

IGNITION OF PROPANE-OXYGEN MIXTURE BY HOT INERT GAS INJECTION

Mohammed H. Elhsnawi and Andrzej Teodorczyk*

Faculty of Engineering, Naser Nation University E-mail address: elhsnawi@yahoo.com

* Institute of Heat Engineering, Warsaw University of Technology, Warsaw, Poland

المخلص

تم إجراء تجارب عملية لدراسة عملية الاحتراق (Pre-mixed ignition process) والتي تحدث عند حقن خليط البروبان والأكسجين في غرفة اختبار بغاز خامل (الارجون أو النيتروجين). تنشأ موجة من اللهب تسمى (Detonation Wave) في الجزء الأول من الجهاز (Driver Section) بواسطة شمعة احتراق في خليط من الاسيتيلين والأكسجين في ظروف ابتدائية تعادل 0.5 بار ودرجة حرارة الغرفة. تتحول موجة اللهب هذه إلى موجة صدمية في الجزء الثاني من الجهاز (Driven Section) خلال الغاز الخامل بعد انفجار العازل الفاصل بين الجزأين. تنعكس هذه الموجة (Incident Shock Wave) مُحدثة (Reflected Shock Wave) عند نهاية الجزء الثاني للجهاز مما يؤدي إلى ارتفاع درجة حرارة الغاز الخامل وضغطه خلف (Reflect Shock Wave) ويؤدي ذلك إلى انفجار العازل الفاصل بين الجزأين الثاني والثالث للجهاز مُحدث منفت (Jet) للغاز الخامل الساخن خلال فتحة قطرها 8 أو 11.2 مم. النتائج العملية دلت على أن عملية الاحتراق تحدث عندما تتجاوز (Static Enthalpy) لكتلة الغاز المحقون قيمة حرجة. تم استخدام برنامج Chemkin II لحساب الزمن اللازم لحدوث عملية الاحتراق ودرجة الحرارة الأديباتية نتيجة لتفاعل خليط الغاز الخامل والبروبان والأكسجين لقيم مختلفة من نسب حجم الخليط.

ABSTRACT

Experiments were performed to investigate the diffusion ignition process that occurs when hot inert gas (Argon or Nitrogen) is injected into the stoichiometric propane-oxygen mixture at the test section. Detonation wave initiated by spark plug in the driver section in stoichiometric acetylene-oxygen mixture at $P = 0.5$ bar and room temperature, propagates as incident shock wave in the driven section through inert gas after bursting the diaphragm separating the sections. At the end of driver section the inert gas is heated behind the reflected shock wave and then injected into the test section with the stoichiometric propane-oxygen mixture through the hole of 8 or 11.2 mm in diameter.

The results of experiments indicate that ignition occurs when the static enthalpy of injected mass of inert gas exceeds some critical value. The induction time and the adiabatic temperature after reaction of mixed inert gas and Propane-oxygen mixture were determined with the use of CHEMKIN II software [1] for different values of mixing volume ratio.

KEYWORDS: Pre-mixed ignition process; Jet ignitions; Detonation

INTRODUCTION

A starting jet flow under the present investigation occurs when a hot gaseous stream is suddenly released through an orifice of a high pressure into cold low pressure surrounding. The starting jet problem occurs in many engineering processes of practical importance, e.g. the ejection of hot gases from the flange gap of flame traps or flame-proof enclosures, the ignition of fire damp atmosphere by the hot gases coming out of flame-proof enclosures or by hot jets of exhaust products of dynamite explosives used for blasting, the bursting of the diaphragm of a safety valve caused by an excess pressure of the reservoir fluid, the sudden opening of the discharge valve of a pressure vessel and the injection of fuel into a combustion chamber of engines. Also, the ignition of combustible mixtures by hot burned gases from flames is of importance in many appliances, such as ramjet burners and rocket combustion chambers. Thus in the design of many engineering equipment, the understanding of starting jet flow is of immense value particularly in safety considerations. The designers would want to know not only qualitatively but also quantitatively the influence of various parameters and the way in which they affect the flow characteristics. The problem of jet ignition was studied extensively in the past by many authors [2-7]. A jet of heated air or other gas, if sufficiently hot, can also produce ignition when it comes into contact with combustible gases or vapors. Such an ignition source may be a problem during the rupture of an oil seal in a jet engine or during blasting operations in a coal mine where hot gases are released from the explosives employed. The temperatures at which combustible gas mixtures can be ignited by laminar jets of hot air and inert gases have been determined only in early years for hydrogen, carbon monoxide, and various low molecular weight hydrocarbons [8, 9, and 10]. In many practical combustion systems ignition may occur through contact with hot burned gases. Such process plays a vital role in flame stabilization on bluff bodies. It is also of importance in the ignition of firedamp by the hot spent gases of explosives used in mines. Hot gas ignitions differ from wire ignitions and auto ignitions in heated vessels primarily in that surface effects are absent with a hot gas heated source, provided the reaction chamber is relatively large. Generally, hot gas ignition temperatures of hydrocarbon combustible mixtures have been reported to agree with corresponding wire ignition temperatures but to be much higher than the auto-ignition temperatures of the mixtures [7]. Supersonic jet flow contains a rich combination of flow interactions and flow physics. These combinations include turbulent mixing and compressibility effects such as isentropic expansion and shock. Other factors may include chemical reactions or shear layer. Subsonic jet flow features are relatively simple. The main variable in the flow is shear layer development along the stream wise direction. In the absence of a pressure gradient, no significant in viscid flow features will appear in a subsonic jet. On the other hand, supersonic jet flow features can be very complex. Because of the supersonic nozzle exit Mach number, jet exit pressure can differ from ambient pressure. This pressure difference between the jet and the ambient fluid must be resolved locally either across an oblique shock, by a prominent streamline curvature at the jet boundary, or by a Mach disk inside the jet. In this paper the hot inert gas (Argon or Nitrogen) have been injected into stoichiometric (Propane-Oxygen) mixture in the combustion chamber.

