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Full Length Article

Feasibility study of water plasma jets for combustion promotion

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HIGHLIGHTS

- Effectiveness of water plasma jets (PJs) for combustion was examined.
- Water PJs are as effective as oxygen PJs at promoting combustion.
- Water PJs are effective because of presence of OH radicals at low specific power.
- Water plasma torch is a practical and useful device for combustion promotion.

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ABSTRACT

Plasma-assisted combustion can be used to achieve combustion of fuels that are difficult to utilize, which can help in combating the current energy and environmental problems. However, current plasma-assisted combustion technologies employ oxygen, which is proficient in reactivity but heavily degrades electrical contacts over time. Therefore, we propose the use of water, which is readily available, low cost, and ecofriendly, as feedstock of plasma jets (PJs), by examining the usefulness of water PJs for combustion promotion. Combustion tests for methane (CH_4)/air mixtures were conducted using our original experiment apparatus with three types of PJ feedstocks, i.e., Ar seeded with O_2, N_2, or H_2O, coupled with numerical simulations of the reaction mechanism. The results revealed that H_2O-seeded PJs, ($Ar + H_2O$) PJs, included O, H, and OH radicals and that for high specific powers to PJs, O and H radicals mainly contribute to combustion promotion, whereas for low specific powers, mainly OH radicals contribute to combustion promotion. At combustion promotion, ($Ar + H_2O$) PJs were almost as effective as O_2-seeded PJs, i.e., ($Ar + O_2$) PJs, which agrees with numerical estimations. Moreover, ($Ar + H_2O$) PJs are preferable because they cause very less wear on the electrodes of a plasma torch. Therefore, we proposed that the utilization of water PJs is a useful approach to promote combustion.

1. Introduction

Plasma-assisted combustion is a good candidate to solve current energy and environmental concerns because it can help achieve combustion under unfavorable conditions such as with lean or rich fuel and enables the use of unutilized energies, e.g., in low-grade fuels [1,2]. Although thermal and non-thermal plasmas are proposed and used for combustion promotion, this study deals with thermal plasma. The thermal plasma method promotes ignition/combustion both thermally and chemically by ejecting high-temperature plasma jets (PJs), which include many chemically active radicals, from a plasma torch nozzle into the combustion field; the PJ feedstock is exposed to arc discharges between electrodes. However, to apply this combustion method to practical devices, basic data on combustion promotion with PJs are required. In previous studies, we investigated the effects of PJs on combustion promotion using an original experimental apparatus with a plasma torch [3–5] and reported that the chemical effect of radicals included in PJs was more advantageous than the thermal effect. In particular, oxygen PJs (O_2 PJs), which include abundant O radicals, were superior to the other PJs in our study. Experiments aimed at enhancing the performance or the exhaust gas purification of internal combustion engines were performed by adding a reaction promotion substance such as ozone, which is decomposed into highly reactive radicals during air or fuel intake to shorten the ignition delay time [6–9]. However, O_2 PJs had one disadvantage: at long operation times, electrodes and nozzles were subjected to significant wear or erosion because of the high reactivity O radicals [10]. Researchers have proposed the use of a hydrocarbon feedstock for PJs to include active CH radicals [11]; however, this

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Nomenclature and units

C	combustion completeness (–)
$CO_{2act.}$	experimental measurement of carbon dioxide concentration in exhaust gas (%)
$CO_{2cal.}$	theoretical calculation of carbon dioxide concentration in exhaust gas (%)
P_{in}	input electric power to plasma jet (W)
$\dot{m}$	mass flow rate of plasma jet feedstock (mg/s)
ø	equivalence ratio of premixed gas (–)
V_m	flow speed of premixed gas (m/s)
t_{ig}	ignition delay time (s)
T_0	initial temperature (K)

Subscript

Ar	argon
O_2	oxygen
N_2	nitrogen
H_2O	water

caused problems such as unstable operation and soot adhesion to the anode nozzle. Therefore, this combustion method has been examined only as an ignition device for supersonic combustion systems [10–21], fuel-rich combustion systems for syngas production [22–25] and for suppression of soot in flames [26,27]; it has not found widespread practical application.

Hence, in this study, we propose a combustion promotion method that adds water to the feedstock to produce highly reactive O, H, and OH radicals when the feedstock is dissociated. Water has advantages compared with other substances: readily available, low cost, and ecofriendly. Moreover, we expect electrode wear to be reduced by the cooling effect of water. If a combustion promotion technology using water PJs was revealed to be effective, it would contribute toward providing a solution to the world's current energy and environmental problems. Despite water PJs being utilized for metal cutting or spraying [28,29], they have scarcely been utilized to promote combustion, and their performance as combustion promoters is virtually unknown.

