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INVESTIGATION OF IGNITION DELAY OF HYDROCARBON FUEL USING SHOCK TUBE

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Abstract: Shock tube facility in the Propulsion and High Enthalpy laboratory, Aerospace Engineering Department, has been extensively used to study the ignition characteristics of fuels by scaling the ignition delay times for various hydrocarbon fuels at high temperatures. The present study of ignition delay is concerned with ethane and acetylene. The fuel is premixed with oxygen along with argon dilution to a desired concentration in the mixing chamber. The measurement of ignition delay times have been made behind the reflected shock region in the temperature range of 800-2200 K and in the pressure range of 9-40 atm at equivalence ratios (ϕ = 0.5 & 1). Driver gas is helium and the pressure ratio (P_4/ P_1) across the diaphragm is changed to create a shock wave of desired Mach number in the driven section of the shock tube and thereby getting the required temperature behind the reflected shock. The measurement of ignition delay is made by measuring the ignition induced pressure rise and CH radical emission simultaneously. It is noted that there is a drop in ignition delay time of ethane as its amount increases. Ethane has a considerably shorter ignition delay than acetylene. From the present study it is noted that the activation energy of ethane lies in the range of 32-37 kcal/mol and activation energy of acetylene lies in the range of 39-42 kcal/mol.

KEYWORDS: Ignition delay, ethane, acetylene, reflected shock, shock tube.

I. INTRODUCTION

The fuels ignition features play an important task in the draft of combustion systems. Compared to acetylene, the delay periods of ethane are much shorter. Fuel ignition delay time is the typical time used to measure the length of the combustion chamber gas flow. This is an important standard to measure the quality of ignition and flame sustainability in an engine [1-4]. Net act of a combustion system can be observed by ignition delay time.

A conventional shock tube is a very effective tool in studying the ignition characteristics of the fuel. Shock tube is used to study the kinetics data and ignition delays for the fuels at high temperature [5-12].

The intention of this conveying is to explain the available shock tube facility at Propulsion and High Enthalpy Laboratory of Aerospace Engineering Department at Karunya University used for measurements of ignition delay time and presents its working details. The present study of ignition delay is concerned with ethane and acetylene for equivalence ratio 0.5 and 1.0.

II. EXPERIMENTAL SETUP

The shock tube found in Karunya University has a circular cross-section with an internal diameter of 80 mm and a wall thickness of 18 mm is made up of stainless-steel material (SS304). A metallic aluminium diaphragm was used to separate the tube into driver (high pressure) and driven (low pressure) sections. Diaphragm station enables employing diaphragms of different thicknesses and groove depth as per the application to achieve the required thermodynamic condition behind the reflected shock wave. The driver section is 2000 mm long and provision with the ports for connecting the high-pressure gas cylinders, pressure gauges and vent line. Likewise, ports are provided in the 5510 mm long driven section for bridging the vacuum pumping system, test-gas feeding system, pressure gauges, high speed pressure transducer to measure the dynamic pressure rise behind the incident and the reflected shock wave. Pressure transducers are mounted at different places of the driven section at a known distance from each other. The shock tube has been hydraulically tested up to a pressure of 280 atm. The problem of a variable dwell time may be substantially reduced by a slight modification in the shock-tube channel [13]. A ball valve of 80 mm internal bore has been introduced at 300 mm from the endwall of the driven section which isolates a small volume test section from the long-driven section, in a way that the reactant test gases are limited only to the region in middle of the ball valve and the end wall of the driven section before shock wave proceed along it.

The endwall of the shock tube has an optical window which can be used to monitor the combustion reaction in the tube with the help of Thorlabs photodiode detector (Model PDA36A-EC). The photodiode detector captures the radical emissions when ignition takes place inside the shock tube. The output signal from the amplified detector is fed into the data acquisition system. Standard instrumentation with PCB Piezoelectric pressure transducers (113B22) and PCB signal conditioners and NI Data acquisition system have been used. The schematic diagram of the shock tube experimental setup is shown in Figure 1. Reflected shock wave initiates the ignition of the fuel/oxygen mixture in the available set of tests.