EXPERIMENTAL SET-UP

The steel (1H18N9T) WUT detonation tube was used, shown schematically in Figure (1) consisted of three horizontal sections of driver, driven, and test sections. The

driver section was 9 cm in diameter, 90 cm long, and filled with stoichiometric acetylene-oxygen mixture at 0.5 bars and room temperature for all experiments. The driver section was separated from the driven section by double diaphragms. Two plastic diaphragms, 30 μm thick were used. The driven and test sections, both have a cross section of 11 x 11 cm. The 2.5 m long driven section was filled with inert gases (argon or nitrogen) to allow the incident shock wave to stabilize before reflection from the end wall. The 40 cm long test section was filled with mixtures under investigation (stoichiometric $\text{C}_3\text{H}_8 + \text{O}_2$). The orifice linking the driven and the test section ranges from 8 to 11.2 mm in diameter and an aluminum diaphragm of 30 μm thick is placed between the two sections in order to prepare the desired mixture. One pressure gauge was also connected to each section to watch the attainment of vacuum as well as to measure the initial pressure of the mixtures. Five PCB piezo-electric pressure transducers are mounted along the tube and record the shock wave pressure and time-arrival of the wave which is used to calculate the shock wave speed. Four pressure transducers were mounted at 6, 100, 210 and 240 cm from the flange at the beginning of the driven section (for convenience, these transducers are marked A, B, C, and D respectively).

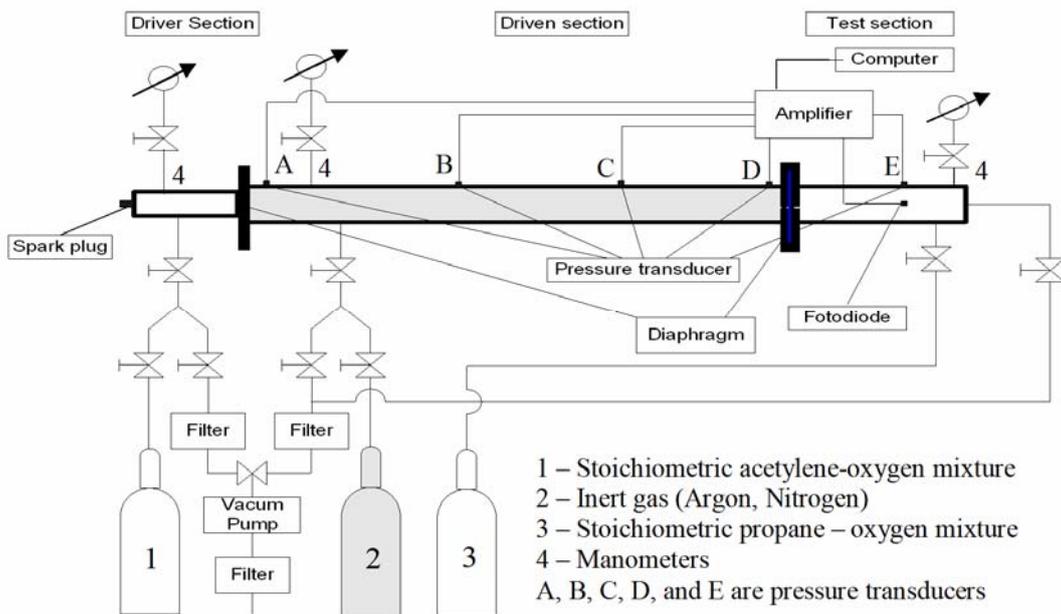


Figure1: Schematic of the experimental setup.

The signal of an incident shock wave detected by pressure transducer A was used to trigger the data acquisition system. The fifth transducer E was used to indicate the ignition caused by hot inert gas and it was located at a distance of 35 cm from the flange containing the orifice and the diaphragm at the beginning of the test section. The occurrence of ignition is additionally confirmed by photodiode located at 35 cm from the beginning of the test section. A vacuum pump was used to evacuate the tube until reaching acceptable vacuum level. Three separate bottles were connected for supply of the mixtures and inert gas when needed. The first one is for the detonable mixture, the second is for the inert gas, and the third is for the combustible mixture under investigation. An automotive spark plug with high voltage discharge was used to initiate

detonation wave in the driver section. The driver and the test sections were mounted on steel rails, allowing them to be moved back and forth in order to replace the diaphragms. The detonable and the combustible mixture was prepared by the method of partial pressure and left for at least 24 hours to allow enough time for complete mixing and diffusion between fuels and oxidizer. PCB piezo-electric amplifier type F483B08 was connected as shown. Experimental results were recorded and processed by automatic data acquisition system and personal computer.

