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Premixed Tulip Shaped Flames in a Rectangular Combustion Chamber

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This work presents the experimental and numerical investigation of premixed flame propagation in a constant volume rectangular channel or combustion chamber. Ignition is followed by the formation of an accelerating mushroom-shaped flame-front. A deceleration of the flame is followed by the formation of a tulip shaped flame-front. Eventually, the flame is extinguished either because of quenching by the upstream cold wall or by collision with a flame that has been ignited on the opposite end of the confined channel. The flame structure and propagation speed are characterized for changes in the initial pressure, timing and placement of the ignition sources. Numerical calculations of the combustion event characterize the influence of pressure waves and flame front instabilities. Transient numerical computations are compared with experimental measurements. A new and novel explanation is provided for the formation of the tulip flame.

1. Introduction

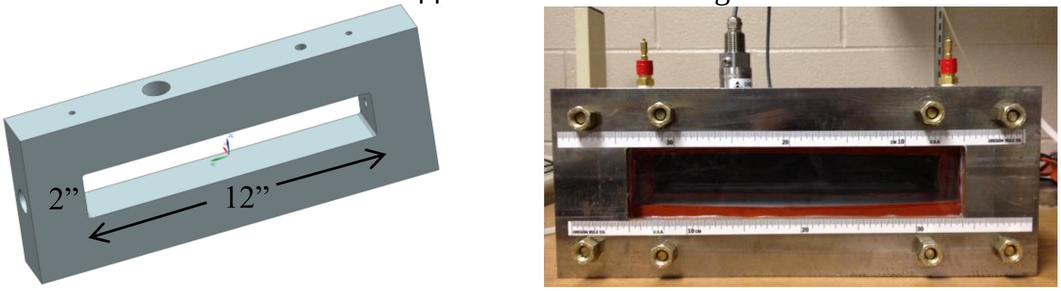
Background: The research described in this article was motivated by the design and construction of a wave disk engine. This engine uses either an external turbine or curved channels to extract shaft work and it employs unsteady compression as a part of the compression stage. The lengthiest process in the cycle, requiring approximately three quarters of the available time, is combustion. Our combustion analysis is focused on a single, stationary, moderate aspect ratio rectangular channel.

Literature Review: There is a substantial literature associated with the study of confined premixed flames in moderate-*AR* (*AR* greater than approximately two) channels. The first published research is found in [1]. An excellent introduction to this problem contains numerous figures and references [2]. Another article in the same volume discusses the general confined flame problem [3]. An outstanding experimental study supporting a physical analysis of the confined premixed flame has been conducted in [4]. This work employed circular tubes, elucidated the separate combustion stages (ignition, skirt flame, tulip flame formation and extinction) and determined the characteristic time scales and characteristic processes associated with each stage. Mechanisms for the formation of the tulip structure have been debated and discussed. From [2]: "the tulip flame occurs when a recirculation generated by the curved flame front suddenly finds itself spinning near the flat flame sheet. The recirculation produces the initial trigger for a Landau-Darrieus instability that then grows into the full tulip." The explanation provided in the present short paper introduces some clarity to the previous description.

Theoretical work for the closed channel with a combustible mixture ignited at one end has been previously presented [5]. A clear and detailed exposition of the basic processes has appeared [6], which also contains a linear stability analysis for the flame front. Instabilities appearing during combustion in open (and closed) channels are generally of three main types. These are: the hydrodynamic Landau-Darrieus instability [7]; thermo-acoustically driven low-frequency oscillations in the longitudinal dimension of the channel; thermo-acoustically driven high frequency oscillations in the transverse dimension of the channel. These instability mechanisms are discussed in [3] and [7].

2. Experiment Description

The experimental setup consists of a constant volume combustion chamber with a square cross section, a high speed camera to capture the ignition and propagation of the flame, a pressure transducer and an ignition control circuit to record the pressure and electronically control the ignition time and a Schlieren diagnostic setup to visualize the density change during combustion. The pressure transducer and the ignition circuit are connected to a computer through data acquisition and control hardware. A LabView program interface is used to initiate the spark and record the pressure inside the combustion chamber. The combustion test section consists of three metal parts, the center plate and two side plates which are bolted together to form a constant volume chamber. The enclosed combustion chamber is *12”* long and has a square cross section with each side measuring *2”*. The total volume is $48\ in^3$. The apparatus is shown in Figure 1.



