embedded in commercially available consequence analysis packages such as PHAST by DNVGL for the oil/gas/petrochemical industry. Some major international companies and consultants have their own in-house package, e.g. CIRRUS in BP, FRED in Shell, etc.

The most widely used commercial package have become the 'industry standard' and their use are sometime written into technical guidance and practices (e.g. (Oil and Gas UK, 2007))

2.1 Basic construct

The word integral refers to each of these models being made up of a number of mathematical calculations. Each describes the specific dispersion behaviour driven by the different dominant forcing at different stages of dispersion (de Visscher, 2013). Previous to release of integral models, each of these constituent methods was carried out separately by hand ((Hanna, S.R.; Briggs, G.A.; Hosker, 1982)).

There are three parts to the integral model i.e. (i) the momentum dominated jet phase, (ii) the cross-wind phase (a plume bends over by the effect of cross wind) and (iii) the passive dispersion phase (atmospheric advection and turbulence). These three mathematical descriptions are integrated together to form the jet dispersion model.

2.2 Source of Construct

The important point is that the basic dispersion engines of these package/tools are near identical. They have the same conceptual representation resulting in virtually the same mathematical formulation and verified by similar set of data.

2.2.1 Jet and crosswind

This covers part (i) and (ii) above. They are based on the work by Ooms (Ooms, 1973) who formulated an integrated mathematical description of a jet in cross wind.

2.2.2 Atmospheric turbulence mixing

When effect of buoyancy and momentum becomes overwhelmed by that of the ambient wind, dispersion is then driven by atmospheric turbulence and advection. Atmospheric turbulence mixes the gas with air; entraining air into the plume, enlarging it and causing it to spread and dilute.

It is common to model the concentration distribution in orthogonal planes (vertical and horizontal) along the plume trajectory by Gaussian distributions. Their use is common to both environmental and safety assessment. The coefficients that define these distributions include factors such as the Pascal weather categories and ground friction (de Visscher, 2013).

2.3 Difference between various models

There are differences between models/packages despite similarity in the core mathematical engine. There are the obvious visible differences presented to the user. User interface of models for input and output, the range of input parameters varies, and information are presented in different forms and details in the output. Some of the key factors which could affect outcome are:

a) Implementation (e.g. differences in coding, level of verification of coding, numerical solving routines, etc.) and source of constants in correlations (e.g. constants to define Gaussian distributions).
b) Description of the source terms (e.g. the inclusion of thermodynamics effect such as Joule-Thompson effect for the release of pressurised gases, handling of rainout, etc.).
c) “Enhancement”. For example, internal interface to link different consequence models. An example is to extend the model to describe time varying releases using the series of quasi-steady calculations.

3 Flammable Hazard modelling

3.1 From Environmental assessment to safety assessment

The safety engineering community adapted the ready-made environmentally derived models for safety hazard assessment. Although this paper limits discussion on flammable hazards, they are equally applicable to toxic hazards in situations where there is non-linearity between concentration and effect.

The range of conditions or scenarios considered in safety assessment is much wider than those for environmental impact assessment at the time these models were developed.

There are constraints imposed by the environmentally based model when applied to flammable hazards. They need to be relaxed by implementing suitable fixes or 'transformation'. The most important one is timescale.

3.2 Timescale to realise environmental and flammable hazards

A calculated concentration based on one averaged over a long period of time is not meaningful for estimating flammable hazard and could grossly underestimate its extent.

3.2.1 Environmental hazards

In a typical environment hazard assessment, the pollutant concentration at the stack exit is relatively low and the impact on vegetation, animal and people's health is due to exposure over long period of time (many hours to months). The concentration appropriate for environmental assessment is one that is integrated or averaged over this "response" period.

If the measurement of gas concentration is made over a long period of time, the concentration distribution about the mean plume centreline is taken as Gaussian. At any instant, gas concentration does not follow this distribution. The plume appears narrower and meanders about the averaged plume centreline. The concentration at any location can be many times higher or lower (or even zero) ((Birch et al., 1981), (Brighton, 1985)). Figure 1 is a schematic of a plume at an instant of time and one averaged over a long period of time.

3.2.2 Flammable Hazards

In contrast to environment impact assessment, the timescale to realise a flammable hazard is much less than a second. It is the instantaneous concentration that matters as the hazard can be realised "instantly" with the introduction of an ignition source. Therefore, it is the characteristics of the flammable plume at the instant of ignition that is relevant, not that derived from the averaged over a long period of time.

3.3 Research underpinning flammability modelling

This issue was recognised at the outset during the development of dispersion modelling for flammable hazards from the 70s. Rather than developing a new mathematical formulation, the approach adopted was on an appropriate interpretation of results, i.e. to estimate flammable hazard from concentration outputs of environmental dispersion models.

Independent research was carried out by major energy companies such as British Gas and Shell, and government laboratories through the 1980s. For example, the authors, while at BP Research, carried out small scale field experiments. These experiments were often costly and time-consuming even at laboratory scale. Many of these works are not accessible as they were only published in companies' internal reports.