EXPERIMENTAL RESULTS

Summary of some experiments performed in this study for ignition of propane-oxygen mixture is shown in Table (1). The value of ignition delay time τ was measured from experimental pressure and photodiode histories as a time between shock reflection from the orifice flange (start of the inert gas jet) and photodiode delay time (experimental). The parameters behind incident shock, reflected shock at the end of the driven section, the parameters at the jet exit (T_{jet} , P_{jet}) and total enthalpy of hot inert gas injected H were calculated from the simple model of Becker, R. [11].

Table 1: Summary of experimental results for $C_3H_8 + 5O_2$ ignition by hot inert gas

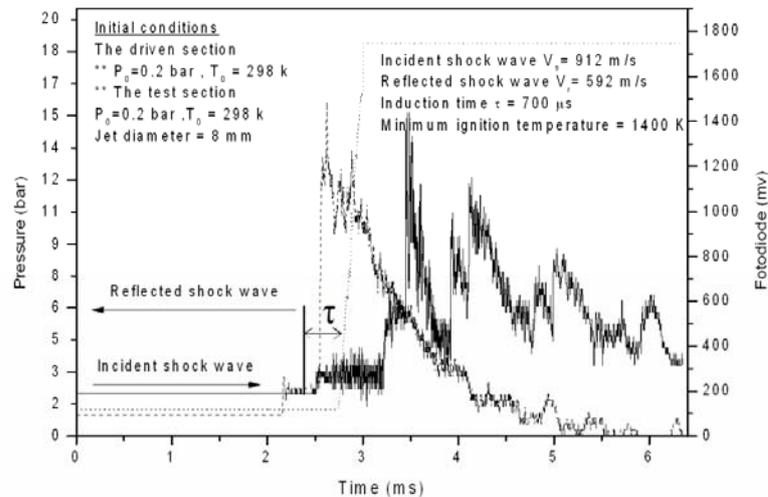
$\Phi = 8$ mm					$\Phi = 11.2$ mm				
Inert gas	P_0 [bar]	H [J]	$T_{Ignition}$ [K]	τ [μ s]	Inert gas	P_0 [bar]	H [J]	$T_{Ignition}$ [K]	τ [μ s]
Argon	0.2	20	1450	700	Argon	0.2	36.5	1470	650
Argon	0.4	21	1090	750	Argon	0.4	36	1050	720
Nitrogen	0.2	29.3	1000	800	Nitrogen	0.2	41.4	1000	600
Nitrogen	0.4	30.7	800	950	Nitrogen	0.4	40.8	770	700

Φ - Orifice diameter, P_0 - initial pressure of $C_3H_8 + 5O_2$, H - total enthalpy of hot inert gas (calculated), $T_{Ignition}$ - temperature of ignition (calculated) and τ -ignition delay time (experimental).

The signal of pressure transducer D indicating the pressure jumps due to the arrival of the incident and reflected shock wave at the end of the driven section and the signal of pressure transducer E located at a distance 350 mm from the flange containing the orifice and the diaphragm at the beginning of the test section indicating the pressure jumps due to the arrival of hot inert gas injection and shows ignition. The minimum ignition temperature of hot inert gas injected giving ignition ($T_{Ignition}$) and ignition delay time (τ) presented in Table (1) is the mean value of all experiments for the case under investigation. For a jet of 8 mm diameter, for the injection of hot argon an increase of initial pressure of combustible mixture in the test from 0.2 to 0.4 bars resulted in decrease of the minimum temperature of injected gas causing ignition from 1450 to 1090 K. At the same time the induction time for ignition process has increased from 700 to 750 μ s. However, for a jet of 11.2 mm, an increase of initial pressure of combustible mixture from 0.2 to 0.4 bars resulted in decrease of minimum ignition temperature from 1470 to 1050 K. At the same time the induction time has increased from 650 to 720 μ s. For the injection of hot nitrogen an increase of the initial pressure of the combustible mixture from 0.2 to 0.4 bars resulted in decrease of the minimum temperature of injected inert gas giving ignition from 1000 to 800 K, and in increase of the induction

time from 800 to 950 μs for a jet of 8 mm diameter. However, for a jet of 11.2 mm, an increase of initial pressure of combustible mixture from 0.2 to 0.4 bars resulted in decrease of minimum ignition temperature from 1000 to 770 K. At the same time the induction time has increased from 600 to 700 μs . As shown in Table (1), an increase of jet diameter from 8 mm to 11.2 mm results in a little effect on the minimum ignition temperatures (specially for Argon), the induction time decreases with increasing jet diameter and the total enthalpy increases. The results indicate that ignition occurs when the static enthalpy of injected mass of inert gas exceeds some critical value.

Figures (2, 3, 4 and 5) show pressure history of incident and reflected shock wave in driven section for different initial pressure (0.2-0.4 bars) and after some delay pressure history of strong ignition caused by hot argon jet in the test section for different jet diameter (8-11.2 mm).



---- Pressure profile of trans.D, ——— Pressure Profile of transE, Photodiode signal

Figure 2: Jet of hot argon to stoichiometric propane--oxygen mixture.

