EXPERIMENTAL STUDY OF HOT INERT GAS JET IGNITION OF HYDROGEN-OXYGEN MIXTURE

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ABSTRACT

Experiments were performed to investigate the diffusion ignition process that occurs when hot inert gas (argon or nitrogen) is injected into the stoichiometric hydrogen-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 MPa 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 wall of driver section the inert gas is heated behind the reflected shock wave and then injected into the test section with the stoichiometric hydrogen-oxygen mixture through the hole 8 mm in diameter. An increase of the initial pressure of the combustible mixture in the test section from 0.2 to 0.6 MPa resulted in decrease of the minimum temperature of injected gas causing ignition from 1650 K to 850 K. At the same time the induction time for ignition process has increased from 190 to 320 µs when hot argon was injected. For the injection of hot nitrogen an increase of the initial pressure of the combustible mixture from 0.2 to 0.4 MPa resulted in decrease of the minimum temperature of injected inert gas giving ignition from 1150 K to 850 K, and in increase of the induction time from 170 to 240 µs. The results of experiments indicate that ignition occurs when the static enthalpy of injected mass of inert gas exceeds some critical value. The mechanism of ignition process was also studied by schlieren photography.

1.0 INTRODUCTION

Ignition of gaseous mixtures by jets has been observed in nature and in many engineering applications. A typical example is ignition in the main combustion chamber of indirect injection diesel engines where fuel is first ignited in the prechamber and than hot jet of products and fuel flows into main chamber. The other examples can be seen in flame propagation through orifice, nozzle or slit in confined or unconfined geometry. The problem of jet ignition was studied extensively in the past by many authors: Charuel and Layer [1], Gussak [2], Oppenheim et al. [3], Hayashi et al. [4] and Chao et al. [5]. Hayashi et al. using LIPF diagnostics have found that two types of jet ignition are possible: one caused by hot products and the other by jet flame. They also pointed out that compression wave interaction may also be involved in the ignition process.

In the present work jet ignition of hydrogen-oxygen mixture was initiated by hot inert gas heated by shock wave and than injected through an orifice. Experiments have been performed for two inert gases, argon and nitrogen, for various temperatures of the injected gas and for two diameters of the orifice. The main objective of the study was to explain mechanism of ignition and to establish critical conditions.

2.0 EXPERIMENTAL

Experiments were carried out using detonation tube (Fig.1) in which detonation wave was initiated by spark plug in the driver section in stoichiometric acetylene-oxygen mixture at P = 0.5 MPa and room temperature. Then, detonation propagates as incident shock wave in the driven section through inert gas after bursting the diaphragm separating the sections. At the end wall of driven section the inert gas is additionally heated behind the reflected shock wave and then injected into the test section with the stoichiometric hydrogen-oxygen mixture of room temperature through an orifice of 8 mm and 11.2 mm in diameter. Ignition in the test section was studied using PCB pressure transducer and photodiode. The mechanism of ignition process was also studied by schlieren photography. Initial pressure of the hydrogen-oxygen mixture in the test section was varied from 0.02 MPa to 0.06 MPa.

