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Flame propagation in multiscale transient periodic flow

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ABSTRACT

The influence of a periodic multiscale transient flow on isothermal-flame propagation is examined computationally. It is found that the increase in flame surface area, and hence the burning speed, due to wrinkling by the flow depends quadratically (linearly) on the intensity of the flow-field velocity fluctuations at low (high) intensities, while the dependence is consistent with a 4/3 power law for an intermediate range of intensities, consistent with results from earlier studies of flame propagation in weakly exothermic turbulent flows. Particular contributions of this work are elucidation of (a) the quantitative extent of the burning-speed enhancement for low and moderate intensities, (b) the influence of the multiscale character of the excitation flow and (c) the stabilization of flame surface-area growth after the initial period of unbounded growth revealed in earlier work. The effect of multiple excitation-flow scales on surface-area enhancement is found to be minor at low excitation-flow intensities but substantial at large intensities.

1. Introduction

The present study investigates solutions of the advection-propagation (AP) equation below, which describes the evolution of the scalar distribution $G(\mathbf{x}, t)$ and the motion of its isoscalar surfaces, which are advected at the local flow velocity $\mathbf{U}(\mathbf{x}, t)$ while propagating relative to the flow at the speed S_N in the direction of its normal $\mathbf{n}(\mathbf{x}, t) \equiv \nabla G/|\nabla G|$.

$$\frac{\partial G}{\partial t} + (\mathbf{U} - S_N\,\mathbf{n}) \cdot \nabla G = 0 \tag{1}$$

Markstein and Squire [1] were the first to use this equation to describe the advection and propagation of flame surfaces, with a particular isoscalar of G defining the spatial location of a flame surface propagating normal to itself into the reactants while being advected by the flow. A form of Eq. (1) describing general interface motion was introduced earlier [2]. The AP equation has been employed in many analytical studies of flame-front stability (e.g., [1,3–5]) and used by others [6–8] to investigate interface propagation in turbulent flow. Osher and Sethian [9] developed the first stable numerical methods for the solution of the equation for front propagation in quiescent flow. Eq. (1) is currently more generally known as the level-set equation, governing the evolution of a level-set function G the isoscalars of which represent surfaces (level sets) moving with the velocity $d\mathbf{x}/dt$ locally. The AP equation is a special case in which $d\mathbf{x}/dt \equiv \mathbf{U} - S_N\,\mathbf{n}$, with S_N representing the local normal propagation speed of a particular level set (e.g., the "zero level set", corresponding to $G = 0$) and $\mathbf{U}$ representing the velocity of its advection by the flow locally.

In general, S_N depends on local properties of the advection field $\mathbf{U}$ (e.g., the strain rate) and the scalar distribution G (e.g., the surface curvature) [1,3,5,7,9–25]. However, the present work is restricted to Huygens propagation, for which S_N is assumed constant and equal to the laminar-flame speed S_L with which an adiabatic planar flame would propagate through the given reactant mixture. This restriction is necessary for elucidation of the role of early-time transient flame-surface growth and stabilization [26,27] on the burning rate in low-intensity excitation flow due to Huygens propagation, independent of thermal-diffusive influences on flame stability (associated with flow strain and curvature) that may be comparable in magnitude.

In the present study the AP equation is solved for the evolution in time of flame-surface area resulting from the corrugation of the flame by a prescribed transient multiscale periodic excitation flow through which the flame propagates. This is of interest because the fractional increase in the burning speed of the flame above the planar-flame speed S_L is a result of and equal to the fractional increase in the flame-surface area above the planar-flame area caused by the excitation flow, as described earlier [5]. Prescription of the excitation flow is possible since heat release by the flame is assumed herein to be negligibly small, so that no influence of flame dynamics on the excitation flow can occur. Many

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Nomenclature

$\mathbf{U}$	flow-field velocity
$\mathbf{u}$	flow-field velocity fluctuation about the mean
u'	flow-field velocity fluctuation intensity
$\hat{u}'$	u'/S_L
S_L	laminar-flame speed
S_N	local normal flame propagation speed
U_T	average corrugated-flame burning speed
G	scalar distribution, level-set function
$\mathbf{n}$	flame surface normal
$\mathbf{u}_{ave}$	average velocity fluctuation over the surface-advection characteristic
$\mathbf{x}_f$	the level set (collection of grid points defining the flame-surface location)
$\hat{A}$	time-dependent ratio of the corrugated-surface area to that of the initially planar flame
N	number of discrete scales (modes) of the excitation flow
L	width of the computational domain along each coordinate in the transverse plane perpendicular to the direction of mean flame propagation
λ	low-intensity burning-speed correlation constant
γ	maximum magnitude of the level-set function
τ_{fn}	fundamental period of surface-area fluctuations
τ_{fn}^0	low-intensity limit of the fundamental period of surface-area fluctuations
τ_s	burning-speed stabilization time

Nondimensionalization units

Length	L
Time	L/S_L
Speed	S_L

earlier studies have considered effects of gas expansion due to heat release on turbulent flame propagation [7,28–39], including its potential role in flame-surface-area destruction in high-Damköhler-number turbulence [40]. However, attention here is restricted to isothermal, solenoidal excitation flow to allow elucidation of the role of early-time transient flame-surface growth and stabilization [26,27] on the burning rate in low-intensity excitation flow due to Huygens propagation, without presence of the Darrius–Landau instability associated with gas expansion due to dilatation. A primary goal of the present work is an evaluation of earlier predictions of the burning speed in weekly turbulent flow under assumptions of negligible flame stretch and heat release, as described below.

