Research Report

Measurement of Equivalence Ratio in Spark Plug Gap for Low Emission Combustor

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Abstract

There are applications where a micro gas turbine (MGT) needs to be started frequently especially when used as a distributed power source. Therefore, stable light-up is a very important characteristic for the low-emission combustor of an MGT. Light-up is affected by several factors, including the equivalence ratios, the temperature of the fuel-air mixture, and the ignition energy. The purpose of this paper is to clarify the relationship between the ignitability and the equivalence ratios of the fuel-air mixture at the tip of the spark plug. We have developed an instrument that uses the principle of infrared absorption by a CH-bond to measure the time-resolved equivalence ratios for the lean premixed combustor. As a result, the mixture could be ignited within an equivalence ratio range of approximately 0.5 to 1.4. These results were found to agree with measurements taken for a homogeneous mixture in a constant volume chamber. In addition, in the case of the fuel supply for combination, the distribution of the equivalence ratio across the diameter had a large slope in the vicinity of the liner wall of the combustor, ralative to the case of the fuel supply for diffusion.

Keywords Gas turbine, Premixed combustor, Ignitability, Equivalence ratio, Infrared absorption

1. Introduction

Good light-up characteristics are essential to the development of a gas turbine. There are applications where frequent ignition is necessary especially when a micro gas turbine (MGT) is used as a distributed power source. The ignitability of the combustor of an MGT is affected by the equivalence ratio, the temperature of fuel-air mixture, the ignition energy and other factors. Among these factors, the equivalence ratio has the greatest effect. However, there are only a few reports[1, 2] that have studied a range of equivalence ratios when a gap-type spark plug is used to light the mixture. In this report, to clarify the relationship between the ignitability and equivalence ratio of the fuel-air mixture in the spark gap, we developed an instrument[3] that uses the principle of infrared absorption by a CH-bond.

2. Experiment setup

2. 1 Low emission combustor

The structure of a Tandem-type Lean Premixed combustor (TLP combustor) is shown in **Fig. 1**. This combustor has two lines in its fuel supply system. One is used for diffusion combustion and the other is for premixed combustion. The fuel for diffusion combustion is injected from several holes at the nozzle tip, with the velocity of the fuel jets being approximately 100 m/s. One of the fuel jets is aimed at the spark plug gap. The fuel for the premixed combustion is supplied from a point upstream to a swirler placed at an inlet to the air passage.

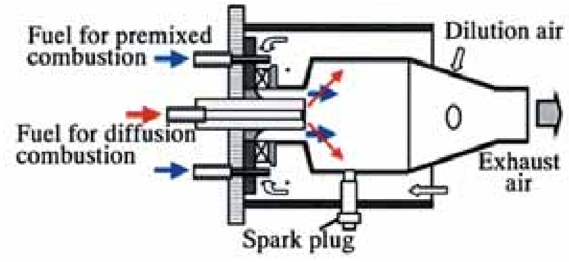


Fig. 1 Structure of TLP combustor.

2. 2 MGT system

An outline of an MGT is shown in **Fig. 2**. City gas is boosted with a gas compressor and then supplied to a combustor through a fuel shutoff valve and a metering valve. The MGT is started with a high-speed generator connected directly to the axis of the compressor/turbine. At the same time, an exciter creates intermittent sparks. The fuel is supplied by opening the fuel shutoff valve once the axis speed of the MGT reaches 5,000 rpm. The sparks usually cause the mixture to ignite at speeds of between 5,200 rpm and 55,000 rpm. To measure the equivalence ratios, the sensor was installed in place of the spark plug.

2. 3 Conditions of experiment

(1) Fuel supply

①Only fuel for diffusion combustion ②Only fuel for premixed combustion ③Combination (fuel for diffusion + premixed combustion)

(2) Equivalence ratio of initial settings

The experiment was repeated seven times with different initial equivalence ratios ϕ_i from 1.7 to 5.6.

(3) Sensor position

To compare the equivalence ratio of the measuring positions, the experiment was repeated three times with different sensor positions L_s between 0.1 and 2 mm from the surface of the wall.

(4) Spark system

The stored energy E_s in the exciter is 1.6 J. The amount of energy discharged between the electrodes of the spark plug is actually 0.39 J. Therefore, the efficiency of the spark energy is 24.4%. The frequency of the spark is 5 Hz.

(5) Fuel: City gas type 13A (CH_4; 88.5%, C_2H_6; 4.6%, C_3H_8; 5.4%, C_4H_{10}; 1.5%)

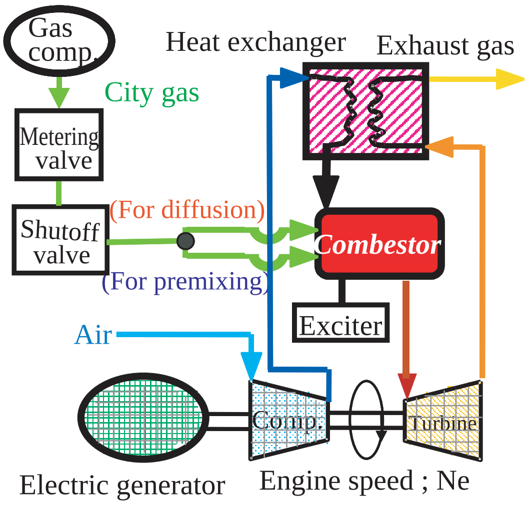


Fig. 2 Outline constitution of MGT.

