Suitability of C₂-, C₃-Hydrocarbon Fuels for Plasma Ignition in High-Speed Flow

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The suitability of hydrocarbon fuels for plasma ignition in high-speed flow was numerically and experimentally investigated. Numerical analysis of ignition delay time showed that the effects of additions of radicals and NO_x on ignition delay times of C_3H_8 and dimethyl ether were very slight in comparison with those for C_2H_4. Ignition tests of C_3H_8 and dimethyl ether fuels by a plasma jet torch in a supersonic flow confirmed such a low sensitivity to additions of radicals and NO_x. The amounts of combustion of C_3H_8 ignited by the plasma jet were smaller than that of C_2H_4, though ignition delay times of those fuels without radical addition were almost the same as that of C_2H_4. In the case of fuel injection upstream of the plasma jet, the amounts of combustion of C_3H_8 and dimethyl ether fuels increased with the mole fraction of O_2 in the feedstock gas to the plasma jet torch, the same as with CH_4 and C_2H_4. This result indicates that the local O_2 concentration around the igniter is very important for success in attainment of strong combustion and flameholding in a high-speed flow.

Nomenclature

E.R. = equivalence ratio
C = mole fraction
P_{in} = electric power input
p_{t0} = total pressure of main flow
p_w = wall pressure
p_0 = system pressure or initial pressure
T_0 = initial temperature
x_i = position of fuel injector

I. Introduction

FUEL selection is one significant issue for a development of high-speed airbreathing engines consisting of the propulsion system of a hypersonic vehicle [1,2]. Hydrogen is considered to be the most promising fuel for such a engine because of its high burning velocity. However, its low density results in large aerodynamic drag due to the large volume of the fuel tank. Recently, hydrocarbon fuels [3–6], which include gaseous fuels, liquid fuels, and fuel thermally decomposed products, have attracted much attention as possible fuels for hypersonic vehicle engines. Burning velocities of hydrocarbon fuels are considerably lower than that of hydrogen, and therefore some mechanisms to enhance ignition and combustion in a supersonic flow are more strongly required for hydrocarbon fuels than for hydrogen. A plasma jet (PJ) (which can directly supply many radicals, NO_x, and a high-temperature jet into the combustion region) is suitable for such a purpose [7]. It is well known that the existence of a small number of radicals drastically reduces ignition delay time of the fuel [8,9]. Ignition tests of low-hydrocarbon fuels such as CH_4 and C_2H_4 by the PJ torch [10–15] in a supersonic flow and theoretical analyses of the effects of the addition of radicals and NO_x on ignition delay of the fuels [13–15] have been widely conducted by many researchers, including the authors.

In contrast to the low-hydrocarbon fuels, the enhancement effect by the addition of radicals on ignition of large-hydrocarbon fuels has rarely been investigated. Only one report can be detected in the past literature in which an effect of initial radical concentration on ignition of C_3H_8/air mixtures was investigated (Buriko et al. [16]) by numerical analysis of ignition delay time. Though the group of Cross et al. [17] developed a PJ torch of a simulated cracked JP-7 feedstock and also conducted ignition tests of kerosene by the PJ torch igniter in a supersonic airflow [18], the degree and the mechanism of ignition enhancement effect of the PJ torch igniter for large-hydrocarbon fuels are unclear. Sensitivity to the addition of radicals strongly depends on the oxidation mechanism of each fuel and the fuel structure, and therefore detailed analysis including a full chemical-reaction scheme of the fuel oxidation is required. In view of such a situation, the effects of the addition of radicals and NO_x on the ignition of C_3H_8 were numerically analyzed and ignition test of the C_3H_8 fuel by the PJ torch in a supersonic flow was conducted in this study as an initial step to clarify the suitability of large-hydrocarbon fuels for plasma ignition in severe conditions including a supersonic flow.

More recently, dimethyl ether (DME) (CH_3OCH_3) [19,20] has also received significant attention as a new fuel in research on internal engines. The reported burning velocity of DME [20] is between that of CH_4 and that of C_2H_4, and its autoignition temperature is lower than those of other hydrocarbon fuels. Therefore, DME is a good candidate as the fuel for the scramjet mode of the dual-mode engine. Ignition tests of DME fuel by a PJ torch and numerical analysis of the effects of additions of radicals on ignition were also conducted in this study. In addition, because the installation of a PJ torch igniter in industrial gas-turbine combustors is being planned on the industrial side, the compatibility of the PJ torch for combustors of large-hydrocarbon fuels and DME is a very important issue.

