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Development of a gas turbine fuel nozzle for DME and a design method thereof

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HIGHLIGHTS

- ▶ We propose a DME nozzle with low NO_x/CO emissions and anti-flashback characteristics.
- ▶ The nozzle design is based on the Wobbe Index and the combustion properties of DME.
- ▶ NO_x at 60 kW is reduced by 8.9% and 23.6% for DME and methane respectively.
- ▶ High CO problem is resolved by achieving under 5 ppm for all test conditions.

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ABSTRACT

DME (dimethyl ether, CH_3OCH_3) is a potentially attractive fuel for gas turbines because of low pollutant emission and easy transportation and storage. However, the high flame speed and a low ignition temperature of DME present a high risk of flash-back, which can be a potentially serious problem. To solve this problem and achieve better combustion performance, the present study contrived a new fuel nozzle for DME that can obtain optimal combustion of DME in the gas turbine combustor, thereby achieving cost reduction of power generation, enhancement in reliability of power plants and diversification of usable fuel. The configuration of a fuel nozzle for DME and a design method using Wobbe Index are both described in detail. The combustion performance of the newly developed DME fuel nozzle was verified through a gas turbine combustion test and the results showed considerable improvement in the performance of NO_x and CO emissions and the prevention of flash-back.

1. Introduction

1.1. Background

Many studies have reported DME as a potential candidate for clean fuel to resolve the significant problems arising at present such as the shortages of fossil fuels and the need for environmental protection [1–3]. In a general power plant using a gas turbine, natural gas containing as much as 85% or more methane (CH_4) is used as a primary fuel, while oil distillates are used as a back-up fuel. However, market prices of such fuel are volatile. To cope with the volatile market price of fuel, there is a need to develop a gas turbine capable of employing diverse fuels for power plants. Particularly, a new fuel, e.g. dimethyl ether (DME), and synthesis gas produced from various raw materials such as natural gas, coal, biomass, and wastes. by a chemical process are expected to be used widely in the future in consideration of economical and technical efficiency. However, since DME has a higher combustion velocity, lower ignition temperature and shorter ignition delay time than methane as indicated in Table 1, a combustor is likely to experience damage caused by flash-back when DME is used in a natural gas-fired gas turbine [4,5]. Further, since DME has a low heating value of 28.8 MJ/kg (59.3 MJ/Nm^3), which is lower than the heating value of natural gas, 49.3 MJ/kg (39.3 MJ/Nm^3), modification of the combustor is necessary. In view of the combustion properties of DME with a high cetane number, it has been studied as an alternative to diesel fuel, and many patents and papers designing a fuel supply system and remodeling the combustor have been proposed to provide a diesel vehicle capable of using DME [6]. However, development of a fuel nozzle of a gas turbine for DME has not been proposed as much. A combustor, according to the present study, is expected to enhance utility and reliability of a power plant through stable operation of a power plant running on DME, while reducing power generation costs with DME.

1.2. Prior researches on a DME combustor for power generation

Numerous researchers around the world have conducted studies of DME combustion of gas turbines for power generation. GE

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Nomenclature

DME	dimethyl ether	$O_{2,m}$	O_2 concentration measured at the exhaust of combustor
T_n	fuel nozzle temperature	WI_{NG}	Wobber Index of natural gas
T_d	dump plane temperature of the combustion chamber	WI_{DME}	Wobber Index of DME
T_e	temperature of exit gas from the combustion chamber	S_n	swirl number
P'_{rms}	root mean square value of dynamic pressures in the combustion chamber	S_{T,CH_4}	turbulent burning velocity of methane
ppm	parts per million	$S_{T,DME}$	turbulent burning velocity of DME
φ	equivalence ratio	γ	specific gravity of gas at 0 °C and 1 atm
LHV	lower heating value	$\dot{Q}$	heat input
D_{swirl_in}	inner diameter of swirler	$\dot{Q}_{NG}$	heat input of natural gas
D_{swirl_out}	outer diameter of swirler	$\dot{Q}_{DME}$	heat input of DME
θ	swirl vane angle	D_{NG}	diameter of natural gas nozzle
$NO_{x,m}$	NO_x concentration measured at the exhaust of combustor	D_{DME}	diameter of DME nozzle
CO_m	CO concentration measured at the exhaust of combustor	K	constant flux coefficient
		p	injection pressure of fuel gas

