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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.

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

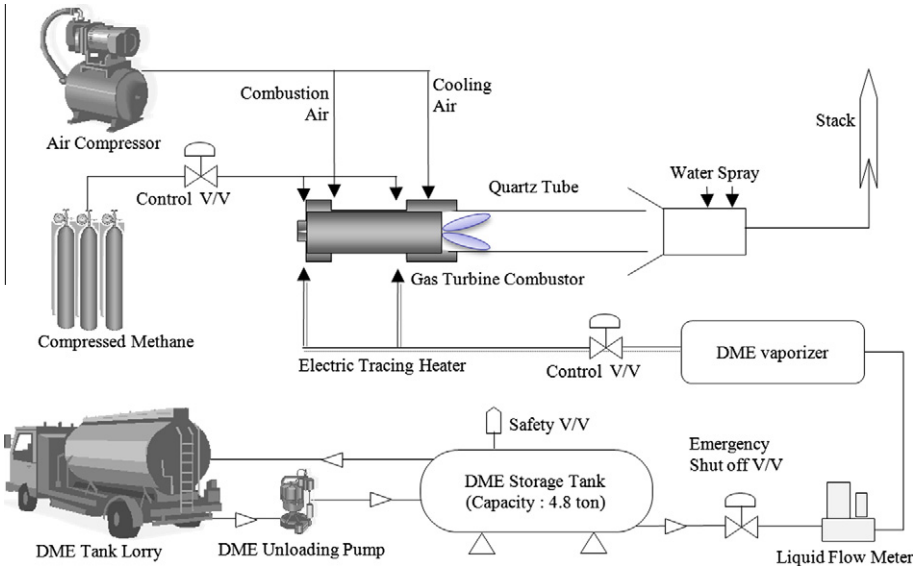


Fig. 1. 60 kW scale gas turbine combustion test facility.

Table 2
Main geometry of M1-combustor.

Nomenclature	Description	M1-combustor (mm)
D_1	Diameter of distillate oil fuel hole	3.2
D_2	Inner diameter of atomizing air hole	2.97
D_3	Outer diameter of atomizing air hole	5.5
D_4	Inner diameter of DeNO$_x$ water hole	8.9
D_5	Outer diameter of DeNO$_x$ water hole	11.4
D_6	Inner diameter of combustion air hole	30
D_7	Outer diameter of combustion air hole	53.5
D_8	Fuel nozzle head diameter	76.3
D_9	Diameter of main fuel injection hole	2.5
D_{10}	Inner diameter of combustion chamber	190
L_1	Length of combustion chamber	900

$$S_n = \frac{2}{3}\left[\frac{1-(D_{swirl_in}/D_{swirl_out})^3}{1-(D_{swirl_in}/D_{swirl_out})^2}\right]\tan\theta \quad (1)$$

where D_{swirl_in}, D_{swirl_out} and θ are the inner diameter of swirler, outer diameter of swirler and swirl vane angle, respectively.

Using temperature sensors and dynamic pressure sensors (Model: PCB 106B, water cooled and mounted type), the following parameters were measured at the location described in Fig. 2c: nozzle temperature (T_n), dump plane temperature (T_d), exhaust gas outlet temperature (T_e), and pressure fluctuation at the combustion chamber liner (P'_{rms}).

To measure the NO$_x$ and CO emissions, the exhaust gas was sampled at the exhaust end of the combustor and analyzed using a TESTO 360 gas analyzer. The measured results for emissions were corrected to 15% oxygen using the following equations [14].

$$(\mathrm{NO}_x \text{ at } 15\%\ \mathrm{O}_2) = \frac{\mathrm{NO}_{x,m}}{29.79}\left\{\frac{4.76\times(2-\mathrm{O}_{2,m})}{1-4.76\times\mathrm{O}_{2,m}}-1\right\} \quad (2)$$

$$(\mathrm{CO} \text{ at } 15\%\ \mathrm{O}_2) = \frac{\mathrm{CO}_m}{29.79}\left\{\frac{4.76\times(2-\mathrm{O}_{2,m})}{1-4.76\times\mathrm{O}_{2,m}}-1\right\} \quad (3)$$

3. Description of the DME combustor and the design methods thereof

The fuel nozzle for natural gas was modified to enhance the combustion performance when DME is fueled. Table 3 compares the original fuel nozzle for natural gas with the modified fuel nozzle for DME. To raise the design idea of fuel nozzle modification, both the fuel properties, such as burning velocity, ignition temperature, heating values and specific gravity, and the characteristics of flow and mixing are considered. The detailed design method of fuel nozzle for DME is divided in three parts as follows.

