On Blow-Out of Jet Spray Diffusion Flames

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1 Introduction

The mechanism of gaseous jet diffusion flame blow-out and stability has been studied both experimentally and theoretically. The question of prime importance concerned the nature of the physical and/or chemical mechanisms whereby the diffusion flame formed as a result of a jet fuel issuing into an oxidizing environment often stabilizes above the jet orifice, yet sometimes is blown out. Van quickenborne and Van Tiggelen [1] studied the stabilization of lifted, turbulent, diffusion methane flames experimentally. They found that the base of the lifted flame anchors in a region corresponding to the formation of a stoichiometric mixture, where the turbulent burning velocity was equal to the flow velocity. They also observed that blow-out in jet diffusion flames is not an extinction phenomenon since the flame can be maintained at various heights, provided there exists a permanent ignition source. Kalghatgi [2] speculated that the blow-out velocity is a function of the laminar flame speed and height of the stoichiometric contour and found a "universal" non-dimensional formula to describe the blow-out stability limit of gaseous jet diffusion flames in still air. Chung and Lee [3] experimentally studied the characteristics of laminar lifted flames stabilized in a non-premixed jet. They identified the tribrachial structure of what was later to become known as an edge flame – with a fuel lean premixed structure on one arm connected to a fuel lean premixed structure on a second arm, with a trailing diffusion flame downstream and anchored in the aforementioned flame root. They found an expression for liftoff height as a function of the flow rate, burner diameter and the Schmidt number, Sc (ratio of viscosity and mass diffusivity). They recognized the key role played by Sc in the stability mechanism for circular jets, noting that the lift-off height will increase with an increase in flow-rate for $Sc < 0.5$ and $Sc > 1$ but will decrease for $0.5 < Sc < 1$.

The basic theory utilized for predicting conditions for flame blow out is summarized in [4] and [5]. It relies on the description of an incompressible jet exiting from a narrow slot and the use of a similarity solution (details of the development are given in [6]) for the governing boundary layer equations. A solution for the Schwab-Zeldovitch parameters equation is also developed in a similar fashion. The latter parameter enables a flame surface (infinitessimally thin) to be defined (infinite chemical Damkohler number). The point(s) of coincidence of the flame surface and the flame speed surface (defined as those points where the axial velocity of the jet is equal to the local burning velocity) indicate whether flame stability is achieved or whether flame blow-out occurs, or, alternatively, (see [5]) whether a lifted or a partial flame is achieved.

It is of interest to note that the crux of this predictive capability banks on the physical description of an edge flame without actually assigning a detailed mathematical description to it. It is for this reason that

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the local premixed burning velocity is exploited even though the concept of burning velocity has no real significance in the context of a diffusion flame.
Many jet diffusion flames are actually fueled by a spray of liquid droplets. Yet the aforementioned analysis has been hitherto restricted to gas flames only. In the current paper we present a new analysis which accounts for precisely this more realistic situation, and examine the way in which the spray impacts upon flame blow out and stability.

2 The Model

We consider two-dimensional jet spray diffusion flame (see Fig. 1). A 2-D liquid fuel spray jet emerges from a narrow slot burner port and entrains surrounding air. Due to the mutual diffusion between the evaporating fuel and the oxygen in the air, a mixing layer is formed above the burner. Under appropriate operating conditions, a 2-D diffusion flame can be established throughout this mixing layer.