II. Numerical Method and Kinetic Models

In numerical simulations, the ignition delay was calculated by using the SENKIN code in the CHEMKIN package [21]. A constant pressure was assumed and the ignition delay was defined as the time when the temperature of a mixture increased by 200 K from the initial temperature. GRI-Mech version 3.0 [22] for CH_4, and Marinov's model [23] for C_2H_4 and C_3H_8 were employed as kinetic models. CH_4 was included for the comparison. A combined kinetic model consisting of Fisher's model [24] and Li's C1 chemistry [25] was used for DME. Table 1 shows the numbers of species and elementary reactions for each fuel. Kinetic models listed in Table 1 were elaborated for the midtemperature self-ignition region and normal flame. In the case of ignition by a thermal plasma such as the PJ torch, ignition occurs in the PJ plume, in which temperature is in the middle

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Table 1   Numbers of species and elementary reactions for each fuel

Fuel	CH_4	C_2H_4	C_3H_8	DME
Kinetic model	GRI-Mech version 3.0	Marinov's model	Marinov's model	Fisher's model plus Li's C1 model
Species	54	127	127	80
Reactions	328	639	639	419

range between the high-temperature PJ core and airflow temperature. Therefore, the kinetic models can be applied. When a fuel injected upstream of the PJ and collided directly with the PJ, ignition occurred at the very-high-temperature region of the PJ core. However, in such a case, ignition delay time was extremely short and the effect of chemical kinetics became relatively very small.

Furthermore, NO_x produced by contact of a high-temperature PJ and the main airflow or that formed in an O_2/N_2 PJ has a strong catalytic effect on the ignition process of hydrocarbon fuels. To predict the NO_x effect more precisely, low-temperature chemistry [26–28] was added to GRI-Mech. version 3.0 [22]. Such chemistry is already incorporated in Marinov's model [23]. Our previous paper [12] showed that low-temperature chemistry played an important role in the catalytic effect resulting from the addition of NO_x. As for DME, the NO_x effect was not investigated because the reaction model did not include the NO_x chemistry.

III.   Experimental Apparatus
A.   Wind Tunnel and Test Section

The experiment was conducted using an intermittent-suction-type wind tunnel. Figure 1 shows a schematic of the test section. Atmospheric air was inhaled and accelerated to supersonic speed through a two-dimensional contoured nozzle. The test section had a 30 mm square uniform cross section and was 320 mm long. The Mach number and the characteristic length for unity Reynolds number of the main flow were 1.7 and 8.9×10^6 m^{-1}, respectively. The stagnation temperature and stagnation pressure were those of room condition. The Cartesian coordinate x was defined as the distance from the center of the torch nozzle. Success of ignition by the PJ was evaluated based on the wall pressure measured by a strain-gauge-type pressure transducer. Pressure taps were installed at 10 mm intervals from upstream of the PJ to downstream of the fuel injector. The signal from the transducer was amplified by a dc amplifier and was recorded by a data recorder. The error of the pressure measurement system was estimated as less than 1.5 kPa.

B.   Plasma Torch

The same plasma torch as that used in a series of previous studies [13,15,29] was employed. The detailed structure has been reported in the cited papers [13,15,29]. The cathode was made of hafnium to attain high durability when oxygen was used as the feedstock. The anode and the nozzle were made of O_2-free copper. The diameter of the nozzle throat was 1.5 mm. N_2, O_2, $O_2(50\%)/N_2(50\%)$, and $O_2(20\%)/N_2(80\%)$ mixtures were used as feedstock gases and their
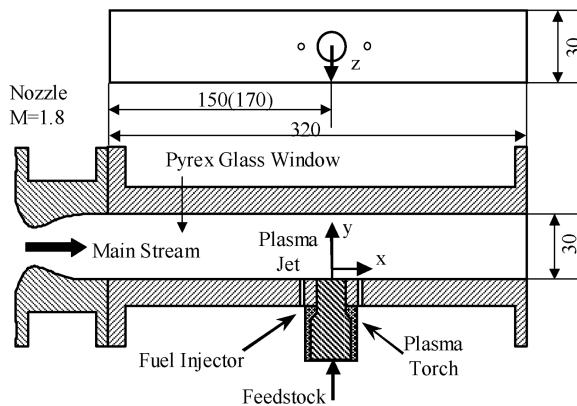
mole flow rates were set at 1.1×10^{-2} mol/s. The error of the flow meter was less than 1.0%.