The key work was by Birch and his co-workers at British Gas Research (Birch et al., 1981). They published a systematic study which initially included experiments of a jet in quiescent environment, then moving onto an elevated jet in a cross wind (Birch et al., 1989).

3.3.1 Jet in quiescent environment

The simplest condition is a release in a totally calm ambient condition. The released jet of gas (carries energy and turbulence) would induce turbulence in surrounding air in its travel. This would create temporal and spatial variation in gas concentrations within and around the jet.

Birch et al. (Birch et al., 1981) carried out wind tunnel experiments on this idealised environment with the jet directed upward. The scale was small: release orifice of < 3 mm and dispersion distance of < 0.5 m. The mean concentration envelope resembles the shape of an ice cream cornet.

They used the concept of ignition probability to analyse their data and found that flammability factor (F), which is the cumulative probability of ignition, to be a reliable indicator of flammability. F matched their data well. Their results showed that at LFL of 0.5 and along the plume axis, F tended to zero.

They concluded that "the mean concentration is not sufficient for the assessment of flammability. However, potential ignition behaviour may be estimated from the cumulative probability of obtaining a flammable mixture. In the absence of intermittency[1], this flammability factor will generally approach zero when the mean concentration falls below half of the LFL for a "static mixture" along the plume axis.

They recognised that a quiescent jet was idealised and far removed from the dispersion behaviour in the atmosphere where turbulence of a range of time and spatial scale gave rise to intermittency. This aspect will be discussed next.

3.3.2 Jet in Crosswind

Birch also carried out this work in a bigger wind tunnel, for the equivalent of an elevated jet in a steady 'wind'. The release orifice was larger at 10 mm. They observed asymmetry in the vertical plane of concentration for light back condition in that the concentration below the centre line was much lower than those above. They concluded that the effect of intermittency induced by higher turbulence in cross flow situation was significant (adding substance to their caution in their conclusion in quiescent environment) and flammability distances were difficult to quantify using mean concentrations.

3.3.3 Passive Dispersion Phase

No equivalent systematic ignition experiments were carried out in the passive phase of dispersions. There were large-scale tests of releases of flammable gases under pressure, such as the release of

[1] Intermittency occurs where the plume meander in and out of detectors.

LPG (Tam, V.H.Y.; Cowley, 1988) and heavy cold gas such as LNG (Puttock et al., 1984). Their common observation was that there were large fluctuations of concentration about the mean. There were periods of time when concentrations were above LFL when the mean concentrations were well below LFL. This fluctuation characteristics were also observed in non-flammable gases in more recent large scale field trials (Witlox et al., 2015).

4 The Birch Guidance

Out of the cautious conclusion by Birch, the last sentence of their conclusion quoted above was gradually adopted by the industry as a guidance to translate atmospheric jet dispersion model for environmental application to flammability hazard.

Therefore, the flammability criterion at half LFL is NOT a safety factor as frequently cited. As can be seen later, when the intermittency is taken into account, it is not even true that flammable gas is not flammable when the mean concentration falls below 0.5 LFL. The probability of ignition is finite and sufficiently significant to appear in incidents. The variability in the cross-axis direction is much higher. This aspect of the results by Birch is often overlooked. The equivalent measure is 0.1 LFL.

4.1 Applicability of the Birch Guidance

It is worth noting that there are three dispersion regimes described above. The Birch Guidance only apply to the first i.e. the jet dispersion phase. It is important to realise that the application of the Birch Guidance in any other area of dispersion study is an assumption, not one supported by experiments or vigorous theoretical study. The implication of this is being examined next later.

4.2 Evolution of the Birch guidance

In time, Birch's conclusion "flammability factor will generally approach zero when the mean concentration falls below half of the LFL for a static mixture" along plume axis morphed into "mean gas concentration below 0.5 LFL is non-flammable".

4.3 Degradation of the Birch Guidance

Although the Birch Guidance only applies to the plume centreline in jet dispersion phase, this gradually extended to the cross-wind (radial) direction and to the other phases of dispersion, and to other modelling methods. Gradually, the Birch Guidance is perceived as a safety factor. Logically, this leads to this 'safety factor' being dropped to reduce conservatism. We have observed this in some risk assessments.

Given the clarity of conclusions of Birch et al. (Birch et al., 1981), and no further experimental studies, it is unclear how the Birch Guidance gets diluted to the extent that many risk analysts regard the Birch Guidance as a safety factor. The UK Health and Safety Laboratory express concern of this practice and recommended against it (Webber, 2002).

5 DISCUSSIONS

5.1 Degradation of the Birch Guidance

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The reasons are probably many. One factor could be a defect in our learning; knowledge passes down and gets eroded through successive generations. We noted also that professional and academic CPD training courses do not routinely include the origin, fundamental assumptions and weaknesses inherent in modelling methodologies. This highlights the importance of critical learning, particularly reference to original source.

5.2 Scale relevant to the Birch Guidance

It is worth noting that the experiments were small scale (of order a metre) with uniform ambient flow characteristics and over a relatively short period of time. The experimental results do not mean that there is no possibility of an ignition below the concentration threshold; rather the probability of ignition is very small over the prescribed conditions during these tests. When a dispersion model applies this result to larger scale, this introduces an untested extrapolation.

