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HIGH-SPEED SCHLIEREN PHOTOGRAPHY OF CONFINED GASEOUS EXPLOSIONS

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ABSTRACT

The tempo-spatial evolution of the combustion kernel in gas phase explosions was experimentally investigated using millisecond-resolution Schlieren photography. Methane and propane -air explosions were initiated in a cylindrical explosion vessel at a range of equivalence ratios ranging from 0.6 to 1.4. All explosions were initiated using a 25 mJ ignition energy source at ambient conditions. The explosion kernel growth rate and cellular flame structure are observed and analyzed. The growth of the primary flame kernel in propane-air explosions was found to be slower than that of the methane-air explosions, for lean mixtures. The opposite was found for stoichiometric and rich mixtures. The establishment of the cellular structure was found to occur after a certain period of time, which varies according to the fuel type and equivalence ratio.

Keyword: Combustion; Explosion; Gas

1. INTRODUCTION

Gas explosion is defined as the process where combustion of homogenous gas mixtures, (i.e. fuel-air or fuel/oxidizer) is causing rapid increase of pressure (Bjerketvedt et al., 1997). In order to sustain, explosions do not require the passage of a combustion wave through the exploding medium (Kuo, 1986). Gas explosions are, traditionally, referred to as deflagrations. There are original and conceptual difference between the two phenomena; deflagration and detonation. The latter is the most devastating mode of gaseous explosions with its characterizing shock waves and supersonic front. In less severe types of explosions, the flame propagates at subsonic velocities, however, the pressure rise across the flame front remains significantly higher than that of other modes of deflagrations. This definition is limited to chemical gas explosions. Other types such as thermohydraulic, mechanical and nuclear explosions, in their essence, have different definitions and natures (Krehl, 2009). Gaseous explosions are mostly classified according to the environment at which the combustible mixture is contained at the instant of explosion. Confined gas explosions are those which occur in tanks, channels or any kind of enclosures. In this mode of explosion, the combustible mixture directly interfaces with the enclosure wall. Partially confined explosions occur when the combustible mixture, in an enclosure, does not have a direct interface with the walls, in the existence of some vented areas with the atmosphere. Gas explosions are deemed to be unconfined when the combustible mixture is not contained in any form of enclosures (Bjerketvedt et al., 1997). The onset of explosion, independently from the class of explosion, depends on the combustion characteristics of the fuel, equivalence ratio, and initial conditions. The fuel type and concentration factors are represented in the upper and lower flammability limits of the fuel. These are experimentally determined data that represent the range of concentrations of a specific fuel in air at which the mixture would burn. Temperature usually increases the flammability range of any fuel, until it reaches to autoignition. As to the mixture pressure, the minimum ignition energy is the corresponding governing factor for the onset of explosion. Although such energy depends on the fuel type, a radical change in the mixture pressure will affect the amount of energy required to successfully ignite the mixture (Zabetakis, 1965). This article investigates the onset of confined gaseous explosions of methane and propane at different equivalence ratios. The temporal and spatial evolution of combustion kernel is studied using Schlieren photography. The data is then analyzed to present a quantitative insight to the phenomenon. The significance of this study is driven from the unrelenting interest to realize the flame physics during the onset of explosion. This, in turn, has a radical role in the sustenance and behavior of the explosion, as well as its interaction with structures and fluids. Another vital issue to the subject of this study is the deflagration to detonation transition. The onset of detonation is mostly deemed to come from localized explosions that derive the first shock waves in the flame front (Radford et al., 1995, Brailovsky and Sivashinsky, 2000, Oh et al., 2001). Thus, investigating subsonic gaseous explosions at their origination might shed some light on producing mechanism of shock waves.

2. LITERATURE REVIEW

The early literature of gaseous explosions in the 20th century was reported by Coker (Coker, 1909), Morgan (Morgan, 1923) and Garner and Saunders (Saunders and Sato, 1927, Saunders, 1927b, Saunders, 1927a, Garner and Saunders, 1926, Garner et al., 1926). The explosion of methane-air mixtures through several narrow channels has been investigated in 1960 (Wolfhard and Bruszak, 1960). In this research, Schlieren photographs were used to identify the propagating mechanism for gaseous explosion through variable cross-section area enclosures. Meyer and Oppenheim (Meyer and Oppenheim, 1971) elucidated two distinct regimes of ignition in gaseous explosions; strong and weak ignition. In their 1971 revolutionary landmark paper, they used stroboscopic laser-Schlieren imaging system to identify the mechanism of confined explosion initiation in gas phase combustion. It was evidently shown that strong ignition is characterized by the instantaneous appearance of a relatively plane pressure front associated with the generation of a flow field across the whole cross section of the tube. In contrast, they demonstrated that mild ignition starts in the form of distinct flame kernels whose growth is comparatively slow and essentially devoid of any gasdynamic effects. The same topic is sometimes involved in measuring the laminar flame velocity of premixed gases. There numerous publications discussing such velocity for single and hybrid fuel/oxidizer mixtures (Ilbas et al., 2006, Zádor et al., 2005, Kawanabe and Shioji, 2005, Kristoffersen et al., 2004, Lamoureux et al., 2003, Lamoureux et al., 2002).

The major focus of such publications was to derive the laminar flame speed of these mixtures in order to provide experimental basis for computational codes of premixed combustion. In 1988, Abdel-Gayed et al measured the flame speed and burning velocity of a turbulent flame during an explosion scenario using high-speed Schlieren photography (Abdel-Gayed et al., 1988). They suggested that the increase in burning velocity during a subsonic explosion is attributed to the influence on the flame-front of an ever-broadening frequency band of the turbulence spectrum. Hence, of the turbulent velocity associated with such band. Flame speed and pressure rise rate during the initiation of cylindrically confined gaseous explosions were analyzed in 1990 (Phylaktou et al., 1990). Based on a high energy ignition source, the latter research measured very fast flame speeds corresponding to high rates of pressure rise in the initial 5-10% of the total explosion time. Throughout this period, 20-35% of the maximum explosion pressure was produced, and over half of the flame propagation distance was completed. The role of pressure waves in the propagation of gaseous explosions immediately after ignition was studied in 1995 by McIntosh (McIntosh, 1995). He investigated the effect of one-dimensional pressure interactions on the deflagration kernel and mass burning rate. In 1996, Radford et al studied the deflagration to detonation transition in a turbulent flame. Their study has firstly pointed out the eminent role of spontaneous localized explosion kernels in developing the leading shock wave of detonation (Radford et al., 1995). The dynamics of laminar spherical flame kernels in hydrogen/air mixtures diluted with steam were studied numerically and experimentally by Kusharin et al (Kusharin et al., 2000). They used the formation of a propagating flame kernel as a criterion for mixture flammability. The characteristic modes of behavior of developing and extinguishing flame kernels were demonstrated and analyzed for near-limit lean hydrogen/air/steam mixtures confined in a spherical laboratory-scale explosion vessel. It was reported that both dynamics and critical size of a flame kernel were strongly affected by hydrogen diffusion and thermal radiation.