C.   Fuel Injector

Ignition tests were conducted for both cases of upstream and downstream fuel injection. The fuel was perpendicularly injected into the main stream at the speed of sound from an orifice located at $x_i = 24$ or -24 mm on the centerline of the bottom wall. The diameter of the orifice was 1.0 mm. Four kinds of hydrocarbon fuels (CH_4, C_2H_4, C_3H_8, and DME) at room temperature were tested. CH_4 was tested for comparison with other fuels, the same as in the numerical analysis. The bulk equivalence ratio was set at 0.060 for all fuels. The dynamic pressure ratios of the fuel jet and the main flow were adjusted to embody the same fuel equivalence ratio for the fuels. Ratios of the amount of heat release via complete combustion of C_2H_4, C_3H_8, and DME to that of CH_4 were 1.11, 1.04, and 1.11, respectively.

IV.   Results and Discussion
A.   Ignition Delay Without Radical Addition

Ignition in the experiments conducted in this study was not homogeneous ignition. However, ignition analysis of individual fuel/air mixtures can be useful to estimate the effectiveness of plasma for ignition enhancement of each fuel, because the enhancement effect consists of a high-temperature (thermal) effect and a chemical effect due to existence of active species such as radicals and NO_x.

The ignition delay of a DME/air mixture is compared with those of CH_4/air and C_2H_4/air mixtures in Fig. 2. The ambient pressure and the equivalence ratio of the mixtures were set at 0.02 MPa and 1.0, respectively, in all cases. The ambient pressure was the almost the same as the static pressure of a supersonic flow of $M = 1.7$ in the ignition tests. The range of initial temperature is considered to be the same order as the temperature around the site of fuel injection ($x_i = 24$ mm) in the case of downstream fuel injection. The temperature of the PJ core ($x = 0$ mm) was estimated as about 5000 K and more by a spectroscopic measurement by the authors and that of the PJ plume 90 mm downstream of the PJ torch was reported as about 400 K by a measurement of thermocouples [29].

Figure 2 shows that the ignition delay of the DME/air mixture was almost the same as that of the C_2H_4/air mixture in a wide range of initial temperature and that it was considerably shorter than that of the CH_4/air mixture. In the authors' previous experiments [13,15], ignition by the PJ and strong combustion more easily occurred for the C_2H_4 fuel than for the CH_4 fuel in a supersonic flow, which clearly reflected the tendency of the ignition delay. From the

Fig. 1   Schematic of the test section.
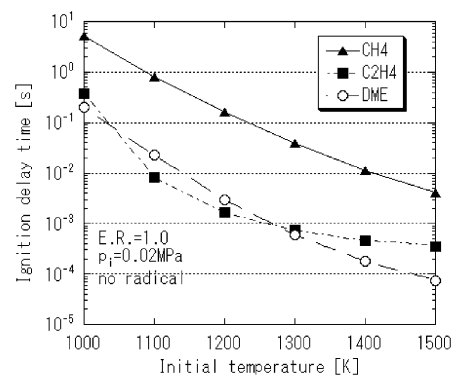
Fig. 2   Ignition delay times of CH_4, C_2H_4, and DME ($P_0 = 0.02$ MPa).

viewpoint of ignition time, therefore, DME was considered to be as suitable as C_2H_4 in the scramjet mode. The ignition delay of the C_3H_8/air mixture was at the same level as those of the C_2H_4/air and DME/air mixtures, though this was not shown in Fig. 2. Because the autoignition delays of hydrocarbon fuels shown in Fig. 2 were much longer than that of H_2 [29], introduction of some ignition enhancement mechanism for hydrocarbon fuel is strongly required.

B.   Effects of Addition of Radicals and NO_x on Ignition Delay

The effects of additions of radicals and NO_x on ignition delays of hydrocarbon/air mixtures under the same condition as the case without radical addition in Fig. 2 were investigated. Figure 3 shows the effects of O radicals and NO_x (NO and NO_2) additions on ignition delay of the C_2H_4/air mixture. The addition of O radicals considerably decreased the ignition delay of the mixture in the whole range of initial temperature. Moreover, additions of NO and NO_2 also decreased the ignition delay at low initial temperature. These results coincided with those obtained by using GRI-Mech [22] in a previous study [15]. It was also shown in the previous paper [15] that the effect of NO_x addition strongly enhanced reduction of the ignition delay of the CH_4/air mixture, due to its catalytic effect via low-temperature chemistry.