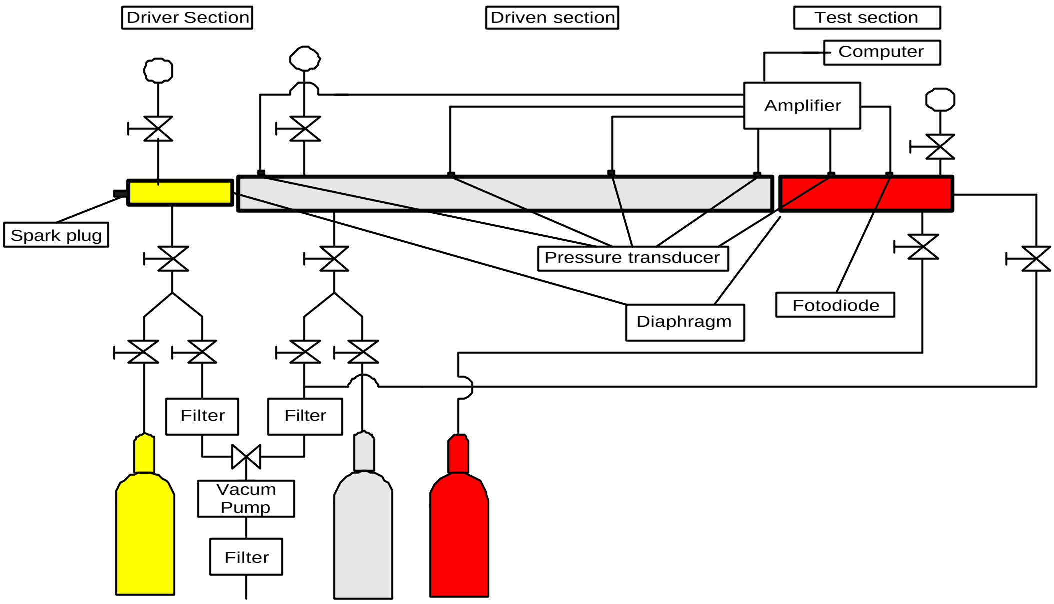

Figure 1. Schematic of the experimental set-up

3.0 RESULTS AND DISCUSSION

Table 1 summarizes all experiments performed in this study. The value of ignition delay time *t* was measured from experimental pressure and photodiode histories. The total enthalpy of hot inert gas injected *H* was calculated from the simple model given below. An increase of the initial pressure of the combustible mixture in the test section from 0.02 to 0.06 MPa resulted in decrease of the minimum temperature of injected gas causing ignition from 1650 K to 850 K. At the same time the induction time for ignition process has increased from 190 to 320 μs when hot argon was injected. For the injection of hot nitrogen an increase of the initial pressure of the combustible mixture from 0.02 to 0.04 MPa resulted in decrease of the minimum temperature of injected inert gas giving ignition from 1150 K to 850 K, and in increase of the induction time from 170 to 240 μs. The results of experiments indicate that ignition occurs when the static enthalpy of injected mass of inert gas exceeds some critical value.

Figure 2 shows pressure history of incident and reflected shock wave in driver section and after some delay pressure history of strong ignition caused by hot argon jet in the test section. The occurrence of ignition is additionally confirmed by photodiode. Figure 3 shows similar pressure histories for nitrogen injection.

Figure 4 shows calculated mass of hot nitrogen versus time of injection for two values of orifice diameter and two values of initial pressure of hydrogen-oxygen mixture in the test section. As expected, higher back pressure decreases mass flow rate of nitrogen and larger orifice diameter increases this mass. Squares 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 the decrease of ignition delay time, however this tendency is more visible for lower back pressure (higher jet velocity). Figure 5 shows similar results for hot argon injection. In this case an increase in orifice diameter from 8 to 11.2 mm, which gives two fold increase in cross section area, results in decrease of ignition delay time by approximately 0.1 ms for both cases of back pressure (0.2 and 0.4 bar).

Table 1. Summary of experimental results

Φ = 8 mm				Φ = 11.2 mm			
Inert gas	P [bar]	H [J]	τ [μs]	Inert gas	P [bar]	H [J]	τ [μs]
Argon	0.2	15	650	Argon	0.2	32	500
Argon	0.4	15	750	Argon	0.4	30	650
Nitrogen	0.2	20	650	Nitrogen	0.2	36	550
Nitrogen	0.4	21	760	Nitrogen	0.4	35	610