Notwithstanding this, it is a common practice in the safety community to interpret the probability of ignition is negligible below this threshold concentration and the ignition probability is set to zero in QRA.

5.3 Model and reality

It may seem obvious; the calculated dispersion properties are very simple representation of an observed plume. The assumptions required by the model that there are uniform conditions (in wind velocity, atmospheric turbulence and releases) are rarely met. Effects such as downwash due to building and stack are ignored.

Some of the representations of reality are poor representation, e.g. close to the vent, the vertical cross section of a plume in cross flow is asymmetric in the vertical plane; it has a kidney shaped instead of oval (Figure 3). So Gaussian distribution in the vertical plane is a poor approximation for flammable hazard assessment.

Let's assume that all the model assumptions are met, it is not expected that the model will predict reality precisely; observed plume properties will scatter about the predicted value. In practice, models have significant inherent biases and variance when evaluated against measurements (Hanna, Steven R; Britter, 2002).

5.4 Extrapolation to complex situations

With time, the conditions of the release become more complex and in environment which deviates significantly from the idealised uniform wind and turbulence fields. This reflects the complexity of real situations. Two generic release situations and two environmental conditions are described below for illustration.

5.4.1 Liquid aerosols in plume

Scenarios involving the release at pressure or from a two-phase source could result in liquid aerosols in the plume. Their effects are usually modelled by changing the properties of a gaseous plume, e.g. altering its molecular weight.

a) 2 phase releases: The release gas contains a small fraction of liquid or solid particles: The large droplets/particles would rain out leaving the finer droplets/particles suspended in the plume.
b) Pressure-drop leading to cooling and condensation: This is similar to liquid carried over, except that the liquid is formed during depressurisation (Joule-Thompson cooling); the droplet sizes from condensation is typically very small.
c) Condensation for very cold releases in tropical region: Discharge of very cold gas causes the water contents in the air to condense forming aerosols or freeze, forming ice particles.
d) Evolution during dispersion: As the plume disperses, the liquid contents may change, such as rainout or evaporation which causes a change in plume temperature.

An example where plume properties do not stay constant is dispersion from a flare. The fluid fed to the flare is intended to be burnt. When it emerged into the atmosphere without burning, the fluid can be multiphase, interact with the air, and generally forming a complex mixture gas and liquid. In a flameout situation, the finer portion of the liquid will be retained as aerosols in the discharged gas while the heavier droplets rain out close to the flare.

5.4.2 Release inside congested areas

This is a common application to assess flammable distances when a release occurs inside or close to congested process plants. Special entrainment factors are assigned in some of the models. This plume usually has a wider profile than an elevated release into open atmosphere.

Congested areas create complex flow and large variation of spatial distribution of turbulence; this is a far cry from the model's assumption of uniform turbulence and flow. It is highly unlikely this would result in a simple Gaussian shape plume with well-defined static envelope.

5.4.3 Topography

The contour of surrounding land could affect the velocity of the wind field and the ambient turbulence level.

For example, if the wind field has a downward component (e.g. lee waves and rotors in stable conditions at the lee of a hill), then the plume from an elevated source could be advected towards the ground, and ground level concentration would be higher than that estimated by integral dispersion model. Nearby buildings and even the size of the vent stack could affect the dispersion behaviour significantly.

5.4.4 Weather

The weather system is complex. The Pascal weather category commonly used in risk analysis is a gross simplification than the range of scales of weather system which affects dispersion behaviour. For example, a small-scale weather system, e.g. clouds, introduce changes in local wind conditions (horizontal wind, updraft and downdraft). It shows up as rapid fluctuations (Figure 4).

This introduce additional uncertainties. The instantaneous picture of a plume does not conform to the simple plume shape predicted by integral jet dispersion model.

a) Near zero wind conditions

The atmospheric dispersion part applies to ambient wind speed above about 1 m/s. Because atmospheric dispersion models assume a minimum amount of atmospheric turbulence. In calm conditions, diffusion dominates. An alternative method are required (Atkinson, 2017).

b) Wind direction with height

Wind speed and direction change with height. This is due to the effect of surface friction, the rotation of the earth and the temperature difference between the equator and the pole. It is possible that the wind direction at the height of the vent is significantly different from that near the ground or the weather station (usually set at 10 m above ground level), Figure 5. The use of wind roses for QRA should be treated with caution.

5.5 Dispersion of Heavy Gas – dispersion at ground level

The dense gas dispersion model is similarly constructed with the jet phase replaced by a gravity driven slumping model. As the heavy gas is dispersed along the direction of the wind, there is no equivalent cross wind phase. The passive dispersion phase for heavy gas is similarly modelled as jet dispersion model. Virtually all heavy gas dispersion models in common use today are based on work by Haven (Spicer and Havens, 1987).

There was no equivalent Birch type experiment determining ignition factor in the gravity driven phase, there is some in the passive atmospheric dispersion phase at ground level.

