CLOUD FIRES - A METHODOLOGY FOR HAZARD CONSEQUENCE MODELLING

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We define a cloud fire as the transient event following the delayed ignition of a release of flammable gas or volatile liquid. If flammable material continues to be emitted, the cloud fire may be followed by a steady state fire (e.g. a jet or pool fire) at the source.

Two forms of cloud fire are identified :

(i) A flash fire is the combustion of cloud of flammable where the dispersing plume is/has grounded.

(ii) A fireball from delayed ignition of a vertical (or near vertical) jet.

A methodology for cloud hazard assessment is presented which has been formulated using large scale experimental data.

1. INTRODUCTION

Following a release of flammable material and formation of a vapour cloud, it is necessary to be able to estimate the hazard consequences should that cloud be ignited. For a release in a congested and/or partially confined environment (e.g. a plant or offshore platform), the principal hazard consequence is a vapour cloud explosion (VCE). The Congestion Assessment Method (CAM) of Shell [Puttock, 1995] or the earlier T.N.O. Multi-Energy Method [van den Berg, 1985] provide a means through which explosion hazards from vapour clouds can be assessed. The latter method has the disadvantage of not providing adequate guidance on source overpressure.

This paper is concerned with ignited hydrocarbon releases in an uncongested/unconfined environment, for which the principal hazard is not overpressure, but rather the radiation and convection from the burning of the cloud - the cloud fire. It should be borne in mind that whilst cloud fires are transient events (lasting of the order of seconds), a steady state fire scenario (e.g. a jet fire or pool fire) may follow on from a cloud fire as it burns back its source. The model presented here seek to address realistic cloud fire scenarios.

Cloud fires can be usefully divided in to two types: flash fires and fireballs. A flash fire (sometimes called just a vapour cloud fire) is the combustion of a grounded (i.e. non-buoyant) cloud of flammable gas in an unconfined and uncongested region, where a delay between the release of flammable material and subsequent ignition has allowed a cloud of flammable material to build up and spread out from its release point. A flash fire is characterised by a "wall of flame" progressing out from the point of ignition at moderate velocity until the whole of the flammable cloud has burned. The combustion products from a flash fire are vented vertically. A method for predicting flash fires hazards is described in section 2.

A fireball occurs when flammable material is propelled upwards and ignition occurs before all of the cloud has slumped - unburned fuel is then carried upwards by the buoyant plume. A BLEVE is an obvious example of a release giving rise to a fireball. A detailed model for evaluating the hazard consequences of BLEVE fireballs has been presented elsewhere [Shield 1993; 1995] and BLEVEs are not discussed here. Ignition of a vertical jet will also give rise to a fireball, provided a delay between the start of the release and ignition has allowed a cloud to form. The combustion products from a fireball are vented radially outwards from the cloud (i.e. in three dimensions). A method for predicting the hazards of fireballs from vertical jet releases is described in section 3.

2. FLASH FIRES

Experimental studies and previous models of flash fires are reviewed in a number of recent texts [CCPS, 1994; Rew et al, 1996; Lees, 1996]. The most widely used model due to Raj and Emmons [1975] is based on correlations appropriate to pool fires. Much of the large scale experimental data on flash fires was accumulated subsequent to the Raj and Emmons model and there is an obvious need to look again at flash fire modelling.

For the purposes of risk assessment, a simple approach to flash fire modelling is to assume that 100% of people within the flammable cloud (i.e. the portion of the cloud with a concentration greater than the Lower Flammable Limit [LFL]) will be fatally burned if the cloud is ignited whilst people outside the cloud are safe. More sophisticated risk models can allow for fatalities outside the flammable cloud (e.g. Considine and Grint, 1984), however as Rew *et al* [1996] have shown, this greater level of sophistication is not always appropriate from the perspective of calculating risk, given the uncertainty in assessing the likely extent of the flammable cloud.

The model for flash fires developed by Shell research assumes that a wall of flame proceeds upwind and downwind from the release point. Figure 1. shows the situation which would pertain for a cloud with negligible source momentum.