(a) (b)

Figure 1. *The combustion channel apparatus. Shown in (a) is the center plate graphics diagram, shown in (b) is the assembled apparatus. Spark plugs to ignite the mixture can be place at both ends.*

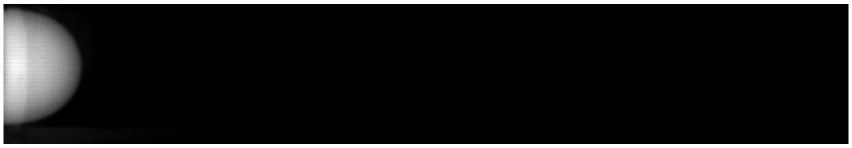
An air-tight seal is formed between the pressure transducer, spark plugs, quick-disconnect valves and the combustion chamber apparatus. To maintain a constant volume during combustion and avoid leakage from the inlet and exhaust ports during rapid pressure changes, quick-connect couplings are mounted on the inlet and exhaust ports. A flush-diaphragm pressure transducer is mounted on the center plate (Figure 1.a) for pressure measurement. Two 10mm spark-plugs are flush-mounted on both ends of the combustion chamber along its length. The plugs are powered by ignition coils that supply *10mJ* for the spark. LabView is used to control the firing of the spark plugs and to record the pressure inside the combustion chamber. The pressure readings are sampled at 10 kHz. The flame propagation is optically recorded using a Photron SA5 high speed camera. The camera is configured to capture the combustion event at up to *20,000 FPS* frame rate.

The test procedure involves filling the combustion chamber with a fuel-air mixture. Upon equilibration, the mixture is ignited with a spark plug. The pressure data along with optical imaging of the flame propagation is recorded electronically. Once the experiment is completed, the recorded images are post processed in MATLAB to obtain the instantaneous position of the flame along with the flame speed.

3. Experimental Results

A premixed methane-air mixture is used for experimental tests. The structure and propagation of flames in a variety of test conditions was studied. We will divide the test results into single spark ignition and dual spark ignition from opposite sides of the channel.

3.1. Single Spark Ignition: Upon ignition, a growing spherical flame kernel is initially formed. The flame front grows faster along the length of the tube when compared to the width (referred to in [4] as the "flame skirt"), which leads to the elongation of the flame. The flame area grows rapidly to form a "finger" shaped flame front. When the sides (the "skirt") of the finger flame touches the cold walls, the skirt is extinguished, and the surface area of the flame rapidly decreases as it progressively flattens, eventually taking the shape of a planar flat flame. The planar flame shape remains for an instant. It almost immediately changes its shape to form an inward pointing cusp near its center; this shape is referred to as the "tulip-flame." The flame front maintains its tulip shape as it propagates along the remaining length of the channel until it is extinguished by the facing cold wall on the opposite end. Small distortions to the tulip flame are observed. The optical record of the flame propagation is shown in Figure 2 for selected *10 ms* time intervals from ignition until extinction.



t=10 ms: Spherical growing flame. Ignition occurred at t = 0s.

t=20ms: Finger-flame formation.

t=30 ms: Planar flame front appears.

t=40 ms: Formation of the tulip flame.

t=110 ms: Collision of the tulip flame with the opposite cold wall.

Figure 2. *High speed video imaging of the flame appearance at 10, 20, 30, 40 and 110 ms from the time of ignition. Note the initial spherical shape of the growing ignition kernel followed by the approach to a plane flame front, the subsequent formation of the tulip flame, and extinguishment at the opposite cold wall.*

Upon ignition, the spherical flame-front grows rapidly and *10 ms* after ignition, a finger flame develops. At *30 ms*, the finger flame skirt is quenched by the cold wall and thereafter the flame surface area rapidly decreases. This causes the flame to slow down. At *40 ms* the flame front collapses to form an inward pointing cusp called the "tulip flame". The flame front eventually collides with the cold wall at the opposite end of the tube at *120 ms* while preserving its tulip shape. The normalized position of the flame front measured along the centerline of the channel is shown in Figure 3. The various stages of flame font structure are marked, following [4]. Stage I indicates the ignition event followed by the initial growth of the spherical flame. Stage II begins with the formation of the finger flame. Stage III indicates the transition from a finger flame to a planar flame. The planar flame which subsequently changes to a tulip flame is shown in stage IV.

