An experimental facility has been designed and fabricated for studying outward propagating spherical flames at elevated pressures and temperatures. The facility can be used in static or dynamic mode. In the dynamic mode, the desirable conditions of elevated pressure and temperature are attained by compression of reactive mixture through a pneumatic drive and hydraulic damping mechanism and a spherical outward propagating flame is initiated through spark discharge in the compressed mixture. A single window coincident optical layout is selected for Schlieren imaging of flame with a high speed camera. Schlieren images are digitally processed to obtain flame radius-time history. A multi-zone model is used to deduce flame speed from the acquired flame radius-time and pressure-time data. In the multi-zone model, flame propagation is taken as the consecutive consumption of unburned gas mixture within the zones. The model accounts and corrects for compression effects. As part of the preliminary characterization, experimental data for flame speed of methane/air mixtures is acquired, interpreted and compared with the data from the literature.

1. Introduction

The phenomenon of flame propagation and flame structure are significantly influenced by mixture pressure and preheating. Since combustion in practical engines takes place at elevated pressures and temperatures, study of flame propagation at simultaneously elevated pressures and temperatures is particularly relevant [1,2]. The importance of investigating high pressure flame propagation and associated chemical kinetics is amply recognized for the development of comprehensive chemical kinetic mechanisms [2,3-8]. As pressure increases, the controlling chemistry changes due to the increased importance of the three-body termination reactions. Investigations with methane and H2 flames at elevated pressures have revealed that the overall reaction order shows a non-monotonic behavior with pressure, which is analogous with the three explosion limits of hydrogen/oxygen mixtures [3]. The overall reaction order initially decreases with increase in pressure due to the increased importance of the termination, H+O2(+M) \rightarrow HO2(+M), over branching reactions, H+O2 \rightarrow OH+O etc., and then it increases again due to the branching pathways from HO2 at higher pressures [3,9]. Consequently, the chemical kinetics in high pressure flames is significantly influenced by HO2 pathways.

The most popular techniques for laminar flame speed measurements are counterflow/stagnation flames [e.g. 10-15] and spherically outward propagating flames (OPF) [e.g. 3-5]. Flat flame and
bunsen burner [e.g.16,17] have also been successfully used. Counterflow burners offer an excellent configuration for determination of stretch-corrected flame speeds, but typical pressures are below 7 atm due to transition to turbulence with increasing pressure. OPFs (constant volume and constant pressure) in optically accessible combustion chambers have been widely used for investigations at elevated pressures, up to 60 atm.

The objective of this work is to develop an experimental facility for investigating flame propagation at elevated pressures and temperatures and subsequently characterize and use the facility for studying flame propagation. In the following a description of the facility is presented, followed by the model for data interpretation and preliminary characterization experiments.

2. Experimental Facility

The working principle of the experimental facility is to attain the desirable conditions of elevated pressure and temperature by compression of reactive mixture in a carefully designed combustion chamber and then initiate a spherical OPF through spark discharge. The obtained images of flame evolution can be processed to yield the data for flame speed vs stretch rate, which can be extrapolated to obtain the unstretched laminar flame speed. The cross-sectional view of the facility is shown in Fig. 1. It consists of a reactor cylinder with nearly hemispherical piston and cylinder head. The combustible mixture in the reactor cylinder is compressed to elevated pressures and temperatures by controlled motion of the piston through a custom-designed hybrid cylinder (pneumatic drive and hydraulic damping) arrangement. After compression, the reaction chamber assumes a nearly spherical shape. The spherical chamber is equipped with optical window, pressure and temperature transducer, rupture diaphragm for safety, and electrodes for initiating an OPF by spark. Spark is initiated after compression in the constant volume spherical chamber, yielding an OPF whose radius-time history is recorded by Schlieren imaging using a high speed camera.