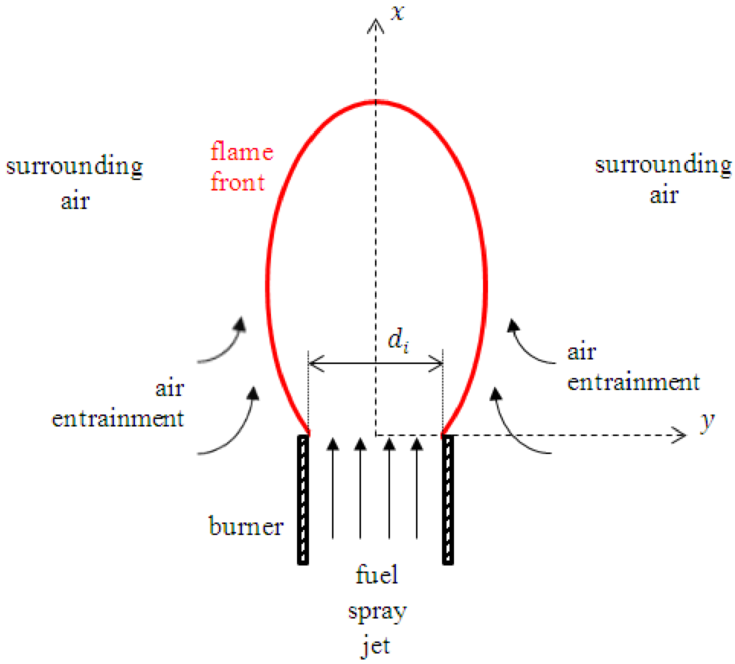

Figure 1. A two-dimensional jet spray diffusion flame

As mentioned in the Introduction, according to classical theory the behavior of a *gas* jet flame is determined by the exit velocity of the fuel jet at the burner port and possible scenarios are summarized in Table 1. The question addressed in the current work is how the summary is altered by the presence of a liquid fuel spray in the supply conditions.

Table 1. Gaseous jet diffusion flame scenarios as described in the literature

Jet exit velocity	Flame characteristics
Lower than the burning velocity.	**Flashback** – The flame enters the burner port and is immediately extinguished due to lack of oxygen.
Slightly higher than the burning velocity.	**Complete and stable flame** – The flame remains attached to the burner port tip (see Fig. 1).
Much higher than the burning velocity.	**Lifted flame** – The flame is detached from the burner port tip and a lifted flame is obtained above the burner. The lift-off height is proportional to the jet exit velocity.
Above the blow- out velocity.	**Blow-out** – The flame cannot remain stable above the burner and moves downstream to a colder region where it is eventually extinguished.

3 Governing equations and solution

The mathematical model for the problem is based on the laminar boundary layer theory for the jet and the sectional approach (assuming a single section for simplicity at the current stage) for the liquid droplets [7]. The dimensionless governing equations are:

Continuity and momentum conservation equations:

$$\frac{\partial u^*}{\partial x^*}+\frac{\partial v^*}{\partial y^*}=0$$

$$u^*\frac{\partial u^*}{\partial x^*}+v^*\frac{\partial u^*}{\partial y^*}=\frac{1}{Re_i}\frac{\partial^2 u^*}{\partial y^{*2}}$$

Mass conservation equation for the fuel droplets:

$$u^*\frac{\partial Y_d^*}{\partial x^*}+v^*\frac{\partial Y_d^*}{\partial y^*}=-C^*Y_d^*$$

Energy and species conservation equations (in Schwab-Zeldovich formulation):

$$u^*\frac{\partial \beta_2^*}{\partial x^*}+v^*\frac{\partial \beta_2^*}{\partial y^*}=\frac{1}{Re_i\cdot Sc}\frac{\partial^2 \beta_2^*}{\partial y^{*2}}+\alpha_i C^* Y_d^*$$

$$u^*\frac{\partial \beta_3^*}{\partial x^*}+v^*\frac{\partial \beta_3^*}{\partial y^*}=\frac{1}{Re_i\cdot Sc}\frac{\partial^2 \beta_3^*}{\partial y^{*2}}$$

In these equations the independent variables are normalized, as are the velocity components $\left(u^*,v^*\right)$, the mass fraction of liquid fuel in the spray Y_d^* and the Schwab-Zeldovitch parameters $\left(\beta_2^*,\beta_3^*\right)$ which are based on Y_F-Y_O/ν_O and $\left(c_pT+LY_F\right)/Q+\left(1-L/Q\right)Y_O/\nu_O$, respectively, where Y_F,Y_O

are mass fractions of fuel vapor and oxygen, ν_O is the stoichiometric coefficient, T is temperature, c_p is specific heat, Q is heat of reaction and L is latent heat of vaporization. Re_i is the Reynolds number, Sc is the Schmidt number, $C^* = Cd_i / U_i$ is normalized sectional evaporation coefficient (d_i, U_i jet width and average velocity, respectively, and C the sectional evaporation coefficient) and $\alpha_i = \left(Y_{F,i} + Y_{d,i}\right) / \beta_{2,i}$, where the suffix i refers to jet inlet conditions.