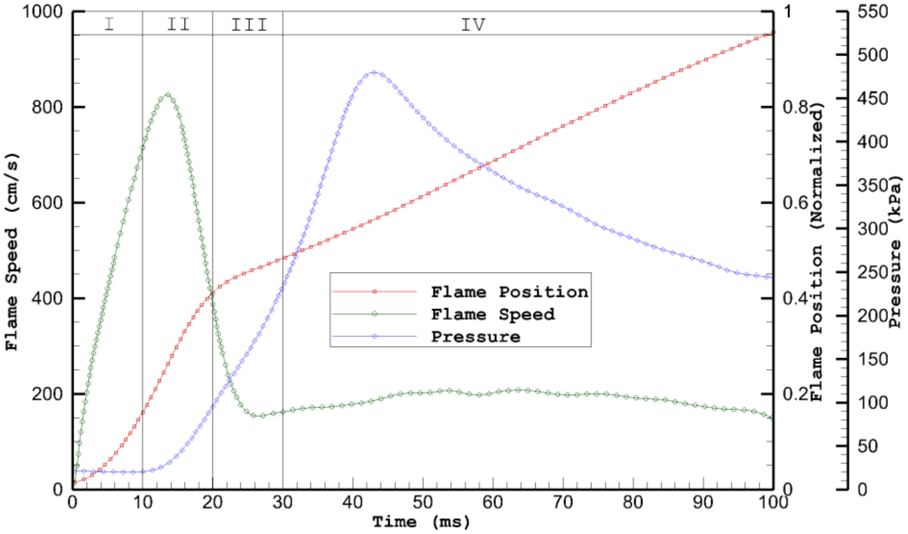


Figure 3*. Flame position, velocity and pressure vs time, showing the four stages of flame propagation (I=ignition; II=finger flame; III=transition to planar flame; IV=propagating tulip flame).*

The normalized flame position data shows the mean position of the flame front for each instant of time. The flame position changes rapidly from *0* to *20 ms*, after which the rate of change in the mean flame position is slower. The flame speed data are also shown in Figure 4. The flame speed data indicates that the fastest physical flame speed occurs shortly after ignition. The spherical flame kernel then accelerates towards the unburned mixture as its surface area increases. At ~ *15 ms*, the surface area of the flame-front reaches its maximum value. The speed of the flame front starts to decrease as the flame shape becomes planar. At ~ *30 ms*, the flame transforms to a tulip shape. The speed of propagation thereafter remains approximately constant until it is quenched by the cold wall on the opposite end of the tube at *118 ms*. Also shown in Figure 4 is the pressure in the channel. The pressure reaches its maximum value about *55 ms* prior to extinction. This occurs because the loss of heat from the burnt mixture to the cold wall causes a decrease in temperature in the burnt mixture and thus a slight decrease of pressure before full extinction.

The instantaneous flame speed versus normalized position in the channel is shown in Figure 4. This figure shows that the transformation of the flame front from planar to tulip shape takes place at almost the half length of the tube. The speed of propagation of the flame front is approximately constant after the tulip has formed.