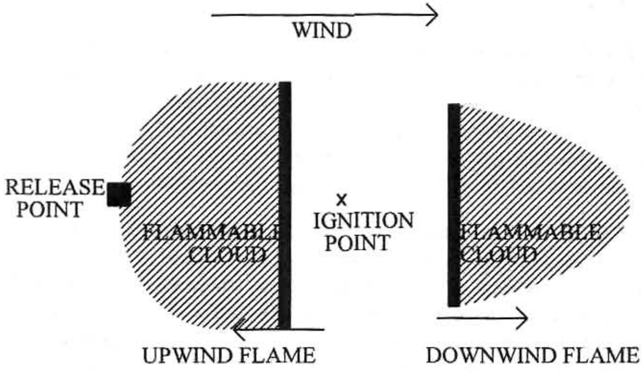

Figure 1. Model for calculation of flash fire radiation (negligible source momentum)

Flame Height

The model we have adopted assumes that flame height at a given position is related to the mass of flammable material in the cloud at that point. Unlike the Raj and Emmons model, the flame height is not related to the cloud width. The simple calculation that we propose can be made assuming that

(i) the products of combustion vent upwards only.

(ii) each mole of flammable material entrains a stoichiometric amount of air.

(iii) the mixture burns at the adiabatic flame temperature.

The volume of hot products per kg of fuel is then given from the ideal gas law by

$$V_{prods} = \frac{RT_{ad}\,N_{prods.}}{P_{atm}} \times \frac{1000}{MWt} \tag{1}$$

where N_{prods} is the number of moles of products and the number of moles of inert species in the air (almost all nitrogen) assuming an initial stoichiometric mix and MWt is the molecular weight of the flammable. Approximate values of V_{prods} for various hydrocarbons in air are tabulated below.

Table 1. Volume of combustion products per kg of fuel.

Fuel	CH_4	C_2H_6	C_2H_4	C_2H_2	C_3H_8	C_3H_6	C_4H_{10}
V_{prods} (m^3/kg)	124	116	104	103	112	124	112

To calculate the flame height, the mass of fuel (before combustion) in the cloud above a unit surface area, M_{area} is determined from a dispersion model (the fuel which is present in the cloud at a concentration below the lower flammable limit is ignored). Using the assumption that venting of products occurs only vertically, the flame height, H, is given by

$$H\,(\mathrm{m}) = V_{prods}\,(\mathrm{m^3/kg}) \times M_{area}\,(\mathrm{kg/m^2}) \tag{2}$$

Roberts [1982] has performed a calculation which suggests that the flame height prediction from equation (2) would remain valid even with significant heat losses and an oxygen rich mixture. Furthermore the level of agreement between experimental observations and predictions using equation (2) provides *a posteriori* justification.

To test the prediction for flame heights, HEGADAS-S (part of the HGSYSTEM dispersion package [Post, 1994]) was used to simulate several of the Maplin Sands trials, conducted by Shell Research in 1980. For example Test 49 [Mizner and Eyre, 1983] was a $2.1 m^3 min^{-1}$ spill of liquefied propane. The spill was halted after ignition (at 130m from the release) took place. The flame height was observed to be 9.0m at 3.4 seconds after ignition and 8.1m at 6.9s after ignition - in good agreement with a predicted flame height of 8.2 m at the ignition point.

Much higher flames were reported in the Coyote tests for LNG and liquid methane spills [Rodean, 1984]. As a typical example, flames of 32m were reported 4s after ignition in Coyote 7, however the spill rate of $14m^3min^{-1}$ was larger than for any of the Maplin tests. Analysis of this test using HEGADAS-S and use of the flame height model gives a flame height of exactly 32m at the ignition point (85m from the source).

Flame speed

The following values are recommended for quiescent clouds of natural gas (from an LNG spill) and propane (either from refrigerated liquid propane or flashed from pressure liquefaction)

NG (from **LNG** spill) : **6**ms^{-1}; **Propane : 12**ms^{-1} [Relative to unburned gas]

The upwind progress of the flame will be given by the flame speed minus the wind speed. The downwind progress will be given by the flame speed plus the wind speed. The Maplin Sands tests [Mizner and Eyre, 1983], the China Lake NWC tests [Schneider, 1980], the Coyote tests [Rodean, 1984] and the TNO Musselbanks tests [Zeeuwen, 1983] are all consistent with these values. The Maplin results do not support a distinction being made between premixed and diffusion flames; on this basis, the above values should be used in both cases.

To look at the effect of cloud turbulence on flame speed, a series of video records have been re-analysed to calculate the flame speed in cloud created from a horizontal jet release of pressurised propane [Hirst, 1986]. The vertical jet releases from this series are discussed in section 3. In the largest ignited horizontal release ($45.11kgs^{-1}$ through a 52.3mm orifice diameter), the jet was ignited by a flare at 20m from the release. Figure 2 shows the flame position plotted against time From the gradients in figure 2, the initial flame speed is about $22ms^{-1}$ but this has decayed at 50m to about $12ms^{-1}$ in agreement with the recommended value. Rew et al [1996] claim that flame speeds of the order of 200 m/s must be possible because flash fire can burn back to a turbulent jet release source with a release velocity of 190m/s. We do not share this view since, whilst the velocity in the centre of a dispersing jet may be very high, the velocity at the edge of the jet where air is entrained and a flammable mixture is formed will be much lower.

