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Proceedings of the Combustion Institute 36 (2017) 1843–1851

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Flame-vortex interaction: Effect of residence time and formulation of a new efficiency function

F. Thiesset [a,*], G. Maurice [a,b], F. Halter [a], N. Mazellier [b], C. Chauveau [a], I. Gökalp [a]

[a] *CNRS ICARE, Avenue de la Recherche Scientifique, Orléans Cedex 2 45072 France*
[b] *University of Orléans, INSA de Bourges, PRISME, EA 4229, Orléans 45072, France*

Received 3 December 2015; accepted 28 June 2016
Available online 18 July 2016

Abstract

In this study, a combined experimental and numerical investigation of a toroidal vortex interacting with a stagnation premixed flame is carried out with the aim of quantifying the ability of such a vortex to stretch the flame. By scrutinizing the literature, it was found that, although inferred from exactly similar numerical simulations, existing parametric expressions for the efficiency function (the ratio of the flame stretch to vortex strain) do not agree in the way the latter should behave when the ratio of the vortex rotational velocity U_θ to the laminar flame speed S_L is increased. These expressions also appear to be unequally accurate when compared to experimental data and do not feature the non monotonic evolution of the efficiency function with U_θ/S_L which is observed in both experimental data and numerical simulations of a 'isothermal' propagating interface. In addition, whilst previous studies have focused only on the impact of U_θ/S_L and R_v/δ_L (R_v being the vortex typical size and δ_L the laminar flame thickness) our study reveals the importance of other parameters, the most important of which being the residence time of the vortex associated with its convection velocity. These results yield a new formulation for the efficiency function which compares favorably well with experimental data.

Keywords: Flame vortex interactions; Flame stretch; Vortex strain; Residence time

1. Introduction

Understanding and predicting the different mechanisms at play in turbulent premixed flames is a tremendously difficult challenge. The main reason is that there is still a lack of knowledge of the turbulent flow structure which features a large variety of turbulent scales. A given eddy thus experiences many different processes induced by turbulent scales of different sizes, such as vortex stretching and sweeping, diffusion by viscosity, these effects being particularly arduous to model. In addition, when reacting flows are concerned, the

* Corresponding author.
E-mail addresses: fabien.thiesset@gmail.com, fabien.halter@cnrs-orleans.fr (F. Thiesset).

http://dx.doi.org/10.1016/j.proci.2016.06.172
1540-7489

flame does not act as a passive scalar because of its propagative character and the inherent heat release that locally modifies the fluid physical properties. The high local flame curvature and strain, also impact its local consumption or displacement speed in a way which remains poorly understood.

There is thus a need for fundamental investigations of the interactions between the fluid motion and a flame in simplified and well controlled situations. One of these is the case of a flame interacting with a single vortex dipole (see the review by Renard et al. [1]). Pioneer studies of Flame-Vortex Interactions (hereafter abbreviated by FVI) emerged in the 90's with notably Poinsot et al. [2], Roberts and Driscoll [3], Wu and Driscoll [4], Roberts et al. [5], Lee and Santavicca [6] and more recently with Renard et al. [1], Colin et al. [7], Charlette et al. [8], Bougrine et al. [9].

Although some effects such as vortex stretching, sweeping, tilting are not present, FVI are expected to mimic, at least partly, the processes at play in real turbulent flames. The aforementioned investigations on FVI have led notably to the construction of the so-called spectral diagrams which allows to identify the conditions needed for a vortex to stretch the flame, to create pockets of fresh gas or to locally quench the flame. In addition, these results yielded expression of efficiency functions, i.e. the transfer function between vortex strain and flame stretch. In this prospect, Colin et al. [7], Charlette et al. [8] have focused on the effect of vortex size R_v relative to the flame thickness δ_L and vortex rotational velocity U_θ relative to the flame speed S_L. More recently, the effect of Lewis number has been incorporated by Bougrine et al. [9]. These efficiency functions are extremely valuable as they are widely used in LES of turbulent premixed combustion in order to model the sub-grid scale wrinkling factor [7–9].

The aim of the present study is to explore one particular aspect of the interaction between the flow motion and a flame, which we referred to as the *strain-sweeping competition* (see for instance the review by Driscoll [10]). This competition can be conceptually described in terms of time-scales. Based on phenomenological arguments [11], the strain-based time scale τ_s of a scale r with characteristic velocity u_r is $\tau_s \propto r/u_r \propto r^{2/3}$. This time-scale is generally referred to as the eddy turn-over time. Previous studies devoted to FVI investigations [2–9] indicate that the smaller this time scale, the larger is the flame stretch. On the other hand, Tennekes [12] suggested that another relevant time scale in a turbulent flow relates to the sweeping effect by energy-containing eddies. He pointed out that a given scale of size r is convected by the large scales, i.e. with characteristic velocity of the order of u', the root-mean-square of the velocity fluctuations. The sweeping time scale as called by Tennekes [12] thus writes $\tau_c \propto r/u'$. This has been verified experimentally by e.g. Poulain et al. [13]. It is worth stressing that these two phenomenology both lead to the same prediction for the scaling exponent of the energy spectra and are therefore undistinguishable in spectral space. In the field of combustion the sweeping time scale is somehow related to the residence time [10] and basically describes the duration of the interaction of a vortex located in the vicinity of the flame. As far as the sweeping (or residence) time scale is concerned, FVI [3,4] corroborates the intuitive statement that the smaller this time scale, the smaller the flame stretch since the vortex spends less time in the vicinity of the flame for rolling it up. In turbulent flames, there is thus a competition between turbulent strain and turbulent convection, the latter phenomenon acts in decreasing the flame stretch whereas the former has the opposite effect. It is thus worth investigating these effects independently in order to give further insight into their respective influence on the flame. Further, a more complete expression for the efficiency function which accounts for both strain and residence time effects could be derived and used in LES.

In the present study, a new experimental set-up was designed in the goal of quantifying the degree of the interactions between a vortex dipole and a stagnation premixed flame. Some simple numerical simulations based on the 'isothermal' G-equation, have been further carried out and validated against experimental data. Such simulations allow to assess the effect of the convection velocity and rotational velocity independently. Finally, the respective effect of these two phenomena on flame stretch are separately quantified, incorporated into a new formulation for the efficiency function, and compared to experimental data.

2. Experimental apparatus

Investigations are carried out in a single jet stagnation flame configuration which is a modified version of that used by Bouvet et al. [14]. A schematic of the burner is provided in Fig. 1. A laminar strained flame is stabilized against a 4-mm-thick stainless steel plate. The stagnation plate is attached to an alumina foam plug selected for its insulating properties. The fuel and oxidizer are introduced through the side of the burner. A so-called 'particle diffuser cone' filled with 6 mm glass beads is used to ensure a homogeneous mixture in the nozzle plenum. The reactive mixture then flows into the burner plenum through a 5 mm thick aluminum grid. It is finally accelerated in the converging section with a $D = 15$ mm outflow diameter, creating an upward-oriented jet with a nearly top hat velocity profile at the burner exit. The burner-to-stagnation plate distance L was fixed to 25 mm, given a L/D ratio greater than unity as usually recommended. Moreover, it allows to stabilize flames sufficiently far from the plate to track the