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Research paper

Experimental investigation on combustion and emission characteristics of a premixed flame in a gas-turbine combustor with a vortex generator

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HIGHLIGHTS

- The effects of a vortex generator on a gas-turbine combustor have been investigated.
- A small-scale combustor is designed and used for the analyses and experiments.
- Experimental work shows that NO_x and CO emissions can be reduced effectively.
- A numerical study reveals that the vortex generator improves mixing characteristics.

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ABSTRACT

An experimental study has been carried out to investigate how a vortex generator affects the combustion and emission characteristics of a swirl-stabilized premixed flame in a gas-turbine combustor. In the experimental analyses, the chemiluminescence signals of OH radicals and gas emissions were measured for various operating conditions, both with and without the vortex generator, and the data were used to compare the two cases.

When the vortex generator was equipped within a combustor and the combustor operated at design operating conditions, the OH radical signal showed broader distribution near the flame, with a 9.5% increase in maximum thickness and over 200% increase in overall area, indicating that the vortex generator stimulates chemical reactions to occur with greater spatial distribution. The gas emission measurement results also revealed that the vortex generator can reduce harmful gaseous emissions: it produced a 21.2% decrease in NO_x emissions and 13.3% decrease in CO emissions.

However, the results were found to differ for various off-design operating conditions, so it could be concluded that the vortex generator positively affects combustion and emission characteristics only when a sufficiently high flow velocity is maintained within the combustor; otherwise the vortex generator has a slightly negative effect.

1. Introduction

Conventional power generation systems consume a great amount of fossil fuel, which consequently results in a significant amount of CO_2 and other harmful emissions, such as NO_x, CO, and particulate matter, being emitted into the atmosphere. However, as interest in the environment has been increasing, strong pressure is being placed on conventional power generation systems to reduce their emissions or to move from conventional to environmentally friendly technologies [1].

Among the conventional power generation technologies, gas-turbines can be regarded as one of the cleanest technologies because they generate electricity at higher efficiencies, which consequently produce less CO_2 and emit less harmful emissions [2]. Furthermore, emissions from gas turbines can be directly reduced by improving the gas turbine combustor without any post-treatment of the combustion gas. In this regard, the use of a gas

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turbine in power generation has become more attractive, and the installation capacity has been increasing in many countries [3].

In recent decades, many emission-reduction methods applicable for gas-turbine combustors have been suggested [4–9]. These methods can be representatively classified into three categories [10]: a quick-quench-lean-burn technique, a catalytic combustion, and a lean burn technique.

A quick-quench-lean-burn technique partially burns the fuel at a fuel-rich condition first and then re-burns the other remaining fuel at a fuel-lean condition. By splitting the combustion process into two extreme cases, the maximum flame temperature can be restricted to a certain limit to suppress the formation of thermal NO_x [4,5]. Catalytic combustion uses an oxidation catalyst, where combustion occurs volumetrically over the catalyst zone, and the temperature can be uniformly distributed over the reaction zone. Through the well-distributed reaction, thermal NO_x formation can be mitigated [6].

In a combustor that incorporates the lean-burn technique, a large amount of excess air is supplied into the primary nozzle together with the fuel. A chemical reaction occurs at a lower flame temperature, and thermal NO_x formation can be avoided [7–15]. The recent achievements in combustor structure design have resulted in the use of the lean-burn technique being widely used in micro-gas turbines [8,9,11–13] and in heavy-duty gas turbines [7,14,15] for power generation. Continuing studies on the optimal design of a gas turbine combustor have been actively performed to further reduce the amount of emissions. Lim et al. [11] performed experimental work on a micro-gas turbine combustor. Two types of combustor-exit designs, block and cone types, were investigated. Based on the experimental results obtained at various operating conditions, the authors concluded that the cone-type is better than the block-type in terms of flame stability and reducing NO_x emissions. Jang et al. [12] also examined how the position of the fuel injection holes affects the emission characteristics of the micro-gas turbine combustor. Two arrangements, single-staged and dual-staged injection holes, were investigated. The results showed that the dual-staged fuel injection exhibited better emission characteristics. Terasaki et al. [13] assessed the effect of the hub diameter on the NO_x formation for a two-staged swirler. From experiments, the authors found that a smaller diameter is favorable to reduce NO_x emissions. Cho et al. [14] numerically investigated the thermal NO_x formation from a heavy-duty gas turbine combustor, and the results showed that NO_x emissions can be improved by optimizing the location and size of the fuel injection holes. The results were also validated with experimental data. Zajadatz et al. [15] reported that the NO_x emissions can be effectively reduced by introducing staged fuel injection into the combustor.