Figure 4 shows the effect of the radical addition on ignition delay of the DME/air mixture, though the effect of NO_x is not shown because of a lack of NO_x chemistry. In contrast to the result for C_2H_4, the effect of radical addition was very slight for the DME/air mixture. The dependence of the effect on radical species also did not appear in Fig. 4. As for the DME, the following unimolecular decomposition (1) and radical formation by secondary reactions that followed reaction (1) are very fast in the oxidation process of the DME, and therefore the initial radical concentration had little impact on ignition:
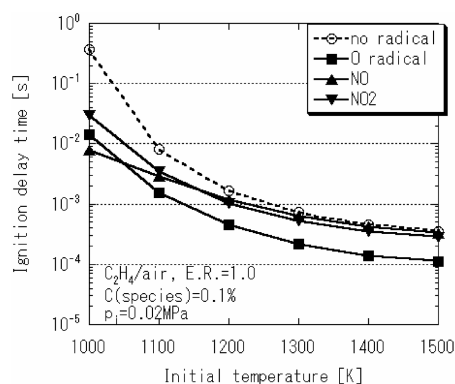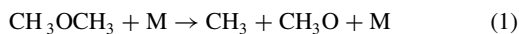
$$CH_3OCH_3 + M \rightarrow CH_3 + CH_3O + M \qquad (1)$$

Figure 5 shows the effects of O radicals and NO_x additions on ignition delay of the C_3H_8/air mixture. The effect of radical addition was very slight, as in the case of the DME/air mixture. Moreover, the effect of the addition of NO_x was smaller than that for the C_2H_4/air mixture, though it slightly appeared at an initial temperature lower than 1200 K. In the case of C_3H_8, the following decomposition reaction (2) occurs in the early stage of the oxidation process, and many radicals are formed by secondary reactions following reaction (2). Therefore, the initial concentration of radicals may not be important, as in the case of DME:

$$C_3H_8 + M \rightarrow C_2H_5 + CH_3 + M \qquad (2)$$

Figures 6 and 7 show comparisons of initial histories of radical formation in the oxidation processes of C_2H_4/air and C_3H_8/air mixtures, respectively, without radical addition at a very low initial

Fig. 5   Effect of the addition of radicals and NO_x on ignition delay of the C_3H_8/air mixture ($P_0 = 0.02$ MPa).

Fig. 3   Effect of the additions of radicals and NO_x on ignition delay of the C_2H_4/air mixture ($P_0 = 0.02$ MPa).

Fig. 6   History of radical formation in the early stage of the combustion reaction of the C_2H_4/air mixture without radical addition ($T_0 = 1000$ K, $P_0 = 0.02$ MPa).
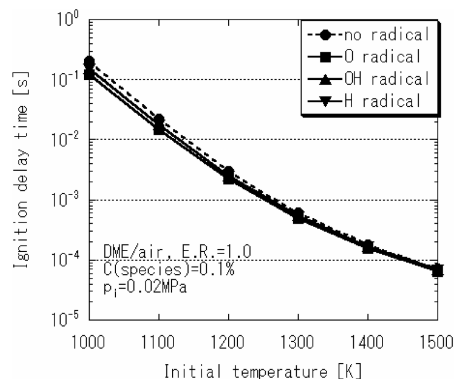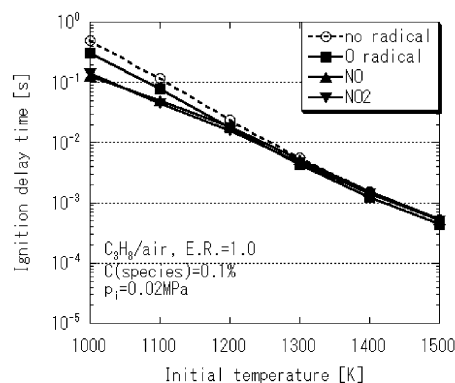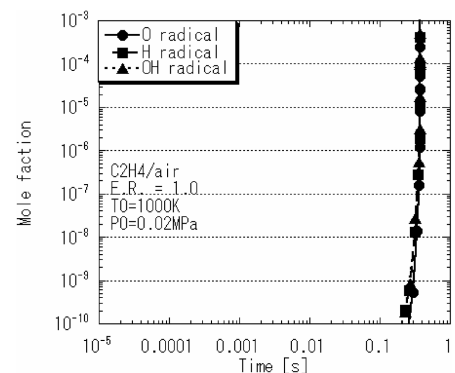