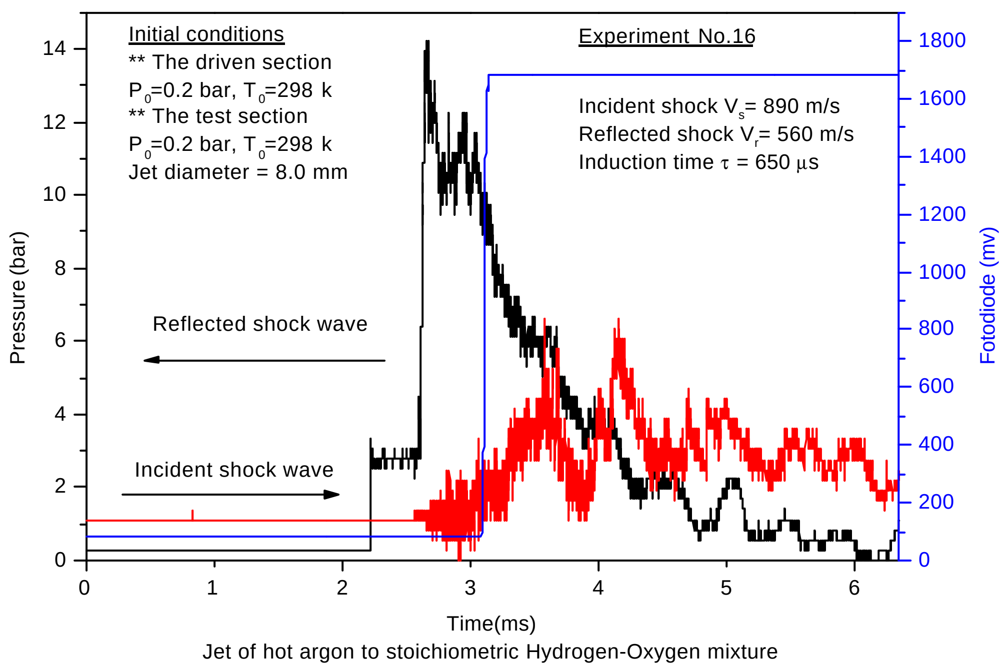

Figure 2. Pressure histories in the driven and test sections for argon injection

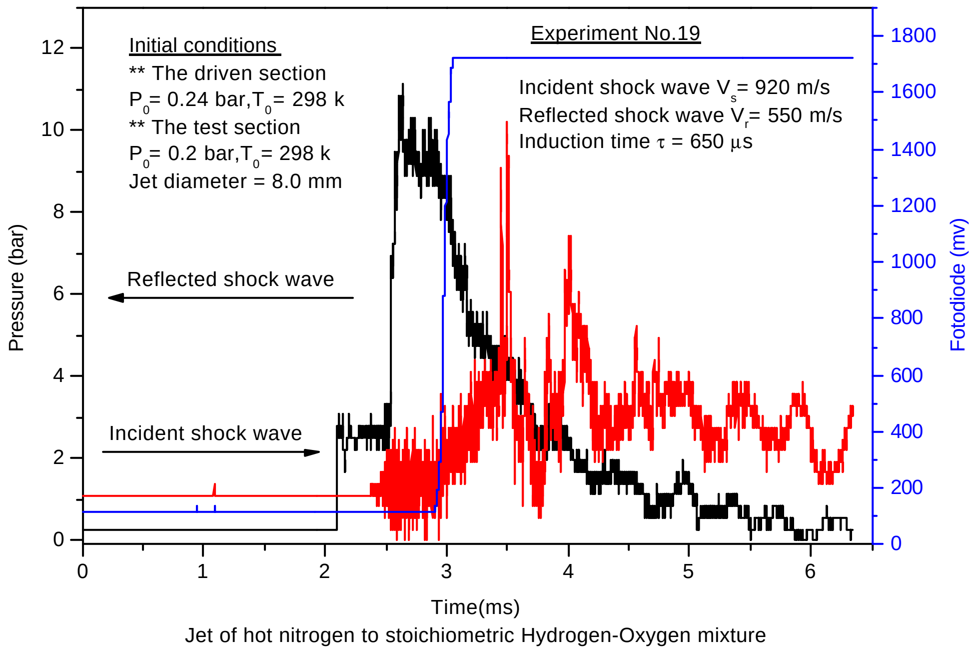

Figure 3. Pressure histories in the driven and test sections for nitrogen injection

