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Computational investigation of the stability of a lifted strongly buoyant jet flame

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ABSTRACT

The present work performs a detailed numerical simulation of a non-premixed turbulent reacting jet at low Reynolds and Froude numbers to investigate the dynamical interaction between the flow field and the embedded flame, with a special focus on the mechanism of flame stabilization. The computations combine a DNS approach for the flow structures, which are fully resolved, with a LES approach for the numerical description of the flame. The results unveil a weak, essentially impeding effect of the flame on the upstream, non-burning flow region. A significant effect is seen in the large-scale motion, which is generated by the periodic formation, growth, and departure of large bulb-shaped low-density structures at the flame base, as it is also seen in experiments. The analysis of the dominant stabilization mechanism of the lifted flame essentially supports the concept of edge-flame propagation. In addition, the buoyancy-driven large-scale flow structures temporarily produce a further strongly destabilizing scenario, where large circumferential sections of the flame base recede deeply downstream, which is shown to be associated with high local values of the scalar dissipation rate. Showing this particular scenario the present work does not only highlight an important stabilization mechanism governed by large three-dimensional ("out-of-the-plane") structures, it also demonstrates the strong relevance of the scalar dissipation rate even when it is far below the extinction limit.

1. Introduction

A major challenge in the development of modern combustion devices is to satisfy the often competing requirements of high efficiency, low pollutant emission, safe and reliable operation. The latter is of special concern to the stabilization of turbulent lifted flames in non-premixed combustion. During the last decades much progress has been made in the experimental as well as computational research to better understand the complex interactions between the chemistry, the instantaneous flow and mixing conditions. Comprehensive reviews of the principal theories, which have been proposed to explain the prevailing mechanisms of flame stabilization, were presented in literature by Lyons [1] and Lawn [2]. Most of the studies carried out on lifted turbulent diffusion flames contend that the flame stabilization is dominated by the premixed flame propagation mechanism. Based on their early measurements Vanquickenborne and van Tiggelen [3] and Kalghatgi [4] claim that the flame base propagates into a fully premixed region ahead faster than with the laminar flame speed. They attributed the increased propagation velocity to turbulence, so that the flame can effectively stabilize in regions, where the velocities exceed the laminar flame speed. Later measurements by Muñiz and Mungal [5] report the same behavior, in that the flame counters oncoming flow velocities up to three times higher than the laminar flame speed. However, they do not observe any significant influence of the turbulence level as suggested by Kalghatgi [4]. This was later also confirmed by Mansour [6] and Upatnieks et al. [7], who rather suggest a laminar flame propagation mode, where volumetric dilatation leads to diverging stream lines ahead of the flame base, so that the reaction zone effectively encounters a reduced oncoming velocity being close to the laminar flame speed. The effect of the heat release on the flame propagation was computationally investigated by Ruetsch et al. [8], who found the increase in the propagation velocity to be dependent on the density ratio of the unburnt to the burned gas up- and downstream of the flame, respectively. Su et al. [9] deduced from their experiments a stabilization model depending on the large-scale mixing field. Their suggested mechanism basically falls into the Large-Eddy concept, which assumes that the flame stabilizes migrating from one large-scale structure to a neighboring one seeking most favorable velocity and mixing

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Nomenclature

Latin symbols

A_R	pre-exponential factor (m, mol, s)
D	nozzle diameter (m)
D_i	mass diffusion coefficient (m/s^2)
Fr	Froude number, $U_J/\sqrt{gD}$ (–)
$\underline{\underline{I}}$	identity tensor (–)
L_x	streamwise computational domain length (m)
N_i, N_R	number of species, reactions (–)
Re	Reynolds number, $\rho_J U_J D/\mu_J$ (–)
R_m	universal gas constant (J/kmol K)
$\underline{\underline{S}}$	rate of strain tensor (1/s)
$\underline{\underline{S}}'$	turbulent strain tensor (1/s)
T	temperature (K)
$T_{0,R}$	activation temperature (K)
W_i	molecular weight (kg/kmol)
W_0	unity mol. reference weight (kg/kmol)
U_J	nozzle exit bulk velocity (m/s)
X_i	molar fraction (–)
Y_i	mass fraction (–)
Z	mixture fraction (–)
c_p	isobaric specific heat (J/kg K)
g	gravitational acceleration (m/s^2)
p	pressure (Pa)
s	flame propagation speed (m/s)
t	time (s)
u	streamwise velocity (m/s)
$\underline{v}$	velocity vector (m/s)
x	streamwise distance (m)
y	cross-stream distance (m)