For the velocity u^* boundary conditions are: symmetry at $y^* = 0$, $u \to 0$ as $y^* \to \infty$ and the total constant axial momentum flux, M^*, specified at the inlet, $x^* = 0$. Similar boundary conditions hold for β_2^* and β_3^*. Also, $v^* = 0$ at $y^* = 0$. For Y_d^* a total flux condition for the liquid fuel is specified at the inlet.

The governing equations were solved using a similarity solution, with similarity variable $\hat{\eta} = \left(Re_i^{2/3} \cdot M^{*1/3} / \left(2^{4/3} \cdot 3^{1/3}\right)\right)\left(y^* / x^{*2/3}\right)$, and the following solutions were obtained (for the case of $\hat{C} = 1$, where $\hat{C}$ is a parameter related to the evaporation rate of the fuel droplets):

$$\left(u^*, v^*\right) = \left(\frac{3^{1/3}\, Re_i^{1/3}\, M^{*2/3}}{2^{5/3}\, x^{*1/3}} sec\,h^2 \hat{\eta}, \frac{\left(M^* / Re_i\right)^{1/3}}{6^{1/3}\, x^{*2/3}} \left(2\hat{\eta}\, sec\,h^2 \hat{\eta} - tanh\,\hat{\eta}\right) \right)$$

In the region with fuel droplets, $\hat{\eta} < \hat{\eta}_d$:

$$Y_d^* = \left(A_d / x^{*1/3}\right) cosh\,\hat{\eta}, \quad \beta_2^* = \left\{\left(D_2\right) sec\,h^{2Sc} \hat{\eta} - \left(2Sc\alpha_i A_d / \left(2Sc + 1\right)\right) cosh\hat{\eta}\right\} / x^{*1/3}$$

and without fuel droplets $\hat{\eta} > \hat{\eta}_d$: $Y_d^* = 0$, $\beta_2^* = \left(B_2 / x^{*1/3}\right) sec\,h^{2Sc} \hat{\eta}$, where $\hat{\eta}_d$ is determined from the streamline beyond which the droplets do not travel in the transverse direction. Finally, $\beta_3^* = \left(B_3 / x^{*1/3}\right) sec\,h^{2Sc} \hat{\eta}$. In these solutions A_d, B_2, B_3, D_2 are constants found using the boundary conditions. The flame front is located at those points where $\beta_2^* = 0$.

4 Results

The shape and characteristics of the flame are determined by the mutual position of two fundamental surfaces – the **flame front surface (FFS)**, on which $\beta_2^* = 0$, and the **flame speed surface (FSS)**, on which $u = S$ (S is the local laminar flame speed). These are drawn in Figs 2 and 3 for different operating conditions. Note that the transverse coordinate has been stretched for clarity – the flames are actually rather thin. The unbroken black line is the limiting contour to the right of which no liquid droplets travel. The blue line delineates flame speed surface. Yellow lines are stable flame fronts. In contrast to the case of a purely gas flame, for which only the Schmidt number and the exit velocity of the fuel jet at the burner port determine the nature of the flame, for the spray flame the droplets content of the fuel jet was also found to play a key role. Consider Fig. 2. For the purely gas flame, the flame front surface (solid read line) lies outside the flame speed surface, thereby ensuring a stable flame anchored to the burner. When the fuel is supplied exclusively as liquid droplets the flame front surface (small dotted line) lies within the flame speed surface whereby flame blow-out occurs. For the case in which the fuel is supplied equally as vapor and liquid fuel droplets the lower part of the flame front surface is within the flame speed surface but subsequently downstream the curves cross and then the FFS lies outside the FSS. This implies that the

