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Characterizing spray flame–vortex interaction: A spray spectral diagram for extinction

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ABSTRACT

The flame–vortex interaction is a preferred configuration for the understanding of flame–turbulence interaction as well as for the development of turbulent combustion models. This configuration has been extensively studied in the literature for gaseous flames. In the present work, we extend this analysis and develop a spectral diagram for the description of spray flame–vortex interaction in analogy to purely gaseous flames in the limit of momentum equilibrium. The focus is hereby on the analysis of competing time-scale effects that are associated with droplet evaporation, mixing and reaction chemistry. Through this analysis, a new extinction scenario is identified that is specific to spray flames as a result of fuel depletion. The derived spectral diagram is confirmed by numerical investigations for n-dodecane counterflow spray flames interacting with a pair of vortices. The different extinction scenarios and their dependence on the evaporation time are numerically studied and verified.

1. Introduction

The fundamental understanding of turbulence-flame interaction is of relevance for practical applications, since turbulence may drastically modify the combustion process by affecting the flame structure, thus possibly impacting pollutant emissions, thermo-acoustic instabilities, local quenching and reignition [1]. With regard to application to Large-Eddy Simulation (LES) and Reynolds-Average Navier–Stokes (RANS) modeling, it is therefore required to accurately model the interaction between the flow field and the flame on the computationally unresolved scales.

In the context of gaseous flames, several studies have been performed to investigate the complex interaction of a vortex with premixed [2–4] and non-premixed flames [5–7] to mimic the turbulence effect on combustion. In particular, a flamelet regime was identified, in which the turbulent flame front is seen as a collection of one-dimensional flames that are stretched and deformed by vortices [5].

Under this assumption, the understanding of flame–vortex interaction is essential for numerous practical combustion applications [1]. The interaction of a pair of vortices with a laminar flame represents a canonical configuration for the theoretical understanding of combustion mechanisms in turbulent flows [8] and the development and validation of turbulent combustion models [9]. Indeed, the effect of a pair of vortices on a laminar flame can be studied to examine several combustion regimes that are representative for turbulent flows [8]. For purely gaseous flames, such an idealized configuration has led to several studies, either in premixed and non-premixed regimes, see [1] for an exhaustive overview. In addition, findings from these studies have led to the construction of combustion spectral diagrams [4,10–12] that are of particular importance for the derivation of new combustion models for turbulent flow applications.

In the context of spray flames, less effort has been made towards the understanding of combustion regimes. In [13], the investigation of a 3D swirled spray flame through Direct Numerical Simulation (DNS) has shown the complexity of spray flames, in which premixed, partially premixed and diffusion reaction zones may coexist. In [14], the authors studied the interaction of a counterflow spray flame with turbulence, confirming the existence of a flamelet regime for spray flames. As such, the study of a spray flame interacting with a pair of vortices may provide a fundamental understanding of the competition between evaporation, mixing and combustion for a range of practically relevant operating regimes. Although flame–vortex interaction is recognized as a canonical configuration for examining the coupling between combustion and turbulence in gaseous configurations, the investigation of spray flames in these configurations has been limited to phenomenological observations [15–18] and asymptotic analysis [19].