In 2003, Dahoe et al proposed a methodology to determine the burning velocity of confined gas explosions. The proposed methodology predicted burning velocities approximately 5-10% higher than the values reported during 1994-2003 for methane-air mixtures (Dahoe and de Goey, 2003). The critical and transition regimes of gaseous explosions were analytically investigated in the same year by El-Sayed (El-Sayed, 2003). His study showed that the critical parameters for constant pressure explosion are lower than those for constant volumes. It was also found that the critical parameters in the temperature-pressure plane were different from those obtained in the temperature-time plane or the pressure-time plane. Very important data on the explosion limits of Methane and Propane were reported by Pekalski et al (Pekalski et al., 2005). They reported the explosion pressure data for methane-air, and propane-air and -oxygen mixtures over their entire flammable range at standard and elevated pressure and/or temperature from experiments conducted in a 20-litre explosion vessel. They compared the experimental results with chemical equilibrium calculations. In their analysis, they concluded that the discrepancy between the results of experiment and calculation mirrors the degree of conversion of the initial mixture and the degree the explosion can be considered adiabatic.

The focus of the present article is providing qualitative description of the onset of gaseous explosions by Schlieren photography. Although the Schlieren techniques has been used in several studies focusing on determining the laminar and turbulent burning velocities of premixed flames (Wang et al., 2010, Zhang et al., 2009, Wang et al., 2009, Jerzembeck et al., 2009, Liao et al., 2007, Ilbas et al., 2006, Leuckel et al., 1991, Huang and Kido, 1991), the instantaneous photographs were provided in a very small number of these researches (Loesel Sitar et al., 1995, Bradley et al., 1994, Lefebvre and Reid, 1966). This article aims at providing a millisecond photograph history of gaseous explosions at ambient conditions. The planar pressure waves as well as refracted and reflected shock waves can be easily observed at such temporal resolution.

3. EXPERIMENTAL SETUP

3.1 Explosion Vessel

Explosion vessel was made of one short steel pipe with flange collars. Both ends of this pipe are sealed with steel discs and gaskets and tied together using bolts and nuts. This explosion closed vessel is illustrated in figure 1.

3.2 Mixing and Gas Filling System

The gas mixing system consisted of a mixing panel, a fuel and gas tanks (Methane, Nitrogen and Oxygen in gas forms), high-pressure valves, a vacuum pump, a circulation pump, digital pressure gauges, as well as the required fittings and hoses, as shown in figure 2. To ensure the homogeneity and fuel concentration of the mixture, each constituent gas flow was controlled through the mixing panel where pressure and flow for the respective gases can be adjusted. The explosion vessel was initially evacuated prior to each filling procedure. The filling procedure is based on the partial pressure technique. In order to get a homogeneous mixture the whole volume is circulated with a circulation pump through a circulation line for 10 minutes. All experiments were conducted at atmospheric initial conditions.

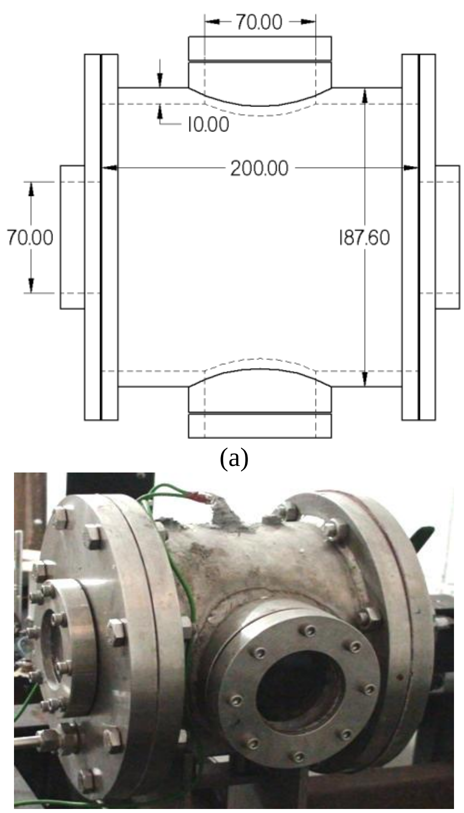


Figure 1. Explosion vessel (a) dimensions in mm and (b) photograph shwoing the inlet pipe and quartz windows

3.3 Ignition System

The ignition system consisted of a couple of electrode copper rod which are using the inductive discharge systems concept. Inductive discharge systems operate on the principle of energy storage in the coil primary windings. When the switching device closes, battery voltage is applied across the coil primary and current builds up. Stored energy is proportional to the coil inductance times the square of the current. By its nature, an inductor tries to maintain a constant current flow. When the switching device opens, the primary current flow is disrupted and current flow transfers to the secondary, firing the electrode rod gap until the stored energy is used up.

3.4 Schlieren Setup

Schlieren photography was invented in 1864 by the German physicist August Toepler. This technique depends on the light refraction due to the change in refractive index of the gas as a result of combustion of heat transfer. Parallel light beams are passed through the section. Due to the large spectrum of refractive indices in the test section, light refracts by different amounts (i.e. different angles). The refracted beams are then filtered, physically, through the sharp edge which blocks the refracted beams, base don the orientation and amount of refraction. As a result of this selective blockage of light, the inhomogeneities (density changes) in the test area show up as intensity gradients in the resultant image, the contrast (fractional change in intensity with respect to the background intensity) of which at a point is directly proportional to the density gradient at the corresponding point in the test flow (Satheesh and Jagadeesh, 2009).