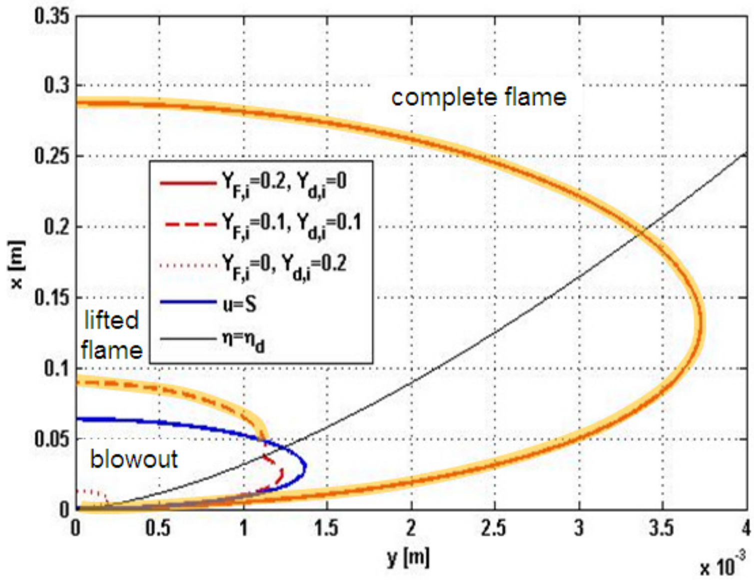

Figure 2**:** The flame front and speed surfaces for $Sc = 1$ and $U_i = 0.95 m / sec$ and different initial droplet loads.

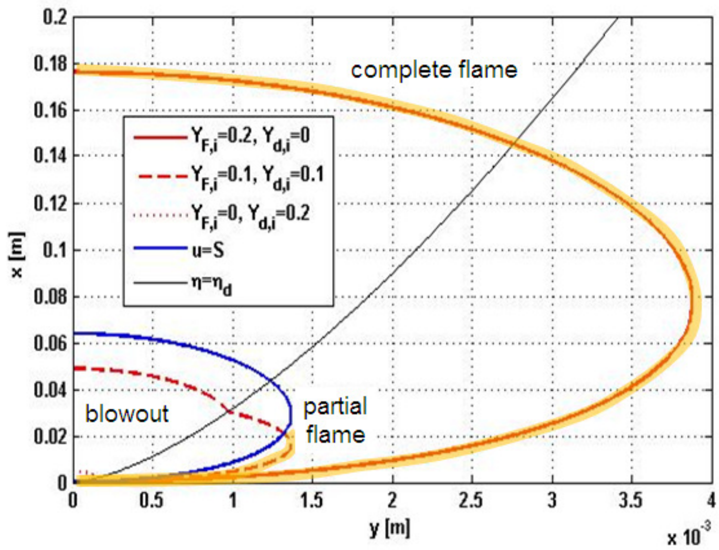

Figure 3: The flame front and speed surfaces for $Sc = 0.5$ and $U_i = 0.95 m / sec$ and different initial droplet loads.

flame is lifted above the burner and stabilizes downstream. For a lower Schmidt number of 0.5 results are shown in Fig.3. A further scenario is observed for the case in which the fuel is supplied equally as vapor and liquid fuel droplets. Here the lower part of the flame is anchored to the burner whereas the upper part of the flame cannot be sustained.

In general, as the liquid fuel content in the total fixed fuel supply increases, the flame shrinks (in its height and width, see both Figs 2 and 3), its temperature decreases (not shown here) and the blowout velocity is reduced. These results can be understood by the fact that as the initial droplet load increases not all the droplets succeed in vaporizing before reaching the flame front leading to a smaller, more compact FFS.

Table 2 summarizes a comparison between the spray flame and its purely gaseous flame equivalent and indicates that in contrast to gas flames, for $Sc \leq 1$ lifted spray flames may exist under certain operating conditions.

Table 2. Comparison between gas fuel and fuel spray jet diffusion flames

Sc	**Pure gaseous fuel jet**	**Fuel spray jet**
< 1	The flame front begins as complete, then becomes partial (open) and eventually blows out, as the velocity increases.	The flame front begins as complete, then becomes partial (open) and/or lifted and eventually blows out, as the velocity increases.
$= 1$	The flame front begins as complete and eventually blows out, as the velocity increases.	The flame front begins as complete, then becomes lifted and eventually blows out, as the velocity increases.
> 1	The flame front begins as complete, then becomes lifted and eventually blows out, as the velocity increases.	The flame front begins as complete, then becomes lifted and eventually blows out, as the velocity increases.

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