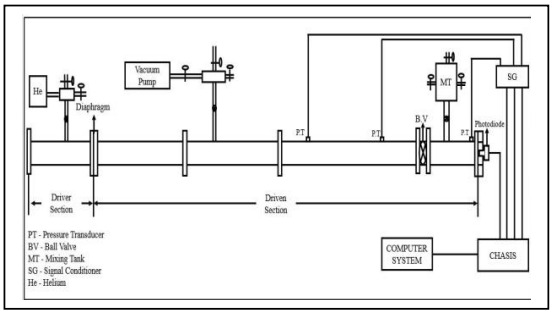


Figure 1. Illustrative diagram of the shock tube and its equipment's.

III. Experiment Technique:

Driver gas is helium and Dilutant is argon in driven section. At a predetermined pressure of the driver section, the aluminium diaphragm will burst open which gives rise to a shock wave that propagates along the low pressure driven section. The test section is charged with the required test gas mixture at a pressure (P_1), and the rest of the driven section is filled with argon gas to the same pressure (P_1), the pressure (P_4) at which the diaphragm ruptures is recorded. By using a PCB piezoelectric pressure transducer mounted at 7 mm from the end wall of the driven section, the pressure rise behind the incident and the reflected shock wave is recorded as shown in Figure 2. The incident shock velocity (M_s) is measured utilizing three piezoelectric transducers mounted at a known distance from each other. The last two transducers give the velocity that is to be considered. From the incident shock Mach number M_s, the reflected shock wave pressure P_5 and temperature T_5 is calculated using the following normal shock relations (Rankine-Hugoniot equation):

$$\frac{P_5}{P_1} = \left[\frac{2\gamma M_s^2 - (\gamma - 1)}{(\gamma + 1)}\right]\left[\frac{(3\gamma - 1)M_s^2 - 2(\gamma - 1)}{(\gamma - 1)M_s^2 + 2}\right]$$

$$\frac{T_5}{T_1} = \frac{[2(\gamma - 1)M_s^2 + (3 - \gamma)][(3\gamma - 1)M_s^2 - 2(\gamma - 1)]}{(\gamma + 1)^2 M_s^2}$$

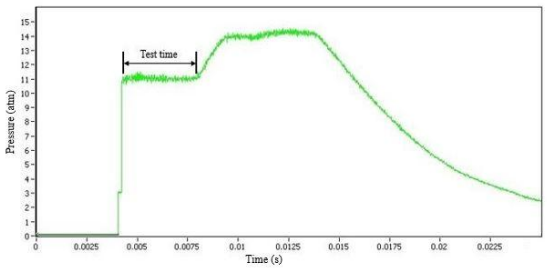


Figure 2. Typical pressure plot showing the primary shock (first rise) and reflected shock (second rise) waves.

From Figure 2, it can be noted that the pressure (P_5) is constant for a certain time (test time), until the incidence of the contact surface. In this time, the temperature T_5 will be constant. The estimated value of P_5 from the above equation compares well with the similar value shown in Figure 2.

IV. Ethane-oxygen Ignition Delay Studies:

The ignition delay studies have been accomplished by many investigators behind the shock waves for Ethane/Oxygen/Argon mixtures at high temperatures. Cooke et al. [14] investigated the ignition delay times of Ethane over the temperature range of 1400-2200 K behind the incident shock waves in the pressure range 150-350 Torr. It was shown that the emission from OH radical gives rise in two phases, the first phase is linked to decomposition of the fuel and second phase linked to the true ignition.

Vries et al. [15] investigated the delay times behind reflected shock waves for $C_2H_6/O_2/Ar$ mixtures by varying concentration in the temperature range 1218-1860 K and in pressure range 0.57-3 atm in a shock tube. A correlation has been developed to provide the dependency of ignition delay time. Lamoureux et al. [16] studied the ignition delay times of Ethane/Oxygen in the temperature range of 1270-1520 K behind reflected shock using ultraviolet emission spectrometry.