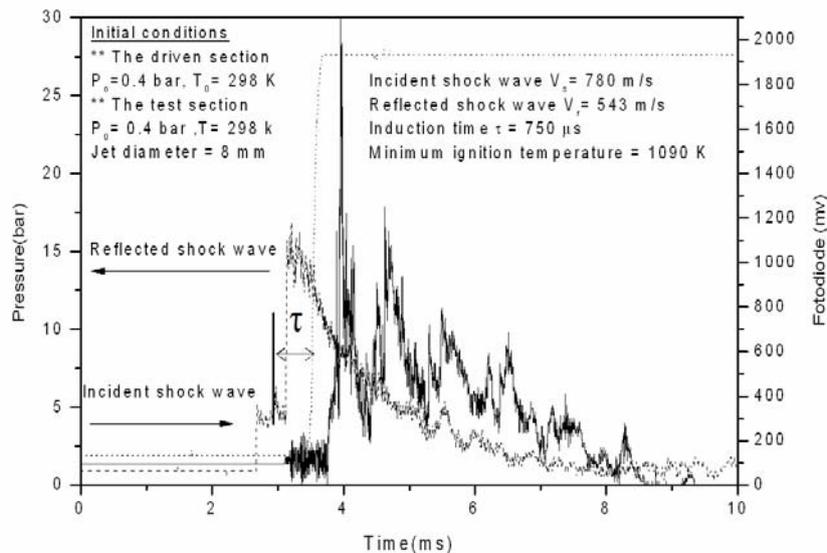


Figure 3: Jet of hot argon to stoichiometric propane--oxygen mixture.

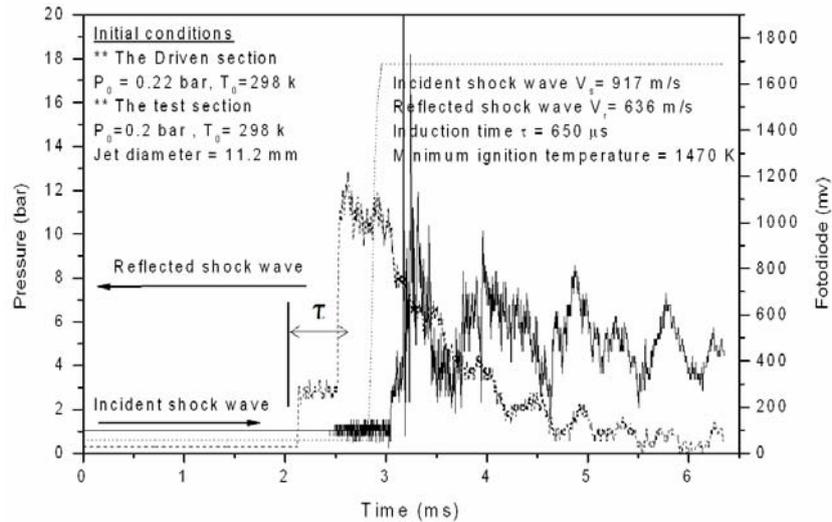


Figure 4: Jet of hot argon to stoichiometric propane--oxygen mixture.

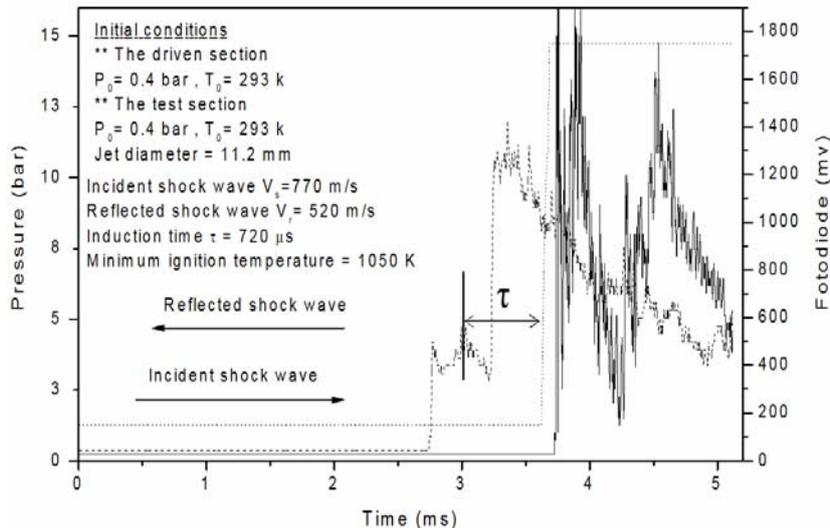


Figure 5: Jet of hot argon to stoichiometric propane--oxygen mixture.

The occurrence of ignition is additionally confirmed by photodiode. Figures (6, 7, 8 and 9) show similar pressure histories for nitrogen injection. Figure (10) shows the calculated mass of hot nitrogen versus time of injection for two values of orifice diameter and two values of initial pressure of propane-oxygen mixture in the test section. As expected, larger diameter increases this mass. Square placed on each curve show the experimental times of ignition in each case. Generally, an increase of mass flow-rate of hot nitrogen results in decrease of ignition delay time, however this tendency is more visible for lower back pressure (higher jet velocity). As shown increasing the cross section area from 8 to 11.2 mm results in decrease of ignition delay time by approximately 0.2 ms for both cases of back pressure (0.2 and 0.4 bars). Figure (11) shows similar results for hot argon injection. In this case an increase in orifice diameter from 8 to 11.2 mm, results in decrease of ignition delay time by approximately 0.05 ms for both cases of back pressure.