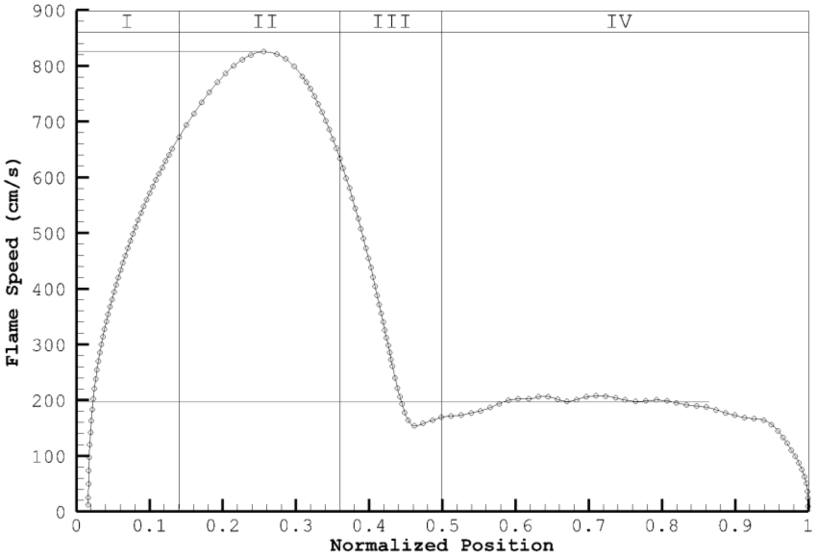
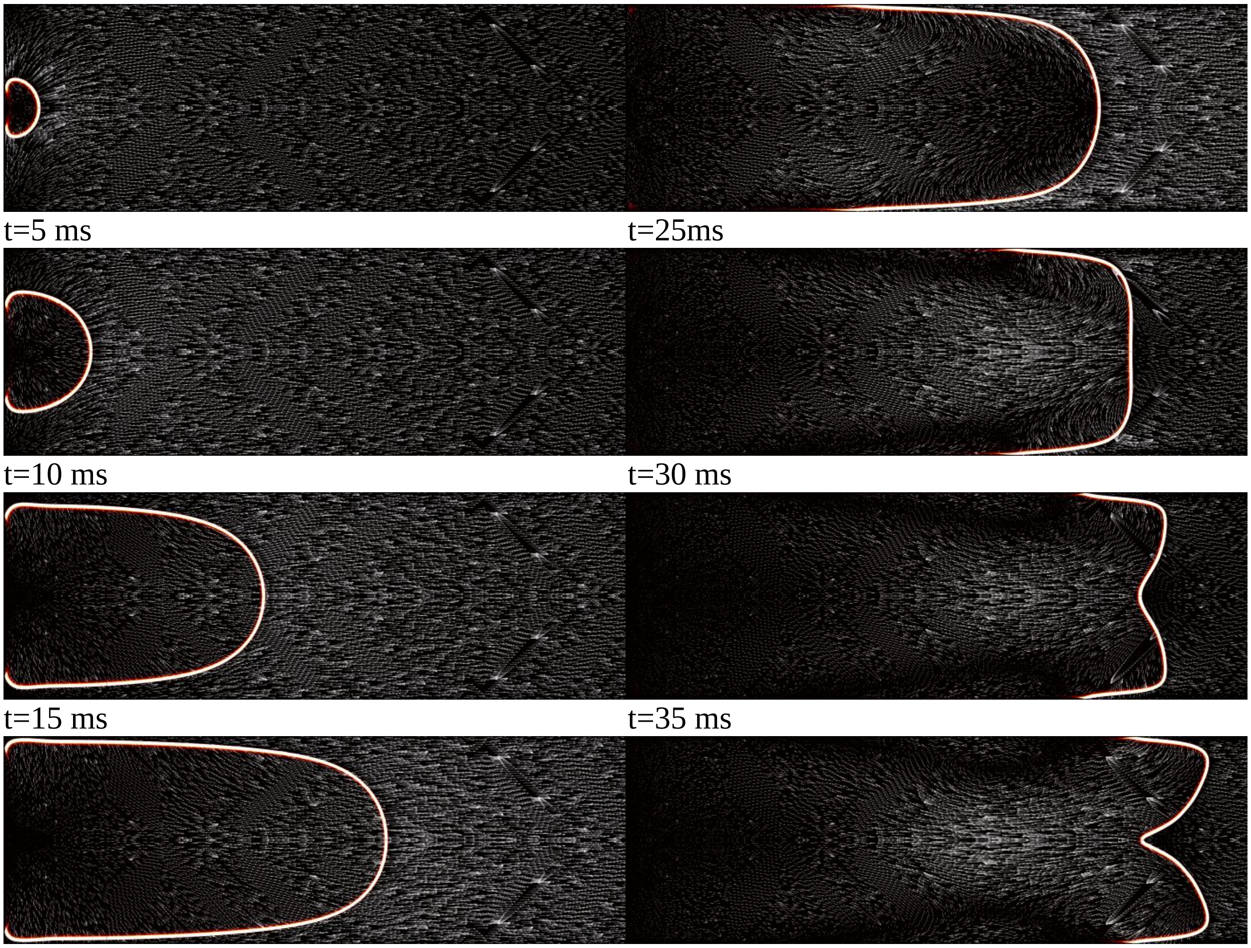


Figure 4. *Flame speed vs normalized position. The peak velocity in the expansion stage is approximately 825 cm/s. In the tulip stage the velocity is approximately 200 cm/s.*