The shock tube is used for ignition delay studies by measuring the ignition delay times of Ethane-Oxygen gas mixtures highly diluted with argon in the temperature range 1190-1760 K. Ethane is having shorter ignition delay than other hydrocarbons and it is in the range of sub millisecond at this temperature range. Experiments are performed with Ethane - Oxygen mixture for equivalence ratio (ϕ = 0.5 & 1). The gaseous mixture is prepared separately in a stainless-steel mixing tank and kept for several hours for the mixture to become homogeneous. The test gas mixture is introduced into the test section at a typical pressure (P_1). Argon was filled in the rest of the driven section at the same pressure as the test section pressure. Before the rupture of the diaphragm, the ball valve is completely opened. In every experiment, the driven section of the tube is vacuumed to less than 10^{-2} torr prior to loading the test gas. The advancement of the reaction is observed by the pressure rise due to ignition and the emission from CH radical at the same time.

Because of the reflected shock in the test section the combustion of the test gas mixture improves the pressure in this region. This increase in pressure is registered by the sensor placed at 7 mm from the end wall signifies the onset of ignition. The ignition delay time is the period between the starting of pressure signal P_5 and the onset of ignition. Oxidation of hydrocarbon fuels cause the formation of CH radicals in excited electronic state, which is quickly extinguished. Independent measure of ignition delay is observed by an emission from the CH radical. The CH emission range prolong from 420 to 440 nm, and its

emission of high intense first-order lies at 431.5 nm. Therefore a photodiode detector which has a range of wavelength from 350 to 1100 nm is used along with the narrow bandpass optical filter (CWL 430±2) to detect the CH emission. DAQ records the emission signal from the ignition of test gas mixture.

Φ	Argon %dilution	T5 (K)	Delay time (μs)
0.5	95	1363	270
0.5	95	1498	90
0.5	95	1314	460
0.5	95	1469	140
0.5	95	1558	50
0.5	95	1558	90
0.5	95	1727	15
0.5	95	1349	230
0.5	95	1374	190
0.5	95	1427	120
0.5	95	1511	70
0.5	95	1193	1410
0.5	95	1299	320
0.5	95	1399	110
0.5	95	1374	150
0.5	95	1604	30
0.5	95	1349	180
0.5	95	1481	50
0.5	95	1256	470
0.5	95	1193	1260
0.5	95	1234	930
0.5	95	1256	540
0.5	95	1435	110
0.5	95	1573	40
0.5	95	1278	470
0.5	95	1301	420
1	95	1580	70
1	95	1753	30
1	95	1438	60
1	95	1462	60
1	95	1462	50
1	95	1549	10
1	95	1381	140
1	95	1472	90
1	95	1277	500
1	95	1365	230
1	95	1293	510
1	95	1340	290
1	95	1291	450
1	95	1365	250
1	95	1340	320
1	95	1331	450
1	95	1307	1130

Table 1. Ignition delay time and temperature data for Ethane

Figure 3 displays the illustrative plot for pressure and CH emission profiles for ethane oxidation.

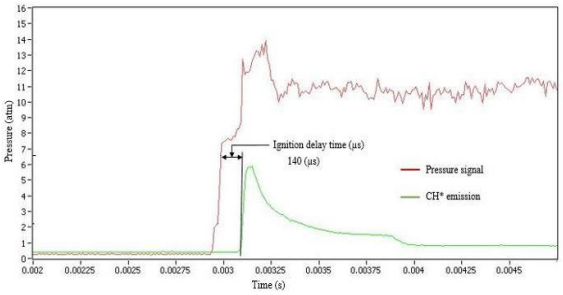


Figure 3. Typical experimental plot for ignition delay measurement for temperature T_5=1469 K and Φ= 0.5.

