Heat release effects in lifted laminar jet diffusion flames

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1 Introduction

Recent analytical developments on triple-flame lift-off devoted to the derivation of a stabilization diagram [1] are used to compare lift-off height prediction against experimental results [2]. To study lift-off properties with an approximate analytical solution, the mixing upstream of the flame base was estimated using a cold flow solution, while the speed of the flame front was obtained from recent derivation of triple flame speed including heat release effects [3]. The comparison between the approximate lift-off height solution and the measurements suggests that some of the specific features of laminar flame lift-off are not included in the cold flow mixing analysis.

To understand the observed discrepancies between theory and measurement, numerical simulations of lifted laminar jet diffusion flames including heat release effects are performed. We compare the simulated lift-off height and blow-out position with their approximations provided by the analytical solution. As with the measurements, it is observed that flames are stabilized closer to the burner and the blow out condition is found for velocity larger than expected.

The analysis of the simulations reveal that heat release effects strongly modifies both the mixture fraction distribution and the velocity fields at the flame base. Accordingly, the stoichiometric location where the flow velocity equals triple flame velocity is shifted upstream from its cold flow position. In consequence, for large values of the jet velocity, stable flames exist in the simulation for downstream streamwise positions where lean mixture, below the stoichiometric point, are expected in the cold flow theory.

Some of the lifted flame properties experimentally observed are discussed at the light of the numerical results.

2 Comparison between cold-flow theory and experiments

A round laminar non-premixed jet issuing in stagnant atmosphere is considered (Fig. 1). Because lifted flames are stabilized at a given height of the nozzle, mixing develops up-

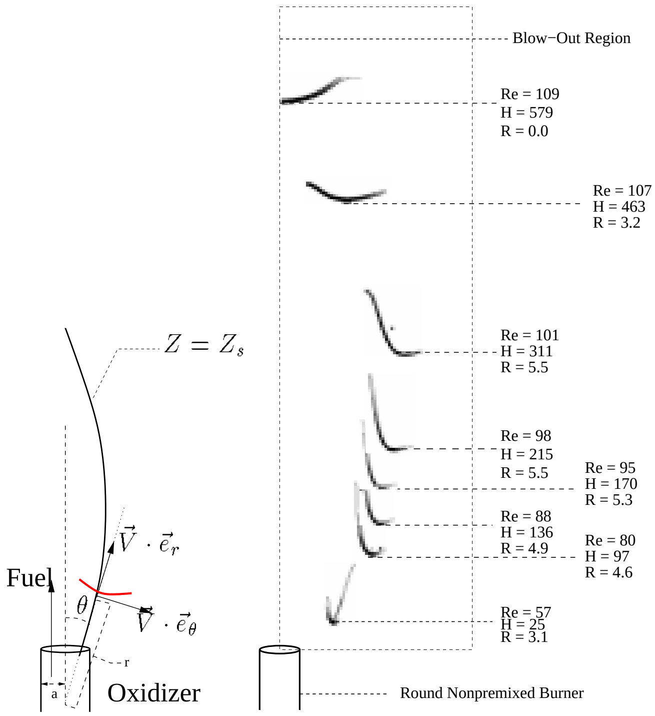

Figure 1: Left: Configuration. Right: Simulations of lifted flames for various conditions. Re: Jet Reynolds Number, H: Lift-off height, R: Radial position of the flame base.

stream of the flame. To describe the mixture feeding the flame base, it is then tempting to use cold flow solutions, as the Landau-Squire expressions [4] providing an auto-similar description of the jet. With the descriptions of the flow properties and species fields together with results on flame propagation, theoretical prediction of lift-off can be achieved. One formulates the hypothesis upon which partially premixed flames develop on the stoichiometric surface at a distance of the nozzle, where the flow velocity balances the deflagration propagation velocity. In recent works [1], this velocity was taken equal to a triple flame velocity for given mixture distribution and including effects of heat release on the burning velocity. The lift-off height is then given by a transcendental equation for determining the normalized lift-off height $x = \theta/\theta_o$:

$$f(x) = (1 + x^2)^{2S_c - 2} \left[1 + Ax(1 + x^2)\right] = B \quad (1)$$

where θ is defined as in Fig. 1, θ_o corresponds to flame attached to the burner, S_c is the fuel Schmidt number, A and B are two parameters depending on the burner geometry and chemical properties [1]. An expression for the blow-out position is obtained when the stoichiometric line crosses the axis of symmetry (i.e. for $\theta = 0$): $h = r(\theta = 0) - (a/\theta_o)$. The coordinate r is defined as in Fig. 1, the blow-out value is given by $r(\theta = 0) = a/(Z_s\theta_o)$, with a the burner radius. All data are normalized by the planar

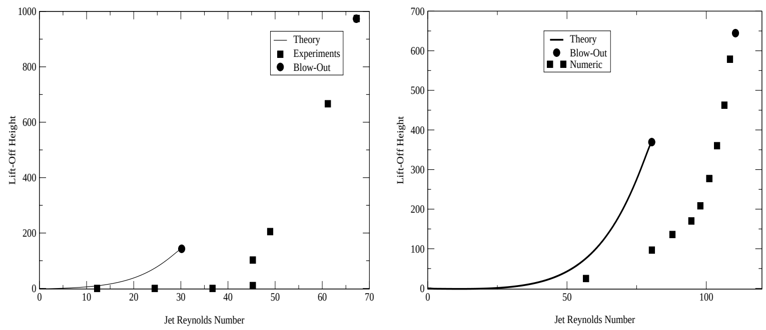

Figure 2: Left: Comparison between measurements [2] and results from Eq. 1. Right: Comparison between simulations and results from Eq. 1.

stoichiometric burning velocity S_l^o and the burner radius a.

