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Full Length Article

Lift-off and blow-off of methane and propane subsonic vertical jet flames, with and without diluent air

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HIGHLIGHTS

- An experimental study of jet flame blow-off with air added to the fuel stream.
- Added air increases blow-off, reducing the blow-off dimensionless flow number.
- Simple jet mixing theory estimates leaning-off of flame and blow-off.

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ABSTRACT

The paper seeks to increase understanding of subsonic jet flame blow-off phenomena, through experimental studies that include the controlled introduction of air into the fuel jet. As the molar concentration of air in the jet flame gas, A_j, is increased the reaction zone becomes leaner, and the flame lift-off distance increases. Eventually, flame oscillations develop and are followed by flame blow-off. A jet mixing analysis enables the extent of the leaning-off of the mixture to be estimated. From this, the reduced mean flamelet burning velocity, u_a, is found at the location of the pure fuel jet flame. The conditions for blow-off are correlated with the last measured stable values of the dimensionless flow number, $U_b{}^*$, for methane and propane jet flames, with and without added air. Values of $U_b{}^*$ decline as the proportion of added air increases, more markedly so with methane. This is attributed to the leaning-off of the flame, and the associated decrease in the flame extinction stretch rate. As $U_b{}^*$ declines in value, with increasing air dilution, the emissions of unburned hydrocarbons just prior to blow-off increase. An underlying generality of the findings is revealed when u_a is introduced into the expression for $U_b{}^*$, and A_j is normalised by the moles of air required to burn a mole of fuel.

1. Introduction

It is important to be able to predict flame lift-off distances, plume heights, and blow-off conditions, of steady jet flames on a burner, in both controlled flaring and the jet flames that follow unintended explosive blow-outs. Such flames become unstable at both low and high jet velocities, the latter ultimately leading to flame blow-off. In controlled flaring, cross winds, fuel dilution, and fluctuations in flow rate can all result in incomplete combustion, flame extinction, and blow-off. Yet high combustion efficiencies are essential in, for example, the flaring associated with hydraulic fracturing to liberate methane, in order to prevent the uncontrolled release of this potent greenhouse gas. Johnson and Kostiuk [1] have shown that the addition of diluents, such as N_2 and CO_2, in sufficient proportions seriously reduces the combustion efficiency. Ingress of air into naturally occurring methane is less well understood, in this regard, as is also the extent to which flare performance might be impaired by flame blow-off at a lower jet velocity. The present paper reports an experimental study of the effect on the blow-off velocity of a subsonic jet of adding air to, respectively, methane and propane fuel jets. In so far as the addition of air aids fuel/air mixing, higher jet velocities might be expected before blow-off occurs. On the other hand, excess air might induce earlier lean flame extinction and blow-off.

There have been significant successes in the mathematical modelling of lift-off distances, *L*, and plume heights for pure fuel jet flames, and in the associated formulation of appropriate dimensionless groups for the correlation of experimental data [2–6]. The region between the exit plane of a fuel jet discharging into the

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Nomenclature

A_j	mole fraction of air in jet flow
D	internal pipe diameter (m)
f	ratio of fuel to air moles in stoichiometric fuel-air mixture
F_j	mole fraction of fuel in jet flow
$(F/A)_j$	ratio F_j/A_j
$(F/A)_s$	ratio F_j/A_j for required near-stoichiometric conditions
L	lift-off distance (m)
P_a	pressure of the ambient atmosphere (MPa)
P_i	initial stagnation pressure (MPa)
r	flame radius (mm)
S_L	maximum laminar burning velocity of the mixture under ambient conditions (m/s)
t	time (s)
u	pipe flow mean exit velocity, or sonic velocity for choked flow (m/s)
u_a	flamelet burning velocity for aerated jet flame at location of ϕ_m contour of non-aerated jet flame (m/s)
U^*	dimensionless flow number, $U^* = (u/S_L)(D/\delta)^{-0.4}(P_i/P_a)$
$U_b{}^*$	dimensionless U^* flow number just prior to blow-off conditions
$U_{ba}{}^*$	dimensionless U_b^* flow number based on u_a
$U_{bo}{}^*$	dimensionless $U_b{}^*$ flow number at $A_j = 0$, $U_{bo}{}^* = U_b{}^*$ at $A_j = 0$
Greek symbols	
δ	laminar flame thickness under ambient conditions (m), given by ν/S_L
ϕ_a	aerated jet equivalence ratio
ϕ_j	equivalence ratio of aerated jet in supply pipe
ϕ_m	equivalence ratio for non-aerated fuel jet flame remote from blow-off
ν	gaseous mixture kinematic viscosity at ambient conditions corresponding to those for S_L (m^2/s)
Subscripts	
j	jet gas mixture
s	stoichiometric, or required near-stoichiometric conditions