Greek and calligraphic symbols

β_{dil}	dilution ratio (–)
Γ	boundary surface (–)
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Pa s)
ν'_{iR}, ν''_{iR}	stoichiometric coefficients (–)
$\dot{\omega}_R$	reaction rate (kmol/kg s)
Ω_i	reactive source term (1/s)
ρ	density (kg/m^3)
Φ	equivalence ratio (–)
χ	scalar dissipation rate (1/s)
$\mathcal{V}$	computational volume (m^3)
$\mathcal{W}$	vorticity (1/s)

Subscripts, superscripts, and operators

J	nozzle exit
R	index of elementary reaction
$c, 0.5$	jet centerline, half-width
fb	flame base
i	index of species
L	laminar
E	edge
$*$	non-dimensionalized
$\boldsymbol{\nabla}$	nabla operator
$\bar{}$, $\langle\rangle$	statistical average

conditions. There is still considerable doubt, if large-scale structures effectively determine the lift-off height, or, if they rather disturb only temporarily the position of the flame. A further debated issue is the effect of unmixedness, which can be basically parameterized by the scalar dissipation rate. Peters and Williams [10] argue that premixing does not reach any significant level ahead of the flame. Consequently, the leading edge of the flame burns in the non-premixed regime, and it stabilizes at a position, where the local scalar dissipation rate falls below the quenching limit. In the strict sense, this hypothesis was not confirmed by experiments, where the dissipation rates near the flame base were generally found to be well below the quenching limits obtained from studies on counterflow diffusion flames [11,9]. However, the scalar dissipation rate exhibits strong turbulent fluctuations in time and space, so that it may reach sufficiently high instantaneous local values to exert a significant effect on the flame propagation.

Although the studies mentioned above were dealing in part with fairly moderate Reynolds and Froude numbers, the effect of buoyancy is therein mostly not addressed. Upstream effects of the flame on the non-burning near field of the jet have been mostly discarded either, or considered as insignificant. The present work puts the focus on these particular aspects investigating computationally the case of a highly buoyant non-premixed methane–air jet flame. A nitrogen-diluted fuel feed is assumed to provide highly sensitive burning conditions, which helps to clearly identify the most relevant mechanisms for the stabilization of the considered flame. As for the relevance of upstream effects of the flame on the non-reacting near field, the spreading and decaying behavior of the fuel jet is of particular interest. It is investigated, to which extent this behavior resembles to that of the non-reacting case, as claimed by most previous studies (e.g., Su et al. [9]), considering a reacting turbulent jet at fairly low Reynolds and Froude numbers. Due to the latter, much attention is spent on the effects of the buoyancy-driven large-scale motion on the temporal evolution of the flow field. Being essentially generated by the reactive heat release the investigated large-scale structures are strongly coupled with the behavior of the flame, so that a significant influence on the flame stabilization is expected. Experimental reference data for the considered flame are available from measurements on a corresponding test facility [12,13].

2. Mathematical model

The present numerical simulation solves the conservation equations for mass, momentum, species and energy in the limit of the low Mach number approximation, which are written as

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\underline{v}) = 0, \tag{1}$$

$$\frac{\partial \rho\underline{v}}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\underline{v}\,\underline{v}) = -\boldsymbol{\nabla}p + \boldsymbol{\nabla}\cdot\left[2\mu\left(\underline{\underline{S}} - \frac{1}{3}\underline{\underline{I}}\boldsymbol{\nabla}\cdot\underline{v}\right)\right] + \rho\underline{g}, \tag{2}$$

$$\frac{\partial \rho Y_i}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\underline{v}Y_i) = \boldsymbol{\nabla}\cdot(\rho D_i\boldsymbol{\nabla}Y_i) + \rho\Omega_i, \tag{3}$$

$$\frac{\partial \rho T}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\underline{v}T) = \frac{1}{c_p}\boldsymbol{\nabla}\cdot(\lambda\boldsymbol{\nabla}T) + \frac{\rho}{c_p}\sum_{i=1}^{N_i}\Omega_i h_{0,i}. \tag{4}$$

Assuming ideal gas behavior the density is obtained from the thermal equation of state as

$$\rho = p_0 \Big/ \left(R_m T \sum_{i=1}^{N_i}\frac{Y_i}{W_i}\right), \tag{5}$$

dependent of the temperature T, and the thermodynamic pressure $p_0 = 10^5$ Pa being constant. $R_m = 8314$ J/kmol K denotes the universal gas constant and W_i is the molecular weight of species i. The