Detonation Properties of Mixed-Fuel-and-Air Gas Mixtures

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Key words: Detonation, Mixed fuel, Cell width

1. Introduction

Pulse detonation engines (PDEs) have been being developed not only as propulsion devices but also as power generators (Endo 2004). In the case of the ground applications, it may be desired that the natural gas can be used as the main fuel. The greatest component of the natural gas is methane, and the detonation cell width of the methane-air gas mixture is about 300 mm at the ambient conditions of temperature and pressure (Shepherd 2002). Therefore, we have to use a large-diameter detonation tube with moderate pressure or a moderate-diameter detonation tube with high pressure. In either case, the discharged energy in one pulse would be very large, and the PDE would be of low controllability.

In this paper, we describe experimental results on the detonation properties, mainly on the detonation cell width, of the gas mixtures of mixed fuels and air. The objectives of this study are to understand how the detonation cell width of a mixed-fuel-and-air gas mixture is determined and to seek a mixed fuel, main component of which is methane, usable in practical PDEs.

2. Experimental Arrangement

Figure 1 shows the experimental arrangement. The detonation properties were measured in the detonation tube. The mixed fuels we investigated were hydrogen-methane, hydrogen-propane, and propane-methane gas mixtures at the ambient conditions of temperature and pressure. The oxidizer was air in all cases. The mixture ratios of these mixed fuels were varied keeping their equivalence ratios unity. In order to initiate a detonation wave in the detonation tube filled with the investigated gas mixture, we used the initiator which was filled with stoichiometric propane-oxygen gas mixture at the ambient conditions of temperature and pressure. Although the propane and oxygen gases in the initiator were mixed in the initiator, the investigated gas mixtures filling the detonation tube were premixed in another tank with a stirrer.

For the measurement of the detonation properties, we used ion probes (I1 and I4) and a soot foil. The soot foil was of stainless steel and of 0.2 mm in thickness. By the ion probes (I1 and I4) and the soot foil, the propagation speed of the flame and the cell width (soot-foil record) of the detonation wave were measured, respectively. In the measurement of the cell width, we used only the latter two thirds of the soot-foil record because the influence of the leading edge was not negligible in the former one third of the soot-foil record. Figure 2 shows an example of the soot-foil record.

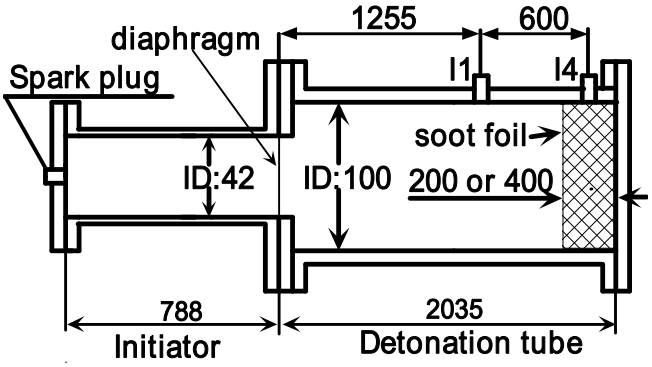

Fig.1 Experimental arrangement.

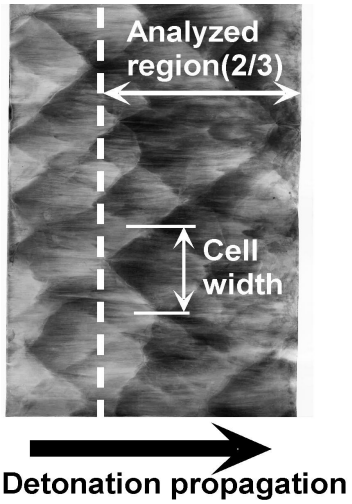

Fig.2 Soot-foil record
200×300mm (100% C_3H_8)

3. Results and Discussions

In order to investigate how the detonation cell width is determined, we carried out experiments on hydrogen-methane-and-air gas mixtures first. Figure 3 shows the dependence of the cell width on the mole fraction of methane in the mixed fuel. The measurements were repeated three times in all cases. The detonation waves successfully propagated in all measurements when the mole fraction of methane was not more than 0.4. However, the detonation waves failed in one of the triplicated measurements when the mole fraction of methane was 0.5, and in two of the triplicated measurements when the mole fraction of methane was 0.6. The error bars in the figure show their standard deviations. Only one cell was observed in the soot-foil record in the case of 60% methane. And when the mole fraction of methane was 0.7 or more, the detonation waves failed in all measurements. The measured detonation speeds were in agreement with the Chapman-Jouguet (CJ) detonation speeds calculated by the chemical-equilibrium software AISTJAN (Tanaka 2004) within ±4% when the detonation waves propagated.