atmosphere and the flame leading edge is one of intense mixing that generates high strain rates. This is illustrated in Fig. 1, derived from the computations reported in [3]. The dashed curves show radial and axial changes in the streamlines, and the full line contours show the mean volumetric heat release rate. The strain rates are initially sufficiently high to not only effectively mix the fuel and surrounding air, but also to exceed the flame extinction stretch rates, and quench any potential flamelets. Further downstream the strain rates relax to the extent that combustion becomes possible in the most reactive flamelets, which also have the highest flame extinction stretch rates, and a laminar burning velocity close to S_L.

With further increases in jet velocity, more air is entrained, localised equivalence ratios fall as the mixture leans off, and flame extinction stretch rates decrease, to the extent that eventually all flamelets are extinguished and the flame blows off. Computations of the distributions of equivalence ratios show that at flow velocities, before approaching blow-off, the peak value in probability density function is close to that for the maximum burning velocity of the mixture. This supports the widespread use of the maximum value of the laminar burning velocity of the mixture, S_L, in dimensionless groups for correlating lift-off distance and blow-off [6,7].

The stretched laminar flamelet modelling in [2–4], in conjunction with experimental jet flame data, have led to more practical, generalised, correlations of experimental jet flame data, involving a dimensionless flow number, U^*, that is closely related to the Karlovitz stretch factor, employed in premixed turbulent combustion [6], where

$$U^* = (u/S_L)(D/\delta)^{-0.4}(P_i/P_a). \tag{1}$$

A normalised flame lift-off distance, $(L/D)f$, was expressed as a function of U^* by:

$$(L/D)f = 0.1U^* - 0.2, \quad \text{for subsonic jets}. \tag{2}$$

Here u is the pipe flow mean velocity (or sonic velocity for choked flow), δ, the laminar flame thickness, at the ambient conditions, given by ν/S_L, with ν the gaseous mixture kinematic viscosity. P_a is the pressure of the ambient atmosphere, P_i the initial stagnation pressure, D, the internal pipe diameter, and f the ratio of fuel to air moles in the stoichiometric fuel-air mixture, which is close to that for the maximum laminar burning velocity of the mixture, S_L. Extensive correlations of flame plume height and $(L/D)f$ in terms of U^*, appear in [6].

However, the prediction of blow-off, as the ultimate limiting condition of lift-off, when localised extinctions cause the flame to simultaneously leave the burner and extinguish, presents more severe modelling problems [5]. They include the development of oscillatory, non-linear phenomena. Because of these complexities it is difficult to formulate correlations of blow-off in a generalised way. No attempt was made to correlate blow-off parameters in [6], while in [8] separate stable values of U^* prior to blow-off, $U_b{}^*$, are

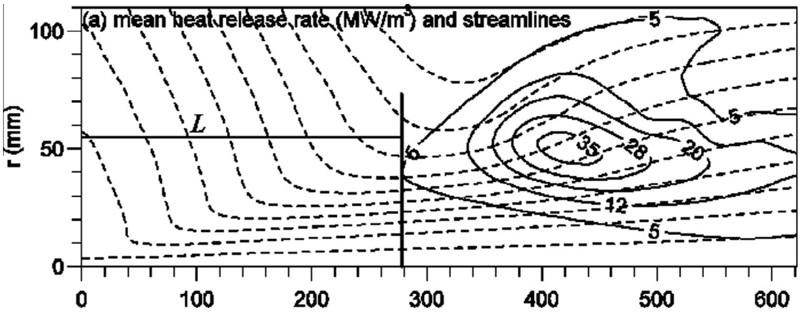

Fig. 1. Computed radial and axial variations of flow streamlines (dotted) and volumetric heat release rate (full contours), of methane jet flame. $D = 9$ mm ($r = 4.5$ mm), all distances in mm. From [3].