Jet fire mathematical models for failure of pipelines carrying flammable substances: Part 1) Literature Review

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Major accident hazard pipelines transport hazardous fluids, such as natural gas, that have the potential to harm people in the vicinity in the event of a release from a pipeline failure. Major accident hazard pipelines are defined under the Pipelines Safety Regulations (1996). Dutyholders must implement effective control measures to prevent pipeline failure. Land-use planning law is an important extra precaution to limit the potential risk to the public. HSE is a statutory consultee for proposed land-use developments. HSE sets land-use planning zones and provides advice to local planning authorities on proposed developments within these zones. HSE uses a quantified risk assessment (QRA) approach as part of its decision making. The QRA uses mathematical models of potential hazards and their consequences. HSE has an ongoing research programme to assess the suitability of these models.

A jet fire is one of the potential hazards for releases from pipelines transporting flammable substances. This report and RR1188 (2022) describe research on the suitability of jet fire mathematical models for use by HSE to estimate the physical dimensions of potential fires. This report describes a review of the scientific literature done as the first stage of the research. The review did not identify any single model that would be suitable for the range of scenarios and substances that HSE models. The review identified models that could potentially be implemented by HSE to more accurately represent the physics of jet fires. RR1188 describes the second stage of this research to consider the performance of these models. These findings are being used to inform assessment of the suitability of the jet fire models that HSE currently (2022) uses and whether updates would be beneficial. The report will be of interest to specialists in risk modelling for major hazards.

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Jet fire mathematical models for failure of pipelines carrying flammable substances: Part 1) Literature Review

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KEY MESSAGES

A review of mathematical models available in literature has been undertaken to assess models that simulate the effects of jet fires resulting from failures of pipelines transporting flammable substances.

The Health and Safety Executive (HSE) model the consequences of a jet fire when assessing the risk to individuals in the vicinity of Major Accident Hazard (MAH) pipelines. This study has been undertaken to assess whether there are options to replace the current jet fire models used in HSE's Quantitative Risk Assessment (QRA) tool for pipelines, MISHAP.

A range of empirical and integral models found from a literature search were reviewed to allow a comparison between published models and those currently used in MISHAP. MISHAP utilises two jet fire models: a model for natural gas jet fires; and a jet fire model for all other flammable substances.

The existing models in MISHAP were implemented a number of years ago and contain some approximations due to computational limitations from when they were first developed.

No single empirical model was identified that would be suitable to model the range of scenarios and range of substances that MISHAP currently models.

Integral models were identified that could be implemented in MISHAP to account more fully with the physics of jet fires and that could be validated more fully against experimental data than the current models used.

Further work is being undertaken to compare the results generated from these potential replacement models with the results generated by the two current models used in MISHAP. This will allow an informed decision to be made on the value of replacing the jet fire models in MISHAP.

EXECUTIVE SUMMARY

Background

The Health and Safety Executive (HSE) is a statutory consultee for Land Use Planning (LUP) developments near Major Accident Hazard (MAH) pipelines that fall under the Pipelines Safety Regulations (PSR).

The MISHAP (Model for the estimation of Individual and Societal risk from Hazards of Pipelines) model is used by HSE to calculate the risks associated with MAH pipelines in Great Britain. The risk levels calculated are used by HSE to determine the distances to LUP zones around the MAH pipeline.

As part of the Quantitative Risk Assessment (QRA) process, MISHAP models fireballs and jet fires as a consequence of a flammable release from a MAH pipeline. For substances other than natural gas, MISHAP additionally models the effects of a flash fire in conjunction with a jet fire.

MISHAP contains two jet fire models: a model for natural gas pipelines; and a model for all other flammable substances.

Aims and Methodology

MISHAP has been undergoing a programme of updates and improvements. As part of this improvement programme, the two jet fire models in MISHAP have been reviewed and compared against other published jet fire models. This has been to establish whether the current models are fit-for-purpose, or whether there are improved models available that could be implemented into MISHAP.

An investigation has been undertaken to establish whether there is published experimental data that could be used to validate the models used in MISHAP.

Findings

The model used within MISHAP for releases of natural gas is a simple model adopted many years ago and seems to be limited by the computational power that was available at that time. It cannot model the effects of wind or angle of tilt on the calculated flame length and trajectory.

The model used within MISHAP for releases of other substances is more sophisticated than that used for natural gas releases. It can be used to model single or two-phase flows, as well as being able to model the effects of wind or angle of tilt on the calculated flame length and trajectory.

Both of the existing models within MISHAP assume that the fireball has already dissipated, i.e. the early stages of a release are not modelled. MISHAP separately models the effects of the jet fire and fireball that may form following a release. The physical reality is that the fireball and jet fire will form concurrently following a release, with the unburned material in the jet fire feeding the fireball as it rises from ground level. The fireball will then dissipate while the jet fire continues to burn for a longer time period.

The fireball model in MISHAP has been the subject of a separate review and this work is detailed in a companion report on the improvements to MISHAP.

An extensive literature review of the various models available for predicting the flame length and lift-off for jet-fires has been conducted. The types of model reviewed fall into two broad categories: empirical and integral. Empirical models offer the advantages of simplicity and are computationally inexpensive. The advantages of the more complex integral models are that they can include sub-models of important physical and chemical processes and can be applied to a wider range of release scenarios.

The majority of the empirical models reviewed are based on data from small scale experiments. These models are often only applicable to one type of fuel. Several of the empirical models use non-dimensional parameters to allow some degree of scalability. It is unclear, however, how accurate the predictions from these would be when applied to larger scale releases.

Conclusions

None of the empirical models reviewed would be able to account for the range of fuels and wide variety of release conditions that need to be modelled within MISHAP. A possible solution would be to use different empirical models as appropriate for the release conditions being modelled. However, this could lead to issues over when the use of a specific model was appropriate, would require a large amount of development and maintenance to implement. It could potentially lead to inconsistences in the results generated from the different outputs generated by the different models.

The integral models reviewed are based on solutions of fluid dynamics equations and some include combustion sub-models, making them particularly relevant to jet fires. These integral models offer the potential for development as predictive tools that can be applied to a wide range of release scenarios, but which have relatively short run times making them ideal for routine use.

Further work in this programme has involved comparing the flame length and lift-off height predictions from the integral and empirical models found in the literature with the results generated by the existing models used within MISHAP. The results have also been compared with the experimental data found. This work is detailed in a companion report to allow an informed decision on the most suitable models to be implemented in MISHAP.

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1 INTRODUCTION

The Health and Safety Executive (HSE) is a statutory consultee for Land Use Planning (LUP) developments near Major Accident Hazard (MAH) pipelines that fall under the Pipelines Safety Regulations (PSR).

HSE use a Quantitative Risk Assessment (QRA) model, called MISHAP (Model for the estimation of Individual and Societal risk from Hazards of Pipelines), to calculate the risks associated with MAH pipelines in Great Britain. The risk levels calculated are used by HSE to determine the distances to LUP zones around the MAH pipeline. The LUP zones are used to inform HSE advice to local planning authorities on the safety of proposed developments near MAH pipelines.

One of the consequences from a release modelled within MISHAP when assessing the risk is a jet fire. This is where a flashing jet formed from the pressurised release ignites forming a torch. People in the vicinity of a jet fire could be exposed to levels of thermal radiation that could lead to harm.

MISHAP models a fireball that forms from a release for all substances. Once the fireball has dissipated, MISHAP models a jet fire from the release. For substances other than natural gas, MISHAP additionally models the effects of a flash fire, in conjunction with a jet fire.

MISHAP contains two jet fire models: a model for releases from natural gas pipelines; and a jet fire model for all other substances. The models were written in the 1990s and early 2000s and contain a number of approximations.

As part of a programme of improvements to MISHAP, a review of the models within MISHAP is being undertaken. A review of published models in the literature is being undertaken to determine if there are alternative models available that could be implemented to bring the models in MISHAP more up-to-date. The review is also assessing where experimental data is available that could be used to validate any model implemented in MISHAP. The focus of this report is jet fire models, whilst fireball models are reviewed in a companion report [1].

1.1 OBJECTIVES

The objectives of the work were:

- To review the existing jet fire models used within MISHAP;
- To review other jet fire models that have been published, focusing on the predicted flame geometries.

1.2 STRUCTURE OF REPORT

The remainder of the report is structured as follows:

- Section 2 provides more detail about the two jet fire models currently used within MISHAP;
- Section 3 reviews published jet fire flame length models derived from empirical data;
- Section 4 reviews published integral models for jet fire flame lengths; and
- Section 5 concludes the report

2 EXISTING JET FIRE MODELS

Two jet fire models are currently used within MISHAP [2]. Detailed explanations of these models, and how they were developed, are given in this section.

i. JIF/MAJ3D: Used to model releases for all of the other substances that can be modelled within MISHAP; and

ii. PIPEFIRE: Used to model releases of natural gas in MISHAP.

2.1 JIF/MAJ3D [2]

JIF/MAJ3D calculates flame length based on a model developed by Chamberlain [3] and is used within MISHAP for all substances other than natural gas. It can be applied to both single and two-phase releases. The Chamberlain model was developed in order to improve the thermal radiation level predictions from single-point-source models. Single-point sources, where the radiation is assumed to be emitted from a point of negligible extent, are used in order to simplify the analysis. Inaccuracies arise from the geometrical inadequacies of the single-point-source model and are most significant when predicting near field radiation levels.

As a starting point for determining the geometry of the flare, Chamberlain's model uses a correlation, Ψ, developed by Becker and Liang [4] for determining flame length in still air, L_{f_0} (m):

$$\Psi = \left(\frac{d_s \beta}{S_f L_{f_0}}\right)^{\frac{2}{3}} = f\left(\xi_{L_0}\right) \tag{1}$$

where:

$$\beta = \left(\frac{MW_\infty T_{ad}}{MW_f T_\infty}\right)^{\frac{1}{2}} \tag{2}$$

- $S_f =$ mass fraction of fuel in a stoichiometric mixture:

$$S_f = \frac{MW_f}{15.816 MW_f + 39.5} \tag{3}$$

- $\xi_{L_0} =$ Richardson number based on the flame length in still air:

$$\xi_{L_0} = \left(\frac{g}{d_s^2 u_e^2}\right)^{\frac{1}{3}} L_{f_0} \tag{4}$$

- $d_s =$ source diameter (m);
- $MW_\infty =$ molecular weight of air (g mol^{-1});
- $MW_f =$ molecular weight of fuel (g mol^{-1});
- $T_\infty =$ ambient air temperature (K);
- $T_{ad} =$ adiabatic flame temperature (K);
- $g =$ acceleration due to gravity (m s^{-2}); and
- $u_e =$ expanded jet velocity (m s^{-1}).

The following correlation obtained by Kalghatgi [5] is used for determining flame length in still air for $1 < \xi_{L_0} < 20$ and Reynolds number at the flame tip greater than 8000:

$$\Psi = 0.2 + 0.024\xi_{L_0} = \left(\frac{d_s \beta}{S_f L_{f_0}}\right)^{\frac{2}{3}} \quad (5)$$

A similar correlation was obtained by Becker and Liang [4] in their original analysis, however Kalghatgi's is preferred as the definition of flame length used is believed to be more accurate.

Equation 5 was obtained using data from experiments conducted with hydrogen, methane, propane and ethylene, and using burner diameters ranging from 1.08 mm to 10.1 mm. For each substance, experiments were conducted that produced a range of velocities at the burner exit plane. These velocities were all subsonic, with the exception of the experiments conducted using hydrogen, which produced both subsonic and choked (Mach no.=1) flows. Although Kalghatgi's correlation is quoted as being valid for $1 < \xi_{L_0} < 20$, closer examination of the results shows that near the forced convection limit (i.e. $\xi \to 0$) where $\xi_{L_0} < 2$, this relationship breaks down and Ψ starts to increase as ξ_{L_0} decreases. This will result in the flame length in still air being over predicted for flames within this region. JIF/MAJ3D currently does not acknowledge this region, and it is assumed that Equation 5 holds true for all values of ξ_{L_0}.

Chamberlain uses a combination of laboratory [5, 6] and large scale field test data in order to develop a correlation that accounts for the effect of wind on the flame. The field tests were all conducted using natural gas, whilst the laboratory tests used either methane or propane. The laboratory releases were all subsonic with Mach numbers ranging from 0.06 to 0.9, whilst the field tests covered both sub and supersonic releases with Mach numbers ranging from 0.03 to 1.53.

For choked flows, the expansion beyond the exit hole is idealised as if it takes place in a convergent-divergent nozzle, using the standard orifice equations for isentropic single-phase flow [3, 4]. These equations produce expressions for the jet velocity, temperature, density and effective source diameter.

For two-phase releases a separate set of orifice equations have been developed by setting the jet temperature to the boiling temperature of the substance. The fluid velocity is set equal to the velocity acquired by the fluid being ejected from a pipe at high pressure, plus the velocity the fluid had inside the pipe. It was found that the effect of wind is to increase the air entrainment rate along the flame and reduce the flame length. A correlation of the form L_{f_w}/L_{f_0}, where L_{f_w} is the flame length in windy conditions (m), will therefore be unity when wind speed, u∞ (m s-1) is zero. The correlation will tend to a constant value at high wind speeds as the total volume of air necessary for complete combustion for the fuel is entrained in a limiting finite distance along the jet axis. For vertical jets the correlation was found to be:

$$\frac{L_{f_w}}{L_{f_0}} = 0.49 + 0.51e^{-0.4u_\infty} \quad (6)$$

Data from laboratory-scale, non-vertical releases was used to determine a correlation for tilted jets, where the hole axis makes an angle θx (º) with the horizontal.

When the hole axis is in the wind direction, the data shows that the flame length reduces as the jet is titled into the wind (i.e. as θx increases) because the air entrainment coefficient increases, giving the correlation:

$$L_{f_w} = 105.4 d_s [1 - 6.07\text{x}10^{-3}(\theta_x - 90)] \quad (7)$$

where ds is the source diameter (m).

By assuming that L_{f_w} scales similarly with θ_x for all wind speeds and directions, the general correlation for L_{f_w} is found to be:

$$L_{f_w} = L_{f_0}(0.51e^{-0.4u_\infty} + 0.49)[1 - 6.07\text{x}10^{-3}(\theta_w - 90)] \quad (8)$$

where θw (º) is the angle between the hole axis and the wind vector in the plane containing the hole axis, flame axis and wind vector.

The value of θw used within MISHAP is currently fixed at 90º, meaning that only vertical jets can be modelled by JIF/MAJ3D. MISHAP could be adapted to model the flame geometry of non-vertical releases. This would, however, first require validation of a couple of the assumptions made by the vertical model. These are: that the scaling assumption for all wind speeds and directions is valid, and that the flame trajectory is straight rather than curved as the flame transitions from momentum to buoyancy dominated along its length. Modelling the radiation emitted from these non-vertical jets, however, may not be straightforward and would need further investigation.

A fit for the angle of tilt (i.e. the angle between the hole axis and the flame axis), θ_t (º) data was found when $\theta_t \xi_{L_0}$ is plotted against the ratio of wind speed to jet velocity, Φ_u. For $\Phi_u \leq 0.05$ the flame is jet dominated and the tilt angle is given by:

$$\theta_t \xi_{L_0} = 8000\Phi_u + \xi_{L_0}(\theta_w - 90)\left(1 - e^{-25.6\Phi_u}\right) \quad (9)$$

For $\Phi_u > 0.05$ the flame tilt angle becomes increasingly dominated by wind forces and a second equation is used:

$$\theta_t \xi_{L_0} = 1726(\Phi_u - 0.026)^{0.5} + 134 + \xi_{L_0}(\theta_w - 90)\left(1 - e^{-25.6\Phi_u}\right) \quad (10)$$

The fit of this correlation becomes markedly less good at values of $\Phi_u > 0.3$. This may be due to the data for values of $\Phi_u > 0.3$ being obtained from large-scale field experiments where the wind forces are likely to be less stable, leading to greater variations in the data collected.

The Chamberlain model [3] idealises the flare flame shape as a frustum of a cone and derives expressions for the length and the widths of both the top and bottom of the frustum. However, for the JIF/MAJ3D model used within MISHAP, only the frustum length L_{vis}(m) is used. This is calculated using:

$$L_{vis} = \sqrt{\left(L_{f_w}^2 - s_l^2 \sin^2 \theta_t\right)} - s_l \cos \theta_t \quad (11)$$

where sl is the frustum lift-off distance (m).

The frustum lift-off distance is defined as the distance along the hole axis from the hole to the point of intersection with the cone axis. The lift-off distance can be calculated geometrically using:

$$s_l = L_{f_w} \frac{\sin K\theta_t}{\sin \theta_t} \tag{12}$$

where:

- K = $(\theta_t - \theta_b)/\theta_t$;
- $\theta_t =$ the angle of tilt i.e. the angle between the hole axis and the flame axis (°); and
- $\theta_b =$ angle between the hole axis and the line joining the tip of the flame to the centre of the hole plane (°).

The geometrical relationship is no longer valid as the angle of tilt approaches zero.

Chamberlain [3] uses the experimental data to correlate K with Φ_u:

$$K = 0.185e^{-20\Phi_u} + 0.015 \tag{13}$$

over the range Φ_u = 0.005 to 3. The lift-off distance reduces to $0.2L_{f_0}$ in still air (θ_t = 0º) or $0.015L_{f_w}$ for flames pointing directly into high winds (θ_t = 180º). The data used has a large amount of scatter, however, and the fit used for the correlation is poor and it is unclear how the range for the fit has been selected.