Fig. 4   Effect of the addition of radicals on ignition delay of the DME/air mixture ($P_0 = 0.02$ MPa).
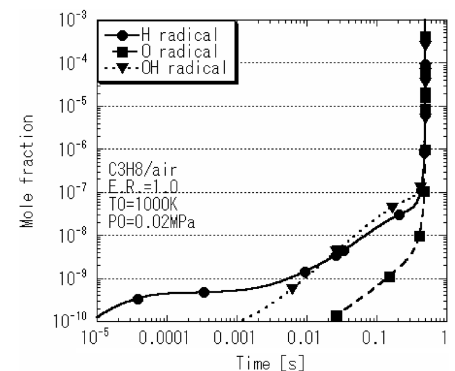

Fig. 7   History of radical formation in the early stage of the combustion reaction of the C_3H_8/air mixture without radical addition ($T_0 = 1000$ K, $P_0 = 0.02$ MPa).

temperature ($T_0 = 1000$ K). It is obvious that many H, O, and OH radicals are formed in the early stage of the C_3H_8 oxidation process by secondary reactions following Eq. (2). On the other hand, no radicals are formed in the early stage of the C_2H_4 oxidation process before radical runaway at ignition.

The preceding results showing the insensitivity of C_3H_8 and DME to additions of radicals and NO_x can be applicable to hydrocarbon s larger than C_3H_8, because decomposition of large-hydrocarbon molecules is rapid in the ignition process. In other words, these results emphasize the ability of plasma to enhance ignition of low-hydrocarbon fuels such as CH_4 and C_2H_4.

C. Ignition Test of Fuel Injected Downstream of PJ

In a previous paper [15], the authors showed that ignition of fuel injected downstream of the PJ solely reflected the autoignition process affected by the radicals, NO_x, and temperature evolution of the PJ plume, though the amount of combustion for downstream fuel injection was smaller than that for upstream fuel injection. As discussed in the next section, the case of upstream fuel injection was more complicated. Therefore, ignition tests of three fuels injected downstream of the PJ were first conducted to clarify the effects of radicals and NO_x on the ignition process.

Figures 8–10 show nondimensional wall pressure increases due to combustion of C_2H_4, C_3H_8, and DME in the supersonic flow, respectively. It is well known that the wall pressure is proportional to the degree of heat release in a supersonic flow and is directly related to the engine thrust. Averaged wall pressure increases due to combustion throughout the downstream region of the PJ were normalized by the total pressure of the main flow. Fuels were perpendicularly injected downstream of the PJ at $x_i = 24$ mm. Pure N_2, pure O_2, and a mixture of $N_2(50\%)/O_2(50\%)$ were tested as the feedstocks to the PJ torches. The $N_2(50\%)/O_2(50\%)$ feedstock was considered to include the largest mole fraction of NO_x. If NO_x has a catalytic effect on the ignition process of C_3H_8 or DME, the N_2/O_2 feedstock can possibly perform better than pure O_2 and pure N_2
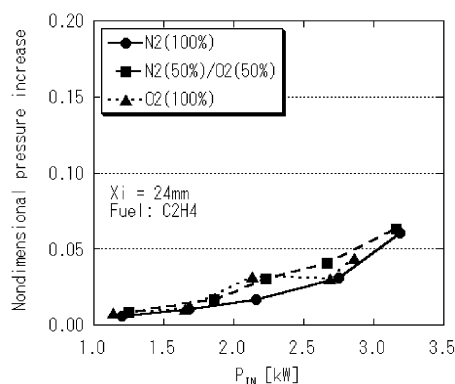

