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On premixed flame propagation in a curved constant volume channel

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ABSTRACT

The objective of this study is to perform an experimental and numerical investigation of a stoichiometric methane/air premixed flame propagating in a curved constant volume channel. The mixture, initially at rest, had temperature 296 K and pressure 102.65 kPa. In the experimental study, a high speed camera and a pressure sensor captured the evolving flame shape and recorded the temporal pressure history during burning. In the numerical study, the commercial computational fluid dynamics package ANSYS Fluent was used to solve the two dimensional, compressible reacting flow and transport equations for 50 species using the San-Diego combustion mechanism under the same conditions as the experiments. It was found that the premixed flame propagating in the curved and converging channel exhibits different features than previously reported in straight or 90° bend channels. There was a definitive curvature effect on tulip flame development. The conversion of the convex tulip flame back into a concave flame revealed the influence of channel geometry on flame evolution: this conversion does not occur in straight channels. The experiments showed that the rate of pressure change eventually becomes negative mainly due to heat losses which engender correspondingly slower flame propagation during the final stage of the tests. The analysis of the numerical results revealed the effect of the interaction between flame front, pressure field and flame-induced flow on flame evolution during all five stages of flame evolution.

1. Introduction

Recently, the structure of the premixed flame in a confined chamber has received considerable attention due to its practical importance in internal combustion engines, pulse detonation engines, the wave rotor and the wave disc engine (WDE). In addition, the study of both premixed flame spread and the explosion of reacting gases in confined spaces is relevant for safety in silos and mines, for example. This particular work is motivated by research and development of the wave disc engine, which was designed and built at Michigan State University (MSU). The thermodynamic foundation of this engine is the Humphrey cycle, which employs the dynamics of pressure waves in the compression and expansion stages. The WDE must work at high frequencies in order to produce power with a reasonable efficiency. Details concerning the wave disc engine concept can be found in [1,2]. It has been demonstrated that the time for combustion inside the WDE channel consumes about 95% of the total cycle time [3]. This indicates that the time required for the burning process limits the WDE from operating at high frequencies, which is a key issue for improving its performance. This also shows that the time remaining for the work extraction stroke is brief compared with the cycle time. Any attempt to extract more work should be accompanied by increasing the time for work harvesting. Accelerating the flame propagation rate inside the WDE channel can reduce the burning time and allow the WDE to operate at higher rotational speeds in order to produce more work [4].

The practical purpose of this article is to better understand the combustion details and flame dynamics inside a WDE channel. This is an essential step toward establishing a reference point from which future advancements in flame and burning acceleration in WDEs can be assessed.

Constant volume (CV) premixed flame propagation has a long and interesting history. This history began over 80 years ago when Ellis published an experimental study of premixed flame propagation inside a closed cylinder, marking the start of a new era in premixed flame research [5]. Subsequent studies have shown that a premixed flame propagating in a channel of aspect ratio larger than approximately two experiences essentially four phases that have been observed and reproduced in numerical and experimental studies [6,7]. These phases are: (a) after ignition, the flame surface propagates spherically at constant flame speed; (b) a finger-shaped flame propagates axially away from the ignition source (spark) with rapidly increasing flame surface area; (c) a flame skirt is formed when the flame touches the sidewalls. The lateral parts of the flame skirt are annihilated by the cold sidewalls leading to a dramatic reduction in the flame surface area, and the flame propagation speed is decreased;

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and (d) the flame subsequently flattens and begins to fold and finally develops into a tulip flame, which propagates to the end of the channel [8–10]. A fifth stage, discussed in this article, is the slow extinction of the flame at the far wall by heat losses.

The evolution of the flame shape leads to an important question. What is the physical interpretation for the flame shape changes, especially the tulip flame, and which flow parameter is most responsible?

Many mechanisms have been proposed to answer this question by studying the key parameters involved in the flame morphology development and evolution. Some of the proposed mechanisms are: Darrieus– Landau and other combustion/heat transfer instabilities [11–14], the interaction between flame and vortex motion generated on the burned gas side due to vorticity produced by the flame [10,15,16], the saddle point motion across the flame front [3], quenching of the flame by the sidewalls and the viscous effect [5,17,18]. Most of these studies were conducted using straight channels and tubes, which in some cases were open and partially open ended [19]. It is important to note that the notion of four stages of combustion ((a)–(d) above) was formalized by Clanet and Searby [19], in whose work on open-ended tubes there was no flame quenching: our work has extended the number of flame stages to five. Concerning the fundamental science of the physics of flame evolution, there is currently no universally acknowledged dominant mechanism for tulip flame formation and evolution in a closed CV chamber. Furthermore, no flow or combustion parameter has been found directly responsible for the evolving flame shape. Thus it is not possible, to date, to neutralize this hypothetical effect in order to generate a confined premixed flame without showing the dramatic shape change from concave initial flame to convex tulip flame [6]. Nevertheless, the work of Hariharan et al. [3,20] and Ponizy et al. [6] has made substantial progress toward this goal. It is instructive to quote from the latter: "It should be stressed that the intrinsic instabilities of the flame front (Rayleigh–Taylor, Richtmeyer–Meshkov or Darrius–Landau) are not involved in this process (of flame front inversion). Indeed, the reverse flow which is responsible for the flame front inversion (concave to convex tulip) always starts in the zone close to the ignition point and not at the flame front." [6]. These statements are supported by the work in [3] which discusses in detail the manifestation of the various flame events in terms of the flow field topology, and specifically in terms of the characteristic saddle point, which propagates through the flow field as a geometric and temporal harbinger of flame front morphological change.