Although MISHAP uses the JIF/MAJ3D model for releases of all substances other than natural gas, the Chamberlain model on which it is based, is based on the results of experiments that used only either methane (laboratory and large scale tests) or propane (laboratory scale tests only).

2.2 PIPEFIRE [2]

PIPEFIRE is used in MISHAP for releases of natural gas and only considers vertical jets in still air. It is split into two sub-models: one for ruptures, referred to as the trench-fire model; and one for holes, referred to as the jet fire model.

2.2.1 Trench-fire model

The trench-fire model represents the jet fire as a vertical, rectangular sheet of flame, using British Gas equations [2] in order to derive relationships for flame height, hf (m):

$$h_f = 5.2\left(\frac{\dot{m}}{\rho_{ng}}\right)^{0.57} \tag{14}$$

and flame diameter, df (m):

$$d_f = 2.7\left(\frac{\dot{m}}{\rho_{ng}}\right)^{0.43} \tag{15}$$

where:

- $\dot{m} =$ mass flow rate (kg s^{-1}); and
- $\rho_{ng} =$ density of natural gas (kg m^{-3}).

Unlike the JIF/MAJ3D model or the jet fire model used for holes, the lift-off distance is not modelled.

2.2.2 Jet fire model

The jet fire model represents the jet fire as a cylinder with flame height, hf (m):

$$h_f = 4.64\left(\frac{\dot{m}}{\rho_{ng}}\right)^{0.63} \tag{16}$$

diameter, df (m):

$$d_f = 0.69\left(\frac{\dot{m}}{\rho_{ng}}\right)^{0.666} \tag{17}$$

and lift-off distance, sl (m)

$$s_l = 4.3\left(\frac{\dot{m}}{\rho_{ng}}\right)^{0.22} \tag{18}$$

3 EMPIRICAL MODELS

The empirical models presented in this section are based on correlations derived from experimental data. These data are collected from many sources, with scales ranging from laboratory flames several centimetres in length to full-scale jet fires that can have lengths over 100 m. Section 3.1 outlines correlations pertaining to the length of the jet fire flame. This is the most important geometry in terms of predicting radiation as it is the largest dimension of the flame. Section 3.2 focuses on the flame lift-off. Flame lift-off refers to the region between the release source and the base of the visible jet fire flame. This region will also have an important effect on predictions for the levels of radiation from the flame as the radiation from this region is low due to the lack of incandescence.

3.1 FLAME LENGTH MODELS

3.1.1 Sønju and Hustad [7]

Sønju and Hustad [7] describe large-scale outdoor and laboratory-scale indoor experiments that were conducted in order to create large turbulent diffusion flames for vertical releases of gaseous fuels up to sonic velocities. The fuels used were propane and methane. A range of circular nozzles were used with diameters ranging from 2.3 mm to 80 mm. The flames were photographed and average measurements were obtained from five photographs taken over a period of several seconds.

The flame height measurements were correlated with a Froude number (Fr) based on the nozzle exit diameter. The Froude number of the flames varied from approximately 80 to 600,000and 500 to 100,000 for the propane and methane flames respectively.

The data was fitted using the same form of a scaling law as suggested by Suris et al. [8]. The correlations derived for Fr < 5, which, for propane, gives:

$$h_f/d_s = 27Fr^{0.2} \tag{19}$$

and for methane:

$$h_f/d_s = 21Fr^{0.2} \tag{20}$$

where:

- h_f = flame height measured from nozzle exit to flame tip (m); and
- d_s = source diameter (m).

For values of Fr > 5, flame height was found to be independent of Froude number. These results are systematically different than those of Suris et al. [8]. For Fr > 5 the correlation for propane is:

$$h_f/d_s = 40Fr^{0.2} \tag{21}$$

and for methane:

$$h_f/d_s = 29Fr^{0.2} \tag{22}$$

where flame height becomes independent of Froude number at Fr = 3 for both fuels. The reason for the differences, described in the paper, are due to uncertainties in flame-height measurements. Sønju and Hustad [7] argue that this is especially true for the large-scale flames, which were

observed to exhibit large fluctuations, and that the extent to which this systematic variation is a function of measurement methods is unclear.

3.1.2 Delichatsios [9, 10]

Delichatsios [9] is concerned with pool fires and buoyant jet fires. Buoyant jet fires are likely to represent one end of the spectrum of turbulent diffusion jet fires considered by this study.

Dimensional analysis is conducted and the flames are characterised by a heat release rate-based fire Froude number, $Fr_{f(\dot{Q})}$, given by:

$$Fr_{f(\dot{Q})} = \frac{Q}{\rho_\infty [\Delta H_c/(S+1)] d_s^2 \sqrt{\{\Delta H_c/[(S+1)cT_\infty] g d_s (\chi_A - \chi_R)\}}} \quad (23)$$

where:

- Q = net heat released by combustion (kW);
- ρ_∞ = ambient air density (kg m^{-3}) ;
- ΔH_c = heat of combustion per unit mass of the fuel (kJ kg^{-1});
- S = mass stoichiometric fuel to air ratio;
- d_s = source diameter (m);
- c = specific heat capacity of the gases (kJ kg^{-1} K^{-1});
- T_∞ = ambient air temperature (K);
- g = acceleration due to gravity (m s^{-2});
- χ_A = combustion efficiency; and
- χ_R = fraction of the theoretical heat release rate that is lost by radiation.

Correlations for dimensionless flame height are derived as functions of the fire Froude number and then compared with experimental data in order to determine the proportionality coefficients. The experimental data is obtained from Zukoski et al. [11], and for buoyancy dominated jet fires ($Fr_{f(\dot{Q})}$> 2) the following correlation was derived:

$$\frac{h_f}{d_s} = 12.52\ {Fr_{f(\dot{Q})}}^{2/5} \quad (24)$$

where h_f is the flame height (m).

In Delichatsios [10], the analysis is extended in order to derive expressions for the flame height of jet diffusion flames over a range from buoyancy to momentum dominated cases. Again, experimental data is used to determine the proportionality constants for correlations derived from theoretical dimensional analysis. This time the experimental data is that of Becker and Liang [4], Delichatsios and Orloff [12], Zukoski et al. [11], and Kalghatgi [5, 6] (only data with no flame lift-off is used). Delichatsios [10] derived the following empirical correlation equation:

$$\frac{h_f}{(S+1)d_s\sqrt{\rho_s/\rho_\infty}} = \frac{13.5Fr_{f(u)}^{2/5}}{\left(1+0.07Fr_{f(u)}^2\right)^{1/5}} \tag{25}$$

where the release velocity-based fire Froude number, $Fr_{f(u)}$, is defined as:

$$Fr_{f(u)} = \frac{u_s}{\left[(S+1)^{3/2}(\rho_s/\rho_\infty)^{1/4}\left(\overline{\Delta T_f}/T_\infty g d_s\right)^{1/2}\right]} \tag{26}$$

and where:

- $\rho_s =$ fuel density at nozzle (kg m^{-3});
- $u_s =$ source exit velocity (m s^{-1});
- $\overline{\Delta T_f} =$ mean peak flame temperature rise (K).

The author stresses that this correlation (Equation 25) is valid for buoyancy-momentum transition and purely momentum dominated flames only, and that the previously derived correlation (Equation 24) should still be used for buoyancy-dominated flames. The transition from the buoyancy dominated to the momentum dominated regime is found to start at $Fr_{f(u)} \approx 3$, and the turbulent diffusion flames are fully momentum dominated for $Fr_{f(u)} >\approx 100$.

3.1.3 Leahey and Schroeder [13]

Leahey and Schroeder [13] developed a simple model for vertically released, wind-affected, momentum dominated jet diffusion flames that estimates flame height, hf (m) and orientation, θ_b (º). As well as assuming that buoyancy forces are negligible, the model assumes that the flame takes the form of a plume ejected from a flare stack, the variables of which have a 'top hat' profile. The model uses the following equations:

$$\frac{h_f}{d_s} = \frac{5}{0.4+1.2U}\left(\frac{1}{\tau\Phi_u}\right)^{1/2} \tag{27}$$

$$\frac{h_f}{x_f} = 0.03\frac{\tau}{\Phi_u} \tag{28}$$

$$\theta_b = 90 - \tan^{-1}(0.03\,\tau/\Phi_u) \tag{29}$$

where:

$$\tau = \frac{T_\infty S_v}{T_f} \tag{30}$$

- $d_s =$ source diameter (m);
- $\Phi_u =$ ratio of wind velocity to stack exit velocity;
- $x_f =$ downwind extent of flame (m);
- $S_v =$ stoichiometric mixing ratio (% by volume);
- $T_\infty =$ ambient air temperature (K); and
- $T_f =$ flame temperature (K).

Flame height and orientation predictions from the model are compared with wind tunnel test data [6] and field test data. The wind tunnel tests were conducted using laboratory-scale flames of methane, propane, ethylene or butane, whilst the field test data were obtained from a stack emitting a mixture of fuel gas (≈ 74% methane) and acid gas (≈ 84% carbon dioxide), with typical volume ratio of fuel gas to acid gas ≈ 40%.

Flame height predictions were found to show reasonable agreement with the wind tunnel data, with the exception of the methane and butane results. The low molecular weight of these two substances is thought to cause greater plume rise than predicted by the model which assumes negligible buoyancy. The flame orientation predictions from the model were also found to show reasonable agreement with the wind tunnel data, with the exception of methane.

The disagreement of the methane results are thought to be due to the model's neglect of buoyancy forces. Although the predicted butane flame orientations showed greater agreement than the methane case, they consistently over predicted the values of αb.

The flame height predictions showed reasonable agreement with the field test data, whilst the flame orientation was slightly over predicted (≈ 5%) by the model. This was again thought to be due to the fact that buoyancy effects are neglected by the model. However, it is hard to draw any conclusions from such a small amount of data (8 tests).

3.1.4 Crocker and Napier [14]

The focus of this paper by Crocker and Napier [14] is mathematical models for fire and explosion hazards of LPG (Liquefied Petroleum Gas), resulting in some discussion of jet fires. For jet fires in still air the correlation of Hawthorne et al. [15] is used:

$$\frac{h_f - s_l}{d_s} = \frac{5.3}{S_{mol}} \sqrt{\frac{T_f}{S_p T_s}\left[S_{mol} - (1 - S_{mol})\frac{MW_\infty}{MW_s}\right]} \tag{31}$$

where:

- $h_f =$ flame height (m);
- $s_l =$ lift-off distance (m);
- $d_s =$ source diameter (m);
- $S_{mol} =$ molar fraction of fuel in a stoichiometric mixture with air;
- $T_f =$ flame temperature (K);
- $T_s =$ temperature of vapour leaving the vent orifice (K);
- $S_p =$ ratio of reactant moles to product mole in a stoichiometric mixture; and
- $MW_\infty/MW_S =$ ratio of molecular weights of the ambient and nozzle fluids.

For jet fires in windy conditions several existing models are proposed and compared. These are a point source model [16], a multiple point source integral model [17], and a solid flame model [6]. There is a lack of agreement between the results of the models, which stems from the fact that each model is based on its own set of premises derived from small scale experiments. The models are then assessed on their original premises, assumptions in the development, ease of manipulation and degree of validation. In the context of these criteria, the solid flame model [6] is found to perform best.

3.1.5 Johnson *et al.* [18]

Johnson et al. [18] adapt and extend the model of Chamberlain [3] in order to predict flame shape and external radiation arising from ignited horizontal natural gas releases. The flame shape is idealised as a frustum of a cone and is described by correlations based on measurements from large–scale experiments [19]. Buoyancy effects are considered, together with the effect of wind momentum.

Chamberlain's model is first used to calculate the overall length of the flame and then the flame trajectory is determined by three non-dimensional numbers. These non-dimensional numbers represent the balance between the initial momentum flux of the jet and respectively, the buoyancy force and the wind momentum flux in the direction of the release and perpendicular to the direction of the release.

The primary focus of this review is on models that can predict the length of jet fires, and, therefore, this model is not given further consideration here. This model might be useful to review in more detail if HSE ever need to further develop modelling capability for non-vertical jet fires.

3.1.6 Blake and McDonald [20, 21], Blake and Coté [22]

Whilst Becker and Liang [4] use a Richardson number to describe the relative influences of buoyancy and momentum on turbulent gas diffusion flames, Blake and McDonald [20] suggest an alternative dimensional analysis to interpret flame length data. This analysis suggests that the non-dimensional flame length is a function of two parameters: the ratio of flame to ambient density, and a density weighted Froude number defined by the momentum of the jet, the ambient density, and a theoretical lateral flame dimension.

The theoretical lateral dimension of the flame, d_f^* (m), provides a length scale for dimensional analysis. Stoichiometry and the conservation of mass and momentum specify this lateral dimension in terms of the driving potential for chemical reaction. When the reactants are not premixed:

$$d_f^* = \frac{2\dot{m}}{S_f\left[\rho_p \pi M\right]^{0.5}} \tag{32}$$

where:

- $\dot{m} =$ mass flow rate of the source jet (kg s^{-1});
- $M =$ momentum of the source jet (N);
- $\rho_p =$ density of products (kg m^{-3}); and
- $S_f =$ mass fraction of fuel in a stoichiometric mixture.

For turbulent diffusion flames, d_f^* (m) is the effective diameter for a jet with an equivalent mass flow rate $\dot{m}/S_f$ (kg s-1), a momentum equal to that of the original source jet M (N), and a density equal to ρp (kg m-3).

The density-weighted Froude number, Fr_ρ, is given by:

$$Fr_\rho = \frac{4M}{\pi \rho_\infty g {d_f^*}^3} \tag{33}$$

where ρ∞ is the density of the surrounding atmosphere (kg m-3)

Plotting non-dimensional flame length data, Lf/d_f^*, from previous studies involving vertical turbulent gas diffusion flames [4, 5, 15, 23, 24, 25] against the density-weighted Froude number, fit the data across the entire range of Fr_ρ from buoyancy- to momentum-dominated limits. For these data, the flame to ambient density ratio, ρp/ρ∞, does not vary significantly with fuel type and its influence is neglected. For small values of the density-weighted Froude number (Fr_ρ <≈ 10) the following correlation is found:

$$\frac{L_f}{d_f^*} = 6.0\left(Fr_\rho\right)^{0.2} \tag{34}$$

For large values of the density-weighted Froude number (Fr_ρ ≈> 10) the flame data, Lf/d_f^*, exhibits an asymptote, independent of Fr_ρ. In agreement with Becker and Liang [4], this asymptote was found to be:

$$\frac{L_f}{d_f^*} = 11 \tag{35}$$

The analysis was also applied to horizontal turbulent diffusion flames. The non-dimensional horizontal, x_f/d_f^*, and vertical, h_f/d_f^*, projections of the flame trajectory measured by Becker et al. [26] were plotted against Fr and compared with the length of vertical turbulent diffusion flames. In the momentum limit, the horizontal projection of the chord length of horizontal flames was found to be identical to the length of vertical flames, whilst in the buoyancy limit, the vertical projection of the chord length was found to approach the length of vertical flames.

3.1.7 Bagster and Schubach [27]

A method for estimating the dimensions of gas jet fires in the buoyancy-dominated regime is proposed by Bagster and Schubach [27]. The method involves estimating the flame length by using the correlation for propane flames from Sønju and Hustad [7] (Equation 19). The flame length estimate is then modified using a 'stoichiometric' factor based on the method of Hawthorne et al. [15], and a momentum factor.

The method is used to convert the results of large-scale experiments conducted by Sønju and Hustad [7] using propane to those that would be expected to be seen for experiments conducted using methane. When the conversions were compared with the results of experiments conducted by Sønju and Hustad using methane, good agreement was observed. However, this method is only valid for buoyancy dominated flames, and no indication is given (in Froude number terms or otherwise) as to when momentum forces become too high and the method is no longer applicable. Also, because the technique essentially scales one set of experimental data in order to make predictions for flames consisting of different fuels, the quality of the output is dependent on the quality of a relatively small amount of input data.

3.1.8 Heskestad [28, 29, 30, 31, 32]

Heskestad [28, 29, 30, 31, 32] developed a correlation model for buoyancy controlled flame heights of vertically oriented turbulent diffusion flames based on the following assumptions:

- infinitely fast reaction kinetics;
- flame extends to a height where the total flux of entrained air at lower levels is sufficient to complete the combustion reactions (recognising that much of the entrained air below the flame tip never takes part in the combustion reactions);
- air demand from the surroundings is proportional to the stoichiometric requirements of the pyrolysis gases; and
- total entrainment rate obeys the relationship established by Ricou and Spalding [33] for the local entrainment in jets of different density to the surroundings.

Non-dimensional flame height is expressed as:

$$\bar{h}_f / d_s = f(N/\chi_c) \tag{36}$$

where N is the non-dimensional group:

$$N = [cT_\infty/(g\rho_\infty^2(\Delta H_c/S)^3)]\, Q^2/d_s^5 \tag{37}$$

- $\chi_c =$ convective fraction of the chemical heat release rate;
- $\bar{h}_f =$ mean flame height (m);
- $d_s =$ source diameter (m);
- $c =$ specific heat capacity at constant pressure (kJ kg^{-1} K^{-1});
- $T_\infty =$ ambient air temperature (K);
- $\rho_\infty =$ ambient density (kg m^{-3});
- $Q =$ net heat released by combustion (mass pyrolysis or gas release rate times the heat of combustion) (kW);
- $\Delta H_c =$ the heat of combustion of the source gas or vapour per unit mass (kJ kg^{-1}); and
- S = mass stoichiometric fuel to air ratio.