Due to its proximity to ground, the plume experiences a lower level of turbulence than at higher elevations. The corresponding instantaneous peak to mean concentration is expected to be lower. Unfortunately, there is no equivalent detailed study as Birch, understandably due to the complexity and cost of such an experiment. Fortunately, a limited large-scale experiment was carried out by Shell Research involving the spill of LPG on a large flat concrete pad; (Evans and Puttock, 1986) reported a 'peak' to mean concentration ratio of 1.4, and a mean concentration threshold of 0.6 LFL for local ignition and 0.9 LFL for light back to source. The analysis leading to their conclusion is complex, involving the use of time averaging measurements (1 s moving average) to represent 'peak' concentration and using mean concentration derived from measurements obtained from separate unignited tests in different conditions and extrapolation by modelling. Webber evaluated this work and concluded that the Birch guidance should also apply to heavy gas dispersion models (Webber, 2002).

5.6 Computational Fluid Dynamics (CFD) Model

CFD model has the advantage in that it can take account of effect of topography and effect of local obstructions. It is appropriate that where equipment, structures, buildings and surrounding topography have significant effects on flow and turbulence field, CFD model is used.

However, virtually all the CFD dispersion calculations for safety analysis makes assumptions that render calculations within cost and time. The key assumption in the context of this paper is steady state (release and atmospheric conditions such as wind) and isotropic turbulence. Thus, the limitations of integral atmospheric dispersion model are inherent in the CFD models.

This issue was highlighted in (Hansen et al., 2013) where the authors described difficulties in validating their dispersion and gas explosion model (FLACS) with one large scale experiment involving pressurised releases of natural gas into a full scale offshore module (Johnson et al., 2012). (Hansen et al., 2013) found that many successfully ignited tests had ignition sources located in regions where the predicted gas concentrations were well outside flammable range. As an illustration, Figure 6 shows an instantaneous and time-averaged picture of a hot gas plume.

6 Ways Forward

1. Recognition that 0.5 LFL is not a safety factor. The factor of 0.5 is necessary for mapping results from a methodology for environmental assessment to flammable hazards.
2. Recognition that calculated flammable distance does not provides absolute limit of flammable hazard. The various conditions render invalid the assumption made in the simple integral atmospheric dispersion model. There will be situations where the plume is flammable beyond the calculated 0.5 LFL envelope. This should be recognised by a revised assessment procedure.
3. Where releases occur in regions where wind flow field is non-uniform (e.g., close to nearby equipment, buildings, or significant topographic features), CFD techniques should be used. Examples of situations where this occur can be found in (Hanna, S.R.; Briggs, G.A.;Hosker, 1982).
4. Similarly, CFD techniques should be use in situations where assumptions inherent in the integral dispersion model are not met, e.g., mass and energy sources and sinks.
5. Hazard management plans should allow for the possibility of flammability hazards beyond calculated flammable distances. One may choose not to change the design basis but to address this through procedures. For example, by understanding the conditions flammable hazards are likely (e.g., under certain wind directions), it is possible to establish operating procedures to mitigate their effect (e.g., in those wind conditions, pay particular attention to hot work).
6. Current integral dispersion model need to be developed for calm conditions, to build on the work by (Atkinson, 2017). As noted above, in calm conditions, these models break down. The alternative is using CFD (Gant and Atkinson, 2011). As there is no atmospheric turbulence in calm condition, correction using flammability factor is not necessary.
7. Develop a JIP to provide necessary data for reliable transformation of current integral and steady state CDF model results for flammability hazard assessment. For example, the flammability factor F devised by Birch et al can be extended beyond the very limited laboratory conditions. Below are some suggested topics:
   - Analysis of incidents of unexplained ignition: The HSE data (Astbury and Hawksworth, 2007) and well documented incidents can be further analysed for characterization of flammability factor(s).
   - Experiments: Systematic sets of experiments can be carried out, building on the work of (Birch et al., 1989)(Birch et al., 1981). We are aware of large-scale tests commissioned for other purposes regularly. Some of these can be modified to allow data for F to be collected. This will require coordination and cooperation across the industry.

. Numerical experiments – using more advanced CFD such as direct numerical simulation (DNS) and large eddy simulation (LES) to extend the wind tunnel work of Birch to more complex conditions. This is not a completely new area scientifically as it has been applied to engine (Lacaze et al., 2009).

7 CONCLUSIONS

"Conservatism" on atmospheric dispersion of flammable releases often cited by risk analysts is often overstated. The half LFL criterion is necessary to translate dispersion model derived for environmental assessment to flammability assessment.

A brief description of the assumptions and applicability of commonly used atmospheric dispersion models are described in this paper.

Suggestions are also given in this paper for: (a) appropriate use of current models and (b) further work on the extension of the flammability factor.

The industry needs to be cognisant of the assumptions and applicability of mathematical models in their application in risk assessment or in engineering applications. For example, flammability hazards extent beyond calculated hazard distances, appropriate management procedure should be put in place.

