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Unsteady effects on flame extinction limits during gaseous and two-phase flame/vortex interactions

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Abstract

In highly fluctuating flows, it happens that high values of the strain-rate do not induce extinction of the flame front. Unsteady effects minimize the flame response to rapidly varying strain fields. In the present study, the effects of time-dependent flows on non-premixed flames are investigated during flame/vortex interactions. Gaseous flames and spray flames in the external sheath combustion regime are considered. To analyse the flame/vortex interaction process, the velocity field and the flame geometry are simultaneously determined using particle imaging velocimetry and laser-induced fluorescence of the CH radical. The influence of vortex flows on the extinction limits for different vortex parameters and for different gaseous and two-phase flames is examined. If the external perturbation is applied over an extended period of time, the extinction strain-rate is that corresponding to the steady-state flame, and this critical value mainly depends on the fuel and oxidizer compositions and the injection temperature. If the external perturbation is applied during a short period of time, extinction occurs at strain-rates above the steady-state extinction strain-rate. This deviation appears for flow fluctuation timescales below steady flame diffusion timescales. This behaviour is induced by diffusive processes, limiting the ability of the flame to respond to highly fluctuating flows. With respect to unsteady effects, the spray flames investigated in this article behave essentially like gaseous flames, because evaporation takes place in a thin layer before the flame front. Extinction limits are only slightly modified by the spray, controlling process being the competition between aerodynamic and diffusive timescales.

Keywords: Non-premixed; Spray; Vortex/flame; Extinction; Unsteadiness

1. Introduction

In non-premixed turbulent flames, chemistry and diffusion processes do not respond to rapidly varying strain fields [1]. The flame acts like a filter, and the scalar fields are only affected by low-frequency, perturbations. When the characteristic timescales of the flow perturbations are comparable to those of diffusion and reaction [2], it is necessary to abandon the steady-state analyses and consider time-dependent effects [3,4]. This aspect is illustrated by experiments of unsteadily strained flames [5,6]. Unsteady effects have also been investigated using time-dependent calculations of strained flames with complex chemistry [7–9] or activation energy asymptotics [10]. It is shown in

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these various studies that, when the frequency of the flow field fluctuation increases, a time-lag appears between the forcing perturbation and the flame response. Above a cut-off frequency the flame response decreases rapidly. It has been observed that the flame can exist beyond the steady-state extinction limit if the modulation frequency is sufficiently high. This is explained to result from an accumulation of reactants in the diffusive layer due to the unsteady straining imposed by the flow [11]. These studies show that the flame response to unsteady strain-rate depends on the fluctuation frequency, the amplitude of this oscillation (related to the maximum strain-rate acting on the flame front), and the initial mean strain-rate. In the present studym this dependence is investigated in the case of flame/vortex interactions.

Vortex/flame interactions are often considered to typify elementary processes of turbulent combustion. During successive interactions, the flame front is submitted to a variable strain field, possibly inducing extinction [12–14]. The fact that a non-premixed flame interacting with a vortex can resist to strain-rates up to 5–10 times the quasi-steady extinction strain-rate [12] once more reveals the importance of unsteadiness in the flame response. The flame response to unsteady strain-rate constitutes a central issue in turbulent combustion [15]. Since the extinction process plays an important role in flame stabilization processes [16], it is of importance to analyse the transition between the non-reacting and the burning state [17]. The present study focuses on the local extinction of non-premixed flames and on the influence of the flow unsteadiness on the flame extinction limits during flame/vortex interactions.

In many practical applications, fuel is introduced in a liquid form, usually as a spray. This modifies the combustion process. Multi-phase turbulent flames typically involve a large set of coupled phenomena such as atomization, dispersion, vaporization, molecular, and turbulent mixing, and chemical reactions. Understanding and modelling of such coupled flow fields is a difficult task. It is, for example, possible to use flamelet concepts for non-premixed turbulent flames extended to spray conditions as discussed in [18]. Understanding the interaction between unsteady laminar flows, sprays, and non-premixed flames may be useful to this type of modelling.

The present study aims at providing information on such processes by considering the interaction between a vortex ring and a non-premixed two-phase counterflow flame. Spray combustion is considered for non-dense droplet clouds in the external sheath combustion regime. The spray vaporizes in an evaporation layer bounding the spray, and the flame is fed by pre-evaporated reactant fluxes. Initial studies of a similar configuration were reported by Santoro et al. [19,20]. It was found that two-phase flames interacting with a vortex sustain instantaneous strain-rates higher than those required for quasi-steady extinction. This conclusion was obtained by comparing two extinction modes, one being the quasi-steady state, the other a vortex-induced situation. In the present experiments, different vortex-induced perturbations interacting with flames are compared to understand how unsteady effects influence the flame response to strain-rate. A non-premixed flat flame is first established near the stagnation plane of a counterflow burner, and vortices are introduced on the fuel-side. The behaviour of the reaction zone is studied using planar laser-induced fluorescence (PLIF) of the CH radical, and vortex-induced strain-rate is simultaneously measured using particle-image velocimetry (PIV). Previous studies were undertaken using qualitative CH concentration and flame surface evolutions during flame/vortex interactions. The influence of the liquid phase on flame extinction and re-ignition is considered in [21]. The strain-rate history is a key parameter in the extinction process. The present study deals with unsteady effects on gaseous and two-phase flame response by analysing the strain-rate at extinction for different unsteady vortex flows.

2. Experimental setup

2.1. Burner device

The experimental device, derived from an initial steady gaseous counterflow burner [22], includes a piston-actuated vortex injection system [23] and a monodisperse spray generator [21].

The burner (Fig. 1) comprises two axisymmetric opposite nozzles of 20-mm diameter, with air in the upper flow and a nitrogen–fuel mixture in the lower flow. The distance between the nozzle outlets is set to 30 mm. The global strain-rate imposed by the steady gaseous injection velocities is kept constant at 90 s^{-1} following the definition of

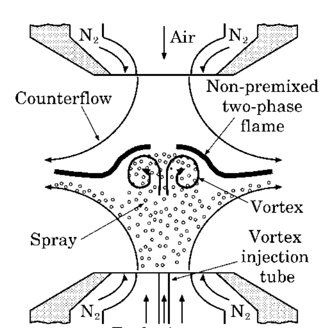

Fig. 1. Schematic representation of a two-phase flame/vortex interaction in opposed-jets burner.