Studies of Self-Ignition Characteristics in H₂-Air-Steam Mixtures

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Abstract

The current work presents research results of self-ignition characteristics in H_2 -air-steam mixtures achieved in a heated shock tube behind the reflected shock wave at the end wall. A time-resolved photographic system was used to study the self-ignition mechanism. Strong and mild ignitions are observed. The locations of mild ignition are random, and sometimes the ignition starts from multi-kernels. The measured ignition delay times show a strong dependence on the steam concentration and the initial temperature, while there is only a weak influence of the initial pressure for the conditions regarded. The measured ignition delay times are consistent with the theoretical prediction only in the high temperature region. In the low temperature region the measured delay times are obviously shorter than those determined by the theoretical prediction.

1 Introduction

Shock tube techniques have been extensively used to study self-ignition characteristics in premixed combustible gaseous mixtures. A large amount of these studies were conducted in H_2 - O_2 and hydrocarbon-air mixtures, e.g. the reviews of Petersen et al. (1995) and Pfahl et al. (1996). Only a few of them were done in H_2 -air system, especially in H_2 -air-steam mixtures which are of importance for nuclear power plant safety. One of the most practical parameters to describe the self-ignition characteristics is the ignition delay time. Upon authors' knowledge there is no data available in the literature on the ignition delay time in H_2 -air-steam mixtures under the conditions that are typical for nuclear reactor applications. The ignition delay time can be ascertained by various methods, e.g. by the measurement of OH-absorption, OH-emission, pressure increase or photographic techniques. A simultaneous application of these methods can help to analyze the signal, and to improve the reliability of the data obtained.

In the present study the self-ignition processes in H_2 -air-steam mixtures were observed by a 24 frame optical system. The ignition delay times were determined according to OH-emission, and confirmed by the schlieren system as well as by pressure signals.

2 Experimental set-up and measurement techniques

A heated shock tube of 141 mm inner diameter and 15.6 m total length, which is divided by a double diaphragm chamber into a high pressure section and a low pressure section, is modified to investigate self-ignition phenomena in H_2 -air-steam mixtures. A test section with 4 measurement ports for pressure gauges and a pair of optical windows with the size of 20 mm x 230 mm is located at the end of the low pressure section. The whole tube can be used up to 20 MPa, and heated to about 480 K.

A 24 frame Cranz-Schardin camera system with a framing rate ranging from 1 μ s to 100 ms is utilized to visualize the ignition processes that are expected to take place behind the reflected shock wave. Five pressure gauges which are installed along the tube in the region between the end wall and 2.05 m away from it, are employed to measure the strength of the incident shock wave, to determine the shock wave reflection at the end wall, and to record the pressure wave development due to the ignition. The conditions behind the reflected shock wave are calculated from the measured incident shock wave velocity and the initial conditions of the test gas in front of it. The onset of the ignition is detected by a photomultiplier which is mounted outside of the shock tube, and receives light through the main optical window from the flame in the test section. To improve the signal of the photomultiplier, we used an interference filter for OH-emission at 306.3 nm.

3 Experimental results

More than 150 experiments were performed for mixtures of 15% H_2 and 85% air diluted with 0 - 40 % steam. The initial temperature, i.e. the temperature behind the reflected shock wave, ranges from 900 to 1350 K, and the initial pressure from 0.3 to 1.7 MPa. The influence of steam was investigated in four series with 0, 15, 25 and 40% steam, respectively. The research on the influence of the initial pressure was carried out at pressures of about 0.45, 0.95 and 1.6 MPa.

3.1 Ignition mechanism

Previous studies of Meyer and Oppenheim (1971), Oppenheim (1985) and Blumenthal et al. (1995, 1996b) revealed that self-ignition can occur in two distinct regimes. One is a mild ignition, starting with flame kernels or "hot spots" which may lead to detonations by a secondary explosion, while the other is a strong ignition, manifesting itself right from the onset in form of a reaction shock. Both regimes were identified in our experiments in H_2 -air and H_2 -air-steam mixtures. In most cases, the mild ignition with a secondary explosion was recognized both by pressure and photoelectric signals and by schlieren photographs. The strong ignition only appeared for very high initial temperatures and the mild ignition without transition to detonation existed only at low initial temperatures. The strong ignition always started from the end wall while for mild ones the ignition locations are random, and sometimes it starts from multi-kernels.

Figure 1 represents a typical result obtained in the case of a mild ignition with a transition to detonation in H_2 air mixtures. It shows the pressure signals measured at four different locations - marked with horizontal dashed lines except for the first one at the end wall - in the low pressure section. The ignition that starts 0.39 ms after the shock reflection, detected by the photomultiplier, generates a smooth increase in the pressure signals. At about 1.1 ms and approximately 200 to 250 mm in front of the end wall a secondary explosion takes place, which generates two waves: one of which moves back to the end wall, while the other one follows the reflected shock wave and eventually merges with it and generates a detonation wave.