Clearly in the analytical results, an important underlying hypothesis is that the presence of the flame base does not disturb the upstream jet features. Previous studies have been conducted on lifted laminar flames from measurements and jet similarities relations [2]. It was concluded that the global shape of the lift-off height h versus jet Reynolds number Re follows a law of the form $h = KRe^n$, where K is a constant and n depends on the Schmidt number. This generic shape is recovered in Fig. 2. However, it appears that theory and experiment lead to different values of K and n. This is visible in Fig. 2 - Left, where for a given Re the flame is stabilized below the predictions of Eq. 1. Moreover, blow-out is found for much larger velocity than expected.

These observations are now studied at the light of numerical simulations of lifted flames (Fig. 1 - right), and Fig. 2 - right shows that analytical predictions do not match either with the lift-off simulations that have been conducted.

3 Numerical procedure

The fully compressible Navier Stokes equations are solved using a Direct Numerical Simulation code. To reduce the cpu time, the calculation of all of the cold and inert flow upstream of the flame is avoided with a computational domain that consists of axisymmetric boxes moving along the axial direction with the flame (Fig. 1). The inlet of the domain is kept far away from the flame, so that the cold flow solution is valid and can be imposed in term of velocity and species. Non-reflecting boundary conditions are otherwise specified. To verify the validity of the computational procedure, one simulation was performed with a full domain. A one step Arrhenius law irreversible chemistry is retained. The computations are with a Zel'dovitch number $\beta = 8$, a stoichiometric mixture fraction point $Z_s = 0.0625$ and a heat release parameter $\alpha = (T_{burnt} - T_{fresh})/T_{burnt} = 0.8$, where T_{fresh} and T_{burnt} denote the temperatures on the two sides of a reference stoichiometric unstrained premixed front. The balance equations are solved using a sixth order PADE scheme [5] combined with a third order Runge-Kutta time stepping and Navier Stokes characteristic boundary conditions (NSCBC) [6].

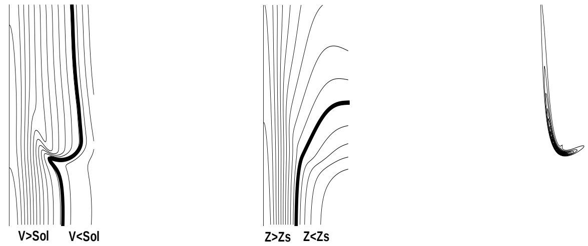

Figure 3: Flame lifted close to burner exit, $Re = 88$. Left: Iso-velocity field, bold line denotes positions where axial velocity V_z equals S_{ol}. Middle : Iso-mixture fraction field, bold line denotes iso-Z_s. Right: Reaction rate.

4 Impact of heat release on lift-off height and flame structure close to blow-out

Figure 3 displays iso-lines for a representative value of the jet Reynolds number ($Re = 88$). It is observed that the flame manages to spread out the jet which has as a consequence to push the stoichiometric line towards lower velocity, allowing the flame to propagate upstream from its expected position. Accordingly, velocity iso-lines are pushed away from the flame front, therefore iso-lines of lower velocity magnitude than expected interact with more rich and stoichiometric mixture fraction fields, also contributing in the reduction of the lift-off height. For the higher part of the jet, thus for

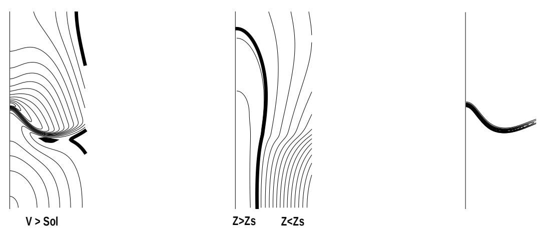

Figure 4: Flame lifted in the upper part of the jet, $Re = 107$. Left: Iso-velocity field, bold line denotes positions where axial velocity V_z equals S_{ol}. Middle : Iso-mixture fraction field, bold line denotes iso-Z_s. Right: Reaction rate.

large exit jet Reynolds number, some flames exist that are not allowed by the cold flow theory. Due to the natural spreading of the jet, the mixture fraction gradient is very low in the upper part. Then, the flame almost behaves as a premixed flame with weakly stratified equivalence ratio along the reaction front (Fig. 4). The presence of the flame as a "hat" covering the top of the jet leads to a large spreading of the fields. This allows to have much richer mixture fraction fields than expected in the lower velocity region of the upper part of the jet, where the stoichiometric line is still observed in the simulation, but not in the cold flow solution. Explaining the disagreement with the flame position predicted by the cold flow theory.

5 Conclusion

Through this investigation, some of the limits of cold flow theory for predicting the behavior of lifted flames are pointed out. The analytical approach is indeed able to provide well pictured lift-off curve, useful to determine the global properties of flame stabilization, but error in lift-off height magnitude should be expected.

The dynamic of the flame base acts locally on small but sufficient distances to make stoichiometric and velocity iso-lines to cross for lower lift-off height than expected in inert jets. This explains some of the real behavior and robustness of lifted non-premixed laminar round jet flames.

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