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Nomenclature

Dimensionless numbers

Symbol	*Description*	*Definition/Units*
Da	Damköhler number	$\tau_c A_0$
Da^e	Damköhler number at extinction	A_e/A_Γ
Lf	Lefebvre number	τ_v/τ_c
Nu	Nusselt number	hd_0/λ
Pe_0	Peclet number of unperturbed flow	$A_0 r_0^2/D_{th}$
Pr	Prandtl number	ν/D_T
Re_Γ	Reynolds number based on vortex strength	Γ/ν
R	Robustness of the flame	A_e/A_0
Sc	Schmidt number	ν/D
Sh	Sherwood number	kd_0/D
St_p	Stokes number based on droplet drag time and characteristic flow time	$a\tau_p$
St_v	Stokes number based on droplet evaporation time and characteristic flow time	$a\tau_v$
$\mathrm{St}_{v,\Gamma}$	Stokes number based on droplet evaporation time and characteristic vortex time	$A_\Gamma \tau_v$
Greek symbols		
δ_L	Flame thickness	m
δ_{ij}	Kronecker delta function	–
ΔV	Control volume	m^3
Γ	Vortex strength	$\mathrm{m}^2\ \mathrm{s}^{-1}$
$\tilde{\Gamma}$	Non-dimensional vortex strength	–
κ	Stretch rate	s^{-1}
λ	Thermal conductivity of gas phase	$\mathrm{W\ m^{-1}\ K^{-1}}$
μ	Dynamic viscosity of gaseous mixture	$\mathrm{kg\ m^{-1}\ s^{-1}}$
$\hat{\mathbf{n}}$	Unit vector normal to flame	–
ν	Kinematic viscosity of the gaseous mixture	$\mathrm{m}^2\ \mathrm{s}^{-1}$
$\dot{\omega}_k$	Net production rate of species k	$\mathrm{kg\ m^{-3}\ s^{-1}}$
$\dot{\omega}_T$	Heat release	$\mathrm{kg\ \ K\ m^{-3}\ s^{-1}}$
$\dot{\Omega}_T^*$	Overall heat release at symmetry axis normalized by steady reference value	–
ρ	Gas density	$\mathrm{kg\ m^{-3}}$
ρ_l	Liquid density	$\mathrm{kg\ m^{-3}}$
σ	Viscous stress tensor of gas phase	s^{-1}
τ_c	Chemical time scale	s
τ_p	Droplet relaxation time	s
τ_q	Quenching time scale	s
τ_v	Droplet evaporation time	s
θ	Angular coordinate in vortex reference frame	rad
Roman symbols (lower case)		
a	Local strain rate	s^{-1}
c_l	Heat capacity of the liquid phase	$\mathrm{J\ kg^{-1}\ K}$
c_p	Heat capacity of the gas phase	$\mathrm{J\ kg^{-1}\ K}$
d_0	Droplet diameter at injection	m
$\mathbf{f}_d$	Drag force acting on droplets	N
f_1	Drag coefficient	–
f_2	Correction factor for heat exchange	–
f_∞	Ratio between laminar flame speed and propagation speed of triple flame	–
h_k	Enthalpy of species k	$\mathrm{J\ kg^{-1}}$
l_T	Characteristic vortex length	m
l_v	Latent heat of vaporization	$\mathrm{J\ kg^{-1}}$
m_d	Droplet mass	kg
$n_{C,k}$	Number of carbon atoms of species k	–
p	Pressure	Pa
p_s	Saturated pressure	Pa
r	Radial coordinate in vortex reference frame	m
r_0	Radius of vortex ring	m
r_v	Inner radius of a vortex	m
$\dot{S}$	Source term induced by spray evaporation	$\mathrm{kg\ m^{-3}\ s^{-1}}$
s	Separation distance between counter-rotating vortices	m
$\mathbf{u}_d$	Droplet velocity	$\mathrm{m\ s^{-1}}$
u_i	ith component of gas velocity	$\mathrm{m\ s^{-1}}$
u_T	Characteristic speed of vortex	$\mathrm{m\ s^{-1}}$
$\mathbf{x}_d$	Droplet position	m
$\tilde{x}$	Physical coordinate along injection direction in vortex reference frame	m
x	Physical coordinate in injection direction	m
x_i	Physical coordinate in ith direction	m
x_v	Initial position of vortex along injection direction	m
x_{st}	Axial position of stagnation plane	m
$\tilde{y}$	Physical coordinate normal to injection direction in vortex reference frame	m
y	Physical coordinate normal to injection direction	m
y_v	Initial position of vortex normal to injection direction	m
Roman symbols (upper case)		
A_0	Unperturbed flow strain rate	s^{-1}
A_e	Critical extinction strain rate	s^{-1}
A_Γ	Strain rate induced by vortex	s^{-1}
B_M	Spalding number	-
D_k	Molecular diffusivity of species k	$\mathrm{m}^2\ \mathrm{s}^{-1}$
D_{th}	Thermal diffusivity	$\mathrm{m}^2\ \mathrm{s}^{-1}$
L_x	Separation distance between injectors	m
L_y	Vertical domain length	m
N_s	Total number of species	–
S_d	Displacement speed	$\mathrm{m\ s^{-1}}$
S_L	Laminar flame speed	$\mathrm{m\ s^{-1}}$
T	Temperature of gas phase	K
T_d	Droplet temperature	K
U_F	Flame-front velocity	$\mathrm{m\ s^{-1}}$
W	Molecular weight of mixture	$\mathrm{kg\ mol^{-1}}$
W_k	Molecular weight of species k	$\mathrm{kg\ mol^{-1}}$
Y_k	Mass fraction of species k	–
Z_g	Gaseous mixture fraction	–

The objective of this work is to extend the knowledge of spray flame–vortex interaction by combining theoretical and numerical analyses. In particular, the interaction of a pair of vortices with a spray flame in the limit of zero slip velocity is considered in order to identify the effect of evaporation on combustion regimes for turbulent spray flames. Particular attention is attributed to the investigation of local extinction. A new combustion diagram that is generalized to spray flames is here analytically derived by following the work of Vera et al. [11] for purely gaseous flames. This regime diagram is subsequently verified through detailed numerical simulations.

The remainder of this paper is organized as follows. We first present in Section 2 the theoretical derivation of the new spectral diagram for spray flame–vortex interaction, following the rationale of [11]. The modeling approach that is used for the computational verification and the computational approach are presented in Section 3. Numerical results are presented in Section 4, first examining the steady state structure of the counterflow flame. Examples of possible scenarios of spray flame–vortex interaction are analyzed to highlight different responses of a spray flame to the vortex passage compared to the corresponding gaseous flame. To verify the theoretically developed spectral diagram, the role of the evaporation time is finally characterized. The paper finishes with conclusions.

2. Spectral diagram for spray flame–vortex interaction

2.1. Background: gaseous flame–vortex interaction

The flame–vortex interaction is a canonical configuration for examining basic phenomena that control the coupling between combustion and turbulence. By considering this configuration, Renard et al. [1] developed a fundamental understanding of different combustion modes that are summarized in a so-called "spectral diagram". With relevance to the present work, we briefly summarize the classical results for gaseous flames.

The configuration consists of a strained non-premixed flame, in which a nitrogen-diluted fuel mixture is injected against an oxidizer stream (see Fig. 1(a)). The flame has a characteristic flame-front