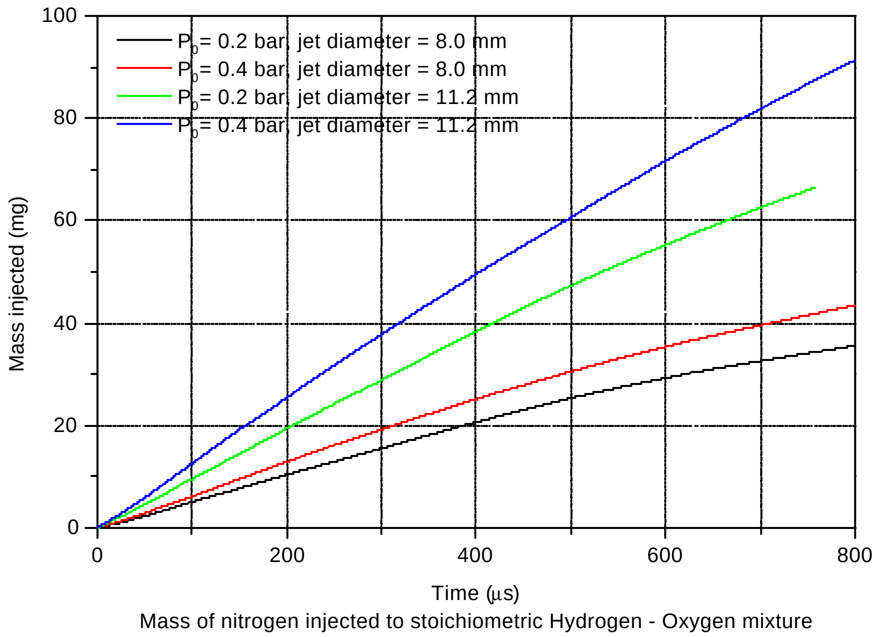

Figure 4. Calculated mass of injected hot nitrogen versus time of injection; square shows the

experimental ignition delay time

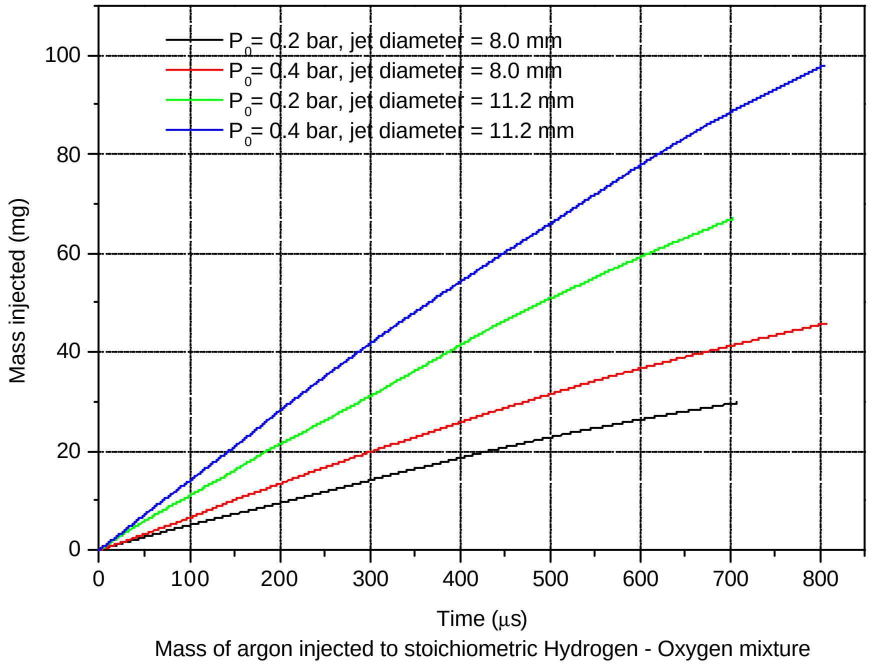

Figure 5. Calculated mass of injected hot argon versus time of injection; square shows the experimental ignition delay time