Step 1: With regard to a conventional natural gas combustor and a DME combustor, Wobbe Indexes (WI) that indicate energy of heat input to the combustor are calculated using the following equation.

$$\mathrm{WI} = \frac{\mathrm{LHV}}{\sqrt{\gamma}} \quad (4)$$

where LHV is lower heating value of fuel (kcal/Nm^3) and γ is specific gravity of gas at 0 °C and 1 atm.

Step 2: Under a condition of equalizing heat input on the basis of the Wobbe Index obtained in the first step, the minimum cross-section sum of the fuel injection ports is calculated. Here, we assumed that the fuel gas injection pressure would be equally applied. This is because an increase in fuel has injection pressure leads to a change in the fuel injection distance and generates nitrogen oxides (NO$_x$) due to incomplete combustion and diffusion combustion [15].

$$\dot{Q} = 0.011\times D^2\times K\times\sqrt{p}\times\mathrm{WI} \quad (5)$$

where $\dot{Q}$ is heat input (kcal/hr), D is the diameter of the nozzle (mm), K is a constant flux coefficient (about 0.8), and P is the injection pressure of fuel gas (mm H_2O)

Thus, the heat inputs of natural gas (NG) and DME are calculated by the following equations.

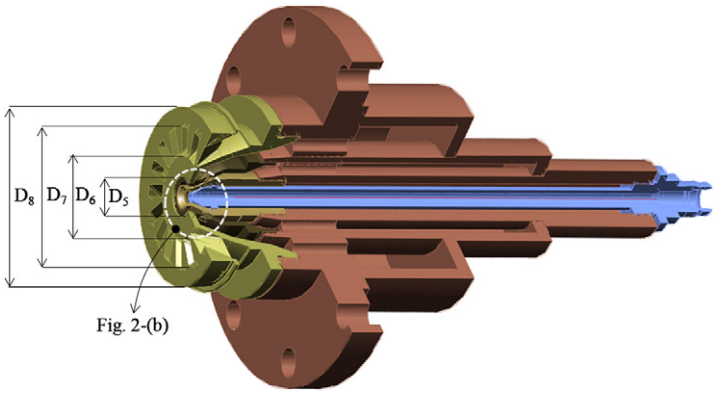
$$\dot{Q}_{\mathrm{NG}} = 0.011\times D_{\mathrm{NG}}^2\times K\times\sqrt{p_{\mathrm{NG}}}\times\mathrm{WI}_{\mathrm{NG}} \quad (6)$$

$$\dot{Q}_{\mathrm{DME}} = 0.011\times D_{\mathrm{DME}}^2\times K\times\sqrt{p_{\mathrm{DME}}}\times\mathrm{WI}_{\mathrm{DME}} \quad (7)$$

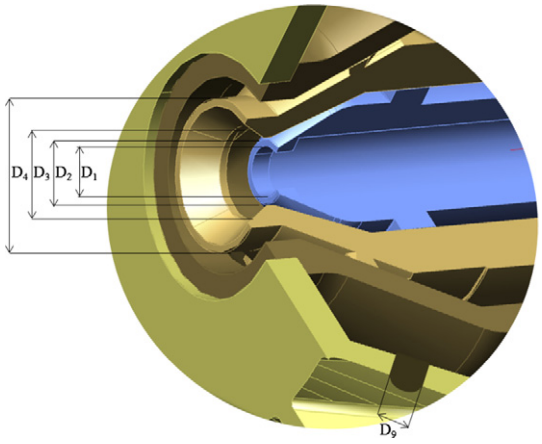
The heat inputs of natural gas and DME should be identical for the gas turbines of the same capacity.