Now the ignition delay time is explained as the time period between the starting of the P_5 signal and the onset of CH emission/pressure rise. The delay correlates to this signal is 140 μs at a temperature of 1469 K. Plot the graph of Arrhenius plot for the ignition-delay time data for ethane-oxygen of equivalence ratio 0.5 and 1. The experimental data clearly shows that the ignition delay times decreases while increasing temperature. From Arrhenius plot the adequate activation energy for ethane ignition is decided to be 32.6 kcal/mol for Φ=0.5 and 36.9 kcal/mol for Φ=1. The experimentally obtained activation energy is given in Table 2 along with earlier surveys on the ignition delay of ethane. For ignition delay measurements the accordance between current study and the earlier reported results are sensible.

Φ	T (K)	Ea (kcal/mol)	Reference
0.5	1265-1767	32.2	[17]
0.5	1448-1887	31.1	[14]
0.5	1190-1730	32.6	Present study
1	1310-1611	38.0	[17]
1	1448-1887	39.6	[14]
1	1270-1760	36.9	Present study

Table 2. Arrhenius parameters for ignition-delay data on Ethane – Oxygen.

Ignition delay times are calculated simultaneously by examining the test section pressure rise and noticing the light emission from CH radicals originated by the onset of ignition of fuel/oxygen blend.

V. Acetylene-Oxygen Ignition Delay Studies:

Acetylene is an outstanding developmental component in the burning of hydrocarbon fuels, and its deteriorating procedure have a large domination on building a core for methods including the combustion of hydrocarbon fuels. Acetylene gas has properties that make it an extremely useful gas in various applications and industries. It is mainly manufactured for chemical synthesis and it forms an

important part of many crucial processes in industries. The research is being conducted to utilize this resource in the most useful manner possible. Less amount of work has been carried out on examination of ignition delay of acetylene/oxygen. K. S. Krishnan et al. [18] experimentally investigated the ignition delay time of acetylene-oxygen mixtures. The research is made over a temperature range of 1400-1900K at pressures between 1 and 4 atm and in all trials, the argon dilution is 90%. It is found that the delay drops with increasing acetylene content.

Yoshiaki Hidaka et al. [19] examined the Pyrolysis and oxidation of acetylene fuel in the temperature range 1100-2000 K at pressures of 1.1-2.6 atm behind reflected shock waves analyzing the reacted gas mixtures. It is found that reactions are crucial to find the data in a broad area of blends.

In the current study, the ignition delay times of Acetylene is experimentally studied behind the reflected shock. The tests are accomplished in the temperature range of 800-2200 K, and in the pressure range of 10-40 atm. A similar experimental procedure as described above is followed to examine the ignition delay times of acetylene utilizing the shock tube facility. Acetylene ignition delay time tests are conducted for mixtures with equivalence ratios of 0.5 & 1 diluted with argon for a desired concentration. Using the partial pressure method of mixing, test mixtures of fuel, oxygen and argon are premixed to acquire the expected composition. The test gas mixtures were stored in a stainless-steel mixing tank and kept for several hours for complete mixing. Before each experiment, the driven section is vacuumed to 10^{-2} torr. The test gas is limited in the area between the ball valve and the end wall. The remaining part of the driven section is brim over with argon at the same pressure identical to the test gas pressure. The valve is completely revealed just prior to the arrival of the shock wave so that the wave propagates throughout the driven section.

Φ	Argon %dilution	T5 (K)	Delay time (μs)
0.5	95	1145.73	2590
0.5	95	926.86	700
0.5	95	842.16	1010
0.5	95	1454.77	570
0.5	95	892.59	640
0.5	95	1670.361	350
1	95	1939.57	1370
1	95	1087.33	1310
1	95	1214.72	410
1	95	2016.36	450
1	95	1765.69	200
1	95	1024.49	1940
1	95	1079.164	2520

Table 3. Ignition delay time and temperature data for Acetylene

The ignition delay time is calculated behind the reflected shock by following the CH radical emission at 431.5 nm and the pressure rise. The ejection from CH radical is observed using a confined bandpass filter and a photodiode detector in that wavelength range. The ignition delay time is the period between the starting of P_5 pressure signal and the pressure rise/CH emission signal due to the ignition of the fuel. Figure 6 exhibits the typical plot for pressure and CH emission profiles for acetylene oxidation.