Educators should consider including fundamentals of mathematical modelling in their syllabus to help students to understand assumptions inherent in the modelling and their impact on limits of applicability.

8 REFERENCES

Astbury, G.R., Hawksworth, S.J., 2007. Spontaneous ignition of hydrogen leaks: A review of postulated mechanisms. Int. J. Hydrogen Energy 32, 2178–2185.

Atkinson, G., 2017. Development of heavy vapour clouds in very low wind speeds. J. Loss Prev. Process Ind. 48, 162–172.

Birch, A.D., Brown, D.R., Dodson, M.G., 1981. Ignition probabilities in turbulent mixing flows. Symp. Combust. 18, 1775–1780.

Birch, A.D., Brown, D.R., Fairweather, M., Hargrave, G.K., 1989. An experimental study of a turbulent natural gas jet in a cross-Flow. Combust. Sci. Technol. 66, 217–232.

Brighton, P.W.M., 1985. Area averaged concentrations height scales and mass balances. J. Hazard. Mater. 11, 189–208.

de Visscher, A., 2013. 1974715-S @ Ebookcentral.Proquest.Com, 1st ed. Wiley.

Esmaeili, M., Afshari, A., Jaberi, F.A., 2015. Turbulent mixing in non-isothermal jet in crossflow. Int. J. Heat Mass Transf. 89, 1239–1257.

Evans, A., Puttock, J.S., 1986. Experiments on the ignition of dense flammable gas clouds. 5th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Cannes, France, September 1986, 35–41.

Gant, S., Atkinson, G., 2011. Dispersion of the vapour cloud in the Buncefield Incident. Process Saf. Environ. Prot. 89, 391–403.

Gant, S., Pursell, M., Newton, A., Bennett, D., O'Sullivan, L., Piper, D., 2016. Investigation of Cargo Tank Vent Fires on the GP3 FPSO, Part 1: Identification of Ignition Mechanisms and Analysis of Material Ejected from the Flare. Inst. Chem. Eng. Symp. Ser. 2016–Janua, 1–11.

Hanna, S.R.; Briggs, G.A.;Hosker, R.P., 1982. Handbook on atmospheric diffusion, US Department of Energy.

Hanna, Steven R; Britter, R.E., 2002. Wind flow and vapor cloud Dispersion at industrial and urban sites. Centeerr for Chemical Process Safety, New York.

Hansen, O.R., Gavelli, F., Davis, S.G., Middha, P., 2013. Equivalent cloud methods used for explosion risk and consequence studies. J. Loss Prev. Process Ind. 26, 511–527.

Johnson, D.M., Cleaver, R.P., Puttock, J.S., 2012. Investigation of Gas Dispersion and Explosions in Offshore Modules, in: Offshore Technology Conference. p. 7.

Lacaze, G., Richardson, E., Poinsot, T., 2009. Large eddy simulation of spark ignition in a turbulent methane jet. Combust. Flame 156, 1993–2009.

Murlis, J., Elkinton, J.S., Cardé, R.T., 1992. Odor Plumes and How Insects Use Them. Annu. Rev. Entomol. 37, 505–532.

Oil and Gas UK, 2007. Fire and explosion guidance, Issue 1.

Ooms, G., 1973. A new method for the calculation of the plume path of gases emitted by a stack. VDI Berichte.

Puttock, J.S., Colenbrander, G.W., Blackmore, D.R., 1984. Maplin Sands Experiments 1980: Dispersion Results from Continuous Releases of Refrigerated Liquid Propane and LNG, in: Air Pollution Modeling and Its Application III. Springer US, Boston, MA, pp. 353–373.

Spicer, T.O., Havens, J.A., 1987. Field test validation of the degadis model. J. Hazard. Mater. 16, 231–245.

Tam, V.H.Y.; Cowley, L., 1988. LPG Release Experiment, in: GasTech, 13th International LNG/LPG Conference. GasTech, Kuala Lumpur.

Tam, V.H.Y., Wang, M., Savvides, C.N., Tunc, E., Ferraris, S., Wen, J.X., 2008. Simplified flammable gas volume methods for gas explosion modelling from pressurized gas releases: A comparison with large scale experimental data, in: Institution of Chemical Engineers Symposium Series.

Webber, D., 2002. On Defining a Safety Criterion for Flammable Clouds. Harper Hill.

Witlox, H.W.M., Brown, J., Holt, H., Armstong, K., Allason, D., 2015. Discharge of CO 2 from large-diameter orifices: Experimental data and data review. Process Saf. Prog. 34, 389–397.

Xu, B.P., El Hima, L., Wen, J.X., Dembele, S., Tam, V.H.Y., Donchev, T., 2008. Numerical study on the spontaneous ignition of pressurized hydrogen release through a tube into air. J. Loss Prev. Process Ind. 21.