$$\dot{Q}_{\mathrm{NG}} = \dot{Q}_{\mathrm{DME}} \quad (8)$$

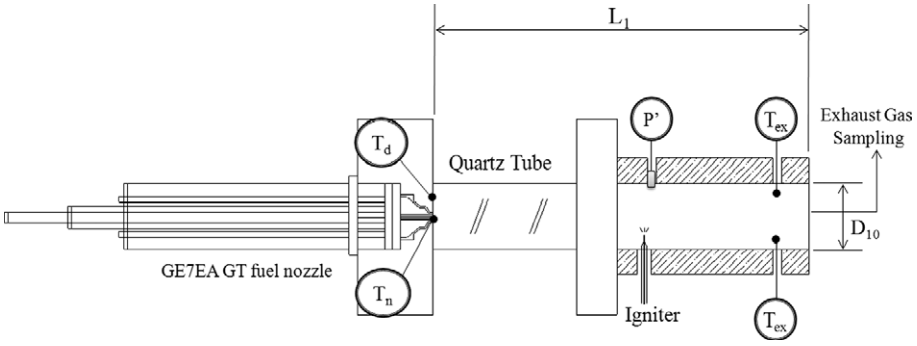
Further, the above equations are rearranged into Eq. (9) by substituting Eqs. (6) and (7) with Eq. (8) and using the physical properties in Table 4.



(a) A fuel nozzle of M1-combustor



(b) Magnified drawing of core section in Fig 2-(a)



(c) Drawing of M1-combustor test rig

Fig. 2. Drawings of a fuel nozzle and test rig of M1-combustor.

$$D_{DME} = \sqrt{\frac{WI_{NG}}{WI_{DME}}} \times D_{DME} = 1.086 \times D_{NG} \quad (9)$$

However, the enlarging ratio (108.6%) of the fuel injection port has to be calculated from the measured heating values of natural gas and DME in Korea, and it may be designed in the range of 105–150% according to the changes in the physical properties of natural gas and DME.

Step 3: To enhance combustion performance such as NO_x reduction, combustion efficiency, and flame-back prevention. under the same heat input condition, the fuel injection port is designed to meet the following conditions I, II and III. The same heat input can be accomplished by adjusting the diameter of the fuel injection port to the resultant value obtained in the second step, but the experimental results showed increased NO_x concentration and reduced combustion efficiency. To complement these results, the number of fuel injection ports is increased to enhance the fuel–air mixing and the fuel injection ports are positioned uniformly in upper and lower streams. Consequently, the combustion efficiency can be increased through flash-back prevention and improved mixedness of fuel and air.

I. To ensure swirling flow of the fuel and air mixture and uniform distribution of fuel, the fuel nozzle of the present invention is designed to have each of the fuel injection ports divided into the upper set of DME injection holes at an upper stream and the

Table 3
Comparison of the original fuel nozzle for natural gas with the modified fuel nozzle for DME.

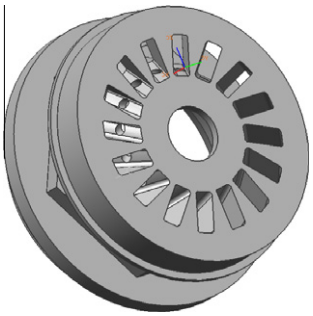
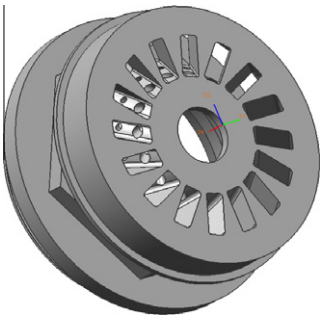
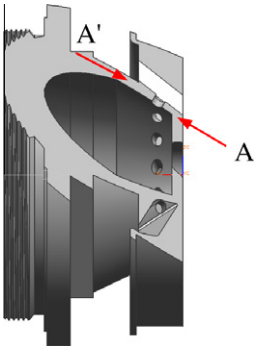
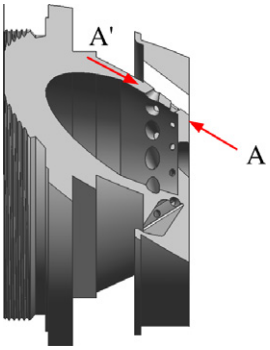
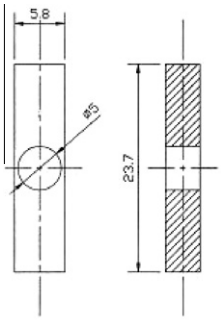
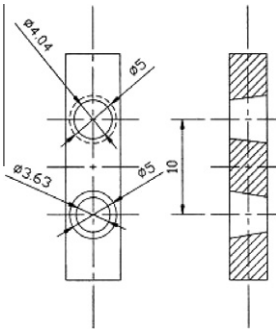
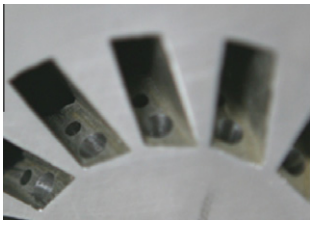
Description	Original fuel nozzle for natural gas	Modified fuel nozzle for DME
Oblique view		
Partially cut-away side view		
Size and number of the fuel holes	5 mm × 16 EA	Upper hole: 4.04 mm × 16 EA Lower hole: 3.63 mm × 16 EA
Enlarged front and sectional views taken along line A–A′		
Partial view of the fuel nozzle used in the test		