A 'Z-type' Schlieren set-up, as shown in figure 3, was used for visualization of the flame propagation in the explosion vessel, wherein a pair of parabolic mirrors of focal length of 864 mm were used to obtain the parallel beam of light and then for focusing it on the sharp edge. In most conventional systems a film camera or a digital camera is used to record the Schlieren photographs. While for long-duration experiments the speed of the camera is insignificant, in short-duration experiments like in shock tunnels, the type of the camera plays a vital role. In the case in hand, where the ignition energy is relatively low, the order of magnitude of the kernel growth is in millisecond. For this reason, a high-speed digital video camera (1000 frame per second) was used to capture the progress of the combustion kernel. Then, the recorded video was decomposed into individual frames each represent 1 ms. To provide at least 20 cm of unencumbered parallel-beam length for the test area, an overall system length of 2.0 meter was chosen in this experiment. This optical setup just fits diagonally on a 60 x 120 cm optical table

3.5 Strategy of Experiments

The major goal of the present study is to visualize the onset of gaseous explosions where the combustion kernel is initiated. In order to realize the parameters governing the tempo-spatial evolution of such phenomenon, several explosions were studied. There were two types of fuel and one oxidizer; methane, propane and oxygen, respectively. The explosion of each of the two fuels was studied at different equivalence ratios. Ignition energy was fixed at 25 mJ using a capacitance discharge ignition system.