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FIGURES

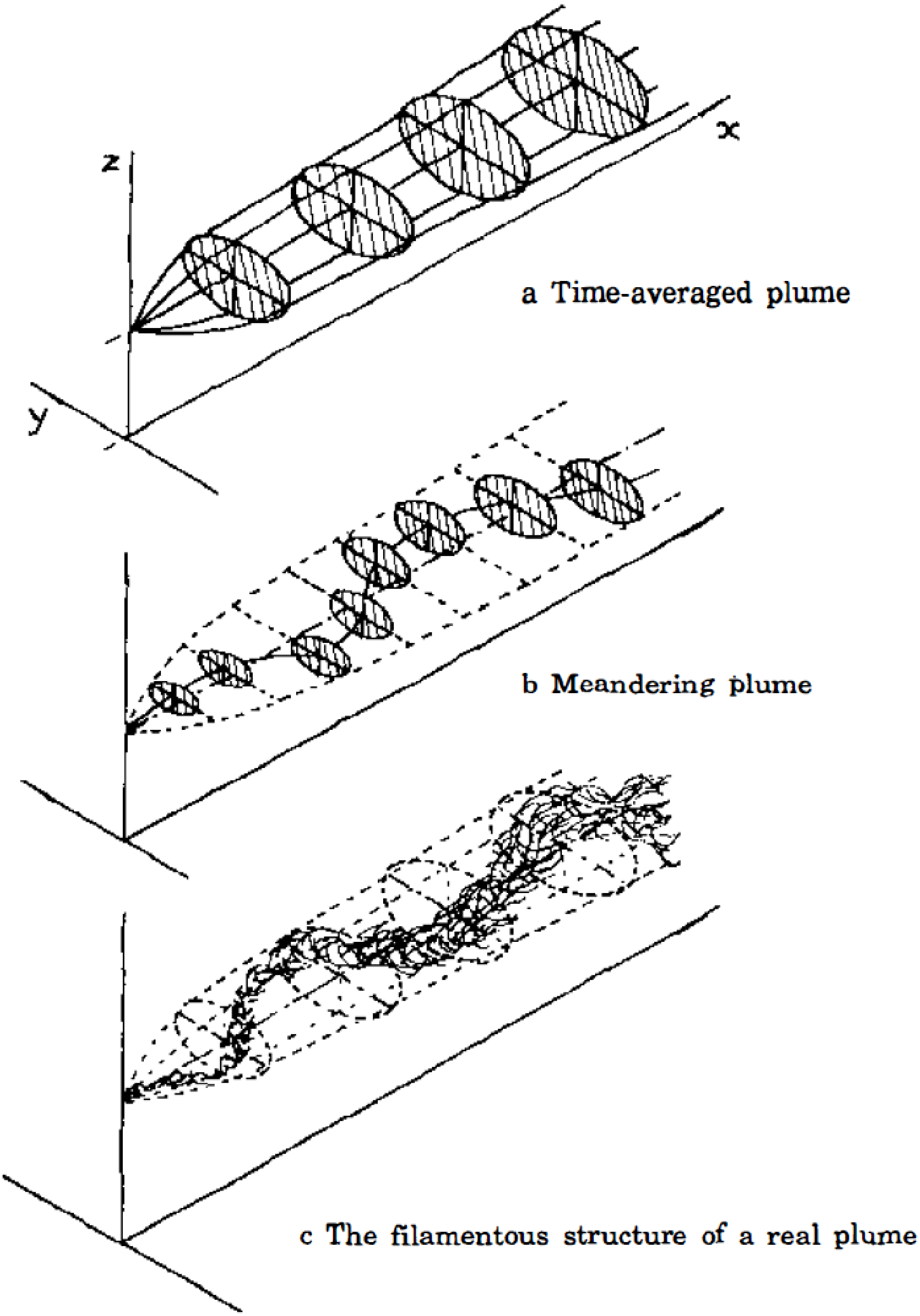

FIGURE 1 schematic diagram showing the appearance of a plume (i) when observation is averaged over (a) a long period of time (hours), and (b) over a short period of time (seconds), and (ii) as a gaussian representation (Murlis et al., 1992).

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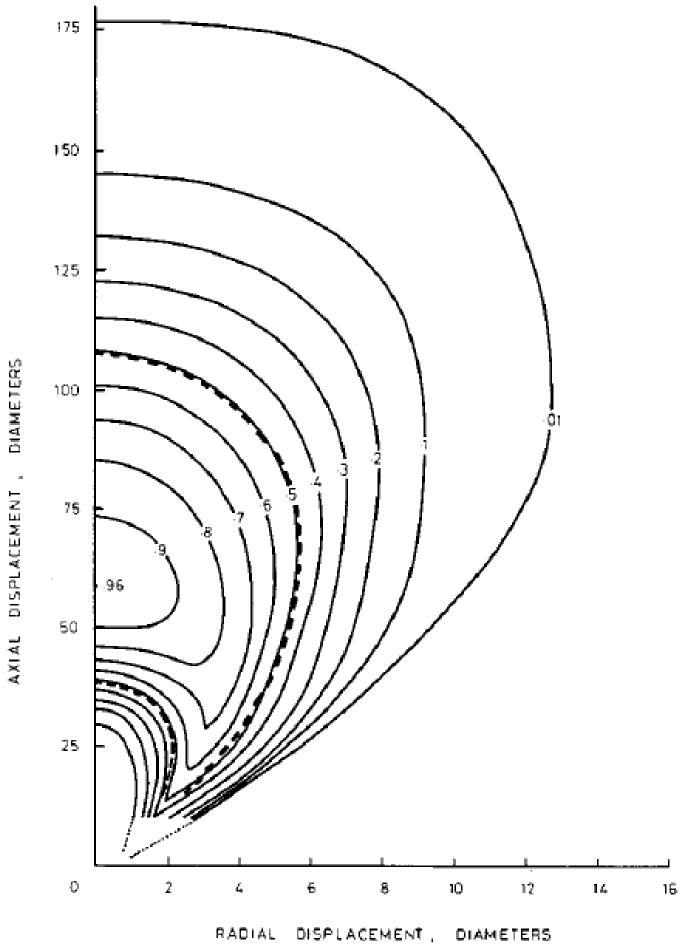