Table 4
Physical properties and Wobbe Index of DME and natural gas.

Property	Unit	DME (A)	Natural gas in Korea (B)	Difference (%) (A − B)/B × 100
Low heating value	MJ/kg (MJ/Nm^3)	28.9[a] (59.5)	54.4[b] (44.0)	−46.8 (34.9)
Specific gravity	vs. air	1.586[a]	0.625[b]	153.8
Density	kg/m^3	2.051[a]	0.808[b]	153.8
Wobbe Index	MJ/Nm^3	47.1	55.6	−15.3

[a] Data reproduced from Ref. [18].
[b] Data reproduced from Korea gas corporation datasheet.

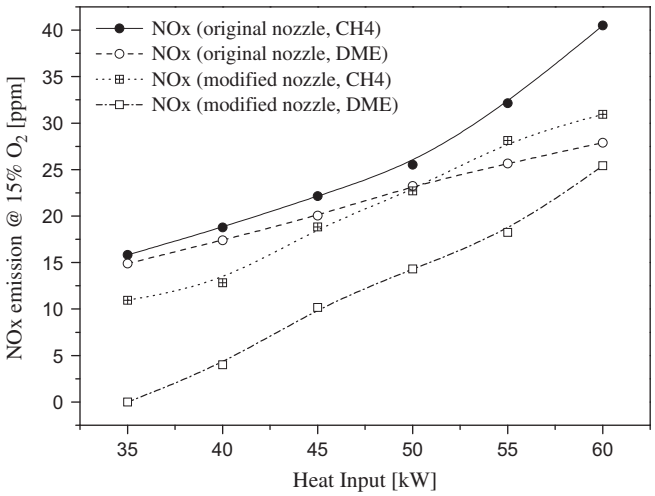


Fig. 3. NO_x emission characteristics of the original and the modified nozzles for methane and DME.

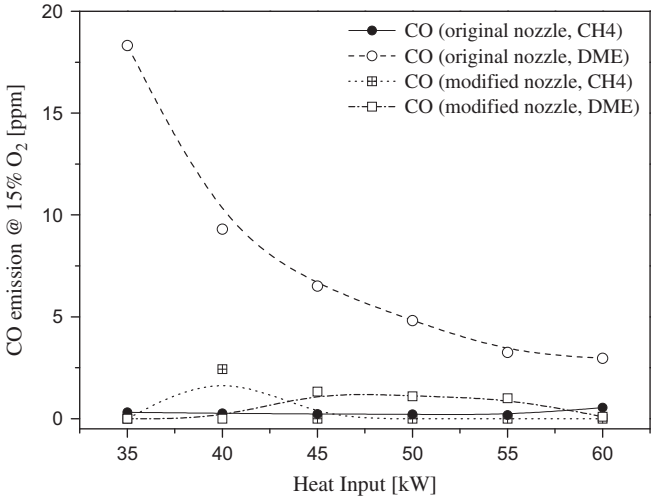


Fig. 4. CO emission characteristics of the original and the modified nozzles for methane and DME.