![Fig. 1 – Cross-sectional view of the experimental facility](image)

It is desirable to have a large and spherical combustion chamber for studying OPFs. A spherical chamber avoids undue distortion of the flame, which happens in the case of cylindrical confinement.
[18], and a large chamber allows constant pressure flame propagation up to a larger radius (and consequently smaller stretch) so that the extrapolation to zero stretch can be done with increased confidence. In the present design of the facility, the combustion chamber is nearly spherical in shape, however, after careful considerations, the diameter of the chamber is taken as 10 cm and the maximum compression stroke length of the facility is 50 cm. An increase in the diameter of the combustion chamber requires a proportionate increase in the length of the compression stroke and exacerbates the possibility of reaction and turbulence during compression. With a combustion chamber diameter of 10 cm, the flame radius-time data up to the flame radius of 2.5 cm (half of the radius of the combustion chamber) may be used for extrapolation [19]. It is noted that at this flame radius, pressure in the combustion chamber may rise by about 15% and temperature also by 5% [19]. However, the influence of these factors on flame speed is typically less than 2% and the experimental data can be extrapolated to zero stretch with confidence when compression correction is taken into account. In literature, most of the experimental data from OPFs is based on flame radius less than 2.5 cm [9,20-21].

The ignition energy for the spark is provided by discharging an automotive coil, saturated through a constant current power supply (GW Instek GPR 1810HD), through a 10 µF capacitor. The ignition energy is easily adjusted by adjusting the current on the power supply. One of the electrodes is modified from a standard spark plug by removing the ground electrode and welding a stainless steel tube and wire to it. The other electrode is adjustable and allows fine adjustment of the spark gap. The pressure in the chamber is measured using a Kistler piezoelectric (6052C) sensor and a charge amplifier. The voltage output of the sensor is used to synchronize the spark generation and image acquisition through a time delay program in Labview.

A single window coincident optical layout is selected for Schlieren imaging. This arrangement, as shown in Fig. 2, requires only one window and minimizes the distortion of the spherical geometry of the combustion chamber. A 48 W halogen lamp source is focused through a condenser lens on a pinhole to provide intense illumination. A 400 mm focal length achromatic doublet lens provides collimated beam through the 5 cm diameter window. A quartz substrate front surface mirror is mounted on the face of the piston, which reflects the light. The reflected light is focused by the lens and beamsplitter on a knife edge. The Schlieren image is acquired by a high speed camera (Photron Fastcam SA 3) with a 50 mm Nikon lens.

Fig. 2 – Set-up of the Schlieren imaging system. (1 Light source; 2 Condenser lens; 3 Pin hole; 4 Beam splitter; 5 Lens; 6 Quartz window; 7 Mirror; 8 Knife edge; 9 High-speed camera with lens)
Sample Schlieren images for methane/air flame with $\phi = 1$ at atmospheric pressure are presented in Fig. 3. These images are digitally processed to obtain flame radius-time data as shown in Fig. 4. Figure 4 also shows the experimentally measured pressure in the combustion chamber. For a flame radius of 2 cm, the pressure rise in the chamber is about 7%. Assuming isentropic compression of the unburned gas, the change in the flame speed due to increased pressure and temperature of the unburned gas is negligible. However, the effect of compression-induced flow velocity may not be negligible and should be accounted for in data interpretation.

![Sample Schlieren images for CH4/air, $\phi = 1$, 1 atm, 296 K. Successive images are 1.75 ms apart.](image)

![Flame radius and pressure history](image)

**Fig. 3** – Sample Schlieren images for CH$_4$/air, $\phi = 1$, 1 atm, 296 K. Successive images are 1.75 ms apart.

**Fig. 4** – Flame radius and pressure history

### 3. Data Interpretation

Flame radius and pressure history is used to deduce the laminar flame speed as follows. For an OPF, the mass of the burned gas, $m_b$, is described as

$$\frac{dm_b}{dt} = \frac{d}{dt} \left( \frac{4}{3} \pi r_f^3 \rho_b \right) = 4 \pi r_f^2 \rho_b \dot{S}_u$$

where $r_f$ is flame radius and $\rho_b$ is the mass averaged density of the burned gas. A rearrangement of the terms gives -

$$\dot{S}_u = \frac{\rho_b}{\rho_u} \left( \frac{dr_f}{dt} \right) + \frac{r_f}{3 \rho_u} \frac{d \rho_b}{dt}$$

In this equation, second term accounts for compression induced flow velocity in the burned gas. The unstretched laminar flame speed, $S_u^o$, can be obtained by linear extrapolation of the stretched flame speed to zero stretch.
\[ S_u = S_u^o - LK \]

where \( L \) is Markstein length and \( K \) is stretch rate, given by \( 2/r_f (dr_f/dt) \). In order to deduce, Markstein length and \( S_u^o \) from the experimental data, it is better to work with the integrated form of the above equation, which avoids amplification of random experimental scatter during differentiation. An integration of the equation gives

\[
\int_{r_0}^{r_f(t)} \left( \rho_b \frac{dr_f}{dt} + \frac{r_f}{3} \frac{d\rho_b}{dt} \right) dt = S_u^o (t - t_o) - 2L \ln \left( \frac{r_f(t)}{r_0} \right) \]