FIGURE 2 Flammability factor F contours on a vertical plane bisecting a vertically released natural gas plume. The dashed line show contours of mean LFL concentration. At mean LFL concentration, cumulative ignition probability is 0.5 (Note: This figure shows half of the plume which has a symmetry plane about the Y axis) (taken from (Birch et al., 1981)).

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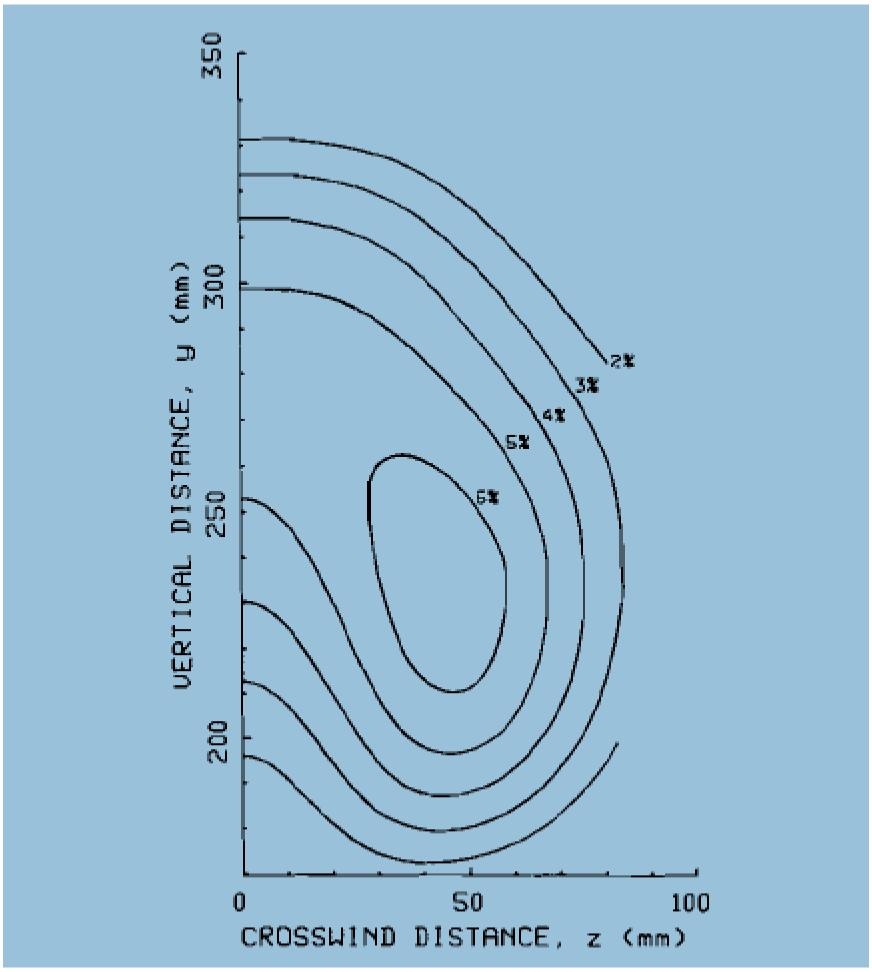

FIGURE 3 Concentration contour on a vertical dissecting a gas plume. This figure shows one half of the plume which has a symmetry plane about the Y axis (taken from (Birch et al., 1989)).