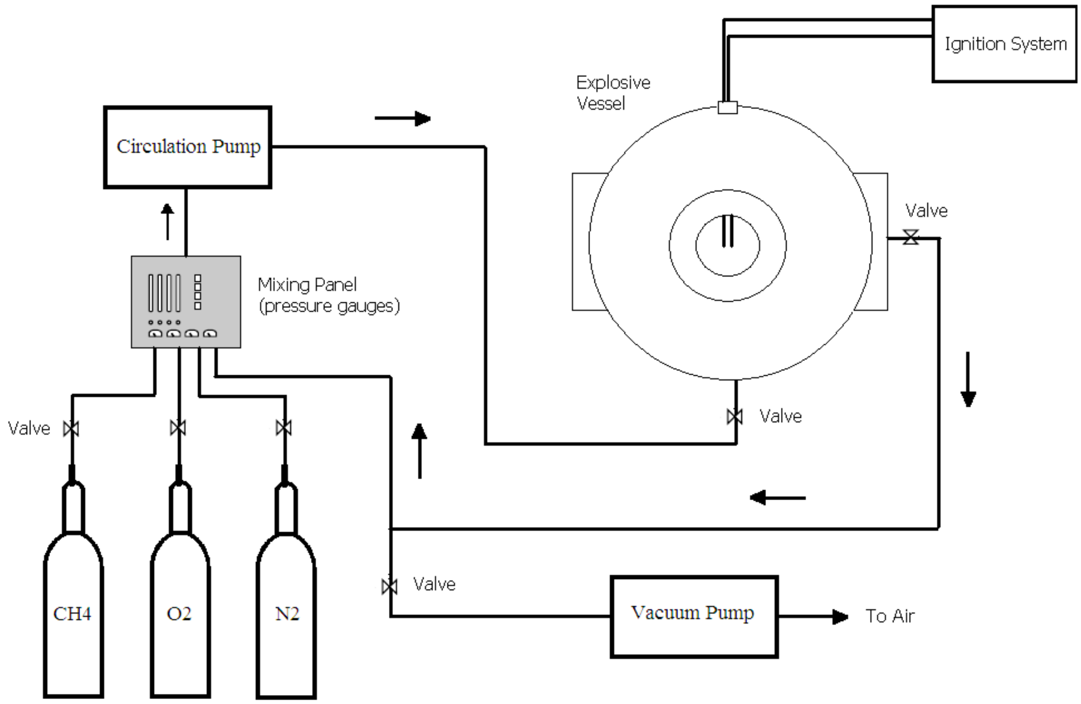


Figure 2. Gas mixing and filling system

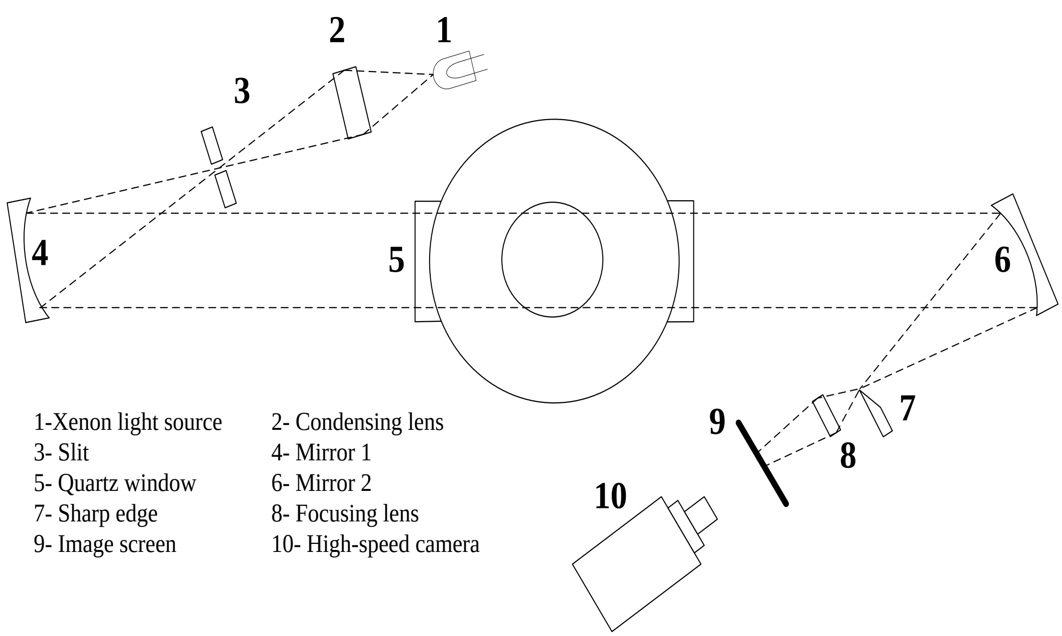


Figure 3. Schlieren setup and system elements

4. RESULTS AND DISCUSSION

4.1 Equivalence Ratio = 0.6

In figures 4 and 5, Schlieren photographs of combustion kernel growth for methane and propane explosions are reported, respectively. In figure 4, the kernel began to be observable by the Schlieren system after 2.0 ms from the instant of ignition. At 8.0 ms, a secondary kernel began to grow. This secondary flame kernel is deemed to grow due to the slow reaction rate characterizing the lean combustion. Propane explosion, in figure 5, did not exhibit secondary combustion kernel. On the other hand, planar pressure waves commenced at time equals to 18.0 ms. Such pressure waves developed significantly through time, leading to pressure wave interaction after 12 ms as shown in figure 6. The role of reflected pressure waves in accelerating the cellular structure of the flame is depicted by the quantitative evolution of such waves on the right hand of the test section, as in figure 6, during 12 ms. Then, the cellular structure took a completely chaotic pattern, until the end of the explosion, as illustrated in second set of photographs in figure 6.

4.2 Equivalence Ratio = 1.0

At the stoichiometric condition, methane-air explosion did not exhibit any secondary kernel growth, since the reaction rate is sufficient to consume the reactants in the faster than that at lean mixture, as it is quantitatively analyzed in section 4.4. Propane explosion at the stoichiometric condition is also characterized by a faster kernel growth than that of the lean mixture. In addition, the cellular structure initiation took place much faster that in the lean mixture. The combustion kernel growth in this case is traced in figure 8.

4.3 Equivalence Ratio = 1.4

In the rich combustion regime, the methane-air explosion was characterized by an accelerated kernel growth and cellular structure coexisting with the flame propagation. The first observation of the reflected pressure wave(s) was after 18 ms from the instant of ignition. The pressure wave interaction consumed 22 ms to reach the complete chaotic cellular structure after 40 ms from the ignition. The development of the combustion kernel and the temporal augmentation of the cellular structure are illustrated in figures 9 and 10, respectively. As to propane explosion, in such rich regime, the explosion was remarkably characterized by a very fast kernel growth and an early appearance of the complete cellular structure. The pressure wave interaction consumed approximately 10 ms to reach to the chaotic cellular structure after 15 ms from the instant of ignition. This progress is explained in figure 11.

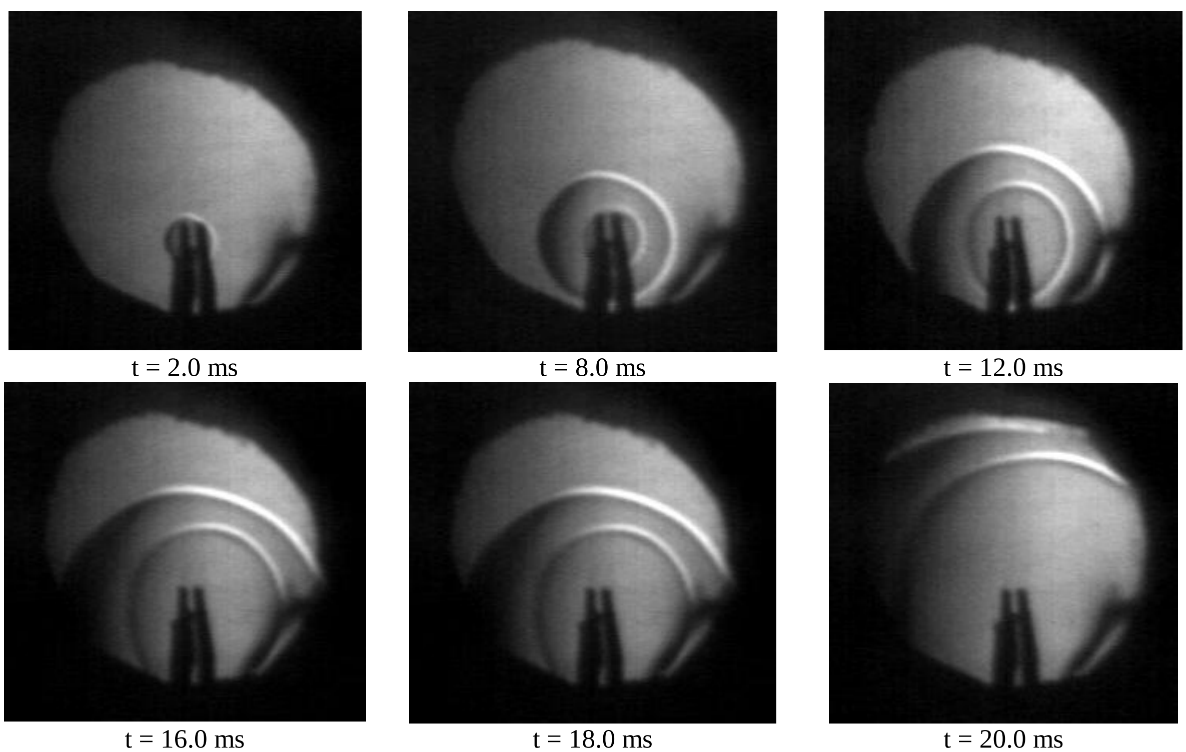


Figure 4. Schlieren photographs showing the methane combustion kernel growth, with millisecond resolution. $\varphi = 0.6$

