

# Critical channel widths and flame front dynamics in curved premixed flames: Mach number dependence

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## ABSTRACT

This study numerically investigates the Mach number influence on the stability limits of stationary curved premixed flames. The numerical study is conducted over a range of realistic Mach numbers and varying channel widths. The results reveal that the stationary flame velocity increases with Mach number, consistent with prior studies. Notably, the study identifies two critical channel widths: (i)  $D_{cr}$ , at which the Darrieus-Landau instability first occurs, and (ii)  $D_{sc}$ , beyond which the flame velocity surpasses theoretical predictions based on weakly nonlinear analyses and the stationary curved flame velocity grows monotonically with increasing channel width. The second limit  $b = D_{sc}/D_0$  is shown to decrease as the Mach number increases. Moreover, the transitions to the asymmetric flame front are observed for nearly isobaric Mach number in wide channels. It is investigated that with the decrease in the Mach number, the stationary curved flame velocity is closer to the analytical prediction.

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## 1. INTRODUCTION

The hydrodynamic instability, first analyzed by Darrieus<sup>1</sup> and Landau,<sup>2</sup> is an inherent feature of all gaseous combustible flames, arising from gas expansion during exothermic reactions. In the description of the Darrieus-Landau (DL) instability, the flame front is conceptualized as an infinitely thin interface of zero thickness that propagates at a constant velocity relative to the fuel. This interface separates the unburned and burned regions, each characterized by constant densities. The discontinuous interface renders the flame front unconditionally unstable, leading to significant effects on both the flame front morphology and the propagation velocity.<sup>3–5</sup>

In the case of an equidiffusive laminar flame, an initially planar flame propagating in channels can develop a stationary curved flame front as a result of the DL instability.<sup>6–7</sup> The planar flame propagates at the laminar burning speed  $S_L$ , which is a fundamental parameter determined by the chemical and transport properties of the fuel

mixture. When the channel width is sufficiently large, the flame front becomes curved and achieves a stationary curved flame velocity  $U_{sc}$  larger than the laminar burning velocity  $S_L$ .<sup>8,9</sup> The dynamics of the hydrodynamic instability during this process have been extensively investigated in both the linear<sup>10,11</sup> and nonlinear regimes<sup>12–14</sup> under the isobaric flow approximation. For two-dimensional (2D) flows, the curved flame velocity with channel width  $D$  can be described by a piecewise parabolic formula,<sup>15</sup>

$$U_{sc} = S_L + 4U_{sc}(N\lambda_c/D)(1 - N\lambda_c/D), \quad (1)$$

where  $N = \text{Sc}[(D/2\lambda_c) + 1/2]$ ,  $\lambda_c$  is the cutoff wavelength, and  $U_{sc}$  represents the maximal flame velocity, which is a function of the gas expansion ratio  $\Theta$ ,

$$U_{sc} = S_L[\Theta/2][(\Theta - 1)^2(\Theta^3 + \Theta^2 + 3\Theta - 1)]. \quad (2)$$

# Dynamics Of Curved Flames In Compressible Flows

**Paul Clavin, Geoff Searby**



## **Dynamics Of Curved Flames In Comprisable Flows:**

*Dynamics of Curved Flames in Compressible Flows* Oleg Travnikov, 1999      Swirling Flows and Flames Toufik Boushaki, 2019-06-26 Swirl flows are used in a wide range of industrial applications In non reacting cases examples of applications include vortex amplifiers and reactors heat exchangers jet pumps and cyclone separators In reacting cases swirlers are widely used in combustion systems such as gas turbines industrial furnaces boilers gasoline and diesel engines and many other practical heating devices Effects of using swirl on flow and combustion are significant and varied and concern for example aerodynamics mixing flame stability intensity of combustion and pollutant emissions The purpose of this book is to present recent research efforts to understand and characterize swirling flows of different types and in different applications These include gaseous liquid and solid fuels in order to enhance combustion systems and their energy efficiency Swirl flows are very complex and the studies proposed in this project are based on different means including theoretical calculations numerical modeling and experimental measurements      Flame Dynamics in Steady Strained Flows Zili Huang, 1999 In this dissertation the response of a premixed flame to time dependent strained flow fields is investigated Because of the potential application to turbulent combustion modeling the main focus is on the particular case of a flame in stagnation point flow with an imposed oscillatory strain rate The flame is modeled as a hydrodynamic discontinuity separating burned from unburned gasses To complete the formulation of the problem conditions relating the fluid variables across the flame front are needed as is a flame speed equation that determines the evolution of the discontinuity These conditions are derived through asymptotic analysis of the flame structure In the first part of this dissertation an existing hydrodynamic model is employed to assess flame response to oscillating stagnation point flow The model is valid for near equidiffusional conditions i e for near unity Lewis numbers Under these conditions the flame speed varies linearly with strain Unlike previous theoretical investigations the present formulation places no restrictions on the amplitude of the oscillations and we account for the full interaction between the flame and the flow Solutions are constructed by a combination of asymptotic and numerical methods Results regarding flame response are in agreement with previous experiments and studies We also obtain the following results as a consequence of the underlying time periodic flow a the mean flame position is shifted upstream from the steady state location b a region of reverse flow appears immediately ahead of the flame front during part of each cycle and c there is a maximum amplitude of oscillation beyond which the flame fails to exist These results are most pronounced at high frequencies and agree with the asymptotic solution constructed in that regime In the second part of this dissertation a new model is derived which exhibits a nonlinear dependence of flame speed on strain The model is valid for arbitrary Lewis number and unlike previous models it allows for an unsteady flame structure Asymptotic methods are used to construct solutions across the narrow flame zone and reaction zone and asymptotic matching then yields the nonlinear flame speed equation The new model is then employed to investigate flame response to unsteady strained flows

