Formation and evolution of distorted tulip flames

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A B S T R A C T

The development and evolution of tulip and distorted tulip flames in closed channels were simulated by solving the fully compressible reactive Navier–Stokes equations using a high-order numerical method and a single-step Arrhenius model for the reactions and energy release in a stoichiometric mixture of hydrogen and air. Important features of the simulations include (1) the development and propagation of acoustic waves and their effects on flame evolution, (2) the formation and collapse of flame cusps, both at the flame front and near the sidewalls, and the effects of cusp collapse on flame propagation, and (3) the appearance of adverse pressure gradients at the onset of the tulip or a distorted tulip flame, which result in reverse flow in the unburned gas. The simulations highlight the coupling between pressure waves, adverse pressure gradients, boundary layers, and the propagating flame front. Whereas the formation of the tulip flame can be attributed to several effects (such as pressure waves, vortex motion and Landau–Darrieus instabilities), the onset of the distorted tulip flame is strongly influenced by the Rayleigh–Taylor instability.

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1. Introduction

The understanding of the dynamics of premixed flames propagating in tubes is important in a wide range of combustion processes and applications, including gas explosions in confined regions and energy production by internal combustion engines [1–12]. A premixed flame propagating in a tube is actually a complicated, dynamic process, involving all of the complexities of ignition, development of a laminar flame, and the subsequent interactions of this flame with boundary layers and pressure wave under changing background conditions. The initial laminar flame that can evolve from a small spark is intrinsically unstable due to a variety of hydrodynamic and combustion instabilities, such as Darrieus–Landau (DL), thermal-diffusive, and Rayleigh–Taylor (RT) Instabilities [2,13,14]. The flame may accelerate quickly and undergo a series of changes in its shape. It may then further evolve into a turbulent flame, and deflagration-to-detonation transition (DDT) is even possible, depending on the reactive material and confinement geometry [1,2,10,15].

In this paper, we examine the development of an initially laminar flame that becomes a "tulip flame," a term that qualitatively describes the flame shape, and subsequently becomes a "distorted tulip flame" (or DTF). The initial laminar flame may be convex, due to the confinement of the tube and interaction with boundary layers ahead of the flame. Subsequently, this shape may invert to become a concave propagating tulip flame. (See, for example, the first figure in [16]). Tulip flames were first observed photographically [17], where it was shown that these structures develop in closed tubes when the aspect ratio of the tube is greater than two. The transition to a tulip flame is also accompanied by a sudden decrease in flame propagation speed. After a tulip flame forms, it generally propagates down the tube until combustion is complete. In very long tubes, for example, tubes with aspect ratios greater than 20, tulip flames collapse at some point, again become convex toward the unburned mixture, and then finally develop again into a tulip flame [18]. In addition, more recent experimental work has shown the development of multiple tulip flame shapes at a flame front [19,20].

There have been many investigations of the physical process leading to formation of a tulip flame. To date, however, there is no decisive, single explanation of the physical mechanism by which they form. Various elements of existing explanations include interactions of the flames with pressure waves [18], effects of viscosity and flame quenching [4,17], hydrodynamic instabilities [16,21–23], vortex structures forming in the burned gas [3,24–26], and Rayleigh–Taylor instabilities [5].

Now we focus on the behavior of a premixed hydrogen–air flame, initially at atmospheric pressure and temperature, propagating in a closed tube. Information from fully compressible two-dimensional (2D) numerical simulations is combined with results of prior experiments [20] to give a detailed description of the evolution of the flame-front structure. We describe the formation of the flame into a tulip flame, and the subsequent development of distorted and multiple tulip flames. All of these complex flame structures evolve

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from a single small ignition. It is hoped that descriptions of the physical processes, derived from the computations, will help us to understand the interactions among the flame front, fluid dynamics, boundary layers, and pressure waves.

2. Background

Here we review a selected group of the many papers on tulip flames, focusing on the work we believe is most relevant to the DTF. In the process, we note those results that seem to be contradictory and that show that we do not completely understand the controlling mechanisms.

Clanet and Searby [5] conducted an experimental and analytical study of tulip-flame evolution. From their analysis, they concluded that neither acoustic effects nor boundary layers are dominant in the tulip flame formation. They also suggested that the RT instability was important, but this mechanism has not been fully supported by their or any later theory. Subsequent numerical simulations, all using zero-Mach-number models [16,24,27], which could not take acoustics into account, showed that tulip flames can be produced without including the effects of pressure waves. In addition, these studies concluded that tulip flame formation is sensitive to system parameters, such as the geometry of the combustion chamber, boundary conditions at the walls, and the mixture composition.

Gonzalez et al. [28] carried out a parametric study of tulip flame formation in an enclosure by means of extensive 2D numerical simulations with a "thickened-flame" model. They concluded that the transverse velocity gradient and DL instability are two crucial mechanisms for the development of tulip flames. As these authors indicated, their simulations suffered from severe inaccuracies in representing the viscosity terms. They also suggested that wall friction is not important for the formation of a tulip flame. In juxtaposition to this, Marra and Continillo [27] argued that wall friction *is* the determining cause for the initiation of a tulip flame. Their conclusions were based on computations that solved the full Navier–Stokes equations, again, assuming zero-Mach number. It is interesting that these models, which did not include acoustic effects, were able to produce tulip flames.