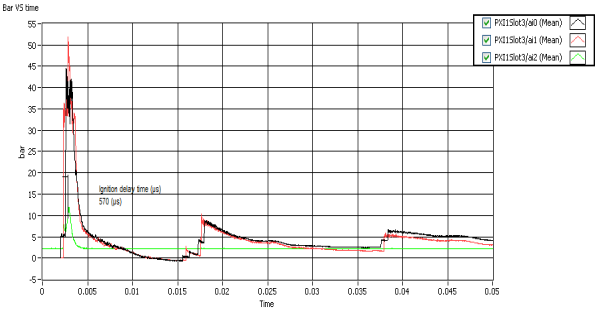


Figure 4. Typical experimental plot for ignition delay measurement for temperature T_5=1454.77 K and Φ= 0.5.

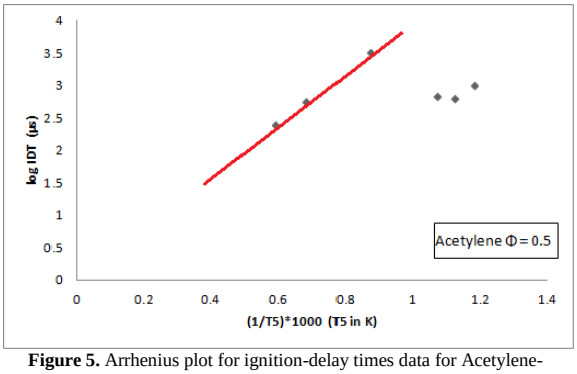


Figure 5. Arrhenius plot for ignition-delay times data for Acetylene-Oxygen mixture at equivalence ratio 0.5.

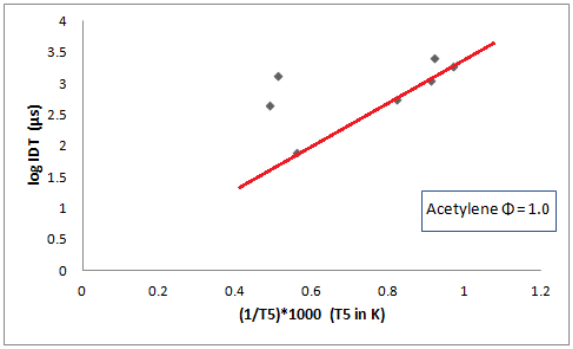


Figure 6. Arrhenius plot for ignition-delay times data for Acetylene-Oxygen mixture at equivalence ratio 1.

The delay equivalent to the above signal is 570 µs at a temperature of 1454.77 K. Arrhenius plot for the ignition-delay of Acetylene-oxygen of equivalence ratio 0.5 & 1 is shown in Figure 7 and Figure 8 respectively. From the study, the adequate activation energy for Acetylene ignition is fixed to be around 39-42 kcal/mol.

Φ	T (K)	Ea (kcal/mol)	Reference
0.5	1625-1818	30	[20]
0.5	900-1400	42	[21]
0.5	840-1500	39.5	Present study
1	1023-1123	55	[21]
1	1558-1665	34	[20]
1	1050-2100	41.5	Present study

Table 4. Arrhenius parameters for ignition-delay data on Acetylene – Oxygen.

VI. Conclusion:

In this paper the experimental results obtained from ethane and acetylene ignition delay studies has been presented and, in an attempt, to clarify the situation, the results are compared with the earlier recorded values. A significant conclusion from the discussion of the result is that the ignition data of ethane and acetylene obtained shows acceptable agreement with the past published works and the methodology to calculate the ignition delay times utilizing shock tube has been validated. The ignition delay time of ethane decreases gradually with increase in temperature. Ethane has a considerably shorter ignition delay than acetylene. From the present study it is noted that the activation energy of ethane lies in the range of 32-37 kcal/mol and activation energy of acetylene lies in the range of 39-42 kcal/mol.

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