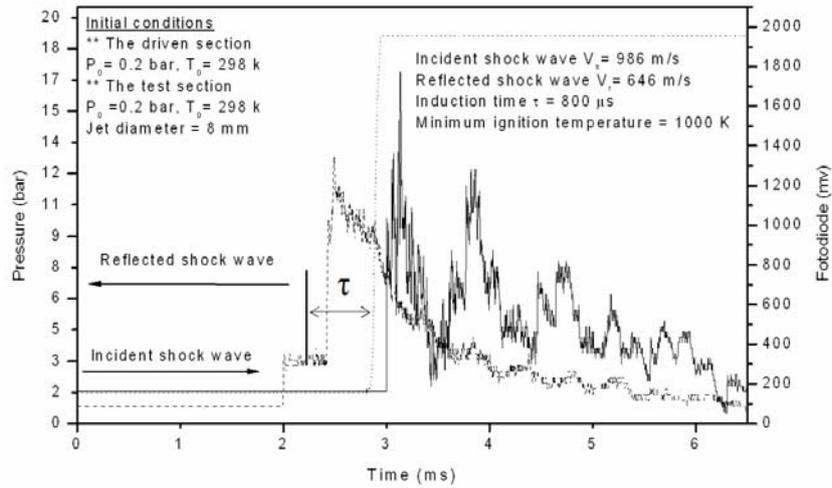


Figure 6: Jet of hot nitrogen to stoichiometric propane--oxygen mixture.

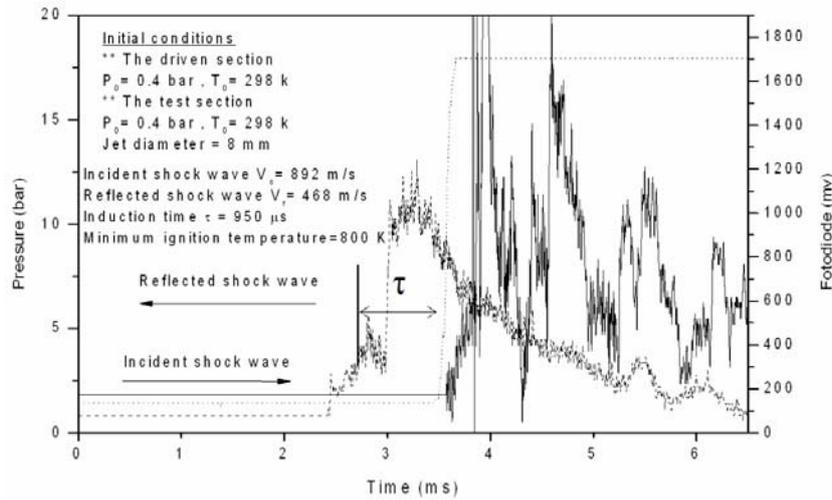


Figure 7: Jet of hot nitrogen to stoichiometric propane--oxygen mixture.

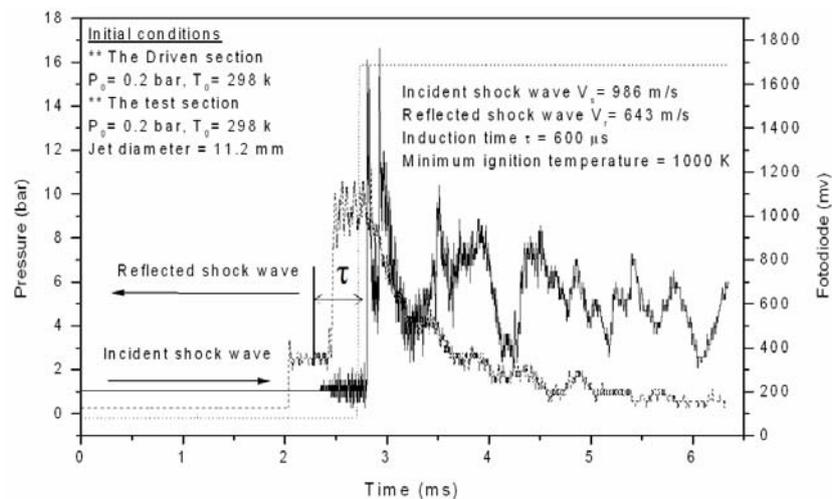


Figure 8: Jet of hot nitrogen to stoichiometric propane--oxygen mixture.

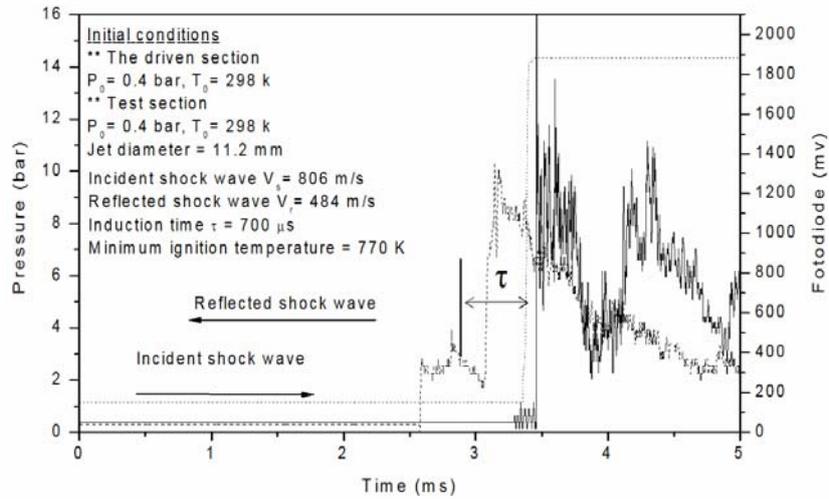


Figure 9: Jet of hot nitrogen to stoichiometric propane--oxygen mixture.