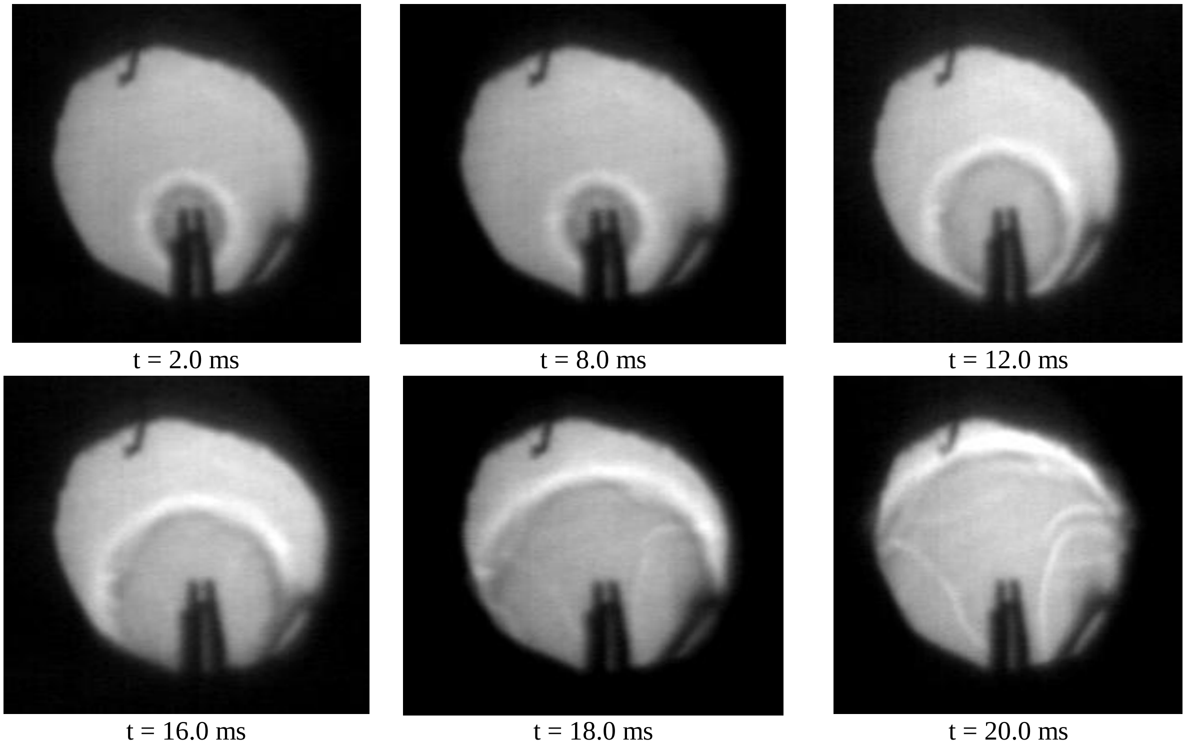


Figure 5. Schlieren photographs showing the propane combustion kernel growth, with millisecond resolution. φ = 0.6

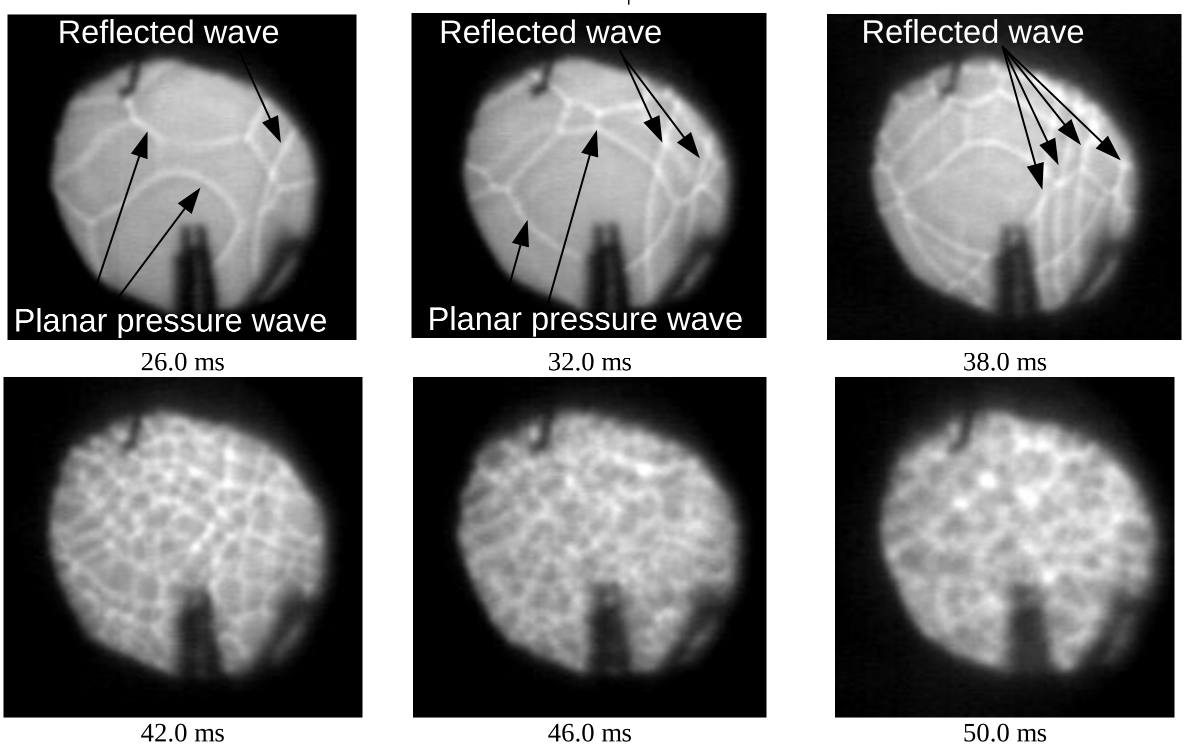


Figure 6. The propagation of the planar pressure waves in propane explosion, wave reflection, and the development of cellular structure . φ = 0.6

