Direct observations of reaction zone structure in shock-induced ignition of methane air mixture

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Ignition of methane/air mixture by the passage of a shock wave is an important issue for understanding more details of its gaseous detonation. The experiments of shock-induced ignition of stoichiometric methane/air mixture were conducted on a shock tube platform. The reaction zone structure in weak and strong ignition cases were investigated by digital chemiluminescence imaging and planar laser induced fluorescence (PLIF) techniques. Due to smaller gradients in induced time in weak ignition, which provided more time to nonlinear chemical reaction process, the results show that the reaction structures are highly nonuniform in those weak ignition cases, which become more regular while induced shock waves become stronger. In strong ignition case, it gives a typical detonation structure. The characteristics of reaction zone released by single-pulsed OH PLIF technique agreed well with other experimental measurements in this paper and were also in accord with the conclusions of previous researches. The successful implementation of the PLIF system has explored a new high temporally and spatially resolved method for the study of interaction between shock wave and gaseous matter in shock tube.

shock-induced ignition, PLIF, chemiluminescence imaging, weak ignition, strong ignition, methane, OH radical

Since methane is flammable and explosive hazard gas as the main composition of mash gas and rock gas, many safety problems related to its explosion have been extensively studied and discussed. In a gaseous detonation, a shock wave compresses the material thus increasing the temperature to the point of ignition, while the ignited material burns behind the shock and releases energy that supports the shock propagation. The Zeldovich-von Neumann-Doering (ZND) explosion theory admits finite rate chemical reactions and indicates an induction region existing between the inducing shock and the exothermic reaction zone. Ignition of explosive fuels by the passage of a shock wave is an important issue from the perspective of safety[1]. In this paper, the shock-induced ignition experiments were conducted in a shock tube. When the separating diaphragm between the driver section and the driven section suddenly burst, a shock wave was produced for the huge pressure difference and travelled down to compress the methane/air mixture sample in the driven section. The sample was preheated by this incident shock wave and finally ignited by the reflect shock wave reflecting from endplate of the shock tube. In usual research of chemical kinetics parameters measurements in shock tubes, the sample injected to driven section is always diluted by a large amount of inert gas so as to reduce the influence by temperature and pressure changes during exothermic reaction. Methane/air mixture at equivalent ratio without any dilution was adopted, as this research focused on the characteristic of the reaction zone structure induced by the shock wave.

Oran et al.[2] and Cheng et al.[3] have pointed out that autoignition in a premixed combustible mixture brought uniformly and rapidly to high temperature and pressure by a shock wave is characterized by two distinct ignition


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modes. Strong ignition, which takes place at high temperature condition, results in a detonation that either is directly initiated by a strong shock or originates from a planar spontaneous wave that forms behind a strong shock. Weak ignition, which occurs at a lower temperature level, created isolated ignition centers, and then the ignition centers interact and develop into an irregular flame.

Brown et al. [4] recorded the shock-induced ignition and subsequent deflagration to detonation transition process of different mixing ratio ethylene and propane mixtures by spark schlieren photography. Herzler et al. [5] took 2D digital images of chemiluminescence in lean \(n\)-heptane/air mixtures shock-induced ignition through a quartz window contained in the end flange of shock tube by an intensified CCD (ICCD) camera. Pervious studies mostly employed pressure tracking, emissions spectrum, absorption spectrum and schlieren photography technology. Contact measurement, such as pressure tracking by transducers, has limited ability to reflect characteristics of reaction zone. And using traditional optical methods, such as emission, absorption spectrum and schlieren photography, would have problems in the signal integration of optical path. Thus could not clearly indicate the complex structure of reaction zone, especially in weak ignition condition as methane is not a high reactive fuel. Planer laser induced fluorescence (PLIF) utilizes a thin sheet of laser light to excite a resonant transition in an atomic or molecular species (OH, CH, NO, etc.) in the flowfield of interest and the resulting fluorescence indicates the distribution of certain species. This technology has been widely used in the diagnostic of either normal or supersonic combustion experiments because of its ability to provide high spatially and temporally resolved, 2D information of certain cross section. However, the first pulse output of pulsed high-powered Nd:YAG laser is unstable [6] and the synchronous control of many equipments for the experiment is difficult. These problems make it difficult to do PLIF measurement of unsteady reacting flow in shock tubes. Gray [7] and Seta et al. [8] studied chemical reactions in shock tubes, using 1D laser induced fluorescence (LIF) measurement to obtain some parameters of reaction rate. McMillin et al. [9] used XeCl excimer laser as the pump laser to take OH fluorescence pictures of argon diluted hydrogen-oxygen mixture autoignition. Though the excimer laser could avoid the instability problem of the first pulse, its power was limited to the small-area detecting.

In this paper, the reaction zone of stoichiometric methane/air mixture ignition induced by different mach number shock waves was studied by chemiluminescence imaging, OH PLIF, pressure and emission tracking techniques in a large size rectangular shock tube with its PLIF measurement platform.

1 Experimental

1.1 Shock tube details

Experiments were carried out in a shock tube with a 130 mm×110 mm rectangular cross section, shown in Figure 1. It has an 8 m-long driver section and 3 m-long driven section. The middle section between them is 20 mm long, in which two diaphragms (BOPP plastic films, within four alternative thicknesses of 20, 25, 50 and 100 μm) could be installed to isolate the gas between driver section and driven section. A thin \(\Phi 120\) μm copper wire is fixed on the diaphragm as the electrical heater. Helium and nitrogen were employed as the driver gas and tailored-interface condition could be achieved by adjusting the mix ratio. This technique allows a maximum experimental time of more than 15 ms to be achieved with the current facility. Before each experiment, the driven section was cleaned and then evacuated to lower than \(10^{-4}\) torr pressure by the vacuum pump system composed of a 2XZ-15 direct connected vacuum pump and a ZJP-70 roots pump. Sample gas was injected to driven section by a gas allocation system and the pressure was monitored by a capacitance diaphragm vacuum gauge. High purity gases (CH\(_4\), 99.995%; O\(_2\), 99.99%; N\(_2\), 99.999%) were used in sample mixture, which was prepared by mixing ratio of 9.5:19:71.5 in a stainless steel...