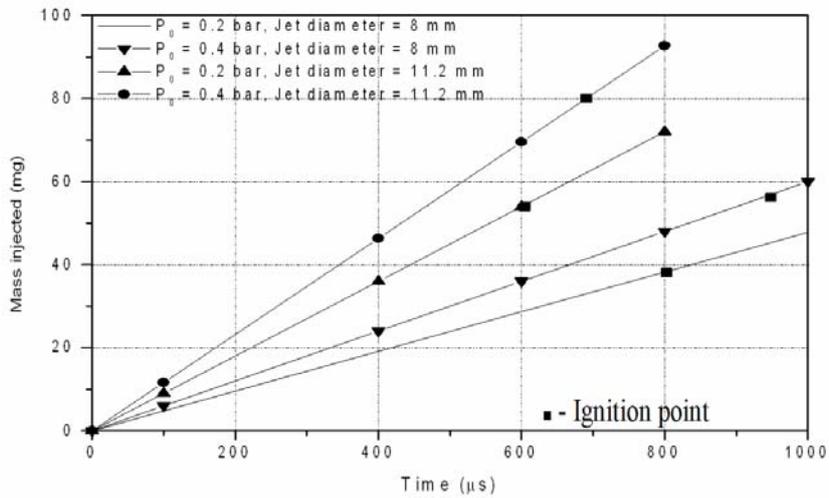


Figure 10: Mass of nitrogen injected to stoichiometric propane--oxygen mixture.

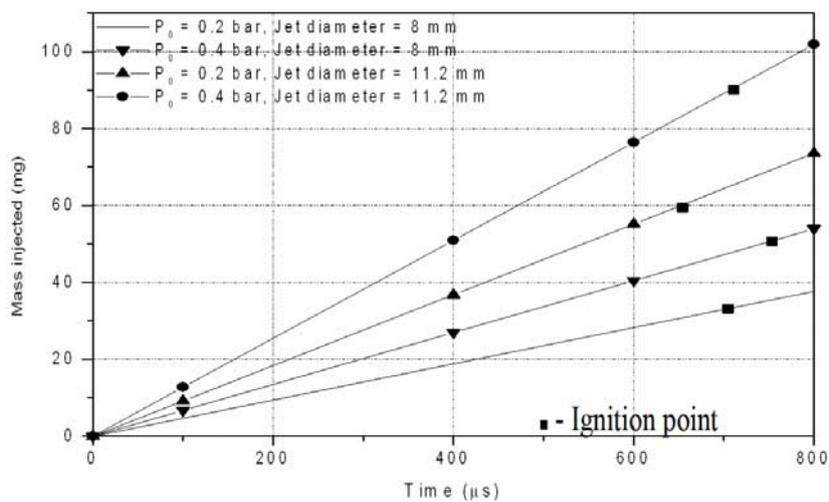


Figure 11: Mass of argon injected to stoichiometric propane--oxygen mixture.

CHEMKIN II SOFTWARE

The original CHEMKIN by Kee, et al [12] was developed in “Sandia National Laboratories”. It is a commercial FORTRAN package solving chemical kinetics. CHEMKIN-II is a revised, improved version of CHEMKIN. The most important new capability is an accurate and efficient means of describing pressure- dependent reactions. It provides flexible and powerful tools (source code) for incorporating complex chemical kinetics into simulation of fluid dynamics. The general objective is to characterize the thermal ignition of combustible gas mixtures. Thermal ignition is the spontaneous explosion that occurs after a chemical induction period for homogeneous mixtures at constant volume.

SIMPLIFIED MATHEMATICAL MODEL OF IGNITION

Ignition and turbulent mixing is extremely difficult to model theoretically since it involves turbulent mixing, shock waves and chemical reactions simultaneously. Experimentally, it is also difficult to obtain a detailed, quantitative observation of the gas dynamics and chemical processes in the mixing zone at the head of the jet. Thus, it is of value to analyze some simple theoretical limiting cases to deduce some qualitative information on the jet initiation phenomenon. It has been assumed that the hot inert gas (initially at the constant volume state) to first expand isentropically to $M = 1$. Then it has been investigated that the non-equilibrium chemical reactions when different amounts of unburned mixtures are mixed with the expanded hot inert gas. By computing the temperature after mixing, T_m the induction time, τ , and the adiabatic temperature, T_a after mixing of hot inert gas and unburned mixtures for different mixing volume ratio, $R = v_{jet} / v_u$, we can gain some insight into most favorable conditions for ignition process of combustible mixtures.

The jet parameters of hot inert gas can be estimated with the assumption of sonic ($M = 1$) and isentropic flow. The temperature and pressure at the jet exit cross section are equal to, respectively:

$$\frac{T_{jet}}{T_r} = \frac{2}{\gamma + 1}$$

$$\frac{P_{jet}}{P_r} = \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}}$$

Where P_r and T_r are the pressure and temperature of gas in driven section of the experimental setup behind reflected shock wave, T_{jet} and P_{jet} are temperature and pressure of gas at the exit from orifice. Next, we shall assume that the given volume of expanded hot inert gas v_{jet} to be mixed simultaneously with a certain volume of cold unburned combustible mixture v_u (at room temperature). The temperature after constant pressure adiabatic mixing T_m can readily be determined from energy conservation, i.e.

$$\rho_{jet} v_{jet} C_{p_{jet}} T_{jet} + \rho_u v_u C_{p_u} T_u = (\rho_{jet} v_{jet} C_{p_{jet}} + \rho_u v_u C_{p_u}) T_m$$

And solving for T_m gives

$$T_m = T_{jet} \left(\frac{1}{1 + \left(\frac{\rho_u C_{p_u}}{\rho_{jet} C_{p_{jet}}} \right) \frac{1}{R}} \right) + T_u \left(\frac{1}{1 + \left(\frac{\rho_{jet} C_{p_{jet}}}{\rho_u C_{p_u}} \right) R} \right)$$

Knowing T_m the ignition induction time τ and adiabatic temperature T_a after reaction of mixed inert gas and combustible mixture are determined with the use of CHEMKIN II software [1] for different values of mixing volume ratio, R .