The gasdynamics of the hot inert jet and chemical processes in the mixing zone with hydrogen-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 we shall first use simple theoretical limiting case. The temperature of hot inert gas T_j after isentropic expansion in hydrogen-oxygen mixture is given by:

$$T_j = T_o \left(\frac{P_c}{p_o} \right)^{g-1/g}$$

where: p_c – pressure of hydrogen-oxygen mixture, T_o, p_o – temperature and pressure of inert gas at the exit from orifice.

Next we assume that given volume of hot inert gas V_j mixes with a certain volume of cold unburned hydrogen-oxygen mixture. The temperature after constant pressure adiabatic mixing T_m can be determined from energy conservation

$$r_j V_j c_{pj} T_j + r_u V_u c_{pu} T_u = \left(r_j V_j c_{pj} + r_u V_u c_{pu} \right) T_m$$

Knowing T_m the ignition induction time t and the adiabatic temperature T_a after reaction of mixed inert gas and hydrogen-oxygen mixture are determined with the use of CHEMKIN software for different values of mixing volume ratio $R = V_j/V_u$.

The results of calculations for the mixing temperature T_m, ignition delay time t and the final adiabatic temperature of combustion products for different mixing volume ratios R are shown in Fig.6

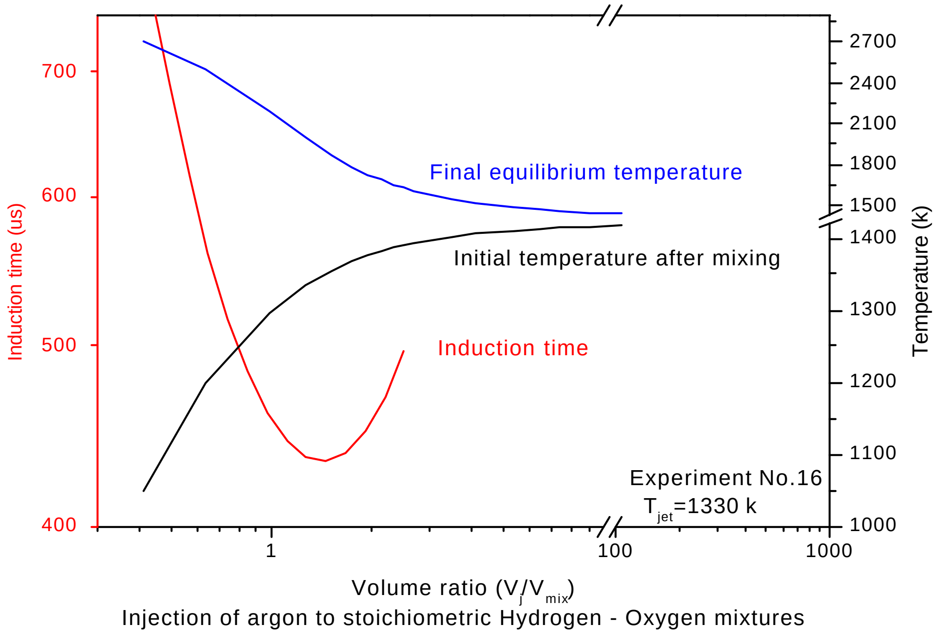

Figure 6. Temperature after mixing, ignition delay time, adiabatic temperature of the products of constant volume combustion and experimental induction time as a function of the volumetric ratio of hot inert nitrogen to unburned hydrogen-oxygen mixture