We designed and developed a plasma torch that enables water to be added to the PJ feedstock; then we evaluated the performance of the water PJ in promoting the combustion reaction. We performed spectroscopic measurements and combustion tests using various feedstocks to probe the combustion reaction using water PJs and other PJs for lean methane (CH_4)/air mixtures. Numerical estimations of the reaction mechanism were also conducted to confirm the level of combustion promotion of the experimental results. Finally, based on our experimental data and numerical results, the potential of applying water PJs for combustion applications will be discussed.

2. Experimental apparatus and test procedure

A schematic of the experimental setup is shown in Fig. 1. A plasma torch is placed at the bottom center of a combustor. The torch has a rod cathode made of thoriated tungsten, which is 2 mm in diameter, and a cylindrical Cu anode with a 1-mm jetting caliber. The cathode is insulated from the plasma torch body by a ceramic pipe. Arc discharge between electrodes is induced using a current-regulated DC power unit (M-3500, DAIHEN Co.). In these experiments, we used three types of PJ feedstocks, i.e., argon (Ar) as the base gas with oxygen (O_2), nitrogen (N_2), or water (H_2O) as an additive and designated as (Ar + O_2) PJ, (Ar + N_2) PJ, or (Ar + H_2O) PJ, respectively. The flow rate and a mixture ratio of the Ar, O_2, or N_2 gas were set using a mass flow controller (8500, Kojima Instruments Inc.); the gas was supplied from the bottom of the plasma torch. Liquid H_2O was supplied through the orifice (50-μm diameter) from a side of the plasma torch at a set flow rate regulated by a needle valve; it then evaporated owing to the heat from the torch. The PJ feedstock was supplied into the anode nozzle through a swirl vane, exposed to arc discharges between electrodes, converted to high-temperature PJs, which include many active radicals, and finally ejected into the combustion chamber.

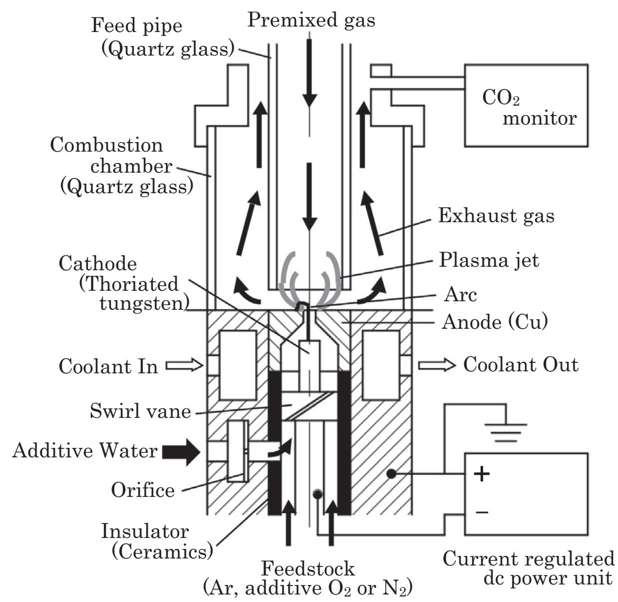

Fig. 1. Schematic of experimental setup.

The plasma torch was water cooled to prevent electrode wear. Fuel/air mixture, methane (CH_4)/air in this study, was supplied to the plasma torch through a quartz glass feed pipe of 16 mm in bore at a set flow rate and mixture ratio, which was determined using mass flow controllers. The combustion chamber was made of quartz glass (38 mm in bore) and surrounded the plasma torch and premixed gas feed pipe for an observation of the combustion state. Premixed gas was ignited and chemically and thermally combusted by exposure to PJs. Discharge current/voltage and carbon dioxide (CO_2) concentration in the exhaust gas were measured using a CO_2 monitor (MEXA-584L, HORIBA Ltd.) during PJ ejection into a premixed gas. The completeness of combustion was determined via visual observation; combustion completeness C is defined as

$$C = \frac{CO_{2act.}}{CO_{2cal.}},$$

where $CO_{2act.}$ is the measured CO_2 concentration in the exhaust gas and $CO_{2cal.}$ is the theoretical CO_2 concentration calculated via chemical equilibrium for application (CEA) [30]; both $CO_{2act.}$ and $CO_{2cal.}$ exclude water.

Spectroscopic measurements were conducted to identify radicals present in the PJ induced with each feedstock. The luminescence from PJs was condensed at one end of an optical fiber by a biconvex lens and fed to a spectrometer (USB2000, Ocean Optics,