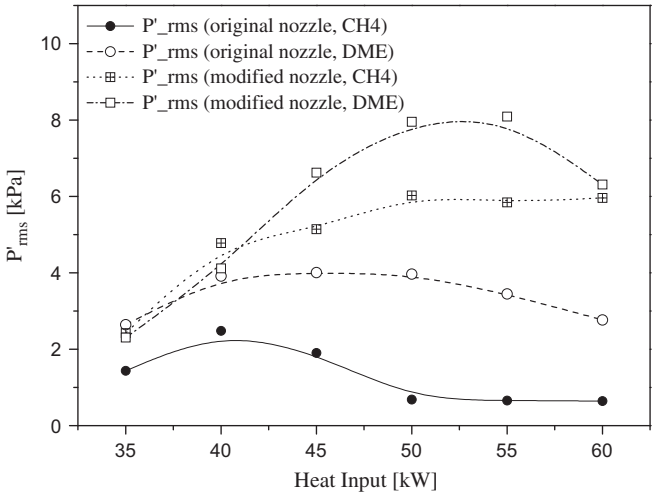


Fig. 5. Pressure fluctuation characteristics of the original and the modified nozzles for methane and DME.

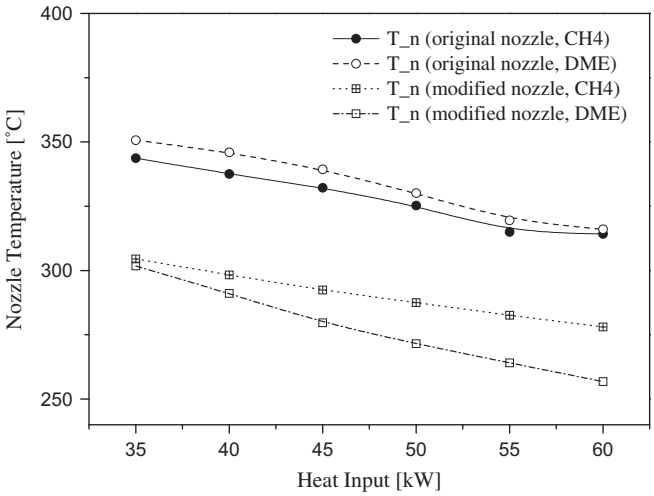


Fig. 6. Fuel nozzle temperature characteristics of the original and the modified nozzles for methane and DME.

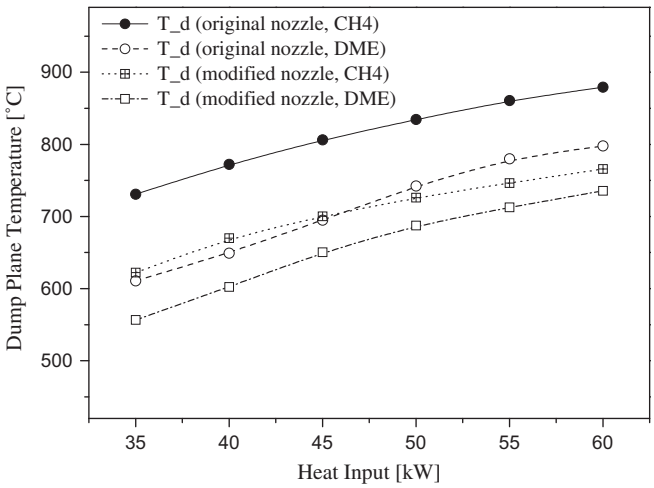


Fig. 7. Dump plane temperature characteristics of the original and the modified nozzles for methane and DME.

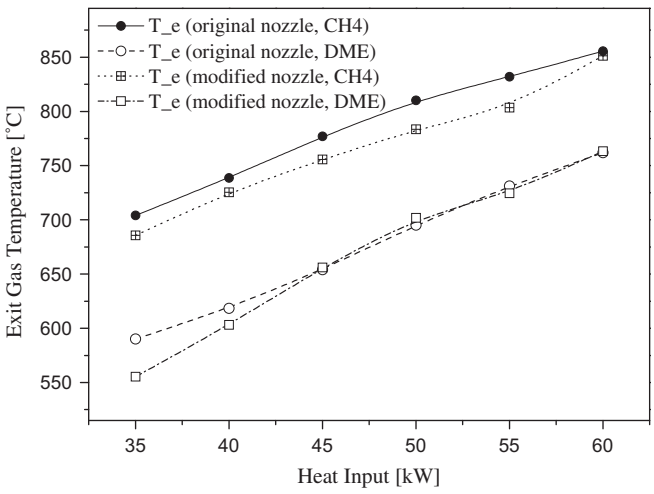


Fig. 8. Exit gas temperature characteristics of the original and the modified nozzles for methane and DME.

lower set of DME injection holes at a lower stream, in which the minimum cross-section sum of total fuel injection holes is equal to Eq. (9) as is obtained in the second step.