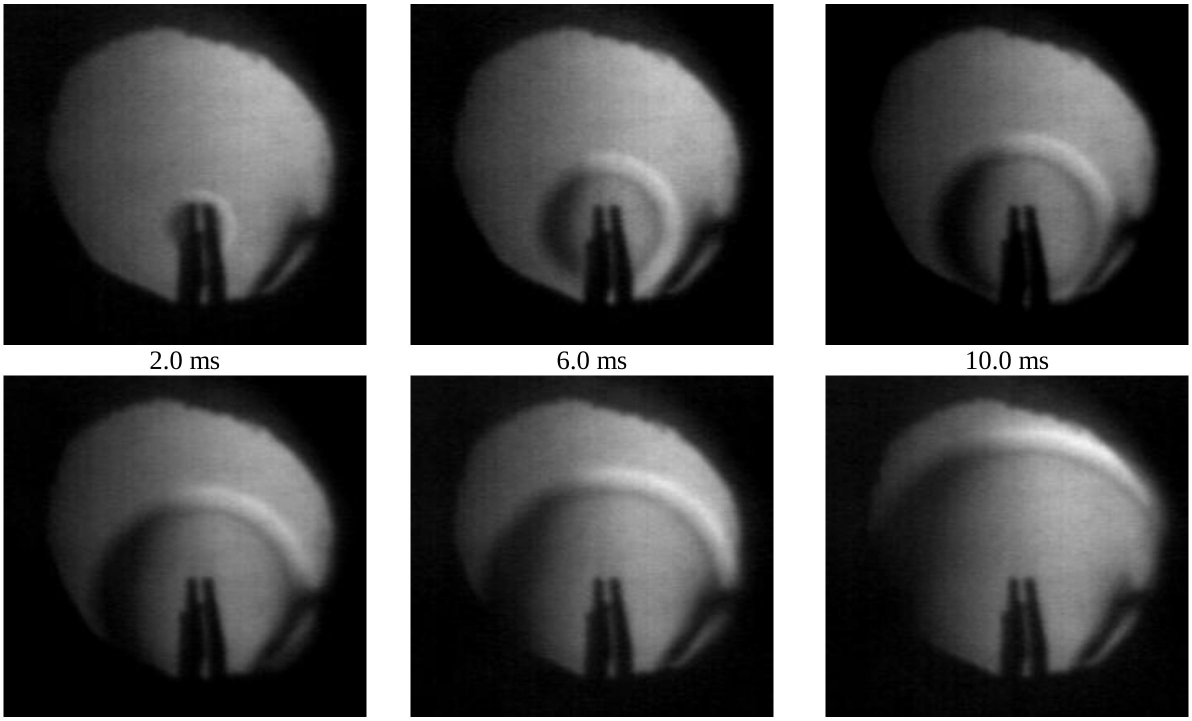


Figure 7. Schlieren photographs showing the methane combustion kernel growth, with millisecond resolution. φ = 1.0

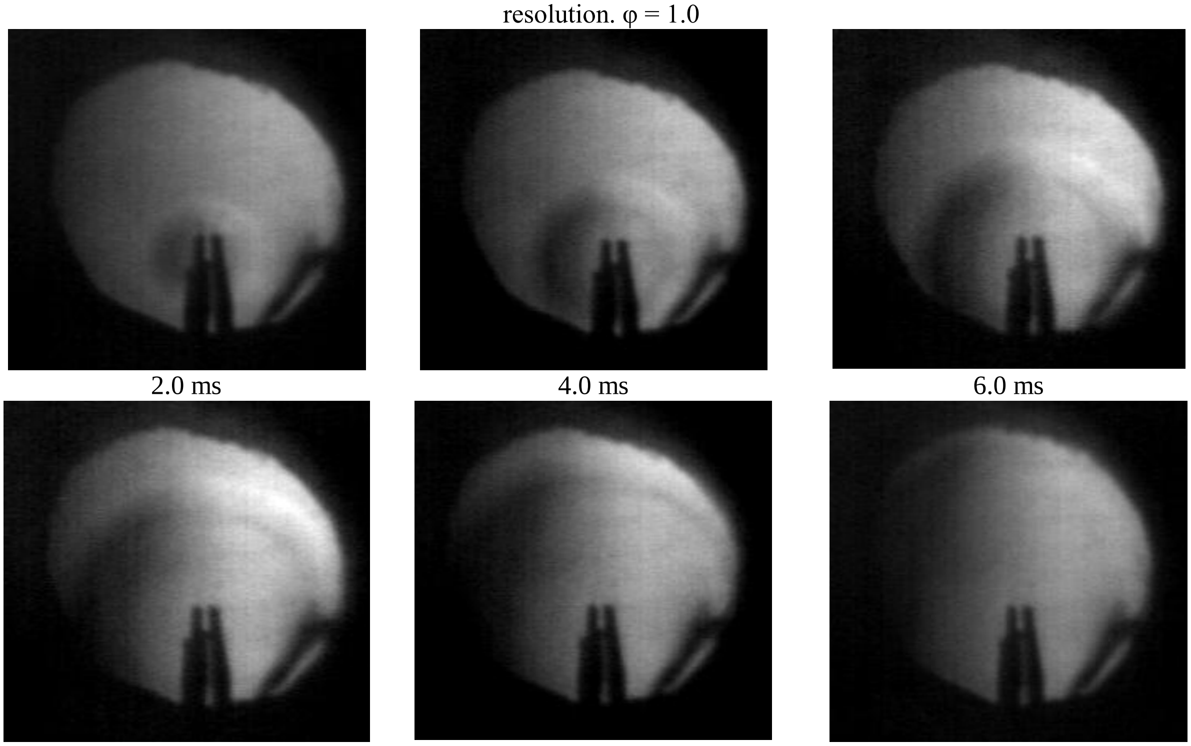


Figure 8. Schlieren photographs showing the propane combustion kernel growth, with millisecond resolution. φ = 1.0