Along with the design optimization of a gas turbine combustor, several devices can be effectively used in the combustor to improve flow characteristics, e.g., a vortex generator can be used to enhance heat transfer [16] or improve flow mixing [17,18]. A vortex generator is a device that generates a local vortex within the fluid flow, which has been used in various applications with design adaptations. Zhu et al. [16] performed a CFD analysis on the internal flow of a pipe, which revealed that the center-equipped vortex generator enhanced flow mixing and created a more even temperature distribution. Saravanan et al. [17] also performed CFD analysis on supersonic gaseous flow and reported that a micro-scale vortex generator significantly enhanced air/fuel mixing. Kim et al. [18] investigated the effect of a vortex generator on the mixing characteristics of a premixed burner using the CFD method. It is expected that a vortex generator primarily reduces NO_x emissions by enhancing air/fuel mixing.

Despite the existence of many different types of applications in other industrial areas, the vortex generator has not received much attention in the combustion area, particularly in gas turbine combustor technology. If a vortex generator is used in a gas turbine combustor accordingly, it could improve flow mixing and consequently reduce emissions. In this regard, this paper focuses on the experimental investigation of how a vortex generator affects the combustion and emission characteristics of a small-scale, swirl-stabilized, lean-premixed gas turbine combustor. For these experiments a radially-swirled, lean-premixed combustor was designed and manufactured, and then used under two conditions, with and without a vortex generator. To support the analyses, a non-reactive CFD analysis was also carried out; through that analysis, the behavior of the fluid flow within the combustor was estimated.

2. Description of the combustor design and experimental method

2.1. Combustor design

Fig. 1 shows the swirler-equipped combustor, combustor assembly, and the experimental setup that were used in this work. Air was supplied into the combustor through two-staged, swirl-equipped entrances. The air supply ratio between the primary and the secondary stages was designed to be 3:1. It was controlled by the area of the two entrances. The swirl number, S_m of each stage was calculated using Eq. (1), which is suggested by Abdulsada et al. [19].

$$S_M = \frac{\left[\pi\left(R_o^2 - R_p^2\right)\left(R_i - t/2\right)\right]}{[n\cdot t\cdot h]R_o} \tag{1}$$

The swirl numbers of the primary and secondary stages were chosen to be 0.7 and 1.2, respectively. Distinct swirl numbers were chosen such that the strongly swirled secondary air can enhance mixing with the weakly swirled primary air. Accordingly, emissions can be reduced [20,21]. Fuel was supplied into the bottom chamber of the combustor and then injected into the air side through twenty small holes.

When the air/fuel mixture flows inside the combustor, local vortices were generated at the surface of the central vortex generator, which enhanced gas mixing via the vortices [17]. To install the vortex generator, screw threads were machined on the surface of the central rod, whereas for the no vortex generator case, a smooth-surfaced rod was used instead. The cross-sectional drawings of the combustor, combustor assembly, and the central rods are shown in Fig. 1(a)–(d). Irrespective of if the vortex generator was used, the combustor exit area was kept the same, where the exiting velocities were set to be equal (20 m/s).

2.2. Experimental apparatus

The experimental setup for the combustor test is shown in Fig. 2. The entire setup consists of a lean-premixed, swirler-equipped combustor, a quartz tube, air/fuel supply units, a gas analyzing unit, and an ICCD camera. High-purity methane (99.95%) was used as fuel, and dry air was used as the oxidizer. The flow rates of the fuel and air were measured and controlled by a coriolis-type mass flow meter and a control valve, respectively. Combustion gas was captured by a water-cooled, triple-pipe-structured sampling probe. Then, the NO_x, CO, and O_2 concentrations were analyzed by a real-time gas analyzer equipped with an electrochemical sensor.

For the flame analyses, an OH radical's chemiluminescence signal can be used to identify the heat release characteristics of the combustion zone and can also be used to determine the flame structure. In this paper, the OH radical's chemiluminescence signal