For a given atmospheric composition, S does not vary appreciably among common fuels. In practice, for common fuels, standard atmospheric conditions and Earth's gravity, the entire square-bracketed quantity in Equation 37 varies very little. Equation 36, with χ_c removed as it is generally unknown and perceived not to vary appreciably, is found by Heskestad [32] to correlate experimental data on flame heights very well over a wide range of fire sizes and combustibles. For fires and gas flames in the approximate N range 10-6 to 105, the following correlation was found:

$$\bar{h}_f / d_s = -1.02 + 15.6N^{1/5} \tag{38}$$

Data on flame heights in the low-N buoyancy regime from a number of sources [11, 30, 34, 35] were compared with Equation 38 and good agreement was found. Data from the investigations of Blake and McDonald [20, 21] were also compared, and for values of N > 2 × 10-3 good agreement with Equation 38 was found. For values of N considerably smaller (N <≈ 1 × 10-5), however, higher levels of scatter were seen in the data.

Heskestad goes on to develop a correlation to describe the length of the region of a jet fire in which momentum forces will be dominant. The total length of the jet fire will be longer as there is likely to be a region beyond the momentum dominated zone where buoyancy forces cause further extension of the flame. This region is not considered in Heskestad's correlation, and therefore it is not considered further in this review. Similar to the model of Johnson et al. [18] (Section 3.1.5), if HSE needs to further develop a non-vertical jet fire modelling capability, then this model should be considered further as the momentum dominated region will have a strong influence of the trajectory of a jet fire.

3.1.9 Cowley and Johnson [36]

Whilst the focus of Cowley and Johnson [36] is set in the context of oil and gas fires on offshore platforms, many of the jet fire models it presents are also relevant to, and often derived from measurements of onshore jet fires.

The report first considers the flame dimensions of vertical jet fires in still air, with flame length defined as the distance from the release point to the defined end of the flame.

For subsonic flare stacks, API R521 [37] recommends the following correlation:

$$L_f = 2.76Q^{0.452} \tag{39}$$

where L_f is the flame length (m) and Q is the net heat released by combustion (MW). This correlation shows reasonable predictions for vertical subsonic flares for a range of gaseous fuels (fuel gas, catalytic reformer recycle and effluent gas, and natural gas) and stack diameters in the range 500 mm to 800 mm.

For sonic releases, the following correlation was found:

$$L_f = 1.422Q^{0.457} \tag{40}$$

An alternative correlation that is used in the Technica package WHAZAN, is the correlation from Wertenbach [38]:

$$L_f = 18.5\dot{m}^{0.41} \tag{41}$$

where $\dot{m}$ is the mass flow rate (kg s-1).

A correlation derived by McCaffrey and Evans [39] is also quoted:

$$L_f = s_l + 200d_e \tag{42}$$

where sl (m) is the flame lift-off distance and d_e (m) is the effective source diameter. The effective source diameter is the actual hole diameter for subsonic releases, but for sonic releases it is the diameter to which the jet has expanded when it has reached atmospheric pressure. McCaffrey and Evan's correlation is based on subsonic and sonic vertical releases of natural gas from 38 mm to 102 mm orifices and a heat release up to 470 MW.

Cowley and Johnson [36] state that the best flame length correlation for a geometric solid flame shape in a crosswind is that of Chamberlain [3] (Equation 8) as it has been fitted to the widest range of experimental data.

Finally, Cowley and Johnson [36] consider models of flame shapes from non-vertical releases. It is observed that there is little data from large scale jet fires of this type, and consequently only a limited number of models that can make validated predictions. One such model is that of Cook et al. [40], which is a centreline trajectory model derived for inclined natural gas flares. It is based on data from 3.5 kg s-1 to 25.0 kg s-1 releases at an angle of 45° to the vertical, pointing into the wind, crosswind or downwind. The curvilinear flame length is given by:

$$L_f = 1.555Q^{0.467} \tag{43}$$

The flame trajectory in this model is determined by balancing the jet source momentum vector and the crosswind momentum vector and a momentum vector due to the buoyancy of the combustion products. The axial velocity decay was correlated with measurements from high pressure unignited jets in wind tunnels [41]. The effective buoyancy velocity is a constant value, which was determined by tuning the model to predict the trajectory of horizontally firing, laboratory scale flames [26].

The geometric flame shape based model of Chamberlain [3] is discussed, as the incorporation of the data of Kalghatgi [6] allows predictions of flame length and tilt to be made for non-vertical releases. This model is thought by Cowley and Johnson [36] to be the best of the geometric flame shape based models as it is the only one to have been validated against large scale vertical natural gas releases. However, only data from small scale experiments has been used to validate the model for gaseous fuels other than natural gas, and for when the release is inclined away from the vertical.

3.1.10 Crawley *et al.* [42]

In Crawley et al. [42], measurements from Kuwaiti oil well jet fires quoted in an HSE Offshore Technology Information (OTI) report [43] are compared with outputs from the model of Chamberlain [3]. The gas-to-oil ratio of these fires is 10% wt/wt which is similar to the crude oil fluids transported in pipelines. The Chamberlain correlation was found to predict approximately 50% longer and wider flames than were observed for the fires detailed in the OTI report. No conclusive arguments are put forward as to why this is the case, but it is speculated that it could be due to the very high relative density of the blow out, the droplets in the released fluids, the relatively high molecular weight of the released fluids and/or the high momentum flux at the source. It is therefore suggested that the application of the Chamberlain model to oil-based releases may be outside the boundary of validation.

3.1.11 Newman and Wieczorek [44]

The main focus of Newman and Wieczorek [44] is the development of a more consistent and less objective method than visual observations for the measurement of flame lengths. The methodology proposed is to measure the “chemical” flame height, which is defined as the distance from the fuel exit plane to the point where the ratio of species yield of carbon monoxide to carbon dioxide approaches the limit for a well-ventilated fire of the particular fuel being considered.

Flame lift-off is not considered. This technique is used to derive flame heights for buoyant jet flames of propane in a quiescent environment [45] and also for high momentum jet flames of acetylene.

The results are compared with predictions of luminous flame heights from Heskestad’s [29] correlation. However, the correlation (Equation 38) is first rewritten as:

$$\frac{h_{f_c}}{d_s} = 15.6\left(\frac{c_p T_\infty}{(\Delta H_c/S)}\right)^{3/5} (Q^*)^{2/5} - 1.02 \qquad (44)$$

where Q* is a fire Froude number:

$$Q^* = \frac{Q}{\rho_\infty c_\infty T_\infty \sqrt{g d_s} d_s^2} \qquad (45)$$

- h_{f_c} = chemical flame height (m);
- d_s = source diameter (m);
- c_∞ = specific heat of air (kJ kg^{-1} K^{-1});

- $T_\infty =$ ambient air temperature (K);
- $\Delta H_c =$ heat of combustion (kJ kg^{-1});
- $S =$ mass stoichiometric fuel to air ratio;
- $Q =$ net heat released by combustion (kW);
- $\rho_\infty =$ density of ambient air (kg m^{-3}); and
- $g =$ acceleration due to gravity (m s^{-2}).

For typical values of c_∞ and T∞, and ΔHc/r for propane, Equation 44 becomes:

$$\frac{h_{f_c}}{d_s} = 3.95(Q^*)^{2/5} - 1.02 \qquad (46)$$

When the chemical flame heights are non-dimensionalised by nozzle diameter and plotted against fire Froude number, the fit for the buoyant jet flame (propane) data was found to be:

$$\frac{h_{f_c}}{d_s} = 4.0(Q^*)^{2/5} \qquad 1.0 < Q^* < 450 \qquad (47)$$

which is in good agreement with Heskestad.

For high momentum jet flames it has been reported that "the flame height ceases to vary with fuel flow rate and is several hundred times the size of the source diameter" [46]. The calculated non-dimensionalised chemical flame heights based on the acetylene data are approximately constant for all fire Froude numbers between 22,000 and 60,000, but the authors point out that this is based on a few data points and that further data would be needed to fully verify the trend.

3.1.12 Santos and Costa [47]

Laboratory-scale experiments are conducted using propane and ethylene and the results are used to derive an empirical correlation based on a jet Froude number, Fr, defined as:

$$Fr = \frac{u_s^2}{g d_s} \qquad (48)$$

where:

- $u_s =$ source exit velocity (m s^{-1});
- $g =$ acceleration due to gravity (m s^{-2}); and
- $d_s =$ source diameter (m).

Three different sized burner nozzles with diameters of 5 mm, 6 mm, and 8 mm were used, and the flame length is defined as the distance between the flame base and flame tip along the centreline of the flame (i.e. flame length does not include lift-off height). The flame length is obtained by taking the mean flame length from digital images over a period of 15s to 25s.

The jet Froude number represents the ratio of jet exit momentum flux to the buoyancy force experienced by the flame, and is used to distinguish between momentum dominated and buoyancy

dominated regimes in jet diffusion flames. The variation of flame length, Lvis (m), normalised by nozzle exit diameter, ds, is plotted against Fr. In the buoyancy dominated regime, the following correlation was found for propane:

$$\frac{L_{vis}}{d_s} = 36Fr^{1/5} \quad (49)$$

and for ethylene:

$$\frac{L_{vis}}{d_s} = 24Fr^{1/5} \quad (50)$$

These correlations were found to show good agreement with the findings of Røkke et al. [48], who proposed the following correlation for buoyancy dominated hydrocarbon turbulent jet diffusion flames:

$$\frac{L_{vis}}{d_s} = 25Fr^{1/5} \quad (51)$$

For momentum dominated turbulent jet diffusion flames, consistent with the findings of Peters and Göttgens [49] and Delichatsios [10], L_{vis}/d_s is constant for both fuels (L_{vis}/d_s ≈ 242 for propane and L_{vis}/d_s ≈ 226 for ethylene), and therefore independent of the Froude number. The transition from buoyancy to momentum regime is found to vary according to the type of hydrocarbon, with the transition occurring at Fr ≈ 2 × 104 for propane and at Fr ≈ 8 × 104 for ethylene.

3.1.13 Lowesmith *et al. [*50*]*

The results of various large and full scale experiments using natural gas, propane, butane and crude oil [19, 51, 52, 53, 54] are used to derive a correlation for flame length L_f (m) as a function of net heat released by combustion Q (MW) (mass flow rate × net calorific value of fuel) in Lowesmith et al. [50]:

$$L_f = 2.8893Q^{0.3728} \quad (52)$$

For releases of natural gas this is then converted to an expression involving hole diameter, ds (mm) and pressure, P (Pa):

$$L_f = 0.933d_s^{0.746}P^{0.373} \quad (53)$$

It is not made clear whether the flame lengths quoted in Lowesmith et al. [50] include lift-off distance.

3.1.14 Kiran and Mishra [55]

Kiran and Mishra [55] describe laboratory-scale experiments conducted using LPG (72% butane and 28% propane). Similar to Santos and Costa [47], the results are used to derive an empirical correlation based on a jet Froude number.

The burner used in the experiments had a diameter of 2.2 mm and, to avoid perturbations from the ambient air, was placed inside a glass enclosure. As with the measurements of Santos and Costa [47] the flame length is defined as the distance between the flame base and flame tip along the centreline of the flame. The flame length is obtained by taking the mean flame length from video images over a period of 30 s to 40 s. The variation of flame length, normalised by nozzle exit

diameter, L_{vis}/d_s is plotted against Fr, and the following correlation is found for the buoyancy-dominated regime:

$$\frac{L_{vis}}{d_s} = 30Fr^{1/5} \tag{54}$$

For the momentum-dominated regime, the non-dimensional flame height remains approximately constant with a value of $L_{vis}/d_s \approx 269$. The transition from buoyancy to momentum regime for the LPG flames is found to occur at Fr = 4.5 × 104, which is higher than that found for propane flames in a similar study by Santos and Costa [47], but lower than that found for ethylene flames. The constant value of non-dimensional flame height that the propane flames approximated to in the momentum regime was different from that observed for LPG flames, indicating that the fuels' flames have different characteristics.

3.1.15 Studer e*t al.* [56]

Studer et al. [56] describe horizontally released laboratory-scale experiments conducted using varying mixtures of hydrogen and methane. The fuel mixtures were released through orifices of diameter ds = 4 mm, 7 mm and 10 mm into still air. The visible flame length Lvis (i.e. not including lift-off distance) (m) was measured by averaging five consecutive frames taken by a high speed digital camera. Following the work of Delichatsios [10] and Schefer et al. [57] correlations were derived for the non-dimensional length, L*, of the jet fire based on the release velocity-based fire Froude number, $Fr_{f(u)}$:

$$L^* = \frac{L_{vis}S_f}{d_s\sqrt{\rho_s/\rho_\infty}} \tag{55}$$

where:

$$Fr_{f(u)} = \frac{u_s S_f^{3/2}}{(\rho_s/\rho_\infty)^{1/4}\left[\left(\Delta T_f/T_\infty\right)g d_s\right]^{1/2}} \tag{56}$$

- $S_f =$ mass fraction of fuel in a stoichiometric mixture;
- $\rho_s =$ jet exit density (kg m^{-3});
- $\rho_\infty =$ ambient density (kg m^{-3});
- $u_s =$ source exit velocity (m s^{-1});
- $\Delta T_f =$ peak flame temperature rise (K);
- $T_\infty =$ ambient air temperature (K); and
- $g =$ gravitational acceleration (m s^{-2}).

All of the experimental data were in the momentum dominated regime ($Fr_{f(u)}$ > 5) and the pure hydrogen jet fires were observed to have an approximately constant non-dimensional flame length of 23, independent of their fire Froude number, in agreement with the findings of Schefer et al. [57] for vertical jet fires. However, when methane was added, the value of the non-dimensional flame length decreased, an observation that is in agreement with the findings of Kalghatgi [5].

The visible flame length was plotted against the release pressure, P (Pa), and the following correlation was found:

$$\frac{L_{vis}}{d_s} = 420P^{0.47} \quad (57)$$

This correlation gives values slightly lower than the findings of Mogi and Horiguchi [58], who derived:

$$\frac{L_{vis}}{d_s} = 530P^{0.43} \quad (58)$$

The visible flame length was also correlated with the square root of net heat released by combustion, Q (W), giving:

$$L_{vis} = 0.0016Q^{1/2} \quad (59)$$

which was found to predict shorter flame lengths by about 15% when compared with a similar correlation from Lowesmith et al. [50].

3.1.16 Gómez-Mares *et al [59]*

Gómez-Mares *et al* [59] describe relatively large scale (≈ 2 m to 8 m) vertical sonic propane jet fire experiments that were conducted in still air. Six exit diameters were used: 10 mm, 12.75 mm, 15 mm, 20 mm, 25.5 mm, and 30 mm. The nozzle exit Reynolds number ranged from 8×10^5 to 3×10^6, which means all flames were in the turbulent regime. The Froude number was always greater than 2.4×10^5 meaning that all flames were momentum dominated.

Only the tests in which the flame was fed by a single-phase gas flow are considered in the derivation of an empirical correlation, as the features of flames fed by gas-liquid mixtures were found to be significantly different. The flames fed by gas were found to be almost transparent, whilst the flames fed by two-phase mixtures were yellow and very luminous, as well as larger (up to ≈ 30%). This is attributed to the increase in fuel mass flow rate due to the presence of liquid fuel droplets.

When the relationship between L_{vis} (m), the visible flame length (i.e. not including lift-off distance), and net heat released, Q (MW), was analysed the flowing correlation was found:

$$L_{vis} = 0.0562Q^{0.4819} \quad (60)$$

which is similar to correlations provided by other authors for other fuels [60, 61].

3.1.17 Palacios and Casal [62, 63]

Two papers are presented by Palacios and Casal [62, 63] that describe sets of similar experiments conducted using sonic and subsonic turbulent vertical jet diffusion flames of propane released in still air. Nozzles of varying diameter were used, ranging from 10 mm to 43.1 mm (the largest value representing a full bore rupture of the pipeline) and flames up to approximately 10 m in height were observed using both infrared and visible light cameras.

The visible flame length, L_{vis} (m), defined as the distance from the base of the lifted flame to the flame tip, was measured. It was found to vary with both mass flow rate of the release and the source diameter, d_s (m), in agreement with Kalghatgi [5]. The non-dimensional flame length ($L_{vis}\ /d_s$) was

correlated as a function of the Reynolds number, Re, and the following relationship was found in Palacios and Casal [62]:

$$L_{vis}/d_s = 6.73Re^{0.27} \quad (61)$$

The following relationship was found in Palacios and Casal [63]:

$$L_{vis}/d_s = Re^{0.4} \quad (62)$$

No reason is given for the difference between these two correlations.

Both papers comment on the simplified shapes used to model jet fires. They note that the frustum of a cone shape used by other authors [3, 6] to model jet fires affected by a significant crosswind are not suitable to describe vertical jet fires in still air. Instead a model based on a cylindrical shape, with diameter equal to that of a cylinder with volume equal to that surrounded by the jet fire surface, was found to give a more accurate measure of the flame shape.