In the Coyote tests [Rodean et al [1984]] observed flame speeds (for LNG) of up to $50ms^{-1}$ adjacent to a jet flame ignition source but these transient high velocities were found to have decayed within 50m. For slightly weaker ignition sources (flares), the transient velocities of $30ms^{-1}$ were observed.

Unfortunately, there is a lack of data on spills of material other that natural gas (from a cryogenic spill) and propane and it is difficult to generalise a model for flame speeds. The flame speed for a flash fire is presumably a function of the laminar flame velocity (measured at a standard reference temperature) and the actual temperature of the gas. Dispersing clouds may contain aerosol particles, however experimental evidence suggests that the burning velocity of an aerosol cloud is unlikely to be significantly enhanced with respect to the burning velocity of a vapour cloud [Bowen and Shirvill, 1994].

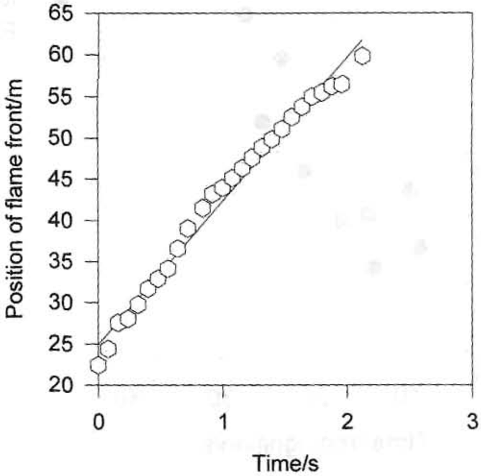

Figure 2. Variation of flame front with time for ignition of vapour cloud produced by 45.1 kgs^{-1} horizontal flashing propane jet.

As a test of the model for flame height and the recommended (quiescent) flame speeds, figure 3 shows the predicted height of the upwind flame for Maplin trial 39 (a continuous LNG spill of 4.5m^3 min^{-1} with a wind speed of approximately 4ms^{-1}). This is in reasonable agreement with measured values[Mizner and Eyre, 1983].

Radiation

The radiation received by an observer will be the product of surface emissive power (SEP), view factor, V_f and the atmospheric transmissivity. From the Coyote and Maplin tests, an SEP of 220kWm^{-2} is reasonable for propane and LNG flash fires for both the premixed and fuel rich portions of the cloud. This value represents an average of those measured during the tests. A simplified radiation calculation may be made by assuming that once the flame has spread across the width of the cloud, the flame travels as a straight wall both downwind and upwind as is shown in figure 1. Calculation of the view factor is then quite straightforward

Thus with a knowledge of the dimensions and concentration of the flammable cloud from the dispersion model together with the expressions for flame speed, SEP, view factor and atmospheric transmissivity, it is possible to calculate the dose of radiation received by an observer upwind or downwind of the flame.

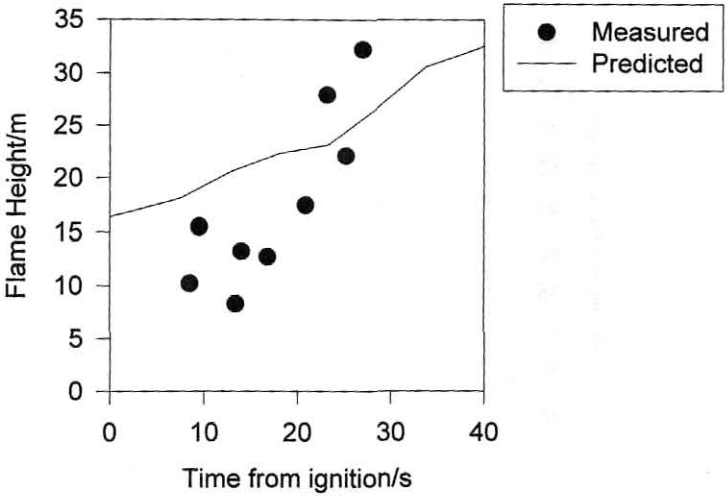

Figure 3. Predicted flame height versus distance from release for Maplin Sands test 39

3. FIREBALLS FROM VERTICAL JET RELEASES

A series of vertical propane jet releases were conducted by Shell Research in 1983 [Hirst, 1986] . The cloud was ignited about 30s after the start of the release once the cloud reached a steady state. Buoyant fireballs were formed shortly after ignition and were followed by a steady state jet fire. Figure 4 shows a typical test (test 23). Video, cine and stills records of the original tests have been re-analysed to develop a model for the fireball growth. This model is presented in the remainder of this section.