Fig. 8 Wall pressure increase due to combustion of C_2H_4 fuel injected at $x_i = 24$ mm in supersonic flow ($M = 1.7$).
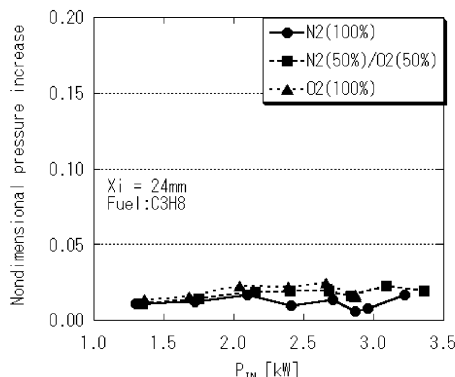

Fig. 9 Wall pressure increase due to combustion of C_3H_8 fuel injected at $x_i = 24$ mm in supersonic flow ($M = 1.7$).
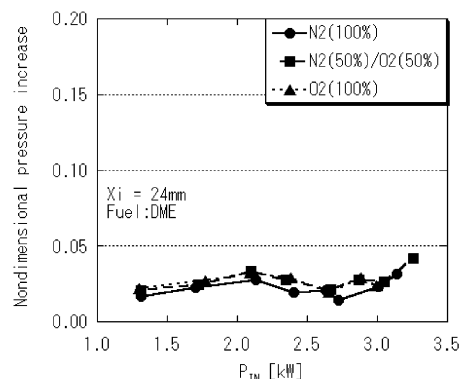

Fig. 10 Wall pressure increase due to combustion of DME fuel injected at $x_i = 24$ mm in supersonic flow ($M = 1.7$).

feedstocks. Actually, the superiority of the N_2/O_2 feedstock over other feedstocks for the H_2 and C_2H_4 fuels in the case of downstream fuel injection has been shown in the authors' previous experiments [15].

In Fig. 8, ignition and spread of the combustion region of the C_2H_4 fuel occurred when an electric power input P_{in} was large. Figure 11 shows a direct photograph of a C_2H_4 flame ignited in the plume of the N_2 PJ ($P_{in} = 2.99$ kW). A blue flame was apparently detected in the yellow-green PJ plume. On the other hand, Figs. 9 and 10 show that wall pressure increases due to combustion of the fuels were not obtained for C_3H_8 and DME, even at the largest P_{in} in this facility. As can be seen in Figs. 2 and 5, the ignition delays for the three fuels without radical addition were almost the same. This superiority of C_2H_4 over C_3H_8 and DME for plasma ignition reflected results of numerical analysis on the effect of radicals on ignition that showed that the radical effect strongly appeared only for C_2H_4, as seen in Figs. 3–5.

Moreover, the dependence of the amount of combustion on feedstock of the PJ torch did not appear for any of the fuels. This result reflected little effect of the existence of NO_x on ignition and agreed with the numerical result, shown in Fig. 5. Though the NO_x effect on ignition delay of the C_2H_4/air mixture appeared at a low initial temperature in Fig. 3, it was still small for the appearance of the enhancement effect in the experiment. One reason for the slight dependence on the feedstock for C_2H_4 was considered to be that the static pressure was too low to obtain the catalytic effect of the NO_x.

D. Ignition Test of Fuel Injected Upstream of PJ

In the case of fuel injection upstream of the PJ [9–14], the PJ acted as a flameholder and strong combustion easily occurred even for CH_4, the ignition delay of which was the longest among the hydrocarbon fuels. The flame region widely spread after local ignition at the site at which the fuel jet directly collided with the PJ. The phenomena in such a case included both features of ignition and of flame propagation, and therefore it was more complicated than that for the case of fuel injection downstream of the PJ.

Ignition tests of C_3H_8 and DME in the case of the upstream injection were conducted and the amounts of their combustion were compared with those of CH_4 and C_2H_4. Figure 12 shows averaged wall pressure increases due to combustion for different electric power input to the N_2 PJ, where the fuel was injected at $x_i = -24$ mm. It can be easily recognized by comparison with the results in Figs. 8–10 that the averaged wall pressure increases due to combustion for all fuels were much larger than those for the
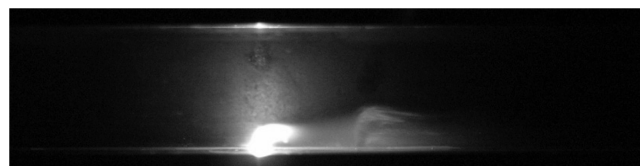