3.1.18 Molokov and Saffers [64]

The focus of this paper is hydrogen jet fires, particularly sonic or under-expanded jet flames. When non-dimensional flame length and Froude number are correlated, the flame length data are found to be highly scattered in the momentum-dominated (high Froude number) region of the correlation It is stated that the simplification of flame length correlations to functional dependence on Froude number only (i.e. ignoring dependence on Reynolds and Mach numbers) is not appropriate when under-expanded/sonic jets are included.

A new dimensionless group is derived that is dependent on Reynolds and Mach numbers as well as Froude number:

$$\frac{g\mu_s}{\rho_\infty c_s^3} ReFr \quad (63)$$

where:

- μ_s = viscosity at nozzle exit (kg m^{-1} s^{-1});
- c_s = speed of sound at conditions of gas in the nozzle (m s^{-1});
- ρ_∞ = density of ambient air (kg m^{-3});
- g = acceleration due to gravity (m s^{-2});
- Re = Reynolds number; and
- Fr = Froude number.

When calculated using conditions at the nozzle exit for hydrogen flows, Equation 63 simplifies to:

$$\frac{\rho_s}{\rho_\infty}\left(\frac{u_s}{c_s}\right)^3 \quad (64)$$

where:

- ρ_s = density of the hydrogen at the nozzle exit (kg m^{-3}); and
- u_s = source exit velocity (m s^{-1}).

When plotted against the non-dimensional flame length L_f/d_s, three distinct correlations in the data are observed, representing the traditional buoyancy-controlled, traditional momentum-dominated "plateau" (expanded jets), and new momentum-dominated under-expanded jet fire "slope" part. These three parts can be approximated by the following equations respectively:

$$L_f/d_s = 1403[(\rho_s/\rho_\infty)(u_s/c_s)^3]^{0.196} \quad \text{for } (\rho_s/\rho_\infty)(u_s/c_s)^3 < 0.0001 \tag{65}$$

$$L_f/d_s = 230 \quad \text{for } 0.0001 < (\rho_s/\rho_\infty)(u_s/C_s)^3 < 0.07 \tag{66}$$

$$L_f/d_s = 805[(\rho_s/\rho_\infty)(u_s/c_s)^3]^{0.47} \quad \text{for } (\rho_s/\rho_\infty)(u_s/c_s)^3 > 0.07 \tag{67}$$

where L_f is the flame length (m) and d_s is the source diameter (m).

These correlations are validated for pressures from nearly atmospheric up to 90 MPa, temperatures down to 80 K, and nozzle diameters from 0.4 mm to 51.7 mm. There is a saturation of L_f/d_s for expanded jet fires as the flow velocity in the actual nozzle exit is approaching the speed of sound. The value of this saturation limit, L_f/d_s = 230, reproduces results of a number of previous studies with expanded jets, though in different coordinates. However, there is no saturation of the dimensionless flame length for choked under-expanded jet flames. Values reported in recent under-expanded hydrogen jet fire experiments [65] are significantly higher than the L_f/d_s = 230 limit, with values up to L_f/d_s = 3000.

One of the advantages of these correlations is the absence of parameters at the effective nozzle exit due to the application of an under-expanded jet theory. The parameters needed to predict the flame length are those at the actual nozzle exit only: diameter, hydrogen density, flow velocity, the speed of sound at the pressure and temperature at the nozzle exit. There is less uncertainty in the calculation of flow parameters at the actual nozzle exit compared with at the effective nozzle exit.

3.1.19 Bradley *et al. [66]*

The paper reports a comprehensive survey of experimental data on the flame dimensions of controlled atmospheric jet flames. It covers six fuels, in flow regimes that range from small laminar flames to turbulent subsonic and supersonic jets. The fuels used are: acetylene, butane, ethylene, hydrogen, methane and propane, with flame heights ranging from 0.08 m to 110 m. Upstream pressures ranged from 0.06 MPa to 90 MPa, and discharge diameters from 4×10^{-4} m to 1.32 m. The mode of release could be horizontal, but was principally vertical, into relatively still air, with wind speeds of less than 2 m s^{-1}.

The experimental data bank is used in the correlation of dimensionless flame heights in terms of the dimensionless group previously defined in Newman and Wieczorek [44]:

$$Q^* = \frac{Q}{\rho_\infty c_\infty T_\infty \sqrt{g d_s} d_s^2} \tag{68}$$

where:

- h_{f_c} = chemical flame height (m);
- d_s = source diameter (m);
- c_∞ = specific heat of air (kJ kg^{-1} K^{-1});
- T_∞ = ambient air temperature (K);

- $\Delta H_c =$ heat of combustion (kJ kg^{-1});
- $S =$ mass stoichiometric fuel to air ratio;
- $Q =$ net heat released by combustion (kW);
- $\rho_\infty =$ density of ambient air (kg m^{-3}); and
- $g =$ acceleration due to gravity (m s^{-2}).

The non-dimensional data fall into two regimes: one for subsonic flows and the other for choked and supersonic flows. The best fit lines are expressed by:

$$\frac{h_f}{d_s} = 3.4Q^{*\frac{2}{5}} - 0.6 \quad \text{for} \quad Q^{*\frac{2}{5}} < 100 \tag{69}$$

in the subsonic regime;

$$\frac{h_f}{d_s} = 1.9Q^{*\frac{2}{5}} \quad \text{for} \quad Q^{*\frac{2}{5}} > 100 \tag{70}$$

in the choked and supersonic regime.

These correlations were found to give good predictions for plume heights, provided there are no large differences in the laminar burning velocity for the different fuel-air mixtures under ambient atmospheric conditions.

3.1.20 Summary of empirical flame length models

A large number of empirical models describing the flame geometry of a jet fire were reviewed, and are summarised in Table 1in Appendix A. Whilst all of these models share a common aim, the data which they are derived from, and validated against, varies greatly. Therefore, the type of jet fire, and the release conditions that a particular model can account for is also hugely varied. Some models are only applicable to jet fires consisting of one type of fuel, whilst others can model various fuels but only if the release is single phase. Separate correlations usually exist for either momentum or buoyancy dominated flames, with the transition point between the two regimes often varying between different models. Some models can take into account factors such as wind, flame tilt and release orientation, whilst others do not. The experimental data used to derive and validate the models is sometimes from both small and large scale experiments, and sometimes only from small scale experiments. Furthermore, there are several different ways of measuring the length of a flame produced during a jet fire experiment, and the technique used varies between models/data sets.

MISHAP is designed to be applicable to a range of fuels, under a wide variety of release conditions. It seems unlikely that just one of the empirical models reviewed here would be capable of accurately modelling the jet fires arising from the whole range of release conditions covered by MISHAP. Therefore, if the existing jet fire models used within MISHAP were to be replaced by new empirical models, it is probable that a combination of several of the empirical models reviewed would need to be used. The model used for a particular run within MISHAP would then be selected depending on the exact release conditions being modelled. This is a less than ideal method for several reasons. Firstly, an additional step is added to the process whereby the program will have to select the appropriate model based on the release conditions being modelled. Whilst this may be obvious in certain situations, the variety of transition points between buoyancy and momentum regimes quoted in the literature indicates that selecting the most appropriate model may not always be

straightforward. Using multiple empirical models may also lead to inconsistences in MISHAP outputs due to differences in the quality of the models being used and/or the data that they are derived from.

To determine how suitable these empirical models would be for use within MISHAP then the results generated from the models would need to be compared with those obtained from the existing models used within MISHAP and also with relevant experimental data.

3.2 LIFT-OFF MODELS

Due to their high momentum, most jet fires have a region of extremely low incandescence immediately after the point of release known as lift-off. The lack of incandescence means that the radiation from this region is low, and will therefore need to be accounted for when modelling the total radiation from the jet fire. This section focuses on the various different empirical models that have been derived for calculating the size of this lift-off region.

3.2.1 Hawthorne et al [15]

Hawthorne et al's [15] equation for describing the dimensionless length of free turbulent flame jets can be used to calculate the lift-off distance, s_l (m), of these flames:

$$\frac{L_f - s_l}{d_s} = \frac{5.3}{S_{mol}} \sqrt{\frac{T_{ad}}{S_p T_s} \left[S_{mol} + (1 - S_{mol}) \frac{MW_\infty}{MW_s} \right]} \tag{71}$$

where:

- L_f = flame length (m);
- d_s = source diameter (m);
- S_p = ratio of reactant moles to product mole in a stoichiometric mixture;
- T_{ad} = adiabatic flame temperature (K);
- T_S = temperature of fluid in the nozzle (K);
- S_{mol} = molar fraction of fuel in a stoichiometric mixture with air; and
- MW_∞ / MW_S = ratio of molecular masses of the ambient and nozzle fluids.

Equation 71 has only been validated for subsonic flames near the forced convection limit, however, and it also requires the visible flame length to be known in order to calculate the lift-off height.

3.2.2 Ricou and Spalding [33]

Ricou and Spalding [33] suggest that the air entrained per unit length into a jet flame is proportional to the square root of the product of the local jet momentum flux, $\dot{M}$(N m^{-2}), and the local air density, ρ_∞ (kg m^{-3}). The luminous flame lift-off distance, sl (m), is found to be given by:

$$s_l = 0.141 \left(\dot{M} \rho_\infty \right)^{\frac{1}{2}} \tag{72}$$

Johnson *et al* [18] use this formula to calculate lift-off within their model for predicting flame shape and thermal radiation from ignited horizontal natural gas releases. As part of the validation of their

model, lift-off predictions from this correlation were compared with measurements taken from large-scale horizontal releases of natural gas carried out by Bennett *et al [19]*, and reasonable agreement was found. Bennett *et al.* state that wind appeared to have no effect on the flame lift-off distance, in contrast to the findings of Chamberlain [3].

Johnson *et al.* [18] state that measurement of the true lift-off distance is impossible as there is a region nearest the release point which burns as a blue flame. This blue region is almost invisible on the video records that the flame lengths were measured from and therefore cannot be distinguished from the true lift-off region. They argue that this is unlikely to have a significant effect on the thermal radiation measurements taken from their model as the level of radiation from this blue region is small compared to that from the luminous yellow region further downstream, which contains incandescent soot.

3.2.3 Becker and Liang [4]

Becker and Liang [4] argue that the approach of measuring visible flame length from the lift-off plane to the flame tip is inconsistent with the theory of turbulent diffusion flames. Ambient air is entrained over the lift-off region and therefore it is part of the progression towards a stoichiometric composition along the flame axis. They argue that visible flame length should be measured from the effective start of the gas jet, even when the combustion zone begins at some distance further downstream.

When a flame is long relative to the effective source diameter, d_s (i.e. cube root of flame Richardson number, ξ_L < 20), the flame jet can meaningfully be thought of as issuing from a point source of momentum, chemical species and energy. This virtual origin has been shown to be located at a distance of $3d_s$ downstream of the burner exit plane [24] and it is from this point that Becker and Liang measured flame length for all flames with ξ_L < 20.

When ξ_L > 20 flames may not be long relative to source diameter. When the distance from the burner exit plane to the virtual origin is comparable to the flame length, then the flame no longer behaves over most of its length as though it arose from a virtual point source. For these flames, Becker and Liang measure flame length from the burner exit plane, and point out that any discontinuity that occurs at ξ_L = 20 is more than masked by the increasing scatter of data at high ξ_L.

3.2.4 Sønju and Hustad [7]

The authors quote a functional dependence of lift-off distance, s_l (m), on strain rates for turbulent flows from Peters and Williams [67]:

$$s_l/d_s = \alpha_H (d_s/u_s)^{-1} \tag{73}$$

where:

- α_H = empirical constant (s);
- d_s = source diameter (m); and
- u_s = source exit velocity (m s^{-1}).

Peters and Williams [67] recommend, based on the analysis of measurements on methane flames, that:

$$s_l/d_s = 3.6 \times 10^{-3} (d_s/u_s)^{-1} \tag{74}$$

When this correlation is compared with results of large-scale and laboratory-scale experiments conducted using vertical methane and propane releases, good agreement is shown. Froude numbers of the experimental flames ranged from approximately 80 to 6×10^5 and 5×10^2 to 1×10^5 for the mostly subsonic propane and methane flames respectively. The nozzle diameters ranged from 2.3 mm to 80 mm, and lift-off distance is defined as the distance from the burner exit plane to where the blue part of the flame first appears.

McCaffrey [68] also found good agreement with Equation 74 when comparing data from methane flames from a 30 mm diameter nozzle.

3.2.5 Schuller *et al.* [69]

Schuller *et al.* [69] fitted the following correlation to data from vertical subsonic propane releases out of 10 mm to 80 mm nozzles to calculate the lift-off distance, s_l (m):

$$s_l = 0.16 {d_s}^{1/2} u_s \tag{75}$$

where d_s is the source diameter (m), and u_s is the source exit velocity (m s^{-1}).

3.2.6 Kalghatgi [5]

Using data from laboratory-scale experiments with vertical hydrogen, methane, ethylene and propane flames in still air, Kalghatgi [5] found that lift-off distance, s_l (m), is independent of burner diameter, d_s (m), and that it increases linearly with source exit velocity, u_s (m s^{-1}). These observations appear to hold for both sub and supersonic releases, but for supersonic cases they have only been verified experimentally using releases of hydrogen.

Based on a theory proposed by Vanquickenbourne and Van Tiggelen [70], Kalghatgi proposes that s_l will be a function of:

- the maximum laminar burning velocity, u_{lam} (m s^{-1});
- source exit velocity, u_s (m s^{-1});
- kinematic viscosity at the jet exit, v_s (m^2 s^{-1}), and
- the density ratio $\rho^* = \rho_s/\rho_\infty$, where ρ_s is the density of the burner gas at the jet exit (kg m^{-3}) and ρ_∞ is the density of the ambient air (kg m^{-3}).

Dimensional analysis gives:

$$\Lambda \equiv \frac{s_l \, u_{lam}}{v_s} = f\left(\frac{u_s}{u_{lam}}, \rho^*\right) \tag{76}$$

Plotting Λ against $\bar{u}_s^*$, where:

$$\bar{u}_s^* = \frac{u_s}{u_{lam}} \, g(\rho^*) \tag{77}$$

and the function g is defined by:

$$g(\rho^*) = 0.04 + 0.46\bar{\rho} + 0.5{\rho^*}^2 \tag{78}$$

then it was found that all the data for hydrogen, methane, ethylene and propane flames fit onto a single curve. In the range $0.5 < \rho^* < 2$, which covers all of these hydrocarbon gases, $g(\rho^*) \backsimeq \rho^{*1.5}$, and to a fairly good approximation the curve was given by:

$$\left(\frac{s_l\, u_{lam}}{v_s}\right) = \alpha_K \left(\frac{u_s}{u_{lam}}\right)(\rho^*)^{1.5} \tag{79}$$

with $\alpha_K \approx 50$.

3.2.7 Cowley and Johnson [36]

Cowley and Johnson [35] discuss the lift-off distance models of Sønju and Hustad [7], McCaffrey [68], Schuller *et al.* [69], Cook *et al.* [71], and Chamberlain [3]. Of these, the authors comment that only Cook's and Chamberlain's correlations have been fitted to a sufficiently wide range of release conditions to be of use in the field of offshore fire protection.

3.2.8 Sugawa and Sakai [72]

Sugawa and Sakai [72] conducted experiments using vertical releases of propane at rates between 100 l/min (≈ 0.8 kg s^{-1}) and 400 l/min (≈ 3.3 kg s^{-1}), and through nozzles between 6.5 mm and 27.6 mm in diameter.

When lift-off distance, s_l (m), is normalised by source diameter, d_s (m), and plotted against dimensionless heat release rate, Q^* (Equation 45), the data fit onto a single curve, expressed empirically as:

$$\frac{s_l}{d_s} = 0.0139 Q^{*\frac{3}{5}} \tag{80}$$

3.2.9 Santos and Costa [47]

Santos and Costa [47] conducted laboratory scale experiments creating vertical buoyancy dominated turbulent diffusion flames with propane and ethylene. Lift-off distance, s_l (m), was found to be independent of source diameter, d_s (m), and linearly proportional to source exit velocity, u_s (m s^{-1}). The lift-off distance was non-dimensionalised by the nozzle exit diameter and the following correlation was found:

$$\frac{s_l}{d_s} = \alpha_S \left(\frac{u_s}{d_s}\right) \tag{81}$$

with the substance specific numerical constant $\alpha_S = 2.6 \times 10^{-3}$ and $\alpha_S = 0.8 \times 10^{-3}$ for propane and ethylene respectively. The higher lift-off distances (and hence lower α value) for propane are consistent with the higher reactivity, and therefore higher laminar flame speed, of ethylene. This observation is, in turn, consistent with the correlation of Kalghatgi [5], which includes laminar flame speed terms, making it applicable to all hydrocarbon fuels.

3.2.10 Kiran and Mishra [55]

Kiran and Mishra [55] show that the normalised lift-off distance, s_l / d_s, of their laboratory scale LPG jet diffusion flames varies with global strain rate, u_s / d_s. In agreement with several studies [73, 74, 75] the data reveals that lift-off distance, s_l (m), is proportional to the fuel jet velocity, u_s (m s^{-1}). The lift-off distance for experiments conducted with higher jet velocities was found to be in good agreement with experiments conducted with propane flames [73, 76].