For propane-oxygen mixture, the variation of T_m , τ , and T_a are illustrated in Figure (12) for argon and in Figure (13) for nitrogen. For argon, the minimum induction time is 200 μ sec and corresponds to a volume ratio of about 11 where $T_m = 1600$ K. However, for nitrogen jet, the minimum induction time is 300 μ sec and corresponds to a volume ratio of about 9 where $T_m = 1500$ K.

The results of calculations indicate the importance of temperature on ignition delay time. The temperature must be sufficiently high in order to achieve a short induction time. Thus, too small a volume ratio of R would quench the reaction when T_m drops below the auto-ignition limit ($\tau \rightarrow \infty$). The adiabatic combustion temperature in the mixing zone decreased as the hot inert gas volume increased but the important measure of the energy released in the mixing zone is denoted by the difference between T_a and T_m . Thus, at high volume ratio, the energy releases decreases as the volume of the hot inert gas in the mixing zone increased.

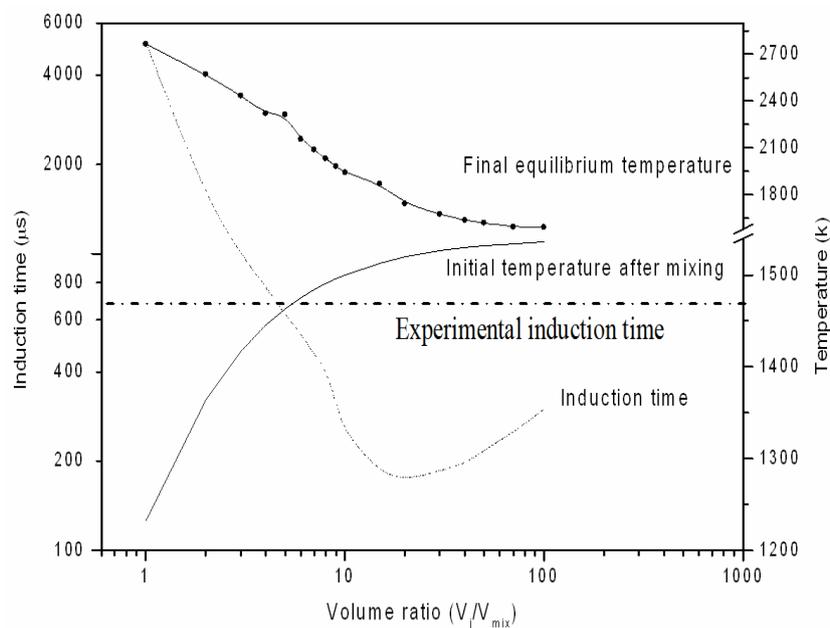


Figure12: Temperature after mixing, ignition delay time, adiabatic temperature of the products of constant volume combustion and experimental induction time as a function of volumetric ratio of hot argon to unburned propane-oxygen mixture.

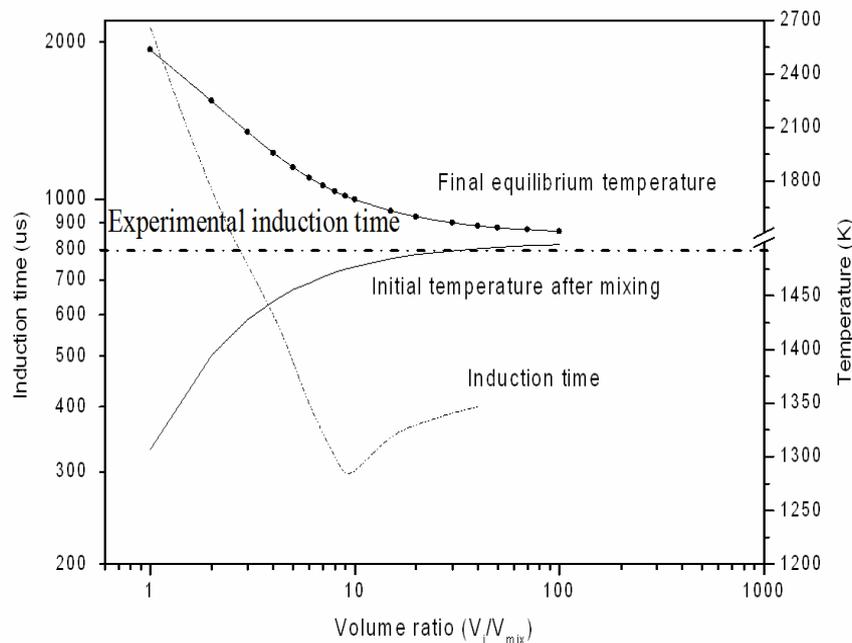


Figure13: Temperature after mixing, ignition delay time, adiabatic temperature of the products of constant volume combustion and experimental induction time as a function of volumetric ratio of hot nitrogen to unburned propane-oxygen mixture.