The mechanism of tulip flame formation and the other flame phases are important for combustion acceleration because the flame shape and surface area have a direct influence on the burning rate. Knowing how to increase the flame surface area under specific conditions is a key aspect of flame acceleration for an increased burning rate. The majority of previous studies were carried out using straight channels or tubes. However, the WDE chamber currently under investigation is shaped by two arcs of different radii (Fig. 1) and thus it is of interest to examine the channel curvature impact on flame dynamics. The study of premixed laminar flame propagation in a closed rectangular channel with a 90° bend has been carried out experimentally and numerically by Zhou et al. [20]. They observed a phenomenon they characterized as "flame shedding" when the flame propagated through the first 45° of the bend. The flame could generate a thrust force pushing the unburned gases forward, producing a flame-induced flow which appeared to be responsible for the tulip flame formation after the flame left the bend vicinity. The influence of mixture composition in hydrogen–methane–air on flames in a 90° pipeline with a high aspect ratio was experimentally investigated by Emami et al. [21]. The bend influences the fluctuation of flame speed and pressure, producing a potential hazard risk for the pipeline. Xiao at al. [22] carried out an experimental and numerical study on a closed combustion tube with a 90° bend. The tulip flame that had developed in the straight channel section disappeared when it entered the channel bend where the lower tongue of tulip flame grew while the upper finger was annihilated. The convex tulip flame evolved, as in the current work, into a concave flame, although the evolution was not smooth.

Some general conclusions may be drawn from these studies: (1) the dynamics of premixed flames propagating in a closed CV chamber is a complex phenomenon that involves the mutually-interacting processes of fluid dynamics, heat transfer and chemical kinetics. No unique and certain mechanism has yet been proposed to explain tulip flame formation. (2) The bending of the combustion chamber has a critical influence on the flame dynamics; it may annihilate the tulip flame and convert it to a concave flame, while producing fluctuations in flame speed and pressure. (3) The previous literature indicates that there is a lack of work on the non-symmetrical confining chamber curvature effect on premixed flame dynamics. These effects can be found in many particular CV chambers like internal combustion engines or the WDE.

This work presents an experimental and numerical investigation of premixed flame propagating in a WDE channel. Experiments are conducted to gain further understanding of flame and pressure dynamics in curved-converged, CV combustion chamber. In addition, a two-dimensional (2-D) numerical simulation employing the detailed 244-step San Diego combustion mechanism explores the interaction between the flame front and the flame-induced flow. The main goal is to establish a fundamental understanding of combustion details and flame evolution inside a channel geometry having a continuous, non-symmetric change of curvature.

2. Physical problem and experimental setup

In this study the WDE channel shown in Fig. 1 was used as the CV combustion chamber. As shown, the channel sidewalls are formed by two circular arcs R_{IN} and R_{OUT}. The inlet and outlet ports of the channel are generated by another two arcs, R_{IP} and R_{OP}. The numerical values of these radii are indicated in Fig. 1. The channel depth is parallel to the line perpendicular to the plane of Fig. 1. The top and bottom sides of the chamber are closed along its depth by two optically accessible, temperature and pressure-resistant glass ceramic sheets which are necessary for our schlieren system.

Fig. 2 shows a schematic diagram of the experimental setup. This is composed, firstly and most importantly, of the wave disc engine channel that serves as the CV combustion chamber. In addition, a piezoelectric crystal Kistler pressure sensor (type 6052C) is connected to a Dual Mode Charge Amplifier (type 5010) to record the pressure–time history. The pressure sensor was calibrated using available data from the literature [23,24]. The pressure sensor reading was sampled at a rate of 5 kHz. The flame propagation was captured using a z-type schlieren photographic system consisting of a high speed video camera (Photron FASTCAM SA4 500K-C1) operating at 3600 fps, a point light source, a knife edge, and two concave mirrors of 6 in. diameter and 60 in. focal length.

The experimental and numerical studies discussed herein were carried out for a stoichiometric methane/air mixture at initial temperature and pressure of 296 K and 102.65 kPa, respectively. The mixture was prepared in a separate vessel to ensure proper mixing using Dalton's law of partial pressures. The mixture was ignited using an MSD 10 mm spark plug mounted on a threaded hole through the center of the chamber inlet port. 10 mJ of electrical energy was supplied to the spark-plug using an MSD Blaster coil. The experimental procedure was as follows:

(1) Flush the channel with compressed air for 30 s to remove any combustion residuals remaining in the channel.
(2) Evacuate the channel up to −720 mmHg (96 kPa) and then fill with combustible mixture. The remaining air inside the channel (5.325 kPa) was taken into consideration according to the