However, for lower jet velocities, lift-off distances were found to be lower than those observed in the other studies. Kiran and Mishra attribute this to the composition of the fuel used, as LPG also contains butane as well as propane. Kiran and Mishra argue that lift-off distance is inversely proportional to the reactiveness of the fuel, characterised by the laminar burning velocity. As the LPG fuel contains butane, its laminar burning velocity is likely to be higher than that of pure propane. Therefore the lift-off distance will be slightly lower, particularly at lower strain rates. As the global strain increases, the local equivalence ratio of the mixture at the base of the flame is likely to be reduced leading to a reduction in local burning velocity due to entrainment of ambient air. Hence the lift-off distance increases gradually with strain rate and at higher jet velocities shows better agreement with flames of pure propane.

From the data a correlation of similar form to that of Santos and Costa [47] is derived for LPG jet diffusion flames:

$$\frac{s_l}{d_s} = 1.8 \times 10^{-3} \left(\frac{u_s}{d_s}\right) \tag{82}$$

where $d_s$is the source diameter (m).

3.2.11 Bradley *et al.* [66]

Bradley *et al.* [66] take the expressions for normalised lift-off distance and dimensionless flow derived by Kalghatgi [5] and apply them to their extensive bank of data collected from experiments involving acetylene, butane, ethylene, hydrogen, methane and propane, with flow regimes ranging from small laminar flames to turbulent subsonic and supersonic jets.

The best fit curve for this data was found to be similar, but slightly different to the correlation derived by Kalghatgi [5], and took the form:

$$\left(\frac{s_l\, u_{lam}}{v_s}\right) = 52.4 \left[\left(\frac{u_s}{u_{lam}}\right)\left(\frac{\rho_s}{\rho_\infty}\right) - 11.8\right]^{1.04} \tag{83}$$

where:

- s_l = lift-off distance (m);
- u_{lam} = maximum laminar burning velocity (m s^{-1});
- u_s = source exit velocity (m s^{-1});
- v_s = kinematic viscosity at the jet exit (m^2 s^{-1});
- ρ_s = density of the burner gas at the jet exit (kg m^{-3}); and
- ρ_∞ = density of the ambient air (kg m^{-3}).

3.2.12 Summary of empirical flame lift-off models

The empirical lift-off models that have been reviewed are summarised in Table 2 in Appendix B. As with the empirical flame length models, there is a wide range of correlations pertaining to, and derived from, many different types of release and for different fuels. However, some of the models do share a common agreement that the non-dimensional lift-off distance is a function of $u_s/\sqrt{d_s}$ [7, 47, 55, 72]. This relationship is then fitted to different sets of data by multiplying it with a fuel-dependent constant.

4 INTEGRAL MODELS

The empirical models described in Section 3 are based exclusively on correlations derived from experimental data and represent the simplest type of model available. Their main advantage is that their simplicity makes them computationally inexpensive. Their main disadvantage is that they have a strictly limited range of applicability, which is dictated by the amount and extent of experimental data available for a given release scenario. Extending them to different release scenarios may introduce errors if relevant experimental data is not available.

Conversely, computational fluid dynamics (CFD) models which involve the numerical solution of two and three-dimensional fluid dynamic equations of turbulent reacting flows, are the most sophisticated approach that can be applied to jet fires. These models can be applied to a wide range of release scenarios with only minor modifications, provided that suitable sub-models of the dominant physical and chemical processes occurring in the modelled flows are included. However, they are computationally expensive and often require long run times, making them unsuitable for routine consequence analysis.

Integral models provide a practical intermediate approach, which can include the concepts employed by CFD models without incurring the high computational costs. Integral models are based on solutions of the fluid dynamic equations and can include sub-models of the important physical and chemical processes. However, the two and three dimensional partial differential equations are reduced to one-dimensional ordinary differential equations by assuming self-similarity within the flow-field. Integral models therefore offer the potential for development as predictive tools that can be applied to a wide range of release scenarios, but which have relatively short run times making them ideal for routine use. Integral models that are potentially applicable to jet fires have been developed, and a number of these models are described in the following sections.

4.1 INTEGRAL JET FIRE MODELS

4.1.1 Morton *et al.* [77]

Morton *et al.* [77] describe the derivation of an integral model for plumes arising from gravitational convection (i.e. buoyancy differences). It is assumed that the source does not produce an appreciable amount of momentum, so therefore it is unlikely that this model is directly applicable to the modelling of jet fires, particularly from high pressure pipelines. However, this integral model is later adapted, and forms the basis of several integral models for jet fires that follow, and so is worth a brief description.

The model is based upon three main assumptions:

1) That the rate of entrainment at the edge of the plume is proportional to some characteristic velocity at that height,

2) That the profiles of mean vertical velocity and mean buoyancy force in horizontal sections are of similar form at all heights,

3) That the largest local variations of density in the field of motion are small in comparison with some chosen reference of density, this reference being taken as the density of the ambient fluid at the level of the source.

Maintained and instantaneous sources, that give rise to plumes and clouds respectively, are both considered by the authors. The models applicable to maintained sources are discussed in this report as they are more relevant to jet fires.

Maintained plumes in uniform ambient fluids are first considered in the paper, assuming the velocity and buoyancy force are constant across the plume (i.e. 'top hat' profiles). Three differential equations representing conservation of volume, momentum and density deficiency (buoyancy) are derived.

A maintained point source in a stratified fluid is considered next in the paper. In this situation, the plume density increases steadily owing to entrainment, whilst that of the ambient fluid decreases steadily with height. At some level, the density difference vanishes; above this level, the forces on the plume field act to reduce its momentum and ultimately bring it to rest. For this situation, rather than 'top hat' profiles, it is assumed that the velocity and the buoyancy profiles are normally distributed curves centred about the axis of symmetry.

The horizontal scale, b, for the plume at any particular height is then the distance from the axis of symmetry to points at which the velocity and buoyancy amplitudes are $1/e$ of those on the axis. Therefore, this does not correspond with the radius that would be observed for such a plume, but is proportional to this radius and can be thought of as an 'effective' radius. The entrainment constant, α_{ent}, is selected in this case so that the rate of entrainment of volume at any particular height is also normally distributed, giving $2\pi b\alpha_{ent}\, u(z)$,where $u(z)$ is the plume velocity at a height z.

Boundary conditions are imposed and used to determine a solution to the differential equations. The solutions are compared with the results of a range of experiments and good agreement is observed.

4.1.2 Morton [78]

Morton [78] extends the model described in Morton *et al.* [77] to model plumes that feature buoyancy, momentum and mass fluxes. The two limiting cases of this type of plume are introduced, which are the jet from a point source of momentum, and the pure plume from a source of buoyancy only. Similar assumptions are made to those in the original model by Morton *et al.* [77], most notably that local density variations are so small in relation to some reference density that the inertia of unit volume of the fluid can be regarded as uniform. This is a drawback when considering turbulent flames as it eliminates the effect of density differences on mixing which may be important when large differences in temperature exist between the plume and ambient fluid. However, the model provides some insight on the effects of buoyancy, momentum and mass fluxes on the characteristics of plumes and jets.

In addition to the entrainment constant that was used in the previous model and which is associated with the velocity profile, a new constant is introduced which is associated with the buoyancy profile. These are universal constants, which must be evaluated experimentally.

Plumes in a uniform environment are first considered. Gaussian profiles of mean vertical velocity are assumed and new differential equations, analogous to those used in the previous model [77], are derived.

Solutions to these equations are found for various scenarios involving sources with different combinations of rate of discharge of buoyancy, momentum and mass. The behaviour of a plume in a uniform environment is found to be characterised by a dimensionless parameter, Γ, which describes the plume in terms of its initial momentum, buoyancy and mass flow. Relative to a straight sided plume from a virtual source of buoyancy, the entrainment near the source is increased when $\Gamma < 1$ and decreased when $\Gamma > 1$.

Morton also discusses plumes in stably stratified environments. For these environments, it is found that the shape of the lower part of the plumes is similar to that predicted for a uniform

environment, whilst the upper part is similar to that of the model used in the previous paper [77]. Further analysis is conducted to find the dependence on rate of discharge of buoyancy, momentum and mass on the height of the plume top, since this depends critically on stratification.

For stratified environments, the use of Gaussian profiles is found to be unsatisfactory and therefore the Gaussian profiles are replaced for this section by 'top hat' profiles. This change of profile does not affect the height calculated for the plume top but it does modify the values of the entrainment and buoyancy constants used within the model.

Equations for plumes with 'top hat' profiles are derived and solutions to these equations are found for various plume scenarios. The effect on the maximum height reached by the plume is observed. For the limiting case of a plume arising from a source of buoyancy only, the non-dimensional maximum height reached is found to be $z_{max} = 2.805$, which is in good agreement with the equivalent plumes modelled in Morton *et al.* [77]. For the other limiting case of a plume arising purely from a source of momentum, the non-dimensional maximum height reached is found to be $z_{max} = 1.70$, and the spreading (i.e. the increase of radius as height increases) is much more rapid than that of a simple buoyant plume.

Of the various plume scenarios considered by Morton [78], the momentum-dominated plumes are likely to be the most relevant to the modelling of jet fires from high pressure pipelines. The accuracy of the model will be increased by including the effects of environmental stratification. However, over the heights typically observed for jet fires changes in air density will be small, especially in comparison to the density difference between the flame and the surroundings. It is therefore unlikely that environmental stratification will have a significant effect on the height or shape of a jet fire.

4.1.3 Turner [79]

Turner's [79] model focuses on the advancing front of a buoyant plume which is being established in a uniform, incompressible environment. Turner [79] models the motion near the advancing front of a vertical plume by suddenly emitting a buoyant fluid at a constant rate from a point source. This type of release has been shown to have some properties in common with a plume, whilst in other respects it behaves more like a 'thermal' released from rest. The author splits the 'starting' plume into two sections: the cap (which forms the advancing front) and the plume (which sits below and feeds into the cap).

The plume part of the model is the same as that for a steady plume in neutral surroundings presented in Morton *et al.* [77]. The cap is treated as a thermal and is modelled as a buoyant vortex ring which is growing, in part, by the turbulent entrainment of external fluid in an atmosphere at rest (i.e. no wind). The other source of the cap's growth is through fluid drawn up into the advancing vortex ring from the plume instead of the environment, adding extra buoyancy and momentum to the cap. The buoyancy distribution is therefore different from that of a typical thermal in uniform density surroundings, since the plume fluid is fed through the centre directly to the front of the cap. The link between the plume and the cap dynamics is therefore accounted for by this model.

Velocity and radial scales are defined and equations are derived describing the fluxes of buoyancy and momentum over a surface moving with the base of the cap. An equation is also described to determine momentum, mean radius and height of the surface as functions of time. These equations are solved to obtain a solution which is consistent both with the plume and vortex ring equations, and which relates the constants describing the behaviour of both parts of the flow. The various constants and ratios used within the model are determined experimentally.

As with the integral models described in Sections 4.1.1 and 4.1.2, the production of extra buoyancy through the release of latent heat (e.g. burning of fuel) is not accounted for by this model, and therefore it is not directly applicable to jet fires. However, like these other integral models reviewed, the Turner model [79] is still worth further examination as it considers the initial stages after release (as opposed to an established 'steady state' plume). The cap part of the model appears to be similar to the fireball that often precedes a jet fire, which is of particular interest when modelling a pipeline fireball and jet fire release.

4.1.4 Becker and Liang [4], Becker and Yamazaki [24]

Becker and Liang [4] and Becker and Yamazaki [24] note that the field of momentum flux density, $\bar{\rho}\bar{u}_z^2$, has a universal pattern in various forms of jet: cold jets, heated jets or flame jets. This field is therefore assumed to be fundamental in characterising properties such as jet spread. A characteristic jet radius, b (m), is defined as the jet radius at the point on the vertical axis, z, where the mean momentum flux density is equal to half the momentum density flux on the axis at the point. Equations for the jet characteristic radius, momentum flux density, mass flux and momentum flux crossing any z-plane are defined for well-developed turbulent forced-convection (i.e. momentum dominated) jets. This is the first of the integral models reviewed to specifically consider flame jets, making it particularly relevant for the modelling of jet fires from high pressure pipelines.

Typical values of the various coefficients used in these equations are calculated from experimental data and are listed in the paper.

The effects of buoyancy on a flame are considered in order to allow the whole range of flame behaviours to be modelled, from full forced convection to full natural convection. The change of regime is governed by the Richardson ratio, $Ri =$ buoyancy/input momentum flux. An expression for the flame buoyancy is derived and shown to approximate to a characteristic measure of $g\rho_\infty z^3$, where ρ_∞ is the ambient density (kg m^3). The majority of jet fires occurring from high pressure pipelines will be dominated by forced convection, especially near the point of release. However, they will also have some natural convection processes, which may become more significant after the initial stages of release and also towards the tip of the jet fire.

Equations for momentum flux density, mass flux and momentum flux are defined for non-purely forced convection flames, and values for the coefficients in the equations are determined experimentally. The coefficients are found to be dependent on the value of Ri for the flame being considered. This is due to factors such as the turbulence structure changing as the value of Ri increases.

4.1.5 Turner [80]

Unlike the earlier study by Turner [79], this paper by Turner [80] only considers established steady flows rather than the stage immediately after the flow has started. It is therefore likely to be most applicable to modelling jet fires from high pressure pipelines after the initial stages of release, once they a quasi-steady state has been reached. The author first sets about using similarity theory in order to demonstrate that for both jets and pure plumes, the mean rate of inflow across a circular boundary (i.e. entrainment) is inversely proportional to height and therefore proportional to the vertical velocity scale

The experimentally determined coefficient of proportionality (or 'entrainment rate') is found to be higher for plumes than it is for jets. The form of dependence on the integral flow properties will be the same in the transition regime between jets and plumes as it is for pure jets and pure plumes, even though there is some uncertainty about the entrainment and dilution rate. In practical

situations, the jet-like region is often small and the buoyancy-generated momentum will dominate above a certain height.

Studies of 'mixed' buoyant jets that have both momentum and buoyancy have shown that they rapidly become plume-like and the mean dilation rates are essentially the same as those observed in pure plumes (and are nearly three times those predicted for a jet).

The ratio, Φ_b, of the radial scale for a dynamic tracer (e.g. temperature), b_θ, to the radial velocity scale, b_u, is found to have nearly the same constant value, $b_\theta/b_u = \Phi_b = 1.2$, for both jets and plumes. The equations of conservation of mass, momentum and buoyancy are derived, using Gaussian profiles and the Boussinesq approximation.

Turner [80] notes that the 'entrainment rate' values are only indirectly related to the angle of spread of the velocity profile in jets and plumes. Thus the angles of spread are little different for jets and plumes, despite the fact that the 'entrainment rates' are substantially different.

Using a fixed value for the 'entrainment rate' will not make a large practical difference to the answer generated as the 'entrainment rate' is not sensitive in the calculations. Turner suggests that the 'entrainment rate' value for plumes is adopted. Relating entrainment to the mean velocity of the jet/plume, $\bar{u}_\mathrm{m}$, and therefore the largest scales of motion in a jet or plume, seems to be the physically most significant step. This assumption works well because the initial mechanism of entrainment is the engulfing of external fluid by large eddies at the edge of the jet or plume. The assumption of similarity means that these large eddies retain the same relation to the mean flow, whatever the scale of motion, and the level of energy at smaller scales is less important.

4.1.6 Cleaver and Edwards [81]

The models discussed in the previous sections have focused on vertical jets or plumes in still or stable conditions. In reality, the wind is likely to affect the rate of entrainment, direction, size and shape of the jet flame. In Cleaver and Edwards [81], an integral model for turbulent jets in a cross flow is developed and the results compared with experimental data. Equations describing the conservation of mass, horizontal and vertical momentum, energy and species are derived.

Additional algebraic relationships connect the values of several of the unknowns: bulk radius and velocity, and density and specific heat.

These relationships give nine equations in nine variables; if the entrainment rate is defined as a function of these variables, then the bulk properties of the jet can be calculated. If required, profiles of the variables in the model can be imposed to relate the centreline values or peak values to the bulk values. In this model, a cosine profile is adopted. The profile relationships are substituted into the integral definitions of the bulk mass, momentum, species and energy fluxes to give four non-linear equations that are solved to find the four unknowns.

The total entrainment is given as the algebraic sum of the various different entrainment mechanisms, which include the relative motion between the jet and the cross-flow, and entrainment due to the effects of atmospheric turbulence.

Values of the coefficients used within the model have been obtained from experimental data [82, 83]. The outputs of the model are compared with other experimental data over a wide range of conditions. Good agreement is shown for momentum dominated releases, either into free air or an atmospheric cross-flow, or in the near-field of buoyancy dominated releases into the atmosphere.

4.1.7 Cook [84] and Caulfield *et al.* [85]

Cook [84] uses a continuity equation formulated in terms of the total mass flux passing through the normal cross-section of a jet fire. This equation contains a term that represents entrainment in the near-field of the jet, where the initial momentum of the jet dominates the flow field, and entrainment is related to the turbulent viscosity. The equation also contains a term representing entrainment in the far-field of the jet where the effect of any cross-flow is assumed to dominate [84].

Cook [84] introduces a function to ensure that the far-field entrainment term is not fully effective until the flow field is dominated by the momentum of the entrained air rather than the source momentum of the jet. This function therefore prevents excessive entrainment of ambient air in the near-field. An empirical factor is also introduced to account for sonic and subsonic flows. The values assigned to this factor were chosen in order to optimise predictions of the model against experimental data [81].