II. The upper set of DME injection holes: since the fuel injection holes are disposed near a combustion chamber, it is necessary to maintain a smooth surface for the purpose of preventing separation of flow to reduce combustion oscillation and to distribute the fuel uniformly. Accordingly, the upper set of DME injection holes is designed to have a channel that gradually widens toward an outlet of fuel.

III. The lower set of DME injection holes: since the fuel injection holes are farther apart from the combustion chamber than the upper set of DME injection holes, it has a longer fuel injection distance toward the air than the upper DME injection, and thus, it is necessary to have a regular jet shape. Accordingly, the lower set of DME injection holes is designed to have a channel tapered toward an outlet of the fuel.

4. Combustion test results and discussions on a DME combustor

When evaluating the combustion performance of the original and modified fuel nozzles, methane fuel is tested instead of natural gas for the following reasons: the composition of natural gas varies with the season and regions, and these variations make it difficult to obtain the exact measured combustion properties such as burning velocity and auto-ignition temperature; on the other hand, the combustion properties of methane are well-known and distinct; and furthermore, methane can reflect the combustion characteristics of natural gas since natural gas contains as much as 85% or more methane. Thus methane instead of natural gas is selected as a test fuel for a more precise and quantitative analysis of the combustion test results by comparing the combustion properties of methane with those of DME.

4.1. NO_x and CO emission characteristics

Figs. 3 and 4 show the NO_x and CO emission performances of the original and modified nozzles for methane and DME. It was confirmed that the emission performance of both NO_x and CO of the modified nozzle improved especially in the low range of heat input, since it makes a more uniform distribution of fuel in the swirling air and enhances the mixing of fuel and air. The relationship between NO_x emission and flame temperature can be easily explained by the fact that the reaction velocity in the Zeldovich mechanism, which is a thermal NO_x generation mechanism, is an exponential function of temperature [15]. Quantitatively, firing 60 kW of DME and methane led to a reduction of 8.9% (27.9 ppm → 25.4 ppm) and 23.6% (40.5 ppm → 30.9 ppm) of NO_x, respectively.

High CO emission problem of the original nozzle for DME at low heat input is resolved by enhancing the mixing from doubled number of fuel nozzle thus achieving more uniform equivalence ratio. By adapting the modified nozzle, CO was emitted under 5 ppm in all ranges of heat input, i.e. almost complete combustion was achieved.