<u>III.2. Dual Spark Ignition:</u> The dual spark ignition setup consists of two spark plugs on the opposite ends of the tube along its length (see Figure 1.a). This allows the influence of multiple-source ignition to be studied in detail. Both spark plugs are flush mounted on the sides of the combustion chamber. The spark discharge time can be electronically controlled through a delay circuit. Experiments are conducted for spark delay timings of *0*, *25* and *50 ms*. The effect of the second spark depends upon which stage the first flame has entered prior to the second spark. We found that the opposite end ignition produced a greater influence when the tulip was fully developed than when the initial flame was still spherical or even planar. Detailed discussion of the dual spark case is beyond the scope of this short communication.

4. Numerical Results

A numerical simulation of the constant volume combustion process was performed. A simplified two-dimensional representation of the combustion chamber is constructed measuring 12” long and 2” wide. The computational domain consists of structured quadrilateral cells, each with an edge of 0.1 millimeters. The domain contains a total of 1.54 million elements. The commercial computational fluid dynamics software *Ansys Fluent* is used to perform the simulations. A Navier-Stokes calculates the transient results using an explicit fourth-order Runge-Kutta solver. The Courant-Friedrich-Levy number is 0.9 for the domain. The control volume is initialized with a stoichiometric mixture of methane and air. A single-step Arrhenius reaction rate mechanism is used. The walls surrounding the control volume are initialized to be a no-slip boundary with constant temperature of 293 K. The combustion process is initialized by patching a localized spot near the physical spark location to 2100 K. The results obtained by uncoupling the pressure waves from the Navier-Stokes (N-S) equations is comparable to those obtained by solving the coupled N-S equations. The trigger for the formation of tulip flame is therefore independent of the influence of pressure waves. The sequence of flame front shapes and events is shown in Figure 5, which should be compared with Figure 2.



t=5 ms t=25ms

t=10 ms t=30 ms

t=15 ms t=35 ms

t=20 ms t=40ms

Figure 5*. Reaction rate contour plot with velocity vector indicated with arrows.*

A detailed analysis of the flow field of the burnt gas during the expansion and subsequent quenching of the finger flame skirts by the cold wall shows a reversal in direction of the local velocity field of the burnt gases as the flame front approaches the cold wall. This induces a recirculation zone near the finger flame skirts. A moving stagnation point along the centerline is formed near the ignition point (see Figure 2) which travels through the burnt mixture towards the flame front. As the stagnation point moves closer to the flame front, a stagnation line eventually merges with the reaction front. When The stagnation point crosses the flame front from left to right, i.e., from the burnt gas side to the unburned gas side, the flame front changes shape from the mushroom of Figures 2.a and b, to the flat flame of Figure 2.c (at the instant of crossing) to the tulip shape of Figures 2.d and e. Thus, we extend the discussion of [2] and provide a revised explanation for the tulip shape as follows: The tulip flame occurs when re-circulating zones of opposed vorticity in front of and behind the flame front combine to form a stagnation point that originates near the ignition point. This stagnation point remains fixed for about half of the burning time but then rapidly accelerates on the burned gas side toward the flame front (i.e., from behind the flame front) and eventually catches the front. When the stagnation point catches the flame front the front becomes perfectly flat. Once the stagnation point moves through the flame front it assumes its characteristic tulip shape. The tulip shape remains largely unchanged because the stagnation point and the flame front travel toward the upstream cold wall at nearly the same speed. Thus, the formation of the tulip front is not a Landau-Darrieus instability process but rather a consequence of direct flame/flow interaction. The fundamental flame morphology remains the same (four nodes, four half stagnation points, and one principal (full) stagnation point along the centerline). As a matter of topology, this flame surface configuration remains topologically invariant during the transition from concave (mushroom) to convex (tulip) flame front shape because there is no external impulse to change it over the sequence of events described. Of course, before ignition there is no flame surface whatsoever and the topological structure of Figure 6 does not exist. Even after ignition, and before the formation of the recirculation and vorticity patterns described above, the topological structure shown in Figure 6 is absent. Once the flame has had sufficient time to interact with the flow field and to self-generate the vortical structures observed in the simulations (Figure 5), the formation of the principal stagnation point is inevitable and the resulting structure must remain intact until eventual flame quenching and extinguishment. In particular, the topological structure evolution shown in Figure 6 must remain invariant during the sequence of events described therein. As a matter of explanation, the Landau-Darrieus instability mechanism appears not to be a component of the tulip formation process