Conservation of horizontal and vertical momentum equations are derived, with a spatially-averaged density term employed in the vertical momentum equation.

The jet radius is related to the prescribed radial profiles for velocity, mixture fraction and mixture fraction variance. Terminating cosine profiles are employed so that the velocity and all scalar variables approach ambient values at the outer edge of the jet.

An average jet radius is found to be more appropriate by Cook [84] for the far-field entrainment term and is defined by the same relationship used by Tamanini [86] for 'top-hat' profiles.

The mixture fraction is defined as the mass fraction of material in the mixture which originated in the fuel stream. Since mixture fraction is invariant to combustion, the conservation of species is satisfied if the total flux of mixture fraction is constant and equal to the source mass flux.

A turbulence model is required for evaluating the turbulent viscosity in one of the entrainment terms in the conservation of mass equation. This is also required to evaluate the mixture fraction variance used to define the probability density function (p.d.f.) required for the combustion sub-model. An integrated one-dimensional k-ε turbulence model is adopted. This model ignores the influence of any cross-flow on fine-scale turbulence, with the wind blown jet simply considered as a free axi-symmetric jet advected by the cross-flow. Comparisons between solutions of the complete model and results obtained from a three-dimensional, numerical model [87, 88], which included the influence of small scale atmospheric turbulence, demonstrated that significant errors were not introduced by adopting this assumption.

The model solves transport equations for turbulent kinetic energy, $\langle k \rangle$, and turbulent dissipation, $\langle \varepsilon \rangle$, and from these the spatially averaged turbulent viscosity is calculated. The values assigned to the various empirical constants used in the model were obtained from Cook [84].

A commonly adopted approach to the modelling of non-premixed turbulent reacting flows [84] is to assume fast chemistry, such that the chemical reactions associated with the high temperature oxidation of hydrocarbon fuels are assumed to have time scales that are short compared to those of the energy containing motions for turbulent transport. The instantaneous scalar fields can then be determined as unique non-linear functions of a conserved scalar, such as mixture fraction. Since these functions are highly non-linear, it is not possible to derive mean properties from temporal or spatial averages of the mixture field. Temporal fluctuations are therefore accounted for by prescribing a two-parameter probability density function (p.d.f.) for mixture fraction. The p.d.f. is

specified in terms of the density-weighted mean and variance of the mixture fraction obtained from solution of the modelled transport equations for these variables.

The spatially-averaged mixture fraction variance is evaluated by solving a transport equation, analogous to the integrated k-ε equations. This can be used to determine the centre-line mixture fraction variance.

Using the mixture fraction and the mixture fraction variance it is possible to construct the p.d.f, at any radial location within the flame. This p.d.f. is a density weighted function which allows the evaluation of both density-weighted and unweighted means. It is also used to determine the mean density of the jet.

Flame lift-off was included using an approach based on the empirical finding of Chakraverty *et al.* [89]. For flames in a quiescent environment, Chakraverty *et al.* found that turbulence time scales are approximately invariant at the base of lifted natural gas diffusion flames. Therefore, combustion is introduced at the downstream location where $\langle k \rangle / \langle \varepsilon \rangle > 5 \times 10^{-3}$ s. Properties in the lift-off region are evaluated assuming isothermal mixing, giving a linear relationship between mixture fraction and inverse density.

The prescribed radial profiles for velocity, mixture fraction and mixture fraction variance were found not to be representative in the core of the jet, leading to velocities greater than the initial source velocity and mixture fractions greater than unity. Therefore, values of velocity and mixture fraction are restricted to physically meaningful limits. The performance of the turbulence sub-model was also improved by introducing additional factors. The form of these factors was determined by comparing model predictions with experimental data and with predictions of a two-dimensional model for a free non-reacting jet.

In Caulfield *et al.* [85], a soot formation and consumption sub-model is introduced. The chemical relations that lead to soot formation and consumption in a flame are relatively slow compared to the timescales associated with the gas-phase reactions. Therefore the assumption that the sooting reactions go to completion as soon as the reactants are mixed cannot be used as the basis of a soot model. The approach must be modified in order to accommodate finite-rate kinetic effects.

The kinetic effects have been included in the overall model by using an extension to the laminar flamelet approach. This approach embodies a two-equation model for the evolution of soot mass fraction and particle number density. These equations contain terms that represent processes of nucleation, surface growth, oxidation and coagulation. The soot mass fraction and particle number density are then used to calculate the mean soot volume fraction.

Caulfield *et al.* [85] assess the usefulness of the complete model for predicting the consequences associated with accidental and operational releases of flammable gases by comparing model predictions with data obtained from both laboratory and field scale experiments [51, 71, 90, 91]. In all cases, predictions of the model were shown to be in good agreement with the available data.

4.1.8 Cleaver *et al.* [92]

A rupture of an underground pipeline will lead to the formation of a ground crater, which in turn significantly influences the nature of the gas release. This paper introduces a crater source sub-model which can be used in conjunction with the Cook [84] and Caulfield *et al.* [85] models described in Section 4.1.7. The following physical phenomena are incorporated into the source sub-model:

- Entrainment into the jets of gas before they impact on each other or the wall of the crater;
- Entrainment due to the jets interacting with each other and the walls of the crater; and
- Momentum loss from the jets to the crater walls during jet interaction.

The sub-model is formulated as a system of four equations. The first two of these equations represent the conservation of mass and momentum, assuming that all excess pressure in the pipeline is converted into momentum. The next two equations are equations of state, assuming ambient pressure and temperature at the crater exit plane, and a definition of mixture fraction, effectively the source gas mass fraction, respectively.

The conservation of mass equation contains a term that assumes that the entrainment into the jets before they impact each other is similar to that of a free jet. Entrainment is taken to be proportional to a representative surface area scale and an appropriate velocity scale, taking into account the ratio of densities of the source gas and atmosphere (similar to the models described in Section 4.1.7). The conservation of mass equation also contains a term that represents the entrainment due to the jets interacting with each other and the walls of the crater. It is formulated in the same way, except that the representative surface area scale is a function of the geometry of the crater, as well as pipeline conditions. The functional form of this entrainment term was determined by a combination of dimensional arguments and observations taken from a series of unpublished laboratory scale experiments.

The conservation of momentum equation contains a momentum loss term, which is derived by assuming that a constant fraction of the excess momentum emerging from the pipes is dissipated. The constant which determines the rate of dissipation of momentum was calibrated using the unpublished laboratory scale experimental data.

Having calculated the crater exit conditions by solving the system of four equations, a complete definition of the effective source is obtained by determining the initial direction of the flow leaving the crater. For aligned pipe ends in the absence of any wind, the angle of rotation with respect to the *x*-axis is taken to be dependent on the pressure imbalance between the two jets.

For the specific cases of balanced flow and a single ended release, the angle of tilt with respect to the z-axis is taken to be 0° and 90° respectively. For unbalanced releases, it is assumed that the angle of tilt depends on the relative pressure imbalance, the fracture length, and the crater wall angle. The value is taken from an empirical correlation fitted to the unpublished laboratory scale experimental data.

For wind-blown releases from aligned pipe ends, it is assumed that the air entrained into the crater carries with it a component of the momentum in the downwind direction. This causes a release to be tilted towards the downwind direction more than would be predicted by the correlations for the angles of rotation and tilt. To account for this effect, the initial direction in a wind-blown release is determined from the vector addition of a source vector representing the source conditions that would occur in the absence of the wind and an effective wind vector based on the atmospheric

conditions. The direction of the source vector is obtained from the correlations for the angles of rotation and tilt, with the magnitude being proportional to the initial momentum of the plume. The direction of the effective wind vector is the prescribed wind direction. The magnitude of the effective wind vector is taken to be proportional to the wind speed and the total mass of air entrained per unit length and time.

The crater source sub-model was used in conjunction with the models described in Section 4.1.7 in order to simulate the experiments conducted by Acton *et al.* [93]. Double-ended nominally balanced and unbalanced releases, and single ended releases were simulated with various different flow rates. The model consistently over-predicted the mean flame lengths by 50% to 60% and under-predicted the mean flame widths by 25% to 45%.

The predicted radiation from the flames was slightly closer to the observed values, and was generally within ±30%. This predicted radiation for the model is closer to the experimental data because the model predicts radiation emitted based on the calculated internal structure of the fire rather than assuming a distribution based on the calculated flame length. Some of the predicted radiation values were significantly over 30% higher than the observed values. It was noted by Cleaver *et al.* that this is because observations indicated that the fire was partially obscured by smoke from burning vegetation at the relevant positions and times.

For three of the four nominally balanced double-ended release simulations, the flame tilt was found to be slightly under-predicted. For the fourth nominally balanced double-ended release, the unbalanced double-ended release and the single-ended release simulations, the predicted source direction and orientation were found to be incompatible with observations. This is believed to be due to the crater source model under-predicting the amount of momentum loss in the crater and hence under-predicting the effects of the wind on the initial release direction downstream of the crater exit.

At times soon after the rupture, when the flows from the pipe ends are approximately balanced and the greatest hazard distances are usually produced, the sub-model's predictions are more reliable. At later times in the release, more complex flows are produced, such as unbalanced or single-ended releases, and more uncertainty is introduced. The authors argue that this uncertainty is not generally significant because, by this time, the fire has reduced significantly in size and the additional contribution to the overall thermal effects is small.

4.1.9 Leroy and Duplantier [94]

Leroy and Duplantier [94] present a one-dimensional axisymmetric model based on simplified fluid mechanics for predicting the flame shape and radiation field for large-scale gas or liquid release jet fires. This model is similar to those described by Cook [84] and Caulfield *et al.* [85] in Section 4.1.7, with equations derived for conservation of mass and momentum.

There are differences between the Leroy and Duplantier model and the Cook [84] and Caulfield *et al.* [85] models. Firstly, horizontally oriented releases are modelled rather than vertically oriented releases. Secondly, an equation representing the conservation of energy is derived based on the enthalpy of the flame. This equation contains a source term related to nominal heat release of the fuel and mass of the reacting gas, which in turn contains a parameter describing the combustion efficiency, χ_a. This approach is effectively a simplified version of the entrainment and combustion sub-models found in the models of Cook [84] and Caulfield *et al.* [85].

The jet axis is split into three regions and the combustion efficiency is varied according to region. In the first region, only a small amount of air is mixed with the fuel because of the high velocity of the jet, leading to limited development of turbulence. If the release is two-phase or liquid, then most of

the energy released in this region is through evaporation. These factors mean that the burning rate is low in the first region, and a low combustion efficiency value is assigned accordingly. In the second region, the gas entering is hot and the mixing is facilitated by developed turbulence and lower velocity. The mixture is better prepared for combustion and the combustion efficiency is close to unity. Finally, in the third region, although the temperature decreases due to the entrainment of air into the jet, buoyancy leads to efficient mixing and the value assigned to combustion efficiency remains high.

The three regions are identified based on a dimensionless variable, s/F_l, where s is the curvilinear axial co-ordinate (m) and F_l is the flame length (m). The first region is positioned as $s/F_l < 0.4$, the second region as $0.4 < s/F_l < 0.7$ and the third as $s/F_l > 0.7$.

The other terms in the conservation of energy equation represent energy consumption for heating non-reacting products, burned fuel products, and unburnt fuel respectively.

4.1.10 Cleaver and Halford [95]

The model developed in Cleaver and Halford [95] assumes that the impulsively started and immediately ignited flow following a pipeline rupture produces a growing 'cap' that sits on top of an underlying plume or 'stalk'. The 'cap' is highly transient and burns out as the 'stalk' is established to form a quasi-steady plume. The plume model of Turner [79] (Section 4.1.3) is extended to include combustion within the stalk and cap and also to include the effects of a crosswind. The Cleaver and Halford model uses the crater source model of Cleaver *et al.* [92] (Section 4.1.8) to describe the initial momentum and dilution of the flow emerging from the crater. It is assumed that the spherical cap entrains surrounding air as it rises and that fluid is also fed into the cap from the stalk below. By modelling all of these features and processes, this integral model theoretically provides the most realistic model of a jet fire from a buried high pressure pipeline.

The stalk is described by a simplified version of the integral model for a jet fire in a cross flow (Section 4.1.7). The equations for the conservation of mass and momentum are as follows:

$$\frac{d\dot{m}}{ds} = e_P \tag{84}$$

$$\frac{d\dot{M}_z}{ds} = \pi b^2 \rho g \frac{(\rho_\infty - \rho)}{\rho_\infty} \tag{85}$$

$$\frac{d\dot{M}_x}{ds} = e_P u_{\infty(z)} \cos \varphi_w \tag{86}$$

$$\frac{d\dot{M}_y}{ds} = e_P u_{\infty(z)} \sin \varphi_w \tag{87}$$

The location of the plume is given by:

$$\frac{dx}{ds} = \frac{u_x}{u} \quad , \qquad \frac{dy}{dt} = \frac{u_y}{u} \quad , \qquad \frac{dz}{dt} = \frac{u_z}{u} \tag{88}$$

where:

- x, y and z form a right handed Cartesian co-ordinate system, with origin at ground level over the centre of a crater that is formed by the release, with the *z*-axis pointing vertically upwards (m);

- e_P = rate at which air is entrained into the plume (kg s^{-1} m^{-1});
- $\dot{m}$ = mass flow rate (kg s^{-1});
- $\dot{M}$= momentum flux in the plume (N m^{-2});
- $\dot{M}_x, \dot{M}_y$ and $\dot{M}_z = x, y$ and z components of the momentum flux (N m^{-2});
- u = bulk velocity of the plume (m s^{-1});
- u_x, u_y and u_z = components of bulk velocity of the plume u (m s^{-1});
- s = curvilinear distance along the centreline of the flame/plume trajectory (m);
- b = bulk radius of the plume (m);
- ρ_∞ = ambient density of air (kg m^{-3});
- ρ = bulk density of the plume (kg m^{-3});
- g = acceleration due to gravity (m s^{-2});
- $u_{\infty(z)}$ = wind speed at height z (m s^{-1}); and
- φ_w = angle of the wind direction with respect to x-axis (º).

The rate at which air is entrained into the plume is given by:

$$e_P = e_{P1} + e_{P2} + e_{P3} \tag{89}$$

where e_{P1} is the air entrainment due to the momentum of the plume (kg s^{-1} m^{-1}), e_{P2} is the wind driven entrainment (kg s^{-1} m^{-1}) and e_{P3} is the air entrainment due to the effects of the crater (kg s^{-1} m^{-1}). The formulae for each of the entrainment terms are as follows:

$$e_{P1} = 2\pi b \alpha_{C_1} \rho_\infty \sqrt{\frac{\rho}{\rho_\infty}} \sqrt{\left| u^2 - u_{\infty(z)}^2 \cos\theta_f \left| \cos\theta_f \right| \right|} \tag{90}$$

$$e_{P2} = 2\pi b \beta \alpha_{C_2} \rho_\infty \sqrt{\frac{\rho}{\rho_\infty}} u_{\infty(z)} \left| \sin\theta_f \right| \tag{91}$$

$$e_{P3} = max\left(\frac{2\dot{m}_{Crater}}{f_l} (f_l - s), 0 \right) \tag{92}$$

where

$$\beta = min\left(1, \sqrt{\frac{(\dot{m} - \dot{m}_0) - u_{\infty(z)}}{\dot{M}_0}} \right) \tag{93}$$

and:

- $\theta_f =$ angle of the plume to the horizontal (º);
- $\alpha_{C_1} =$ numerical constant with value 0.07;
- $\alpha_{C_2} =$ numerical constant with value 0.7;
- $f_l =$ length of fracture in pipeline (m);
- $\dot{m}_0 =$ initial mass flow rate (kg s^{-1});
- $\dot{M}_0 =$ initial momentum flux (N m^{-2}); and
- $\dot{m}_{Crater}$ = mass of air entrained from the crater (kg s^{-1}).

Turner [80] quotes values of $\alpha_{C_1} = 0.05$ for pure jets and $\alpha_{C_1} = 0.08$ for pure plumes. The value of 0.07 quoted in Cleaver and Halford for α_{C_1} for stalks that have both jet and plume qualities (i.e. momentum and buoyancy) therefore seems reasonable.

A simple combustion model is used to calculate the rate at which the fuel burns, and other quantities such as the mass fractions of air, fuel and combustion products, and the bulk temperature. The composition of the stalk is calculated using the following equations:

$$\frac{\mathrm{d}\left(\mathrm{F}_f \dot{m}\right)}{\mathrm{ds}} = -\mathrm{SB} \tag{94}$$

$$\frac{d(F_\infty \dot{m})}{ds} = e_P - B \tag{95}$$

$$\frac{d\left(F_p \dot{m}\right)}{ds} = (1 + S)B \tag{96}$$

where:

- F_∞, F_f and $F_p =$ mixture fractions, or mass fractions, of air, fuel and combustion products respectively;
- $S =$ mass stoichiometric fuel to air ratio; and
- $B =$ rate at which air in the stalk is consumed in the combustion process, and is given by:

$$B = \lambda(e_{P1} + e_{P2}) + \lambda_{Crater} e_{P3} \tag{97}$$

λ is a parameter that describes the effectiveness of the eddies in mixing the air entrained into the jet and the fuel in the jet. It is defined as the ratio of the advection timescale of the flow to the turbulent diffusion timescale across the flow, that is:

$$\lambda = \frac{t_a}{t_d} \tag{98}$$

where:

$$t_a = \int \frac{1}{u} ds \tag{99}$$

$$t_d = \frac{b}{\chi} \tag{100}$$

where $\chi = 0.14u$ is a measure of the rate of mixing of air across the stalk. Note that this is the equivalent of Leroy and Duplantier's [94] 'combustion efficiency' parameter, which could potentially be used instead of the above.