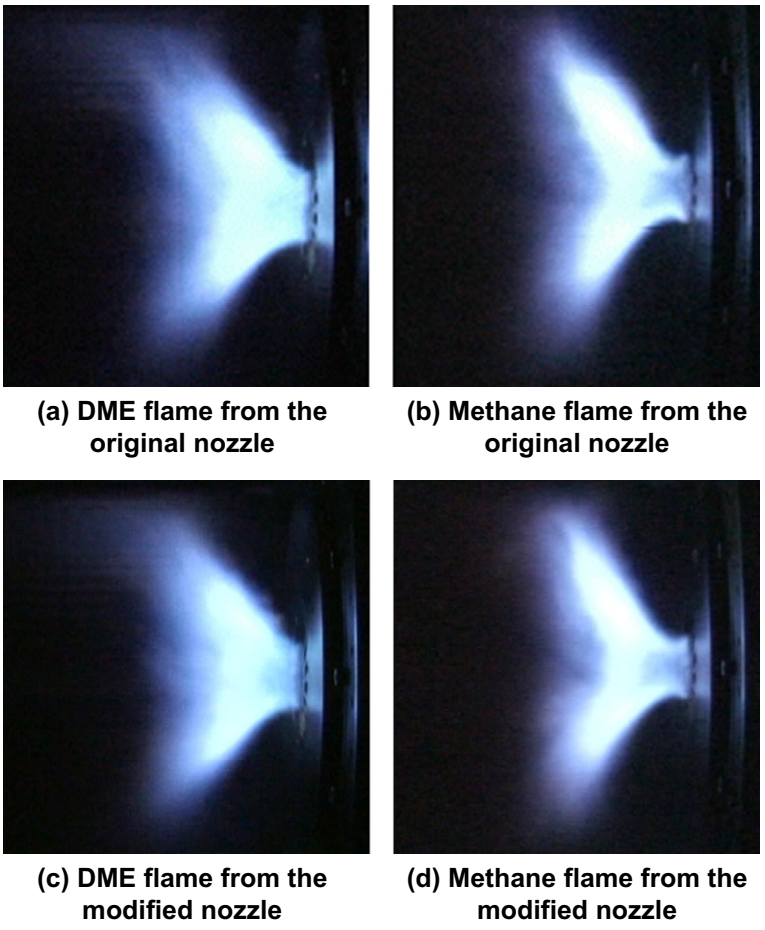


Fig. 9. Direct photos of the original and the modified nozzles for methane and DME.

4.2. Combustion oscillation characteristics

The combustion oscillation characteristics of the original and modified nozzles for methane and DME are compared in Fig. 5. The pressure fluctuation of DME is higher than that of methane for both nozzles, which means that the flame configuration of DME is eager to interact between the heat releases and pressure fluctuations as DME burns near to the fuel nozzle [16,17]. However, this may not be a significant issue in stable operations because the values are lower than 13.8 kPa (=2 psi), the regulated value of the combustion vibrations for an industrial gas turbine.

4.3. Temperature characteristics

Figs. 6–8 show the temperature characteristics of the fuel nozzle (T_n), dump plane (T_d) and exit gas (T_e) of the original and the modified nozzles for the fuel of methane and DME.

As shown in Fig. 6, T_n of DME was slightly higher than that of methane due to the higher turbulent burning velocity ($S_{T,CH_4} = 167$ cm/s, $S_{T,DME} = 176$ cm/s [11]) and the lower injection velocity of DME fuel. The injection velocities of DME and methane are easily calculated from the heating values based on volume, and the velocity of methane is 1.65 times higher than that of DME. Fuel nozzle temperatures of the DME and methane in the case of original nozzle were higher than that of modified nozzle by more than 40 °C for all heat inputs. This anti-flash-back characteristic results from the improved mixing and heat transfer. Enhanced fuel/air mixing caused by the doubled number of holes lowers the equivalence ratio in the combustion area, and thus decreases the local flame speed near the fuel nozzle. The doubled number of holes also enhances the heat transfer from heated nozzle to fuel gas because of an increased contact area between fuel gas flow and fuel nozzle. Fig. 9 also supports the fact that flame seldom attaches to the modified nozzle in comparison to the original nozzle since the weak luminescence near the modified is observed. From these results, it can be concluded that the design of the modified nozzle prevents flash-back to the fuel nozzle.

T_d of the modified nozzle was lower than that of the original nozzle. As previously mentioned in subchapter 4.1, enhanced mixing slightly lowers flame temperature since it makes a more uniform distribution of fuel in the swirling air. Thus, as with the similar reason of T_n, T_d was decreased when firing in methane and DME in modified nozzle. The tendency and steepness of T_d were almost similar in all the tested cases and the temperatures of DME were lower by 30–100 °C than those of methane. Lower temperature characteristics of DME conform well enough with flame images. As shown in Fig. 9, DME flame was formed farther from the dump plane since DME is heavier than methane. Accordingly, DME flame heated up the dump plane less.

T_e of the modified nozzle was almost equivalent to that of the original nozzle, which means similar power output can be obtained from both fuel nozzles since the power output of a gas turbine is controlled by turbine inlet temperature (TIT, almost similar to T_e). In addition, the tendency and steepness of the exit gas temperature from the combustion chamber were almost same in all of the tests. On the other hand, the temperature difference of the fuels resulted from the differing levels of heat loss incurred by convection and radiation though the combustion chamber. Detailed discussion on the difference of T_e can be found in our previous research [11].

5. Conclusion

The fuel nozzle for DME was successfully developed by considering Wobbe Index, the combustion properties of DME and the results of previous researches. The performance of the newly developed nozzle was verified through a comparison with the original nozzle. The proposed fuel nozzle enabled stable operation of the gas turbine combustor for DME with prevention of flash-back and reduced emissions of harmful gases such as NO_x and CO. Accordingly, the present development is expected contribute to the promotion of utility of DME as a fuel for power plants while achieving cost reduction of the power plants, enhancement in reliability of the power plants and diversification of usable fuels. Furthermore, the design methodology can be applied similarly to other new fuels such as coal-derived synthetic gas, biogas and blast furnace gas.