CONCLUSIONS

Ignition of stoichiometric gaseous fuel-oxygen mixture (propane-oxygen) by hot inert gas jet (argon and nitrogen) was studied experimentally and theoretically. In the experiments the inert gas in the driven section were heated behind the incident shock wave and additionally heated behind the reflected shock wave and then injected into the test section with stoichiometric gaseous Propane-oxygen mixture under investigation at room temperature through an orifice of 8 mm and 11.2 mm in diameter. Initial pressure of gaseous Propane-oxygen mixture in the test section was varied from 0.2 bars to 0.4 bars. In the theoretical study the gas dynamics of hot inert gas jet and chemical process in the mixing zone with Propane-oxygen mixture are extremely complex since they involve turbulent mixing, shock waves and chemical reactions simultaneously. Thus, for the qualitative analysis of jet initiation phenomenon simple theoretical limiting case was used first. The jet parameters of hot inert gas were estimated with the assumption of sonic ($M = 1$) and isentropic flow. The temperature after constant pressure adiabatic mixing can be determined from energy conservation. The induction time and the adiabatic temperature after reaction of mixed inert gas and fuel-oxygen mixture were determined with the use of CHEMKIN II software for different values of mixing volume ratio. The results of calculations indicate the importance of temperature on ignition delay time. The temperature must be sufficiently high in order to achieve a short induction time. Thus, too small a volume ratio of R would quench the reaction when T_m drops below the auto-ignition limit ($\tau \rightarrow \infty$). The adiabatic combustion temperature in the mixing zone decreased as the hot inert gas volume increased but the important measure of the energy released in the mixing zone is denoted by the difference between T_a and T_m . Thus, at high volume ratio, the energy release decreases as the volume of the hot inert gas in the mixing zone increased.

- For injection of hot argon to stoichiometric propane-oxygen mixture through 8 mm jet an increase of the initial pressure of combustible mixture in the test section from 0.2 to 0.4 bar resulted in decrease of the minimum temperature of injected gas causing ignition from 1450 to 1090 K. At the same time the induction time for ignition process has increased from 700 to 750 μ s. However through 11.2 mm, the minimum temperature of injected argon causing ignition decreased from 1470 to 1050 K and the induction time of ignition process has increased from 650 to 720 μ s.
- For the injection of hot nitrogen through 8 mm jet an increase of initial pressure of combustible mixture from 0.2 to 0.4 bars resulted in decrease of the minimum temperature of injected inert gas giving ignition from 1000 to 800 K, and in increase of induction time from 800 to 950 μ s. However through 11.2 mm, the minimum temperature of injected nitrogen causing ignition decreased from 1000 to 770 K and the induction time of ignition process has increased from 600 to 700 μ s. The results of experiments indicate that ignition occurs when the static enthalpy of injected mass of inert gas exceeds some critical value.

REFERENCES

- [1] Kee, R. J., Ruphley F. M. & Miller J. A. 1991 "Chemkin-II: A FORTRAN Chemical Kinetics Package for the Analysis of Gas-Phase Chemical Kinetics". Sandia Report, SAND89-8009B. UC-706
- [2] Charuel, P. & Leyer, J. C. 1983 "Hot Jet Ignition of Unconfined Hydrocarbon-air Mixture". 9 ICDERS
- [3] Gussak, L. A. 1975 "High Chemical Activity of Incomplete Combustion Products and a Method of Prechamber Torch Ignition for Avalanche Activation of Combustion in Internal Combustion Engines". SAE Paper 750890
- [4] Hayashi, A. K., Ito H., Uchida, N., Watanabe, Y., Suetake, M. & Karasawa. H. 1997 "Ignition Mechanism by Hydrogen Flame Jet through an Orifice". 21st International Symposium on Shock Waves, Great Keppel Island, Australia.
- [5] Oppenheim, A. K., Teichman K. & Stewart, H. E. 1978 "Jet Ignition of an Ultra-Lean Mixture". SAE Paper 780637
- [6] Wolanski, P., 1996 "Application of Pulsed Jet Combustion to Internal Combustion engines", in Dynamics of Exothermicity, J. Ray Bowen Ed. Combustion Science & Technology Book Series, Vol. 2, Gordon and Breach Publishers, pp. 131-150
- [7] Wolfhard, H. G. 1958 "The Ignition of Combustible Mixtures by Hot Gases". Jet Propulsion, V. 28, p. 798.
- [8] Vanpee, M. & Bruszak, A. E. 1963 "The Ignition of Combustible Mixtures by Laminar Jets of Gases". BuMines RI6293.
- [9] Vanpee, M. & Wolfhard, H. G. 1960 "Ignition by Hot Gases". BuMines RI5627.
- [10] Kuchta, J. M. & Cato, R. J. 1966 "Hot Gas Ignition Temperatures of Hydrocarbon Fuel-Air Mixtures". BuMines RI6857.
- [11] Becker, R., 1922 Z. Phys., 8, 321
- [12] Kee, R. J., Miller, J. A. and Jefferson, T. H. 1980 "Chemkin: A General-Purpose, Problem- Independent, Transportable, FORTRAN Chemical Kinetics Code Package" Sandia National Laboratories Report, SAND80-8003.