Theoretical modeling has predicted quadratic dependence of the overall propagation rate U_T of a weakly wrinkled quasi-planar premixed-flame surface with constant local normal propagation speed $S_N = S_L$ on the fluctuation intensities of a stationary advection field [6,41–43]. Specifically, these models predict that

$$U_T/S_L - 1 = \lambda\left(u'/S_L\right)^2,\ u'/S_L \ll 1, \tag{2}$$

where u' is the root mean square of the advection-field velocity fluctuations, assumed to be isotropic, and λ is a constant numerical factor equal to 0.5 [43], 1 [41] or 2 [6,42]. However, the work of Kerstein and Ashurst [27] suggests that the quadratic dependence of the flame speed on intensity given in Eq. (2) likely holds only for the earliest stage of flame wrinkling in turbulent flow and that quasi-steady front propagation is governed by a less sensitive dependence according to

$$U_T/S_L - 1 \sim \left(u'/S_L\right)^{4/3},\ u'/S_L = O(1), \tag{3}$$

at a later stage where influences of Huygens front propagation are important.

Batchelor predicted analytically that the area of a non-propagating material surface increases exponentially in time by the action of turbulent strain [44]. Recently, it has been demonstrated both analytically and numerically [26] that without Huygens surface propagation ($S_N = 0$) the area of a surface advected by a temporally and spatially periodic excitation flow increases monotonically in time and without bound under conditions consistent with those considered in the earlier investigations of Clavin and Williams [41] and Aldredge [6]. This instability of the non-propagating surface is due to the nonlinearity of the level-set equation governing the evolution of the surface location, in which the excitation-flow velocity $\mathbf{U}(\mathbf{x}, t)$ in Eq. (1) must be specified at locations $\mathbf{x}$ on the evolving surface—c.f., Eq. (13) in [26] and discussion therein. The instability becomes apparent at all excitation-flow intensities unless the nonlinearity of the level-set equation is neglected, as in the earlier linear analyses of Clavin and Williams [41] and Aldredge [6] used to predict the correlation in Eq. (2) above for the limit of low-intensity excitation flow. The instability is eventually terminated when it reaches equilibrium with the balancing influence of surface-area annihilation associated with Huygens surface propagation. The final extent of surface corrugation when this equilibrium is achieved and it's dependence on the multiscale nature of the excitation flow at low, moderate and high excitation intensities is the subject of the present study.

2. Formulation

As in the earlier referenced analyses [6,26,41], the excitation flow prescribed in the AP equation is assumed to have the mean speed S_L along the mean direction (x) of quasi-planar flame propagation and to satisfy Taylor's hypothesis:

$$\mathbf{U}(\mathbf{x}, t) \equiv S_L\hat{\mathbf{e}}_x + \mathbf{u}(x - S_L t,\ y,\ z) \tag{4}$$

Introducing the decomposition specified in Eq. (4) into Eq. (1) and transforming to the nondimensional coordinates $(\bar{\mathbf{x}}, \bar{t})$ of a reference frame moving at the mean flow-field velocity S_L gives

$$\frac{\partial \bar{G}}{\partial \bar{t}} + \bar{\mathbf{u}}(\bar{\mathbf{x}}) \cdot \bar{\nabla}\bar{G} = \left|\bar{\nabla}\bar{G}\right|, \quad \bar{\mathbf{x}} \equiv (\bar{x}, \bar{y}, \bar{z}) \tag{5}$$

where the overbars denote nondimensionalization according to $\bar{x} \equiv (x - S_L t)/L$, $\bar{y} \equiv y/L$, $\bar{z} \equiv z/L$, $\bar{\nabla} \equiv L\nabla$, $\bar{t} \equiv t\,S_L t\,/L$, $\bar{\mathbf{u}} \equiv \mathbf{u}/S_L$ and $\bar{G} \equiv G/L$; where L is the width of the computational domain, assumed to be the same along each of the coordinates in the transverse plane perpendicular to the direction of mean flame propagation. Eq. (5) will be solved computationally, subject to the following initial and boundary conditions.

$$\left.\begin{aligned} \bar{G}(\bar{\mathbf{x}}, \bar{t} = 0) &= \bar{x} \\ \bar{G}(|\bar{\mathbf{x}} - \bar{\mathbf{x}}_f| > \gamma, \bar{t}) &= \gamma\, sign(\bar{G}) \\ \bar{G}(\bar{x}, \bar{y} = 1, \bar{z}, \bar{t}) &= \bar{G}(\bar{x}, \bar{y} = 0, \bar{z}, \bar{t}) \\ \bar{G}(\bar{x}, \bar{y}, \bar{z} = 1, \bar{t}) &= \bar{G}(\bar{x}, \bar{y}, \bar{z} = 0, \bar{t}) \end{aligned}\right\} \tag{6}$$

These conditions define an initially planar flame in the transverse plane $(\bar{y}, \bar{z})$ as the zero level set ($\bar{G} = 0$). Negative values of $\bar{G}$ correspond to regions of reactant flow upstream of the propagating flame, while positive values correspond to regions containing combustion products. Periodic conditions are satisfied by $\bar{G}$ on the domain boundaries along the $(\bar{y}, \bar{z})$ axes, while $\bar{G}$ is prescribed a maximum (minimum), constant value of γ $(-\gamma)$ in product (reactant) regions sufficiently far away from the flame location ($\bar{\mathbf{x}}_f$), in order to facilitate the reinitialization of $\bar{G}$ during the computational simulation to achieve $|\bar{\nabla}\bar{G}| = 1$ near the flame surface, for improved accuracy.

Both monochromatic and multiscale solenoidal excitation flows are considered herein, with $\bar{\mathbf{u}} = \mathbf{u}_N/S_L$ as defined below representing an excitation having N disparate scales. The monochromatic