(1)

Experimental data of pressure and radius can be used to evaluate the integral in the above equation, and \( S_u^o \) and \( L \) can be determined from a linear regression. Note that \( \rho_b \) and \( \rho_u \) are time dependent. Determination of \( \rho_u \) is straightforward from isentropic compression of the unburned gas by using

\[
\int_{t_i}^{t_f} \frac{\gamma}{\gamma - 1} \frac{dT}{T} = \ln \left( \frac{P(t)}{P_i} \right)
\]

where subscript \( i \) denotes initial conditions at the time of spark discharge and \( \gamma \) is temperature dependent specific heat ratio of the unburned gas mixture.

In order to determine \( \rho_b \), a multi-zone model is used that utilizes the experimental time-radius-pressure data. In the multi-zone model, flame propagation is taken as the consecutive consumption of unburned gas mixture within the zones. The number of zones equals the number of time-radius-pressure data points that are available from the experiment. After ignition, the flame front consumes zone I first. The post combustion radius of zone I at this instant, \( t = t_1 \), is taken as the first radius point available from the experimental data and its temperature is deduced by first calculating the isobaric equilibrium temperature of the burned gas based on initial temperature and pressure, \( T_i \) and \( P_i \), and then correcting for the isentropic compression of the burned gas from \( P_i \) to \( P_1 \). This gives the burned gas temperature and density of Zone I at time \( t_1 \). Mass of the burned gas in zone I is also calculated. After the combustion of the first zone, combustion of the second zone occurs at a higher unburned gas pressure, \( P_1 \), and temperature, which is determined from isentropic compression of the unburned gas. After the combustion of zone II, the outer radius of the zone II is taken as the next available time-radius-pressure data points. The temperature of the zone II is deduced by first calculating the isobaric equilibrium temperature of the burned gas based on temperature and pressure of the unburned gas after the consumption of zone I and then correcting for the isentropic compression of the burned gas. Combustion of zone II also leads to compression of zone I, and its temperature can be calculated from isentropic assumption. Also, since the mass of gas in zone I is already known, its radius at the present time step can also be updated. This process is followed for the subsequent zones. Note that in this model, every zone is considered adiabatic even though temperature gradients are established in the burned gas. NASA chemical equilibrium program from Gordon and McBride is used to evaluate the burned gas temperature, molecular weight and specific heat ratio. Figure 5 shows an example of output from the model. It is noted that there is a small increase in the unburned gas temperature and density. The burned gas density also increases due to compression, and temperature gradient is present in the burned gas temperature profile.

Based on this model, flame speed vs stretch rate and linear interpolations are plotted in Fig. 6. For linear interpolation, only flame radius from 0.6 to 2 cm is taken to avoid the effect of initial spark-induced flame acceleration. Figure 6 also shows a comparison of data interpretation by
including and excluding the effect of compression induced flow velocity and variable density ratio. When these effects are excluded, $d\rho_b / dt$ term in equation 1 is neglected and the density ratio $\rho_b / \rho_i$ is determined based on the initial unburned gas temperature and pressure. An underprediction of 4.2% in $S_u^0$ is noted when these effects are excluded.

Fig. 5 – Time evolution of a) Unburned gas density b) Unburned gas density c) Unburned gas temperature. d) Temperature profile of burned gas at flame radius of 2 cm. Calculations from the Multi-zone model.

Fig. 6 – Experimental data of stretch rate vs flame speed and linear extrapolations. CH₄/air, $\phi$=1, 1 atm, 296 K
4. Preliminary Validation Experiments

Initially, the facility has been used only in static mode and flame speed has been determined for methane/air flames at atmospheric pressure. Fig. 7 shows a comparison of the present data with the data from the literature. An excellent agreement is noted. In the near future, the facility will be characterized and used in dynamic mode where compression stroke of the facility will be used to obtain higher pressures and temperatures before spark discharge.

![Comparison of present flame speed data with literature](image)

**Fig. 7** – Comparison of present flame speed data with literature [11]. CH₄/air, 1 atm, 296 K

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References