Fig. 11 Direct photograph of N_2 PJ and C_2H_4 flame ($P_{in} = 2.99$ kW).
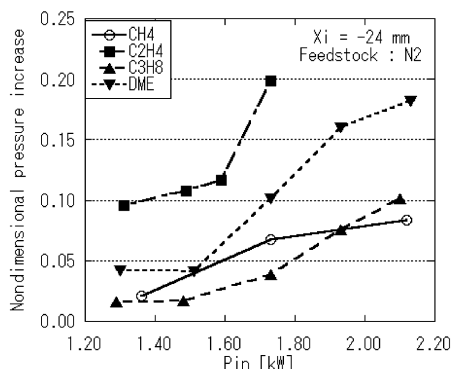
Fig. 12 Dependence of wall pressure increase due to combustion on electric power input in cases of fuel injection upstream of PJ ($x_i = -24$ mm).

downstream fuel injection. The amount of combustion was in proportion to the electric power input. This result indicates that thermal effect of the PJ is dominant, because larger electric power input directly results in higher temperature of the PJ. The order of the amount of the wall pressure increase was C_2H_4, DME, CH_4, and C_3H_8. This order was almost the same as that of burning velocity [20]. Differences between fuels clearly appeared at large electric power input, and the superiority of DME fuel to CH_4 and C_3H_8 was profound.

Figure 13 shows the dependence of the wall pressure increase due to combustion on the mixing ratio of the N_2/O_2 feedstock mixture. The amount of combustion increased with the mole fraction of O_2 in the feedstock. Pure O_2 resulted in the largest wall pressure increase. These results were common to all fuels in Fig. 13 and were clearly different from the results in cases of downstream fuel injection [15,29], in which the performance of the N_2 PJ was almost the same as that of the O_2 PJ. This superiority of O_2 feedstock over other feedstock gases was not due to the O radical effect, but rather to the increase in the local O_2 concentration around the ignition site, because the effects of radicals on ignition of DME and C_3H_8 were very slight, as shown in the previous section. The authors confirmed by additional calculation of the ignition delay of mixtures with different O_2 mole fractions that the increase in the O_2 mole fraction caused the ignition delay of the mixture to decrease. As a result, the increase in the local O_2 concentration around the ignition site was the key factor that enhanced ignition and combustion in high-speed flow. There have been many reports [10,14,30] on the superiority of O_2 feedstock and explanations of this based on the role of the effect of radicals. Quenching of O radicals by the recombination reaction $O + O + M \Rightarrow O_2 + M$ is very fast in the PJ plume and results in an increase of the mole fraction of high-temperature O_2 molecules, which may be highly vibrationally excited around the local ignition site. This process must be the essence of the superiority of the O_2 feedstock.

V. Conclusions

The effects of additions of radicals and NO_x on ignition delays of the C_3H_8/air and the DME/air mixtures were very slight. This low sensitivity to the effects of the addition of radicals and NO_x was confirmed in tests of ignition by the PJ torch in cases of fuel injection downstream of the PJ. The low sensitivity to radicals and plasma is applicable to larger hydrocarbon fuels. In other words, these results reflect the strong sensitivity of small-hydrocarbon fuels such as CH_4 and C_2H_4.

In the case of the fuel injection upstream of the PJ, the amount of combustion of C_3H_8 and DME increased with the O_2 mole fraction in the feedstock to the PJ, as in the case of other low-hydrocarbon fuels. This result indicates that the local O_2 concentration around the ignition site is very important for successful enhancement of ignition and combustion in high-speed flow.

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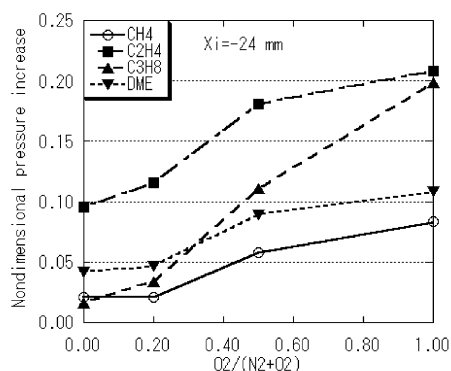   doi:10.2514/2.6116

Fig. 13 Dependence of wall pressure increase due to combustion on mixing ratio of feedstock to PJ torch in cases of fuel injection upstream of PJ ($x_i = -24$ mm).

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