λ_{Crater} is a parameter that describes how effectively the air entrained into the jet in the crater is mixed with the fuel. This mixing is assumed to occur more rapidly in the crater than the mixing in the jet, so λ_{Crater} has a larger value than λ. The choice $\lambda_{Crater} = 0.7$ was found by Cleaver and Halford [95] to give a good fit to experimental data.

As the fuel burns, the plume becomes hotter, the enthalpy flux of the mixture in the stalk is:

$$\frac{d(H_P \dot{m})}{ds} = e_p H_\infty + BS\Delta H_c(1 - F_{rad}) \tag{101}$$

where:

- $H_\infty =$ specific enthalpy of air at ambient temperature (J kg^{-1});
- H_P = specific enthalpy of the plume (J kg^{-1});
- $\Delta H_c =$ heat of combustion (J kg^{-1}); and
- F_{rad} = fraction of the heat of combustion that is radiated externally, and depends on the mass flow rate and the wind speed:

$$F_{rad} = min\left(0.5, \dot{m}_0^{-1/6}\right)\left(0.28 + 0.31e^{(-0.2u_{\infty(10)})}\right) \tag{102}$$

with an imposed lower limit of F_{rad}= 0.07 and an upper limit of F_{rad}= 0.35. The term $u_{\infty(10)}$ (m s^{-1}) is the reference wind speed at 10 m elevation.

Assuming the specific heat capacities of the fuels remain constant over the temperature range of interest, and that changes in temperature of ambient air with height are negligible compared with temperature differences between the jet fire and the ambient air, Equation 101 can be integrated to give:

$$H_P \dot{m} = H_\infty \left(F_\infty + \frac{1}{1+S}F_p\right)\dot{m} + H_{F0}\left(F_f + \frac{S}{1+S}F_p\right)\dot{m} + \frac{S}{1+S}F_p \dot{m}\Delta H_c(1 - F_{rad}) \tag{103}$$

where H_{F0} is the specific enthalpy of the fuel at release conditions (J kg^{-1}).

These assumptions allow other parameters needed in the fluid flow equations to be calculated directly. The specific heat capacity of the stalk can be calculated from its composition:

$$c = F_\infty c_\infty + F_f c_f + F_p c_p \tag{104}$$

where c is the specific heat capacity of the bulk mixture in the plume (J kg^{-1} K^{-1}), and c_∞, c_f and c_p are the specific heat capacities of air, fuel and combustion products (J kg^{-1} K^{-1}).

The bulk temperature of the stalk, T_f (K), is calculated from the enthalpy, using:

$$T_f = \frac{H_P}{c} \tag{105}$$

Hence, the mean bulk density of the stalk, $\bar{\rho}$ (kg m^{-3}), needed by the fluid flow model, can be calculated from:

$$\frac{1}{\bar{\rho}} = \frac{F_\infty}{\rho_\infty} + \frac{F_f}{\rho_f} + \frac{F_p}{\rho_p} \tag{106}$$

where ρ_∞, ρ_f and ρ_p are the densities (kg m^{-3}) of the air, fuel and combustion products at the bulk temperature of the plume respectively, which can be calculated from their molecular weights, as follows:

$$\rho_\infty = \frac{P_{atm} MW_\infty}{RT_f}, \quad \rho_f = \frac{P_{atm} MW_f}{RT_f} \text{ and } \rho_p = \frac{P_{atm} MW_p}{RT_f} \tag{107}$$

where:

- MW_∞, MW_f and MW_p = molecular weights of air, fuel and combustion productions respectively (kg mol^{-1});
- P_{atm} = atmospheric pressure (Pa); and
- R = gas constant (J mol^{-1} K^{-1}).

4.1.11 Summary of integral flame length models

The integral model for purely buoyant plumes derived by Morton *et al.* [77] forms the basis for all of the subsequent integral models reviewed. Initially this model is adapted so that it can be applied to either buoyancy or momentum dominated plumes/jets [78]. Values for a number of constants introduced into the models are experimentally determined for both the buoyancy and momentum limiting cases, as described in [78], [4], [24] and [11]. However, models that just focus on these limiting cases are unlikely to be suitable for use within MISHAP as the jet fires modelled are likely to contain varying elements of buoyancy and momentum depending on the exact release conditions under consideration.

Adaptations to the models are also made in order to account for the effects of density stratification in the surrounding environment [80]. However, none of the models reviewed have considered the effect that combustion within the plume or jet will have on its density. These density differences are

likely to have a far more significant effect on the plume or jet behaviour than those arising from stratification of the ambient environment.

Turner [79] introduces modifications to the Morton *et al.* model [77] that enable the modelling of the initial stages immediately after a release. A 'cap' (or fireball in the case of an ignited release) rises up from ground level followed by a 'stalk' (plume). The cap eventually dissipates leaving behind the full developed quasi-steady state stalk, which will be similar to the plumes predicted by the earlier Morton *et al.* [77] and Morton [78] models. The Turner model [79] is more detailed than these previous models (and those currently used within MISHAP), and can potentially provide a much more accurate prediction of jet fire properties, such as radiation emitted, during the initial stages of a release.

Many of the later models reviewed include the effects of both combustion and crosswinds on the plume/jet dynamics and also account for lift-off height of the jet fire, as described in [81], [84] and [85]. However, none of these models incorporate Turner's [78] 'cap and stalk' model for the initial stages after release and assume that a quasi-steady state is instantly reached.

Cleaver and Halford's model [95] combines the Turner 'cap and stalk' model [79] with a combustion model. Although the focus of Turner's 'cap and stalk' model is the initial stages of a pipeline release, Cleaver and Halford's model is not necessarily only applicable to the initial stages of a release. The effect of a crosswind on entrainment of ambient air into the jet fire and on its angle of tilt are also included within the model. Many of the parameters used within the model implicitly account for the balance of buoyancy and momentum forces, whilst the values used for some of the constants represent the mid-point between those used for the purely buoyant and purely momentum-driven limiting cases.

A sub-model that attempts to model the additional air that can be entrained into the jet fire from the crater that is created when an underground pipeline ruptures [92] is also included within Cleaver and Halford's model [95]. The results produced by this sub-model have been shown to over-predict flame lengths and under-predict flame widths by about 50%. The major advantage integral models have over empirical models is that, by including all the relevant sub-models, a single model can potentially be adapted in order to be applicable to all release conditions modelled by MISHAP, rather than having to use a combination of several different empirical correlations.

4.2 INTEGRAL FLAME LIFT-OFF MODELS

4.2.1 Cook *et al.* [71]

Cook *et al.* [71] measure the lift-off distance up to the base of the luminous flame envelope (i.e. where it becomes yellow), as they argue that the infra-red radiation from the preceding blue zone is insignificant.

A method of predicting the distance to the luminous zone is developed by assuming that this distance is a function of the residence time of a gas pocket in the initial non-reacting region of a jet fire and in the non-luminous, combusting region. This residence time is then assumed to determine the distance taken for the gas pocket to produce significant amounts of soot and hence become luminous.

The calculation of residence times requires knowledge of the velocity decay along the centreline of a jet. However, the authors were unable to obtain such data for field scale jet fires, so instead utilised results of a laboratory scale study of high pressure air jets, as described in Birch *et al.* [41].

Birch *et al.* were able to correlate axial velocity decay in the fully developed self-similar region of both subsonic and sonic, under-expanded jets using the following relationship:

$$\frac{u_{ax}}{u_s} = \frac{k_s}{(s/d_s) - \Omega} \tag{108}$$

where:

- k_s = a decay constant;
- Ω = virtual origin parameter;
- s = curvilinear distance along the centreline of the flame/plume trajectory (m);
- d_s = source diameter (m);
- u_{ax} = local axial velocity (m s^{-1}); and
- u_s = source exit velocity (m s^{-1}).

The decay constant, k_S, and the virtual origin parameter, Ω, were found by Birch *et al.* to be constant for subsonic jets, but to be functions of the jet stagnation or driving pressure for sonic flows. Equation 108 was assumed to apply at all points downstream of the potential core of a jet, the latter region being defined as the zone where the local velocity, u_{ax}, has not decayed below the source exit velocity, u_s. The length of the potential core, s_{pc}, was calculated by solving Equation 108 for s by equating u_{ax} to u_s. Values of k_s and Ω were obtained from data within Birch *et al.* [41].

The residence time of a gas pocket traversing the lower regions of a jet fire via an axial path was calculated by integrating the inverse of the axial velocity between the release point, $s = 0$, and the base of the luminous zone, s_l, according to:

$$t = \int_0^{s_l} ds/u_{ax} = \frac{s_{pc}}{u_s} + \int_{s_{pc}}^{s_l} \frac{(s/d_s) - \Omega}{k_s u_s} ds \tag{109}$$

This equation is used to calculate the time to the luminous zone from measured values of s_l for all the jet fires examined in the field scale experiments. The resulting residence times were found not to exhibit a strong dependence on any parameter, so an average value of $t = 0.037$s was taken as uniquely defining the time taken to reach the luminous zone in natural gas jets. Equation 109 is solved and re-arranged as a quadratic in s_l, the upper root of which can be equated to the distance to the luminous zone:

$$\frac{s_l^2}{2d_s k_s u_s} - \frac{\Omega s_l}{k_s u_s} + \left[\frac{s_{pc}}{u_s}\left(1 + \frac{\Omega}{k_s} - \frac{s_{pc}}{2d_s k_s}\right) - t\right] = 0 \tag{110}$$

This equation was applied, with $t = 0.037$s, to the conditions of the field scale experiments and the predictions were found to agree reasonably well with the experimental measurements.

The method described above was also applied to the laboratory scale measurements on wind-blown propane flames reported by Gollahalli *et al.* [96]. For those flames with a velocity ratio $u_s/u_\infty > 20$, approximately equivalent to the field scale data, a value of $t = 0.016$s for propane was derived from Equation 109. Equation 110 was subsequently used to predict values of s_l with reasonable success.

5 CONCLUSIONS

HSE use jet fire models within their MISHAP software to model the consequences of releases of flammable gases. There are currently two models that are used; one for releases of natural gas, and another for releases for other substances modelled within MISHAP. The model used for releases of natural gas is a simple model introduced many years ago that was limited by the computational power available at the time [2]. The model is unable to model the effects of wind or angle of tilt or release on flame length and trajectory.

Both of the existing models within MISHAP assume that a fireball has already dissipated (i.e. they do not model the early stages of a release). MISHAP currently models the jet fire and fireball that may form following a release separately. In reality, the jet fire will initially feed fuel into the fireball as it rises from ground level, the fireball will then burn out while the jet fire continues to burn for a longer time period.

An extensive literature review of the various models available for predicting the flame length and lift-off for jet fires has been conducted. Being able to accurately model these dimensions is important as these parameters will have a significant effect on the amount of radiation emitted by the jet fire. The types of model reviewed fall into two broad categories: empirical and integral. Empirical models offer the advantages of simplicity and are computationally inexpensive; while the advantages of the more complex integral models are that they can include sub-models of important physical and chemical processes and can be applied to a wider range of release scenarios.

The majority of the empirical models reviewed are based on data from small scale experiments and are often only applicable to one type of fuel. Although several of the empirical models use non-dimensional parameters, it is unclear how accurate these models would be when applied to large scale data. For the range of fuels and wide variety of release conditions that can be modelled within MISHAP, it seems unlikely that just one of the empirical models reviewed would be capable of accurately modelling all of the possible jet fire scenarios. Therefore different empirical models would have to be used depending on the exact release conditions being modelled, which could potentially lead to inconsistences in the outputs.

The integral models reviewed are based on solutions of fluid dynamics equations and some include combustion sub-models, making them particularly relevant to jet fires. The two and three dimensional partial differential fluid dynamics equations that underpin them are reduced to one-dimensional ordinary differential equations by assuming self-similarity within the flow-field. These integral models therefore offer the potential for development as predictive tools that can be applied to a wide range of release scenarios, but which have relatively short run times making them ideal for routine use.

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7 APPENDIX A – TABLE OF EMPIRICAL FLAME LENGTH MODELS

Table 1 Summary of empirical flame length models

Author(s)	*Correlation*	*Fuel*	*Flame orientation*	*Buoyancy/ momentum dominated flames*	*Sonic/ subsonic release*	*Single phase/ two-phase fuel*	*Scale of data*	*Wind*	*Flame tilt*	*Notes*
Sønju and Hustad [7]	$h_f/d_s = 27Fr^{0.2}$	Propane	Vertical	Buoyancy and momentum	Sonic and subsonic	Single phase	Large and small scale	No	No	Only valid for $Fr < 5$
	$h_f/d_s = 21Fr^{0.2}$	Methane	Vertical	Buoyancy and momentum	Sonic and subsonic	Single phase	Large and small scale	No	No	Only valid for $Fr < 5$
Suris *et al.* [8]	$h_f/d_s = 40Fr^{0.2}$	Propane	Vertical	Buoyancy and momentum	Sonic and subsonic	Single phase	Large and small scale	No	No	Only valid for $Fr < 3$
	$h_f/d_s = 29Fr^{0.2}$	Methane	Vertical	Buoyancy and momentum	Sonic and subsonic	Single phase	Large and small scale	No	No	Only valid for $Fr < 3$
Delichatsios [9, 10]	$\frac{h_f}{d_s} = 12.52\ {Fr_{f(\dot{Q})}}^{2/5}$	Methane	Vertical	Buoyancy	Subsonic	Single phase	Small scale	No	No	Only valid for $Fr_{f(\dot{Q})} > 2$
	$\frac{h_f}{(S+1)d_s\sqrt{\rho_s/\rho_\infty}} = \frac{13.5Fr_{f(u)}^{2/5}}{\left(1+0.07Fr_{f(u)}^2\right)^{1/5}}$	Methane propane ethylene hydrogen	Vertical	Momentum and Buoyancy-momentum transition	Sonic and subsonic	Single phase	Small scale	No	No	Only valid for $Fr_{f(u)} > 3$

Author(s)	***Correlation***	***Fuel***	***Flame orientation***	***Buoyancy/ momentum dominated flames***	***Sonic/ subsonic release***	***Single phase/ two-phase fuel***	***Scale of data***	***Wind***	***Flame tilt***	***Notes***
Leahey and Schroeder [13]	$\frac{h_f}{d_s} = \frac{5}{0.4 + 1.2U}\left(\frac{1}{\tau\Phi_u}\right)^{1/2}$	Methane propane butane ethylene	Vertical	Momentum	-	Single phase	Large and small	Yes	Yes	-
Crocker and Napier [14]	$\frac{h_f - s_l}{d_s} = \frac{5.3}{S_{mol}}\sqrt{\frac{T_f}{S_p T_s}\left[S_{mol} - (1 - S_{mol})\frac{MW_\infty}{MW_s}\right]}$	LPG	Vertical	Momentum	-	-	Small scale	No	No	-
Blake and McDonald, Blake and Coté [20, 21, 22]	$\frac{L_f}{d_f^*} = 6.0\left(Fr_\rho\right)^{0.2}$	Methane propane, ethylene hydrogen	Vertical and horizontal	Buoyancy and momentum	Sonic and subsonic	Single phase	Small scale	No	No	Only valid for $Fr < 10$
	$\frac{L_f}{d_f^*} = 11$	Methane propane, ethylene hydrogen	Vertical and horizontal	Momentum	Sonic and subsonic	Single phase	Small scale	No	No	Only valid for $Fr > 10$
Heskestad [28, 29, 30, 31, 32]	$\bar{h}_f / d_s = -1.02 + 15.6N^{1/5}$	Methane	Vertical	Buoyancy	Subsonic	Single phase	Small scale	No	No	Only valid for $N < 10^5$
Cowley and Johnson [36]	$L_f = 2.76Q^{0.452}$	Methane	Vertical	Buoyancy and momentum	Subsonic	Single phase	Large scale	No	No	-
	$L_f = 1.422Q^{0.457}$	Methane	Vertical	Momentum	Sonic	Single phase	Large scale	No	No	-
	$L_f = 18.5\dot{m}^{0.41}$	-	-	-	-	-	-	-	-	-