Fireball Growth

Fireballs are considered to be spherical for modelling purposes. The maximum diameter of the fireball, w_{max} (m) was found to correlate with $\dot{m}$ the mass flow rate (kg/s), and v_{wind}, the wind speed (ms^{-1}) according to

$$\frac{w_{\max}}{\dot{m}^{2/5}} = 4 + 6\exp(-0.25 v_{wind}) \qquad (4)$$

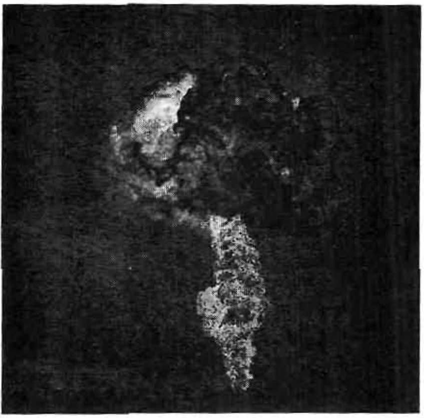

Figure 4. Fireball from delayed ignition of a 41 kgs^{-1} vertical propane jet [Hirst, 1986]

Experimental data and the correlation is shown in figure 5. Other power laws for mass flow were tested but a 2/5 power law was found to provide the best fit. The 2/5 power on mass flow is consistent with Froude number modelling of flame size for buoyant turbulent hydrocarbon diffusion flames [see for example McCaffrey, 1988].

Wind clearly has an significant effect on fireball diameter. Wind enhances dispersion and so with increased wind there will be less fuel with concentration above the LFL in the steady state plume prior to ignition. Runs with the jet dispersion model AEROPLUME (part of the HGSYSTEM package [Post, 1994]) confirm that this is the case, however it does not fully explain the reduction in fireball diameter with wind. An alternative explanation is that prior to ignition of a vertical jet, air is entrained as a result of shear forces between the jet and the surrounding air. Ignition causes additional entrainment as the buoyant upward flow of hot gases is replaced by cold ambient air drawn in to the fire column. If a steady state plume has formed prior to the ignition then fuel from the dispersed plume will be entrained into the jet along with the air. This leads to unburned fuel being transported upwards by the vortical motion and hence to the formation of the fireball. Wind will cause the steady state plume to be asymmetric about the release axis, so that most of the fuel in the plume lies downwind of the release. Thus less unburned fuel will be entrained in to the nascent fireball thereby limiting the maximum size.

From the video records, the time taken for the fireball to reach its maximum size is given by

$$t_{\max}(\mathrm{s}) = 0.11 w_{\max}\ (\mathrm{m}) \tag{5}$$

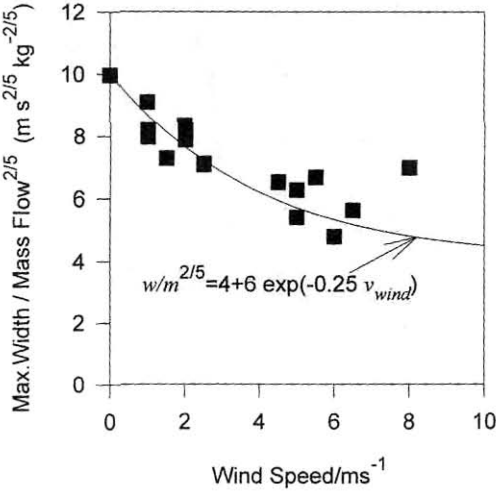

Figure 5. Relationship between fireball width, mass flow rate and wind speed for propane fireballs.

The fireball grows linearly until it reaches its maximum width

$$w(t) = w_{\max}\frac{t}{t_{\max}} \qquad t \le t_{\max}$$
$$= w_{\max} \qquad t > t_{\max} \tag{6}$$

Fireball Rise

The fireball height (measured from the ground to the fireball centre), h, is approximately equal to the fireball width while the fireball is growing to its maximum size. Once the fireball has reached its maximum size, it continues to rise linearly:

$$h(t) = w_{\max}\frac{t}{t_{\max}} \tag{7}$$

Fireball Radiation

The propane fireballs analysed in these tests are luminous up to the point where they reach maximum diameter. They then become abruptly less luminous. In this respect they differ from BLEVE fireballs, the lifetimes of which are determined by the burning of droplets. The spot SEP measurements made during the experiments varied widely and the best value to use would be one appropriate to a propane jet fire ~250kWm^{-2}. This choice can be justified by comparing results of the model with measured data (see below).