It has also been shown that the vorticity field is important. In the process of tulip flame formation, vortices created near the flame front in the burned gas were reported in many experimental and numerical studies [6,19,29–31]. Matalon and Metzener [3,26] proposed a mathematical theory to support the explanation that the tulip flame is caused by vortical motion in the burnt gas. Nevertheless, an inviscid numerical simulation with restrictions to irrotational flow described by Dunn-Rankin et al. [16] showed the formation of a tulip flame in the absence of vorticity effects. Vortices can also be generated by a curved flame [32]. For example, a pair of vortices in the burnt region can be created by the cusp of a curved flame arising from DL instability. Although the onset of flame-front inversion that leads to a tulip flame may be related to the DL instability [21,33], the tulip flame cannot be explained simply by linear stability analysis of DL instability [3,26].

Bychkov et al. [34], following the work of Clanet and Searby [5], suggested an analytical model for the acceleration of a finger-shaped flame and the initiation of a tulip flame in the early stages of laminar flame propagation in open long tubes. They found that the acceleration of the finger-shaped flame and tulip flame formation do not depend on Reynolds number. For fast flames propagating in these tubes, such as those of hydrogen–oxygen flames, compressibility can play a role in the flame acceleration and tulip flame evolution [35].

Recently, an additional complication was added by the discovery of the distorted tulip flame [19,20,36]. These structures appear as additional cusps on the lips of the original tulip flame. Under some conditions, a second DTF formed on the lips before the first DTF collapsed [20]. The experiments [19,20,36] demonstrated that DTFs can be pro-

duced in the equivalence ratio range $0.84 \leq \phi \leq 4.22$ in premixed hydrogen–air (corresponding to hydrogen concentration 26–64% by volume in air). The distortions, which appeared as secondary cusps, originated in the vicinity of the tips of the primary tulip flame lips and moved toward the primary cusp as the flame evolved. (This is discussed and shown more clearly in text below). The initiation of a DTF is consistent with a sudden decrease in both the speed of the leading flame front and the growth rate of the pressure. The authors suggested that these phenomena, which were accompanied by flame oscillations, may be due to the strong coupling between the flame and pressure waves. Another speculation is that cellularity due to thermal-diffusive instabilities might be of minor importance for the formation and evolution of DTFs, since the Lewis number for a mixture that generated a DTF ranged from approximately 0.9–2.2 [37].

The mechanism of the DTF formation remains unresolved. Previous numerical studies [19,38] could not resolve enough of the possible controlling phenomena because they used numerical algorithms that were both too diffusive with inadequate resolution. As a result, they could not provide enough detail to analyze the interactions among the flame front, pressure waves and boundary layers. Although a second DTF was observed in the previous experiments [38], until now we did not have simulations that would allow us to explore how the flame evolves after the second DTF, and then through to the final stages of combustion.

What is needed for further discussion of DTFs is an understanding of the interaction between the flame fronts, boundary layers, and pressure waves generated by the flame as it propagates down the tube, and how these interactions might affect flame instabilities. As noted above [20], it was suggested that pressure waves might play an important role in the formation of the DTF, possibly because of a RT instability. There is, however, neither a rigorous demonstration nor a detailed examination of the interaction between the DTF and pressure waves. For example, it is not clear how pressure waves are generated, propagate, and play a role in flame instabilities.

The purpose of this paper is to study the dynamics and evolution of DTFs using unsteady, fully compressible solutions of the Navier–Stokes equations with accuracy and resolution sufficient to resolve pressure waves and their interactions with flames and boundary layers. These results are then described and compared to prior experiments.

3. Physical and numerical models

Now we describe the physical and numerical models, and then compare the numerical results to the theoretical predictions [39] and the prior experimental observations [20]. The current numerical model has been extensively used in a variety of combustion and explosion problems [10,40–46]. Comparisons shown below provide further tests and demonstration of its reliability and accuracy for predicting transient combustion processes.

The 2D computational domain considered in Fig. 1 shows a $d \times l$ cm closed rectangular channel. Note that only half of the channel is simulated. Extensive prior tests comparing full and half channel
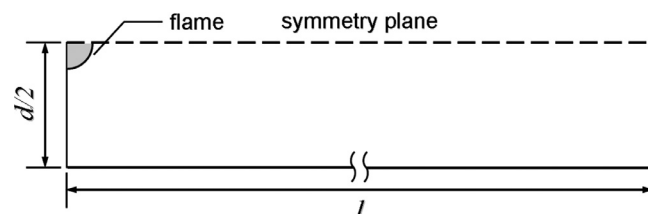

Fig. 1. Computational domain. All walls are adiabatic with no-slip reflecting boundaries.