According to the investigation by Austin and Shepherd (Austin and Shepherd 2003), the detonation cell width is proportional to the reaction-zone length that is defined by the

distance from the shock front to the surface where the mole fraction of OH radical has its peak. Figure 4 shows the dependence of the measured cell width on the reaction-zone length which was calculated by using the gas flow velocity at the von Neumann spike and the reaction time. The reaction time was calculated by using an elementary-reaction model, where GRI-Mech 3.0 was used, under the condition of adiabatic and isochoric process, and was defined as the time when the mole fraction of OH radical had its peak. As shown in Fig. 4, the cell widths were almost proportional to the reaction-zone length when the reaction-zone length was less than 2 mm, and the ratio of the cell width to the reaction-zone length was 46 ± 10. On the other hand, when the reaction-zone length was more than 2 mm, corresponding to the case that the expected cell width from the reaction-zone length was larger than the inner diameter of the detonation tube, the above proportionality was violated, and the detonation waves could not propagate in some cases. Furthermore, it is interesting that the cell widths seemed to be quantized as the fundamental length of about 150 mm, which approximately corresponds to a half of the circumference of the inner surface of the detonation tube, and its second harmonic, although it may be a weak quantization because the cell structure observed was not so regular.

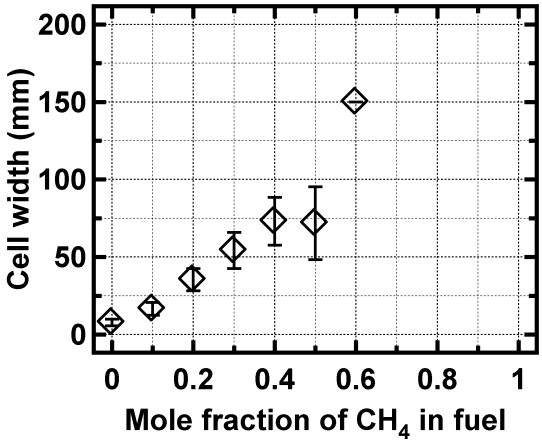

Fig. 3 Cell width in the case of H_2-CH_4 mixed fuels.

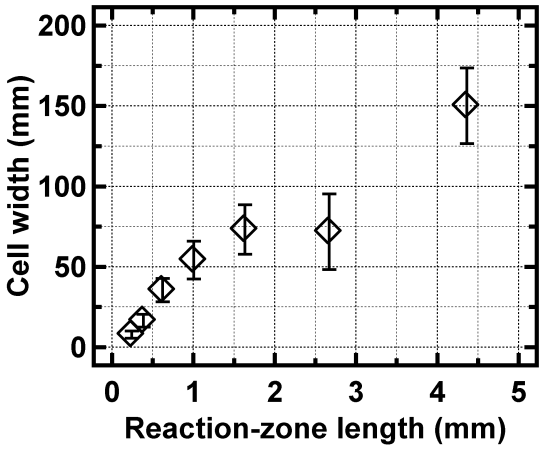

Fig. 4 Cell width in the case of H_2-CH_4 mixed fuels versus reaction-zone length defined by the location of the OH peak.

In the above-described experiments, namely the experiments on the hydrogen-methane mixed fuels, the cell width of the 100%-methane case was too large compared against the inner diameter of the detonation tube we used. This made the results rather complicated. That is, the cell width was governed not only by the reaction-zone length but also by the geometrical restriction, namely, the inner diameter of the detonation tube. In order to make

the influence of the geometrical restriction smaller, we carried out experiments on hydrogen-propane mixed fuels.

Figure 5 shows the dependence of the cell width on the mole fraction of propane in the mixed fuel. We varied the mixture ratio of the hydrogen-propane mixed fuel from 100% hydrogen to 100% propane. The measurements were repeated three times in all cases. In all measurements, the detonation waves successfully propagated. And the propagation speeds of the detonation waves were in agreement with the CJ detonation speeds within ± 3%. It was remarkable that the cell widths were almost constant when the mole fraction of propane in the mixed fuel was between 20% and 70%. The calculation of the reaction-zone length for the hydrogen-propane-and-air mixtures is under preparation because the elementary reactions including propane fuel are more complicated compared against those for the hydrogen-methane mixed-fuel case.