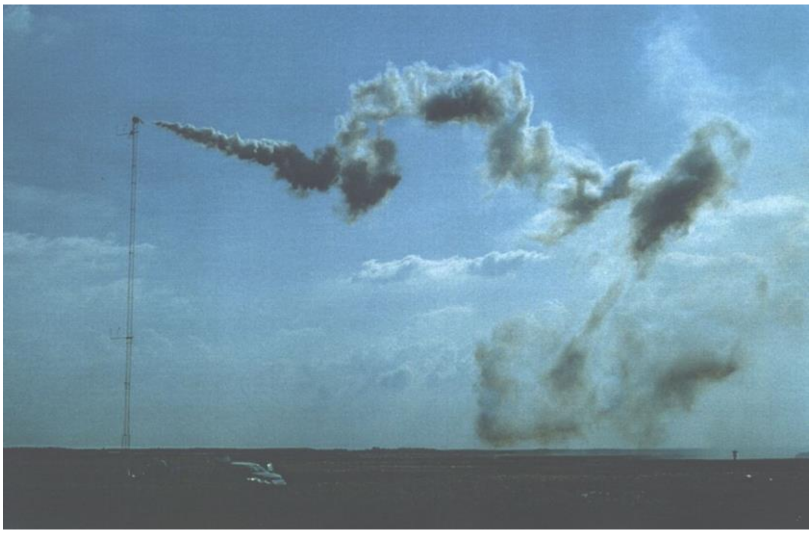

FIGURE 4 A picture of a smoke plume taken during midday on a sunny day. It shows the effect of convective conditions on the plume path. There are large vertical air movements. This picture was taken by Prof t Mikkelsen of Technical University of Denmark

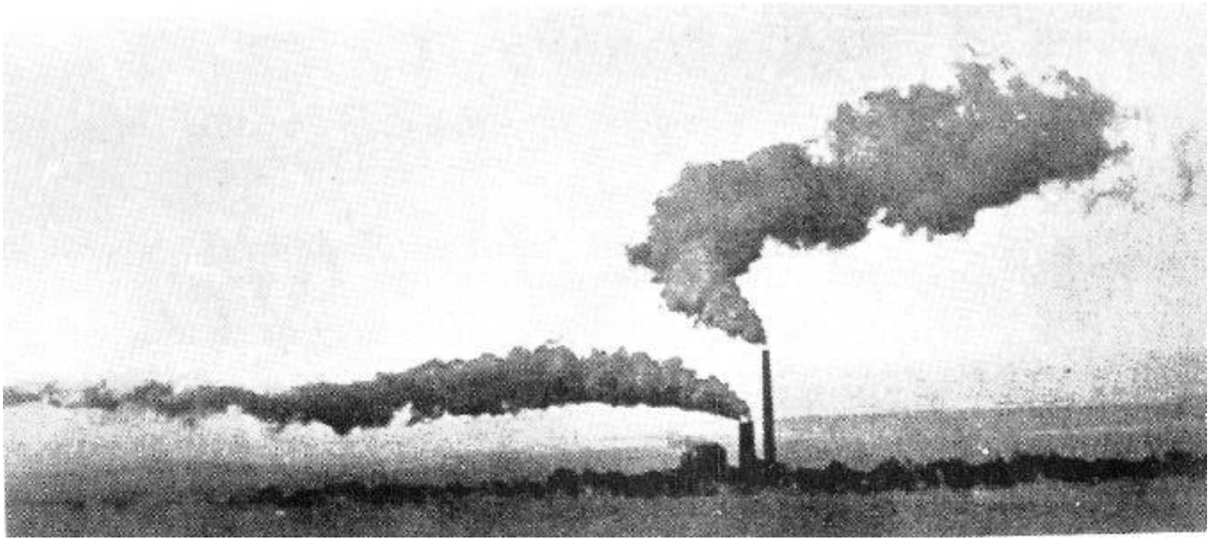

FIGURE 5 Wind direction changes with height near the surface of the earth. Occasionally, this change could occur over a short vertical distance**.**

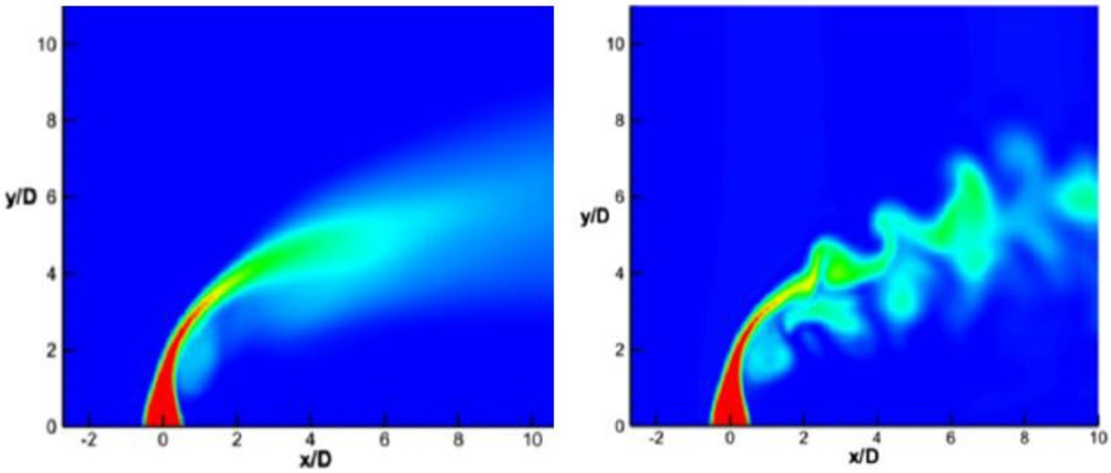

FIGURE 6 Wind Temperature field from (left) time averaged and (right) instantaneous hot plume (taken from (Esmaeili et al., 2015)).