Energy conducted a combustion test on a mixed solution of DME, methanol and water by means of a bench-scale burner, and reported that the mixture could be utilized in a commercialized gas turbine of its own. It then obtained a patent on the concentration and usage range of the fuel mixture [7]. Hitachi of Japan developed a 25 MW scale DME burner, which is a full-size multi-cluster burner composed of coaxial jet cluster nozzle burners [4]. Tokyo Electric Power Company conducted a study on the application of DME to a micro gas turbine for LPG, and reported that it obtained equivalent or superior operational performances with DME in comparison with LPG [8]. Jiang et al. studied a plat flame micro combustor burning DME for thermoelectric power generation [9]. Recent studies by Lee et al. reported successful demonstrations, burning DME in a bench scale combustor [10] and a scaled-down GE7EA single combustor [11] (the MS7EA gas turbine of the GE Energy Company [12]). As a continuation of these previous studies [10,11], the present study proposes a fuel nozzle of a gas turbine combustor for DME and a design method thereof that can obtain optimal combustion of DME in a gas turbine, thereby achieving cost reduction of power plants, enhancement in performance of the power plants and diversification of usable fuel.

2. Description of test methods

2.1. Gas turbine combustion test facility

A 60 kW scale gas turbine combustion test facility capable of supplying air of 0.2 kg/s at 400 °C with a fuel supply system for DME and methane was installed for the purposes of this study. As shown in Fig. 1, an air compressor, an air storage tank, an air heater, and air supply lines for cooling and combustion were built in the gas turbine combustion test facility. In addition, the entire system incorporated a DME storage tank, a DME vaporizer, DME pre-heating lines, fuel supply lines, a flow meter and controllers, water sprayers for cooling exhaust gases, atmospheric pressure burners, control systems, and an outer stack.

2.2. Model gas turbine combustor and test methods

A GE7EA heavy duty gas turbine (model name: MS-7001EA; simple cycle power output: 89 MW; simple cycle efficiency based on LHV of natural gas: 32.7%) of the GE Company is composed of 10 combustion chambers in a circle and adopts a combustion system of the multi-can annular type. In this test, the model combustor of a GE7EA gas turbine (M1-combustor) was designed and manufactured by scaling down one of the ten combustors. The scale-down ratio was approximately 2:1. Table 2 shows the dimensions of the main parts of the M1-combustor, while its configuration is shown in Fig. 2a and b. The dynamic pressures of the combustion chamber and the concentration and temperature at the flame and liner of the combustor were measured individually in order to diagnose combustion performances. The swirl number of the combustor, of which the inner and outer diameter are defined as D_6 and D_7 respectively, was 0.801, which was calculated by the following equation [13].

Table 1
Properties of DME and other gases.

Property	Unit	DME	Methane
Chemical formula	–	CH_3OCH_3	CH_4
Boiling point	°C	−25.1[a,b]	−161.5 [b]
Liquid density	g/cm^3	0.67[a,b]	N.A.
Specific gravity (vs. air)	–	1.59[a,b]	0.55[b]
Vapor pressure at 25 °C	atm	6.1[b]	246[b]
Flammable limits in air	%	3.4–18.6[a,f]	5.0–15.0[f]
Minimum auto-ignition temperature	°C	235[a]	600[d]
Maximum laminar flame speed at 25 °C and 1 atm	cm/s	46.1[c]	37.3[b,e]
Stoichiometric air/fuel ratio	kg/kg (m^3/m^3)	9.0[a,b] (14.3)	16.9[b] (9.52)
Lower heating value	MJ/kg (MJ/Nm^3)	28.9[b] (59.5)	50.2[b] (36.0)

[a] Data reproduced from Ref. [6].
[b] Data reproduced from Ref. [18].
[c] Data reproduced from Ref. [19].
[d] Data reproduced from Ref. [20].
[e] Data reproduced from Ref. [21].
[f] Data reproduced from Ref. [22].