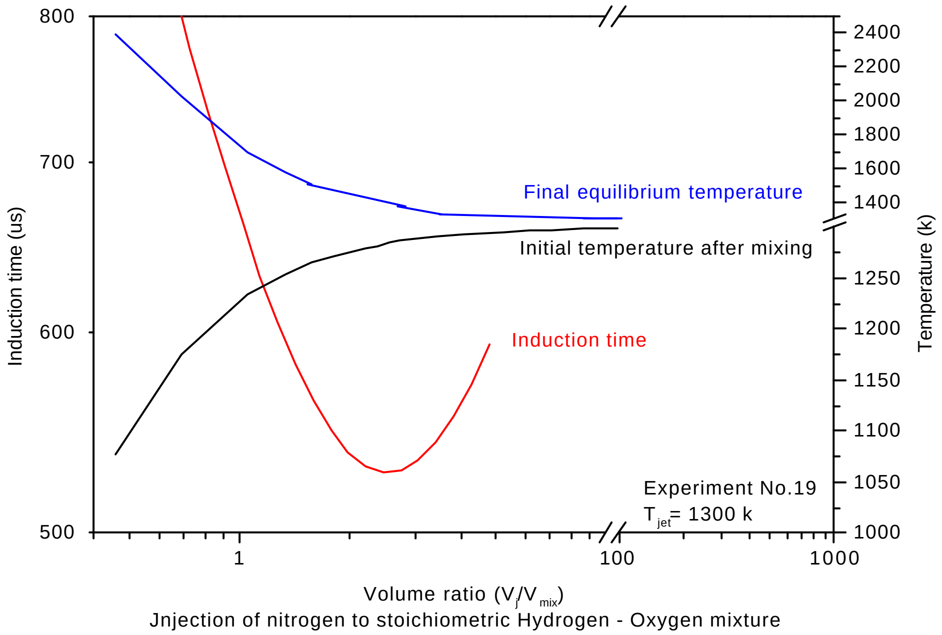

Figure 7. Temperature after mixing, ignition delay time, adiabatic temperature of the products of constant volume combustion and experimental induction time as a function of the volumetric ratio of hot inert argon to unburned hydrogen-oxygen mixture

for nitrogen and in Fig.7 for argon. For low values of R (small mass flow rate of hot inert gas) the final temperature after mixing is low and accordingly, the ignition delay time is large. With R and T_m increasing the rapid decrease in ignition delay time occurs. The experimental induction time is also shown in these figures. The results of calculations indicate the importance of temperature on ignition delay time. The comparison of experimental ignition delay time with the value obtained from CHEMKIN calculations gives temperature in mixing zone equal to about 1400 K and the volume ratio of about 3.

5. CONCLUSIONS

Ignition of hydrogen-oxygen mixture by hot inert gas jet was studied experimentally in a chamber with the orifice of 8 mm or 11.2 mm. Ignition occurs in the turbulent mixing zone at the edges of the jet. The volumetric ratio of hot inert gas to unburned medium in the mixing zone plays an important role in setting temperature of this zone and results in ignition delay time. Further studies by computer simulations are planned to reveal more details of the process.

REFERENCES

1. Charuel, P., Leyer, J.C.: Hot Jet Ignition of Unconfined Hydrocarbon-air Mixtures, Proceedings of 9th ICDERS, 1983
2. Gussak L.A.: 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, 1975

3. Oppenheim, A.K., Teichman, K., Hom, K, Stewart, H.E.: Jet Ignition of an Ultra-Lean Mixture, SAE Paper 780637, 1978
4. Hayashi, A.K., Ito, H., Uchida, N., Watanabe, Y., Suetake, M. and Karasawa H.: Ignition Mechanism by Hydrogen Flame Jet through an Orifice, 21st International Symposium on Shock Waves, Great Keppel Island, Australia, 1997
5. Chao, J., Ng, H.D., Ramamurthi, K., Higgins, A. and Lee J.H.S.: Detonation Initiation via Jet Mixing, 29th Symposium (International) on Combustion, The Combustion Institute, 2002