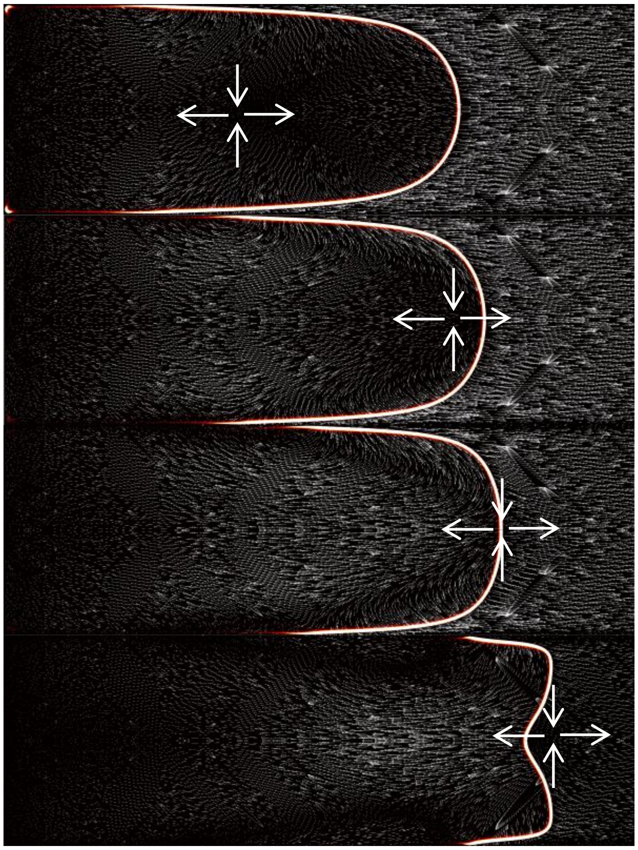


***Figure 6**. Reaction rate contour plot with stagnation point indicated.*

The location of the stagnation point and the flame front from ignition event to the formation and propagation of the tulip is shown in figure 7.

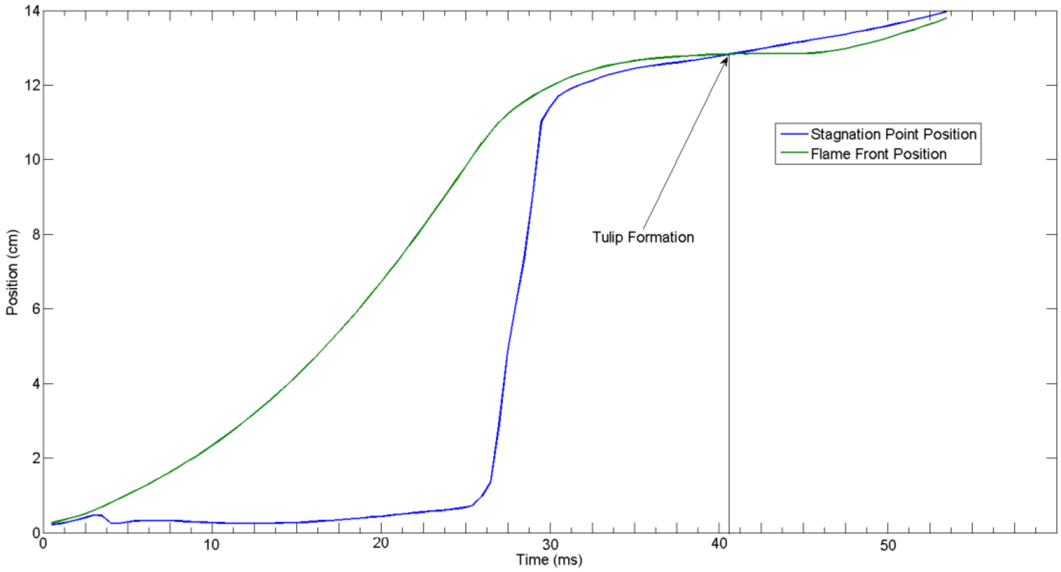


***Figure 7**. Location of flame front and stagnation point*

Acknowledgements

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