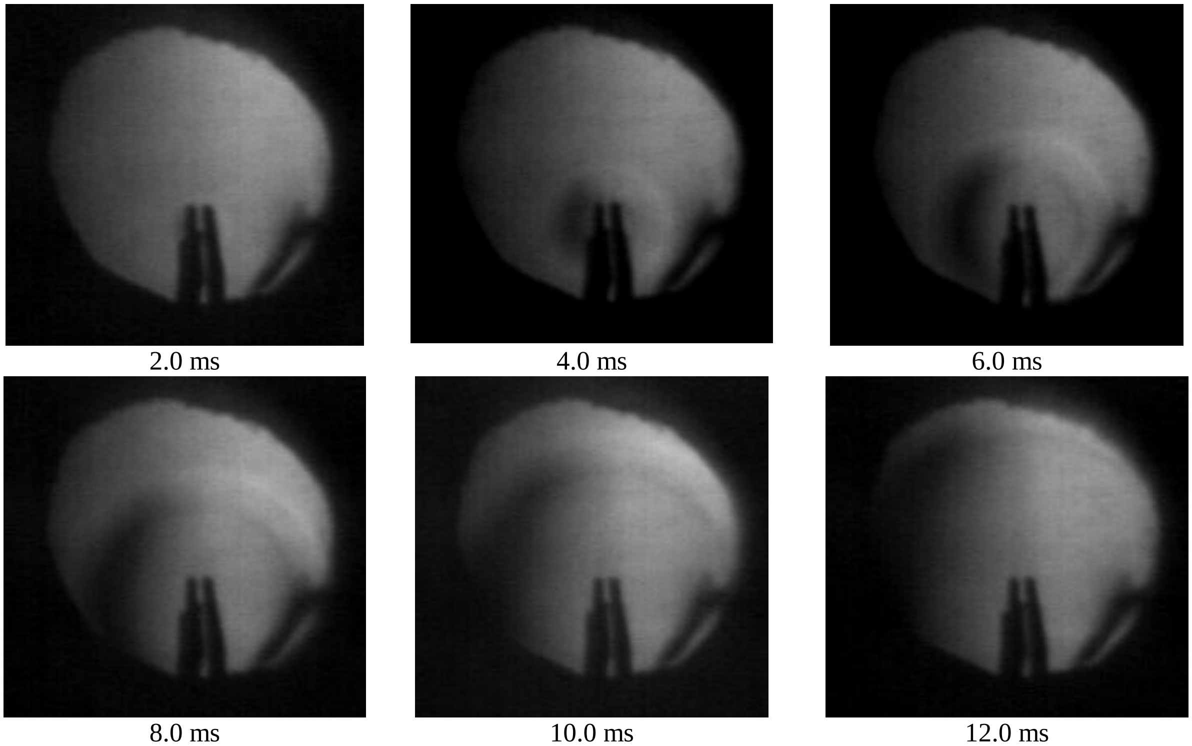


Figure 9. Schlieren photographs showing the methane combustion kernel growth, with millisecond resolution. φ = 1.4

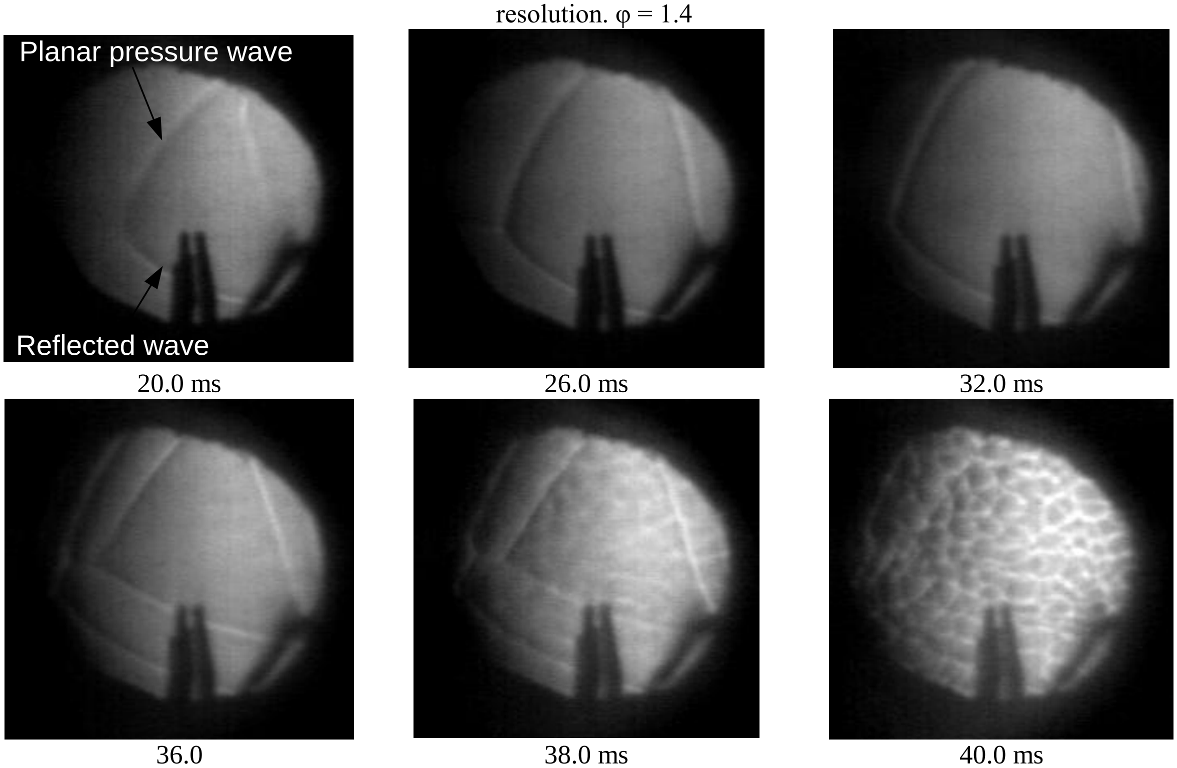
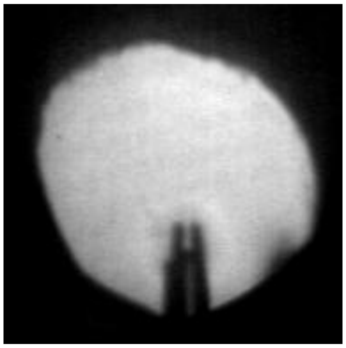
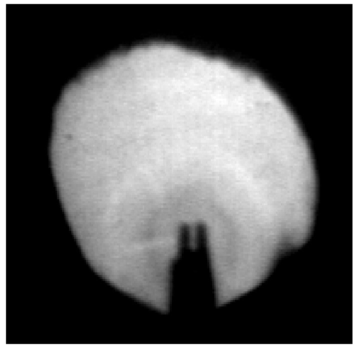


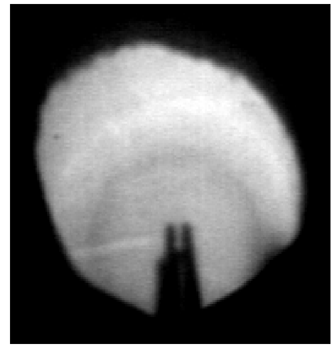
Figure 10. The propagation of the planar pressure waves in methane explosion, wave reflection, and the development of cellular structure . φ = 1.4