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References

[1] Semelsberger TA, Borup RL, Greene HL. Dimethyl ether as an alternative fuel. J Power Source 2006;156:497–511.
[2] Cocco D, Tola V, Cau G. Performance evaluation of chemically recuperated gas turbine (CRGT) power plants fuelled by DME. Energy 2005;31:1146–58.
[3] Song J, Huang Z, Qiao X, Wang W. Performance of a controllable premixed combustion engine fueled with dimethyl ether. Energy Convers Manage 2004;45:2223–32.
[4] Kobayashi N, Inoue H, Koizumi H. Robust design of the coaxial jet cluster nozzle burner for DME fuel. In: Proc of ASME Turbo EXPO 2003; GT2003:38410.
[5] Chen Z, Qin X, Ju Y, Zhao Z, Chaos M, Dryer FL. High temperature ignition and combustion enhancement by dimethyl ether addition to methane-air mixtures. Proc Comb Inst 2007;1:1215–22.
[6] Arcoumanis C, Bae C, Crookes R, Kinoshita E. The potential of di-methyl ether (DME) as an alternative fuel for compression-ignition engines: a review. Fuel 2008;87:1014–30.
[7] Basu A, Gradassi M, Sills R, Fleisch T, Puri R. Use of DME as a gas turbine fuel. In: Proceedings of ASME Turbo EXPO 2001; GT2001:0003.
[8] Tsuchiya T, Okamoto M. Evaluation and demonstration of DME as an alternative fuel for micro-gas turbines. In: Proc of the Asian Congress on Gas Turbines 2005; ACGT2005:066.
[9] Jiang LQ, Zhao DQ, Guo CM, Wang XH. Experimental study of a plat flame micro combustor burning DME for thermoelectric power generation. Energy Convers Manage 2011;52:596–602.
[10] Lee MC, Seo SB, Chung JW, Joo YJ, Ahn DH. Combustion performance test on the new fuel DME to adapt to a gas turbine for power generation. Fuel 2008;87:2162–7.
[11] Lee MC, Seo SB, Chung JW, Joo YJ, Ahn DH. Industrial gas turbine combustion performance test of DME to use as an alternative fuel for power generation. Fuel 2009;88:657–62.
[12] Loprinzo AJ, Maughan JR, Black SH, Dean AJ, Bechtel WT, Luts A. Dual-fuel nozzle for inhibiting carbon deposition onto combustor surfaces in a gas turbine. US patent 1997; US6123273.
[13] Mathur ML, Maccallum NRL. Swirling air jets issuing from vane swirlers part-1; free jets. J Inst Fuel 1967;39:214–25.
[14] Turns SR. An introduction to combustion. Singapore: McGraw-Hill; 1999. p. 527–60.
[15] Warnatz J, Maas U, Dibble RW. Combustion. 2nd ed. Germany: Springer; 1999. p. 219–31.
[16] Lieuwen T, Torres H, Johnson C, Zinn BT. A mechanism of combustion instability in lean premixed gas turbine combustors. J Eng Gas Turbine Power 2001;123:182–9.
[17] Lee JG, Santavicca DA. Experimental diagnostics for the study of combustion instabilities in lean premixed combustors. J Propul Power 2003;19:735–50.
[18] Matsumoto R, Ozawa M, Terada S, Iio T. Low NO_x combustion of DME by means of flue gas recirculation. Challenges Power Eng Envir 2007;14:1247–51.
[19] Vries JD, Lowry WB, Serinyel Z, Curran HJ, Petersen EL. Laminar flame speed measurements of dimethyl ether in air at pressures up to 10 atm. Fuel 2011;90:331–8.
[20] Robinson C, Smith DB. The auto-ignition temperature of methane. J Hazard Mater 1984;8:199–203.
[21] Vagelopoulos CM, Egolfopoulos FN. Direct experimental determination of laminar flame speeds; 1998. p. 516–9.
[22] Zabetakis MG. Flammability characteristics of combustible gases and vapors. U.S. Depart mines bull 1965;627:21.