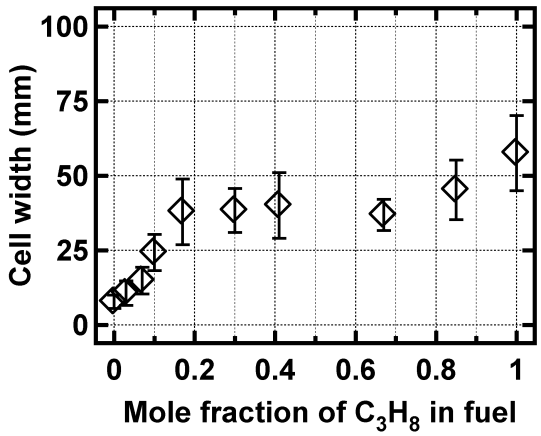

Fig. 5 Cell width in the case of H_2-C_3H_8 mixed fuels.

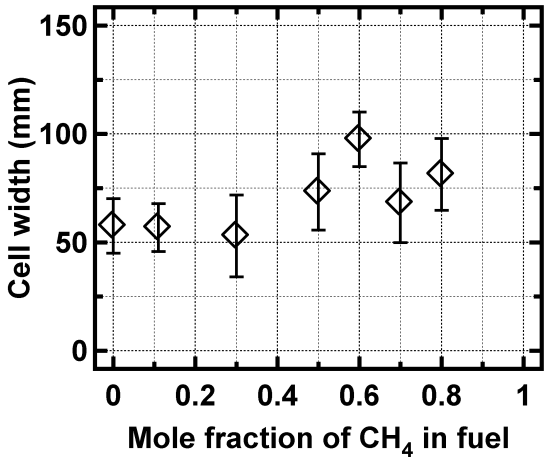

Fig. 6 Cell width in the case of C_3H_8-CH_4 mixed fuels.

Finally, we carried out experiments on propane-methane mixed fuels. The propane-methane mixed fuels may be more practical than the hydrogen-methane mixed fuels for the ground use of PDEs. Figure 6 shows the dependence of the cell width on the mole fraction of methane in the mixed fuel. The detonation waves successfully propagated in all measurements when the mole fraction of methane was not more than 0.3. However, the detonation waves failed in one of the triplicated measurements when the mole fractions of methane were 0.5, 0.6, and 0.8. Further, no detonation wave propagated when the mole fractions of methane were 0.9 or more. It was remarkable that the detonation waves successfully propagated in all triplicated measurements when the mole fraction of methane

was 0.7. The measured detonation speeds were in agreement with the CJ detonation speeds within ±2% when the detonation waves propagated. The experimental fact that no detonation failure was observed in the case of 30%-propane-and-70%-methane mixed fuel in the 100-mm-diameter tube is very encouraging, although the measurements were repeated only three times. This suggests the possibility of mixed fuel, main component of which is methane, usable in practical PDEs.

4. Conclusions

We experimentally studied the detonation properties of the stoichiometric mixed-fuel-and air gas mixtures. The mixed fuels we investigated were hydrogen-methane, hydrogen-propane, and propane-methane gas mixtures at the ambient conditions of temperature and pressure. The detonation cell width was almost proportional to the reaction-zone length when the cell width was less than the inner diameter of the detonation tube. However, when the expected cell width from the reaction-zone length was comparable with or more than the inner diameter of the detonation tube, the cell width was significantly influenced by the geometrical restriction and showed a weak quantization. In the experiments on the propane-methane mixed fuels, no detonation failure was observed in the case of 30%-propane-and-70%-methane mixed fuel in the 100-mm-diameter tube. This suggests the possibility of mixed fuel, main component of which is methane, usable in practical pulse detonation engines although the measurements were repeated only three times and the reason of this stability has not been understood yet.

References

J. M. Austin and J. E. Shepherd 2003 “Detonations in hydrocarbon fuel blends” Combustion and Flame **132**: 73-90.

T. Endo, T. Yatsufusa, S. Taki, and J. Kasahara 2004 “Thermodynamic analysis of the performance of a pulse detonation turbine engine” Science and Technology of Energetic Materials **65** (4): 103-110 (in Japanese).

J. E. Shepherd 2002 “Cell width vs initial pressure; CH_4-Air in Detonation Database” http://www.galcit.caltech.edu/detn_db/html/CH4-Air1.html.

K. Tanaka 2004 “Combustion Properties of Gaseous Explosives” http://www.aist.go.jp/RIODB/ChemTherm/aistjan_e.html.