Schlieren photographs from the same experiment are presented in Fig. 2. As can be observed in the second frame, taken at 700 μ s after the shock reflection, there are many flame kernels, which give evidence of a mild ignition. The reflected shock wave, moving away from the end wall, can be seen in the first frame (100 μ s). The reflection of the blast wave, generated from the secondary explosion, at the tube inner wall and at the end wall causes the complicated wave structure in the third frame (1400 μ s).





Fig. 1. Pressure histories at different positions. Mixture: 15% H₂ + 85% air, P₅ = 0.5 MPa, T₅ = 1030 K; IS: Incident shock wave; RS: Reflected shock wave; SE: Secondary explosion

Figure 3 represents a strong ignition in the mixture with 15% steam. Black areas at the left side of some photographs are due to the restricted mirror size of the optical system. The reflected shock wave can be seen in the first five photographs, as it moves away from the end wall. Here no deflagration wave is visible. The ignition between the third and fourth photograph directly generates a relatively planar reaction shock wave which moves with an average velocity of about 1200 m/s, lower than the CJ detonation velocity (1508 m/s) in the region behind the reflected shock wave. At about 50 μ s the reaction shock wave overtakes the reflected shock wave, generates a detonation wave moving forward and a compression wave moving back to the end wall. The compression wave can be seen in the photographs at t = 56 and 64 μ s, even after its reflection from the end wall in the photographs from t = 80 to 184 μ s. From the overtaking position the detonation wave propagates first as



Fig. 3 Schlieren photographs of an ignition in the mixture: 12.75% H₂ + 72.25% air + 15% steam. Initial conditions: P₅ = 0.5 MPa; T₅ = 1233 K

For comparison some results for the same gaseous mixture but without steam from the studies of Blumenthal et al. (1996a, b) are also cited. The solid line represents a theoretical prediction for an initial pressure of 0.4 MPa, the hollow triangles the measured ignition delay times. The present results are consistent with Blumenthal's ones for the same gas mixture. The small difference can be attributed to experimental errors and different procedures to measure the ignition delay time. The an overdriven detonation with a velocity of about 1100 m/s, higher than the absolute CJ velocity of 637 m/s in the region in front of the reflected shock wave, then decelerates to a normal detonation wave. The transverse waves in the detonation wave can be observed in the photographs from t= 64 μ s on. Since the states in front of and behind the reflected shock wave are different, the overtaking process forms a contact surface which generates the black lines in the photographs from t = 64 to 184 μ s. The contact surface is almost stationary, and remains about 24 mm away from the end wall.

3.2 Influence of steam and initial pressure on the ignition delay time

The ignition delay time is defined as the time from the reflection of the shock wave at the end wall to the onset of a deflagration flame. The optical studies show that it is possible for the weak ignition at low temperature to be started at a certain distance away from the end wall. In this case the ignition delay time defined as above is longer than the time during which the gaseous medium is heated by the reflected shock wave. The difference is less than 40%.

The measured ignition delay times for different steam concentrations for an initial temperature range from 950 to 1350 K at an initial pressure of about 0.45 MPa are summarized in Fig. 4. The solid triangle, diamond, square and circular symbols correspond to the mixtures with 0, 15, 25 and 40% steam, respectively. It can be seen that the measured delay times strongly depend on the initial temperature and steam concentration. For the same gas composition the delay time increases almost exponentially with the decrease of initial temperature, and for the same initial temperature it increases with the steam concentration, especially in the mixtures with small amounts of steam. The data show a good repeatability except those for 15% steam at the temperature of about 1110 K.



Fig. 4 Influence of steam concentration on the ignition delay time

results show that for H₂-air mixtures for the pressure range of about 0.4 MPa there is a good agreement between the theoretical prediction and the measurements in the high temperature range, but for the low temperature range ($T_5 < 1040$ K) the theoretically predicted ignition delay time is much longer than the measured ones. This tendency is in agreement with experimental results of Gelfand et al. (1997) in H₂-O₂ mixtures.

The influence of initial pressure on the ignition delay time in the mixture with 25% of steam is shown in Fig. 5. For these experiments the initial pressure was varied from 0.4 to 1.7 MPa. It can be concluded that for the conditions regarded, there is no obvious influences of the initial pressure on the ignition delay time. Again the experiments show a good repeatability.



Fig. 5 Influence of initial pressure on the ignition delay time

4. Conclusions

With a 24 frame schlieren Cranz-Schardin camera system strong and mild ignitions in H_2 -air and H_2 -air-steam mixtures are observed in our heated shock tube. The strong ignition always starts from the end wall. The locations of mild ignition are random, and sometimes the ignition starts from multi-kernels. The measured ignition delay times show a strong dependency on the steam concentration and the initial temperature, while there is a weak influence of the initial pressure for the conditions regarded. The measured ignition delay times are consistent with the theoretical prediction only in the high temperature region. In the low temperature region the measured delay times are obviously shorter than those determined by the theoretical prediction. This is in agreement with experimental results of other authors. But the reason for the discrepancy is not yet fully understood.

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