Author(s)	*Correlation*	*Fuel*	*Flame orientation*	*Buoyancy/ momentum dominated flames*	*Sonic/ subsonic release*	*Single phase/ two-phase fuel*	*Scale of data*	*Wind*	*Flame tilt*	*Notes*
	$L_f = s_l + 200d_e$	Methane	Vertical	Buoyancy and momentum	Sonic and subsonic	Single phase	Large scale	No	No	-
	$L_f = 1.555Q^{0.467}$	Methane	Horizontal	Buoyancy and momentum	N/A	Single phase	Large scale	Yes	Yes	-
Newman and Wieczorek [44]	$\frac{h_{f_c}}{d_s} = 4.0(Q^*)^{2/5}$	Propane	Vertical	Buoyancy	-	-	Small scale	No	No	Only valid for $1 < Q^* < 450$
Santos and Costa [47]	$\frac{L_{vis}}{d_s} = 36Fr^{1/5}$	Propane	Vertical	Buoyancy	-	-	Small scale	No	No	Only valid for $Fr < 2 \times 10^4$
	$L_{vis}/d_s \approx 242$	Propane	Vertical	Momentum	-	-	Small scale	No	No	Only valid for $Fr > 2 \times 10^4$
	$\frac{L_{vis}}{d_s} = 24Fr^{1/5}$	Ethylene	Vertical	Buoyancy	-	-	Small scale	No	No	Only valid for $Fr < 8 \times 10^4$
	$L_{vis}/d_s \approx 226$	Ethylene	Vertical	Momentum	-	-	Small scale	No	No	Only valid for $Fr > 8 \times 10^4$
Lowesmith *et al.* [50]	$L_f = 2.8893Q^{0.3728}$	Methane propane butane crude oil	Vertical	Buoyancy and momentum	-	Single and two-phase releases	Large scale	No	No	-
Kiran and Mishra [55]	$\frac{L_{vis}}{d_s} = 30Fr^{1/5}$	LPG	Vertical	Buoyancy	-	-	Small scale	No	No	Only valid for $Fr < 10$
	$L_{vis}/d_s \approx 269$	LPG	Vertical	Momentum	-	-	Small scale	No	No	Only valid for $Fr > 4.5 \times 10^4$

Author(s)	***Correlation***	***Fuel***	***Flame orientation***	***Buoyancy/ momentum dominated flames***	***Sonic/ subsonic release***	***Single phase/ two-phase fuel***	***Scale of data***	***Wind***	***Flame tilt***	***Notes***
Studer *et al.* [56]	$\frac{L_{vis}}{d_s} = 420P^{0.47}$	Methane/ Hydrogen	Horizontal	Momentum	-	Single phase	Large scale	No	No	-
	$L_{vis} = 0.0016Q^{1/2}$	Methane/ Hydrogen	Horizontal	Momentum	-	Single phase	Large scale	No	No	-
Gómez-Mares *et al.* [59]	$L_{vis} = 0.0562Q^{0.4819}$	Propane	Vertical	Momentum	Sonic	Single phase	Large scale	No	No	-
Palacios and Casal [62, 63]	$L_{vis}/d_s = 6.73Re^{0.27}$	Propane	Vertical	-	Sonic and subsonic	-	Large scale	No	No	-
	$L_{vis}/d_s = Re^{0.4}$	Propane	Vertical	-	Sonic and subsonic	-	Large scale	No	No	-
Molokov and Saffers [64]	$L_f/d_s = 1403[(\rho_s/\rho_\infty)(u_s/c_s)^3]^{0.196}$	Hydrogen	Vertical	Buoyancy	Subsonic	Single phase	Small scale	No	No	Only valid for $(\rho_s/\rho_\infty)(u_s/c_s)^3 < 0.0001$
	$L_f/d_s = 230$	Hydrogen	Vertical	Momentum	Subsonic	Single phase	Small scale	No	No	Only valid for $0.0001 < (\rho_s/\rho_\infty)(u_s/c_s)^3 < 0.07$
	$L_f/d_s = 805[(\rho_s/\rho_\infty)(u_s/c_s)^3]^{0.47}$	Hydrogen	Vertical	Momentum	Sonic	Single phase	Small scale	No	No	Only valid for $(\rho_s/\rho_\infty)(u_s/c_s)^3 > 0.07$
Bradley *et al.* [66]	$\frac{h_f}{d_s} = 3.4Q^{*\frac{2}{5}} - 0.6$	Acetylene butane ethylene hydrogen methane propane	Horizontal and vertical	Buoyancy and momentum	Subsonic	-	Large and small scale	Yes $< 2\ m\ s^{-1}$	-	Only valid for $Q^{*\frac{2}{5}} < 100$

Author(s)	*Correlation*	*Fuel*	*Flame orientation*	*Buoyancy/ momentum dominated flames*	*Sonic/ subsonic release*	*Single phase/ two-phase fuel*	*Scale of data*	*Wind*	*Flame tilt*	*Notes*
	$\frac{h_f}{d_s} = 1.9Q^{*\frac{2}{5}}$	Acetylene butane ethylene hydrogen methane propane	Horizontal and vertical	Buoyancy and momentum	Sonic	-	Large and small scale	Yes $< 2\ m\ s^{-1}$	-	Only valid for $Q^{*\frac{2}{5}} > 100$

8 APPENDIX B – TABLE OF EMPIRICAL FLAME LIFT-OFF MODELS

Table 2 Summary of empirical flame lift-off models

Author(s)	***Correlation***	***Fuel***	***Release/ Flame regime***	***Notes***
Hawthorne *et al.* [15]	$\frac{L_f - s_l}{d_s} = \frac{5.3}{S_{mol}}\sqrt{\frac{T_{ad}}{S_p T_s}\left[S_{mol} + (1 - S_{mol})\frac{MW_\infty}{MW_s}\right]}$	-	Subsonic	-
Ricou and Spalding [33]	$s_l = 0.141\left(\dot{M}\rho_\infty\right)^{\frac{1}{2}}$	Methane	Sonic and subsonic	-
Sønju and Hustad [7]	$s_l/d_s = 3.6 \times 10^{-3}(d_s/u_s)^{-1}$	Methane propane	Subsonic	Valid for $10^1 <\approx Fr <\approx 10^5$
Schuller *et al.* [69]	$s_l = 0.16{d_s}^{1/2}u_s$	Propane	Subsonic	-
Kalghatgi [5]	$\left(\frac{s_l\, u_{lam}}{v_s}\right) = \alpha_K\left(\frac{u_s}{u_{lam}}\right)(\rho^*)^{1.5}$	Methane propane ethylene hydrogen	Sonic and subsonic	Valid for $0.5 < \bar{\rho} < 2$
Sugawa and Sakai [72]	$\frac{s_l}{d_s} = 0.0139{Q^*}^{\frac{3}{5}}$	Propane	-	-
Santos and Costa [47]	$\frac{s_l}{d_s} = 2.6 \times 10^{-3}\left(\frac{u_s}{d_s}\right)$	Propane	Buoyancy	-
	$\frac{s_l}{d_s} = 0.8 \times 10^{-3}\left(\frac{u_s}{d_s}\right)$	Ethylene	Buoyancy	-
Kiran and Mishra [55]	$\frac{s_l}{d_s} = 1.8 \times 10^{-3}\left(\frac{u_s}{d_s}\right)$	LPG	-	-
Bradley *et al.* [66]	$\left(\frac{s_l\, u_{lam}}{v_s}\right) = 52.4\left[\left(\frac{u_s}{u_{lam}}\right)\left(\frac{\rho_s}{\rho_\infty}\right) - 11.8\right]^{1.04}$	Acetylene butane ethylene hydrogen methane propane	Sonic and subsonic	-

9 APPENDIX C – TABLE OF INTEGRAL MODELS

Table 3 Summary of integral jet fire models

Author(s)	*Buoyancy/ momentum dominated releases*	*Orientation of release*	*'Cap and stalk' model*	*Combustion model*	*Initial stages of release or quasi steady state*	*Cross flow/wind*	*Turbulence model*	*Flame lift-off*	*Soot model*	*Crater model*	*Notes*
Morton *et al.* [77]	Buoyancy	Vertical	No	No	Quasi steady state	No	No	No	No	No	-
Morton [78]	Momentum and buoyancy	Vertical	No	No	Quasi steady state	No	No	No	No	No	-
Turner [79]	Buoyancy	Vertical	Yes	No	Initial stages	No	No	No	No	No	-
Becker and Liang [4] and Becker and Yamazaki [24]	Momentum and buoyancy	Vertical	No	Yes	Quasi steady state	No	No	No	No	No	-
Turner [80]	Momentum and buoyancy	Vertical	No	No	Quasi steady state	No	No	No	No	No	-
Cleaver and Edwards [81]	Momentum and buoyancy	Vertical	No	No	Quasi steady state	Yes	No	No	No	No	-
Cook [84] and Caulfield *et al.* [85]	Momentum and buoyancy	Vertical	No	Yes	Quasi steady state	Yes	Yes	Yes	Yes	No	-
Cleaver *et al.* [92]	Momentum and buoyancy	Vertical	N/A	N/A	Initial stages and quasi steady state	Yes	N/A	N/A	N/A	Yes	Crater model only
Leroy and Duplantier [94]	Momentum and buoyancy	Horizontal	No	Yes	Quasi steady state	Yes	No	Yes	No	No	-
Cleaver and Halford [95]	Momentum and buoyancy	Vertical	Yes	Yes	Initial stages	Yes	No	No	Yes	Yes	-
Cook *et al.* [71]	Momentum and buoyancy	Vertical	N/A	Yes	Quasi steady state	Yes	No	Yes	Yes	No	Flame lift-off model only

10 GLOSSARY

b = plume/jet radius (m)

b_u = radial velocity scale

b_θ = radial scale for a dynamic tracer

B = rate at which air in the jet is consumed in the combustion process (kg s^{-1} m^{-1})

c = specific heat capacity (kJ kg^{-1} K^{-1})

c_∞ = specific heat capacity of air (kJ kg^{-1} K^{-1})

c_f = specific heat capacity of fuel (J kg^{-1} K^{-1})

c_p = specific heat capacity of combustion products (J kg^{-1} K^{-1})

c_s = speed of sound at conditions of gas in the nozzle (m s^{-1})

d_e= effective source diameter (m)

d_f = flame diameter (m)

d_f^* = theoretical lateral dimension of flame (m)

d_s = source diameter (m)

e_P = rate at which air is entrained into the plume (kg s^{-1} m^{-1})

e_{P1} = air entrainment due to the momentum of the plume (kg s^{-1} m^{-1})

e_{P2} = wind driven entrainment (kg s^{-1} m^{-1})

e_{P3} = air entrainment due to the effects of the crater (kg s^{-1} m^{-1})

F_∞, F_f and F_p = mixture fractions, or mass fractions, of air, fuel and combustion products respectively

F_{rad} = fraction of the heat of combustion that is radiated externally, and depends on the mass flow rate and the wind speed

Fr = Froude number based on the nozzle exit diameter

$Fr_{f(u)}$ = fire Froude number (release velocity-based [10, 56])

$Fr_{f(\dot{Q})}$ = fire Froude number (heat release rate-based [9])

Fr_ρ = density-weighted Froude number

g = acceleration due to gravity (m s^{-2})

h_f = flame height (measured from nozzle exit to flame tip) (m)

$\bar{h}_f$ = mean flame height (m)

h_{f_c} = chemical flame height (m)

ΔH_c = heat of combustion (kJ kg^{-1})

H_{F0} =specific enthalpy of the fuel at release conditions (J kg^{-1})

H_P = specific enthalpy of the plume (J kg^{-1});

H_∞ = specific enthalpy of air at ambient temperature

k_s = decay constant

K = constant based on angle of tilt and angle between hole axis and flame

L^* = non-dimensional length of jet fire

L_f = flame length (m)

L_{f_w} = flame length in windy conditions (m)

L_{f_0} = flame length in still air (m)

L_{vis} = visible flame length (m), defined as the distance from the base of the lifted flame to the flame tip (i.e. not including lift-off height)

f_l = length of fracture in pipeline (m)

$\dot{m}$ = mass flow rate (kg s^{-1})

$\dot{m}_0$ = initial mass flow rate (kg s^{-1})

$\dot{m}_{Crater}$ = mass of air entrained from the crater (kg s^{-1})

M = momentum of the source jet (N)

$\dot{M}$ = momentum flux (N m^{-2})

$\dot{M}_x, \dot{M}_y$ and $\dot{M}_z$ = x, y and z components of the momentum flux (N m^{-2})

$\dot{M}_0$ = initial momentum flux (N m^{-2})

MW_∞ = molecular weight of air (g mol^{-1})

MW_f = molecular weight of fuel (g mol^{-1})

MW_p = molecular weight of combustion products (g mol^{-1})

MW_s = molecular weight of nozzle fluid (g mol^{-1})

N = non-dimensional group [32]

P = pressure (Pa)

P_{atm} = atmospheric pressure (Pa)

Q = net heat released by combustion (MW)

Q^* = fire Froude number/dimensionless heat release rate [44]

R = gas constant (J mol^{-1} K^{-1})

Re = Reynolds number

Ri = Richardson ratio

s_l = flame lift-off distance (m)

s = curvilinear distance along the centreline of the flame/plume trajectory (m)

s_{pc} = length of potential core (m)

S = mass stoichiometric fuel to air ratio

S_f = mass fraction of fuel in a stoichiometric mixture

S_v = stoichiometric mixing ratio (% by volume)

S_{mol} = molar fraction of fuel in a stoichiometric mixture with air

S_p = ratio of reactant moles to product mole in a stoichiometric mixture

T_∞ = ambient air temperature (K)

T_f = flame temperature (K)

$\overline{\Delta T_f}$ = mean peak flame temperature rise (K)

T_{ad} = adiabatic flame temperature (K)

T_S = temperature of fluid in the nozzle (K)

t_a = advection timescale of the flow

t_d = turbulent diffusion timescale across the flow

u = bulk velocity of the plume (m s^{-1})

u_{ax} = local axial velocity (m s^{-1})

u_e = expanded jet velocity (m s^{-1})

u_{lam} = maximum laminar burning velocity (m s^{-1})

$\bar{u}_m$ = mean plume velocity (m s^{-1})

u_s = source exit velocity (m s^{-1})

$\bar{u}_s^*$ = non-dimensional velocity

u_x, u_y and u_z = components of bulk velocity of the plume u (m s^{-1})

u(z) = plume velocity at height *z*

$u_{\infty(z)}$ = wind speed at height z (m s^{-1})

$u_{\infty(10)}$= reference wind speed at 10 m elevation (m s^{-1})

u_{∞}= wind speed (m s^{-1})

x, y and z = right handed Cartesian co-ordinate system, with origin at ground level and z-axis pointing vertically upwards (m)

x_f = downwind extent of flame (m)

z_{max} = maximum height reached by the plume (m)

α_{C_1} = numerical constant [95]

α_{C_2} = numerical constant [95]

α_{ent} = numerical entrainment constant

α_H = numerical constant (s) [7]

α_K = numerical constant [5]

α_S = numerical constant [47]

β =entrainment function [95]

Γ = non-dimensional parameter that describes a plume in terms of its initial momentum, buoyancy and mass flow [78]

θ_b = angle between the hole axis and the line joining the tip of the flame to the centre of the hole plane (º)

θ_f = angle of the flame/plume to the horizontal (º)

θ_t = angle of tilt (i.e. the angle between the hole axis and the flame axis) (º)

θ_w= angle between the hole axis and the wind vector in the plane containing the hole axis, flame axis and wind vector (º)

θ_x = angle between hole axis and the horizontal (º)

λ_{Crater} = parameter that describes how effectively the air entrained into the jet in the crater is mixed with the fuel

λ = parameter that describes the effectiveness of the eddies in mixing the air entrained into the jet and the fuel in the jet

Λ = non-dimensional parameter [5]

μ_s = viscosity at nozzle exit (kg m^{-1} s^{-1})

ν_s = kinematic viscosity at the jet exit (m^2 s^{-1})

ξ_{L_0} = Richardson number based on the flame length in still air

ξ_L = flame Richardson number

ρ = bulk density of the plume (kg m^{-3})

$\bar{\rho}$ = mean bulk density of the plume (kg m^{-3})

$\rho^* =$ density ratio

ρ_f = density of fuel (kg m^{-3})

ρ_{ng} = density of natural gas (kg m^{-3})

ρ_p = density of products (kg m^{-3})

ρ_s = nozzle/jet exit density (kg m^{-3})

ρ_∞ = ambient air density (kg m^{-3})

$\tau =$ temperature scale

$\Phi_b =$ ratio of b_θ / b_u

Φ_u = ratio of wind velocity to jet/exit velocity

φ_w = angle of the wind direction with respect to x-axis (º)

$\chi =$ rate of mixing of air across the stalk (m s^{-1})

χ_A = combustion efficiency

$\chi_c =$ convective fraction of the chemical heat release rate

χ_R = fraction of the theoretical heat release rate that is lost by radiation

Ω = virtual origin parameter

Major accident hazard pipelines transport hazardous fluids, such as natural gas, that have the potential to harm people in the vicinity in the event of a release from a pipeline failure. Major accident hazard pipelines are defined under the Pipelines Safety Regulations (1996). Dutyholders must implement effective control measures to prevent pipeline failure. Land-use planning law is an important extra precaution to limit the potential risk to the public. HSE is a statutory consultee for proposed land-use developments. HSE sets land-use planning zones and provides advice to local planning authorities on proposed developments within these zones. HSE uses a quantified risk assessment (QRA) approach as part of its decision making. The QRA uses mathematical models of potential hazards and their consequences. HSE has an ongoing research programme to assess the suitability of these models.

A jet fire is one of the potential hazards for releases from pipelines transporting flammable substances. This report and RR1188 (2022) describe research on the suitability of jet fire mathematical models for use by HSE to estimate the physical dimensions of potential fires. This report describes a review of the scientific literature done as the first stage of the research. The review did not identify any single model that would be suitable for the range of scenarios and substances that HSE models. The review identified models that could potentially be implemented by HSE to more accurately represent the physics of jet fires. RR1188 describes the second stage of this research to consider the performance of these models. These findings are being used to inform assessment of the suitability of the jet fire models that HSE currently (2022) uses and whether updates would be beneficial. The report will be of interest to specialists in risk modelling for major hazards.

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