Our results predict that the flame becomes most sensitive to fluctuations in the flow as steady state extinction conditions are approached. Also at high frequency the flame response is the same regardless of the mixture properties. These results are in good agreement with experiments.

Dynamics of Interacting Turbulent Flames Ankit Tyagi, 2019. This dissertation investigates the physics of interactions between turbulent premixed flames. It is known that multiple flame configurations provide better stability characteristics compared to a large single flame. However, the advantages of multiple flames are limited by flame proximity as flame-flame interactions tend to reduce the burning efficiency of the reactant gases. Previous studies have shown that interactions between multiple flames directly impact the flame structure and its propagation, resulting in reduced burning efficiency. Previous experimental studies of interacting flames addressed flame-flame interactions by investigating their effects on combustor stability and efficiency from a global perspective. However, the local flame-flame interaction physics was not addressed comprehensively in part because these studies were limited to specific flow and flame configurations. In particular, these studies focused on swirling flames in bluff body configurations typical of modern combustor geometries. Furthermore, these studies lacked flowfield measurements and were limited to flame structure and heat release rate measurements due to the complex nature of the experimental configurations. Much of the work to date on understanding the local physics of interactions comes from direct numerical simulations (DNS), but these studies treated idealized configurations of limited practical utility. To bridge these two gaps, an experimental investigation of flame-flame interactions was performed using a dual burner rig composed of two flames built to facilitate precise variations in flame spacing. This rig was designed to operate in different configurations. These facilitated the focus on local interaction physics. In particular, the rig was built to study interacting V flames and Bunsen flames. Moreover, the design of the dual burners permitted conducting studies of nonreacting flow interactions with flames to better understand local physics of the flame. Direct flame and flow measurements were performed to characterize the mutual interaction of flame and the local flowfield. In particular, flame structure and flow were characterized using synchronized OH planar laser induced fluorescence (OH PLIF) and stereoscopic particle image velocimetry (sPIV). These measurements were performed at a sampling rate of 10 kHz to obtain converged statistics on flame-flame interactions. A novel image processing technique was implemented for robust detection and characterization of flame-flame interaction events from OH PLIF images. Using this experimental approach, the following studies were conducted: i) effects of flame spacing on flame structure of interacting V flames; ii) effects of multiple flames on frequency topology and orientation of local flame-flame interactions; iii) effects of high mean shear flow on flame-flame interactions; and iv) effects of pocket formation on flame dynamics. In the first study, flame spacing variations in V flames were found to directly impact flame attachment. For smaller flame spacings, recirculation of hot combustion products near the bluff bodies facilitated a secondary flame branch attachment in the shear layers in the interaction regions. For larger flame spacing, the secondary attachment became intermittent, indicating that closer flame spacing resulted in better attachment.

and stability characteristics for these flames In the second study the presence of adjacent flames was found to directly impact the frequencies of flame flame interaction events Dual flames showed lower reactant side interactions rates and higher product side interactions rates when compared with single flames For dual flames comparisons between interaction orientation and local strain rate orientation showed that compressive forces led to flame front merging or pinch off The third study which focused on how mean shear affects the local flame dynamics found that high mean shear flows entrained the flame away from the center of the burner This entrainment directly reduced interaction event frequencies along the flame branch closest to the high mean shear flow while interaction event frequency in the other branch increased Finally flame pocket formation was investigated and results showed that a majority of the reactant pockets burned out while a majority of the product pockets merged with the flame surface These results suggested that pocket behavior in turbulent flames can change local flame dynamics and it is important to capture these effects to accurately predict flame behavior Additionally limitations of planar high speed imaging techniques were explored and a statistical framework using probabilistic models was presented in the context of reactant pocket propagation The outcome of this work provided improved uncertainty estimation for planar measurements in three dimensional flows This experimental investigation provided deeper insights into the local physics of flame flame interactions in practical configurations using detailed flame and flow measurements The presence of adjacent flames influenced the attachment characteristics and local flame structure that directly impacted the stability of these multiple flame configurations Local compressive forces facilitated the occurrence of these events highlighting the importance of changes to the flowfield due to adjacent flames Pocket formation which directly affected reactant gas burning efficiency was found to occur frequently Taken together these results provided comprehensive insights into the effects of flame flame interactions that enhance our understanding of the nature of interacting flames

**Combustion Waves and Fronts in Flows** Paul Clavin, Geoff Searby, 2016 A self contained presentation of the dynamics of nonlinear waves in combustion and other non equilibrium energetic systems for students and specialists

**Sæsonudjævning** Erhvervs- og byggestyrelsen, 2004

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