The view factor, V_f, for the worst case of an observer looking directly at a spherical fireball is given by

$$V_f(t) = \frac{(w(t)/2)^2}{X^2 + h(t)^2} \tag{8}$$

where X is the distance from the observer to the release point (the observer is assumed to be at the same height as the release).

Figure 6 shows the radiometer trace from test 23 (a 41kg/s vertical propane release) of the series reported by Hirst [1986]. The radiometer was located at 108m from the release point and tilted so as to receive approximately the maximum radiation from the fireball. The radiation calculated from the model is also shown on the plot. The radiation decays to a value appropriate to a steady state jet fire; this was calculated using an in-house Shell Research model. Atmospheric attenuation of radiation was also included in the calculation. For the example shown it can be seen that the model gives reasonable agreement with experiment, both in terms of fireball duration and radiation. It should be noted that because video records of this particular test were unavailable, this data set was not used in developing the correlation.

It can be seen that the steady state jet fire makes a significant contribution to the dose of radiation to a receiver. If escape is impossible, the radiation from the steady state jet fire will be the most significant hazard associated with the event.

Applicability of the fireball model to other flammables

The model described in this section has been parameterised from the data obtained at Spadeadam for flashing propane releases [Hirst, 1986]. Under normal temperatures, there is no droplet rainout for a propane release. For liquids with less propensity to flash, there will be a certain amount of rain-out possibly leading to a pool fire on the ground as well as a jet fire and transient fireball. The model for the fireball size presented in this work is likely to be somewhat conservative as compared to the case where there is droplet rain-out because of mass loss from the flammable cloud. For liquids with no propensity to flash, e.g. LNG, dead crude, the only scenario from a vertical jet release is a pool fire (with a jet fire if the liquid can be sufficiently atomised [Bowen and Shirvill, 1994])

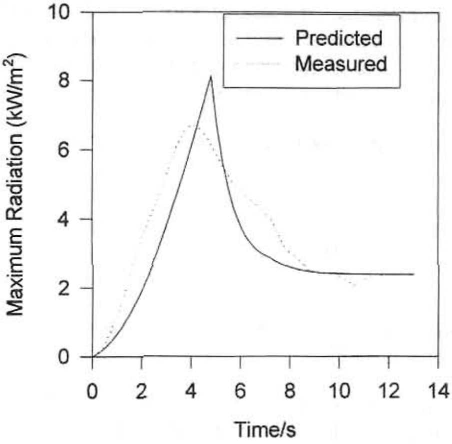

Figure 6. Measured and Predicted Radiation at 108m from a 41kg/s vertical propane jet.

For gases lighter than propane (e.g. ethane, natural gas at ambient temperature), the unignited plume will be more naturally buoyant. The dispersion process for a vertical jet is dominated by "cross wind entrainment" which requires that the dominant velocity of the release is normal to the wind. An upward buoyancy force will augment the release velocity and hence increase the rate of dispersion so that less fuel will get entrained in to the nascent fireball and the fireball will be smaller. Since the upward velocity is dominated by the release, this effect will not be large. Thus the model for fireball size is expected to be valid (but slightly conservative) for releases of gases lighter than propane. The major difficulty arises in the choice of SEP value. Spectral bands tend to be significant in the radiation emitted from methane/air fires and it is not strictly correct to use the grey gas approximation. Also, if methane/air fires are treated as grey emitters the surface emission will increase with fire size until the fireball is optically thick. A value of $250kWm^{-2}$ is likely to be reasonable for optically thick fireballs from vertical jets.

CONCLUSIONS

Models have been presented that permit calculation of radiation from both flash fires and fireballs from vertical jet releases. Both models has been tested against Shell Research experimental data.

Results from the flash fire model suggest that fatal burns are unlikely for a receiver downwind of the spill point who is outside the flammable region. The model does not address heat transfer to structures and personnel caught within the flammable cloud at ignition, however fatal burns would be expected for a normally clothed person. The greatest uncertainty is the accurate prediction of the extent of the flammable cloud - the distance to LFL is very sensitive to both surface roughness and atmospheric conditions.

For a fireball from a vertical jet, the steady state jet fire which follows the fireball is likely to dominate the hazard, especially if escape of personnel is impossible. The model can be used with reasonable confidence for propane. The applicability of the model to other hydrocarbons has been discussed in the text.

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