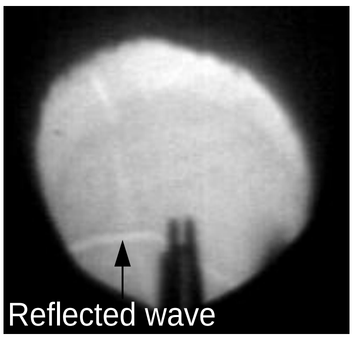
1.0 ms



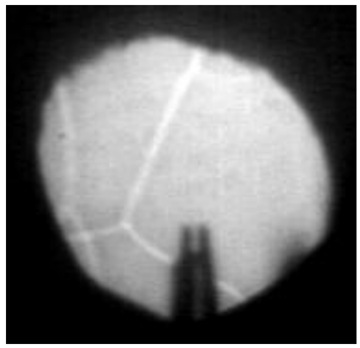
2.0 ms



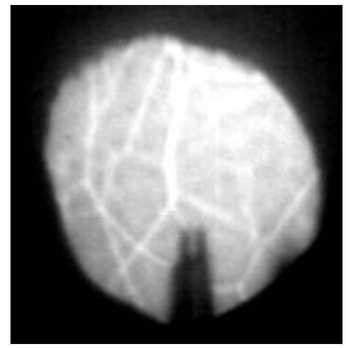
3.0 ms



5.0 ms



10.0 ms



13.0 ms

Figure 11. Schlieren photographs showing the propane combustion kernel growth, with millisecond resolution. φ = 1.4

4.4 Quantitative analysis

The observed kernel growth at different equivalence ratios for the two fuels was quantitatively analyzed through scaled measurement at the image screen. The radius of the kernel - if perfect kernel sphere is assumed - is an indication on the flame speed. In figures 12, 13 and 14 the kernel radius for methane and propane explosions are plotted at equivalence ratios equal to 0.6, 1.0 and 1.4 respectively.

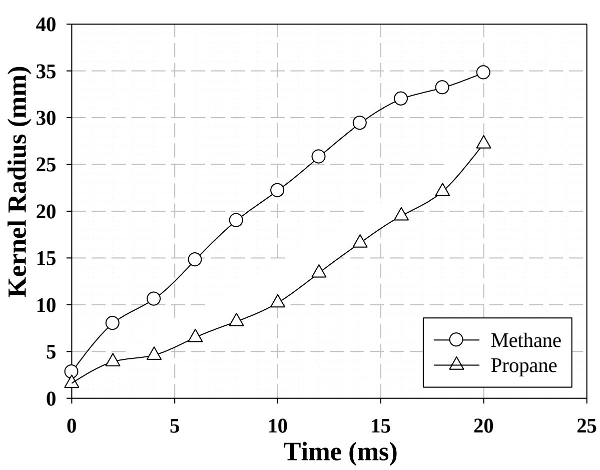


Figure 12. Temporal growth of flame kernel radius at φ = 0.6

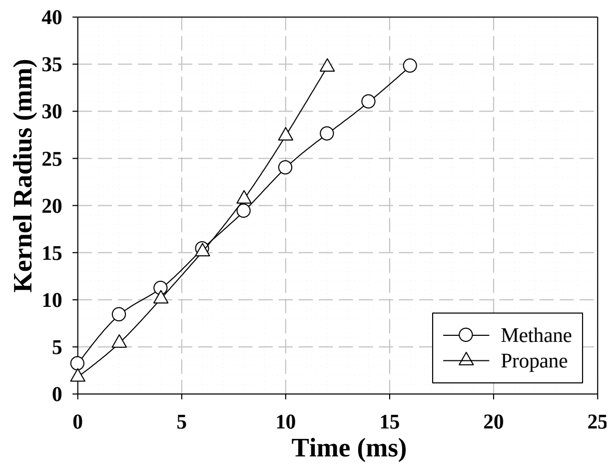


Figure 13. Temporal growth of flame kernel radius at φ = 1.0

It is evident, from figures 12-14, that the flame velocity of propane has a remarkable direct proportionality with the equivalence ratio, much higher than methane. In the lean combustion regime, the methane flame propagation velocity - represented by the temporal growth of the combustion kernel - is higher than propane flame propagation velocity. In stoichiometric and rich regimes, the propane flame propagation velocity exceeds that of methane after 6 and 2 ms, respectively. With the increase of the flame propagation velocity, the observable flame kernel disappears faster from the visible test section. This supports, essentially, the results obtained from the scaled measurements.

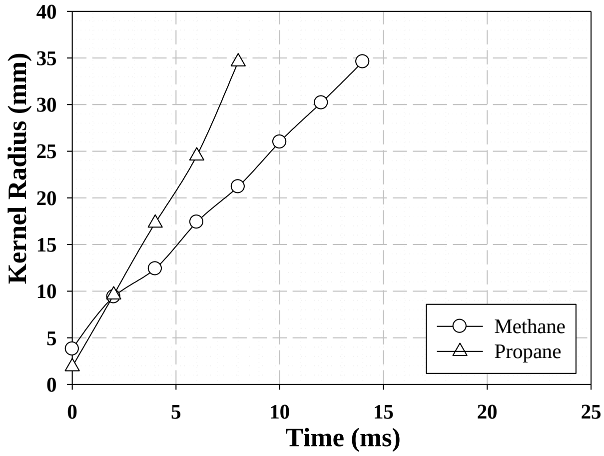


Figure 13. Temporal growth of flame kernel radius at $\varphi = 1.4$

5. CONCLUSION

The growth of combustion kernel in methane and propane - air explosions has been investigated. It was observed that the kernel growth rate during the initiation of the explosion is subjected to the fuel concentration. Generally, the kernel growth rate was found to be directly proportional to the fuel concentration. Propane (C_3H_8) had less kernel growth rate than methane (CH_4) in lean mixture. In stoichiometric and rich mixtures, propane had a higher kernel growth rate after a certain period of time, which is reversibly proportional to the fuel concentration. The cellular structure subsequent to the explosion initiation was also studied. In the lean mixture, cellular structure was only observed for propane. In stoichiometric and rich explosions, the cellular structure was observed for both fuels. The time consumed to form a completely chaotic cellular structure is shorter in propane than methane. Additionally, such time has shown a significant decrease when the equivalence ratio was increased from 1.0 to 1.4.

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