3. Measuring the equivalence ratio

3. 1 Theoretical description

The measuring method, that uses the principle of infrared absorption, is shown in **Fig. 3**. City gas is contained within a chamber. A beam of strength I_0 is emitted from a laser light source (wavelength 3.39 μm) and then attenuated to I as a result of absorption by the CH-bond. There are three reasons for the optical attenuation. One is the optical scattering caused by the molecule, the second is photoabsorption by the fuel (CH_n), and the last is the reflection on the two surfaces of the chamber's glass window. In addition, we considered that neither optical scattering nor reflection affected the attenuation, assuming that the optical strength received by the detector was I_0 when the chamber was filled with air. The relationship between the optical strength I, I_0 , the absorption coefficient of the fuel μ(m^2/mol), the optical path length L(m), and the fuel molar concentration C(mol/m^3) can be approximated by Eq. (1).

$$\mathrm{Ln}\,(I/I_0) = -L\cdot\mu\cdot C \quad \text{......................................(1)}$$

3. 2 Sensor structure

As shown in **Fig. 4**, the structure of the sensor imitates that of a spark plug. The distance from the installation seat to the spark plug gap is 40 mm. The structure of the sensor is such that there is a gap of 5 mm between the end of the optical fiber cable led through the center and the mirror that reflects the infrared laser light. The averaged equivalence ratio of the fuel-air mixture in this space is measured. The length L of the optical path is 10 mm as the laser light shuttles between the end of the fiber and the mirror.

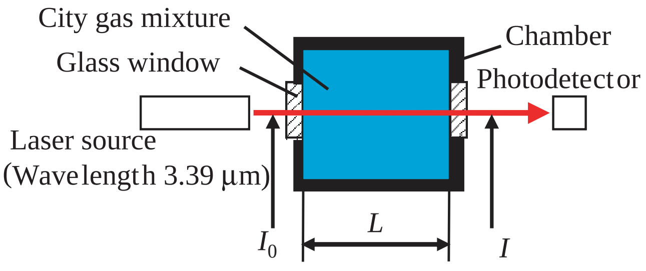


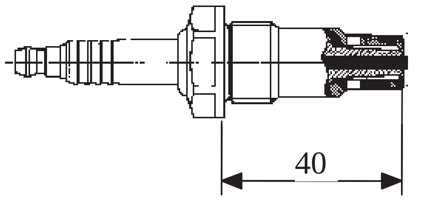
Fig. 3 Method applied the principle of infrared absorption.

3. 3 Optical instrument

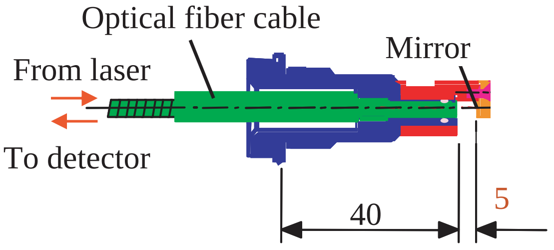
Figure 5 is a photograph of the optical instrument that we developed. This instrument consists of an He・Ne laser, a chopper to change the continuous light beam into intermittent light, and a photodetector to detect the light from the sensor.

3. 4 Measurement of absorption coefficient

To estimate the absorption of the CH-bond, experiments were conducted at room temperature and atmospheric pressure. The absorption coefficient of μ = 21.6 (m^2/mol) was calculated from Eq. (1) because the optical path length was L = 0.01 m. The relationship between the equivalence ratio ϕ and Ln (I/I_0) can be understood by converting the molecular concentration C into equivalence ratio ϕ.



(a) Spark plug



(b) Sensor

Fig. 4 Structure of spark plug and sensor.

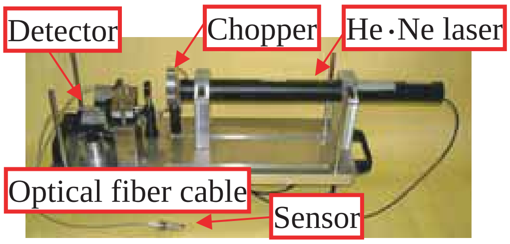


Fig. 5 Photograph of the developed instrument.

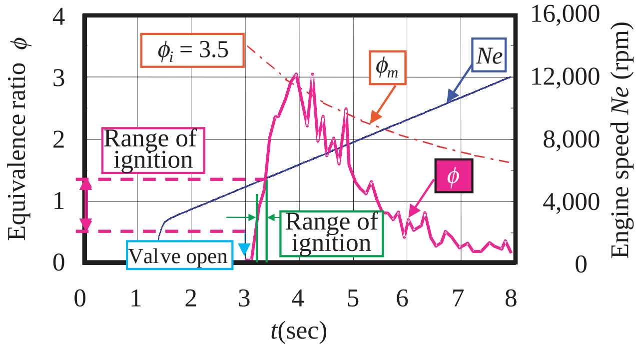
4. Results

4. 1 Influence of fuel supply

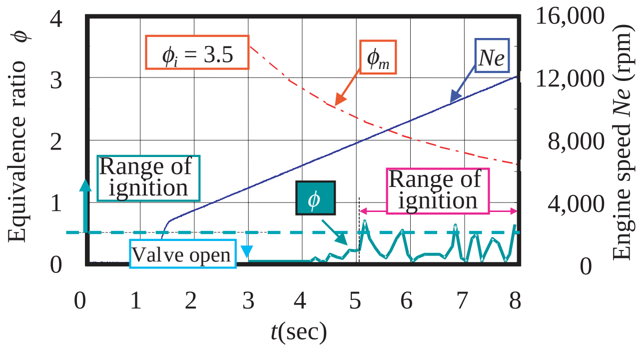
The equivalence ratio ϕ in the sensor gap and the engine speed Ne relative to the elapsed time t are shown in **Fig. 6**(a) for the fuel supply for diffusion. The equivalence ratios for the fuel supply for combination are shown in Fig. 6(b). In both cases, the equivalence ratio ϕ_i for the initial setting is set to 3.5 when the fuel shutoff valve opens. In addition, the averaged equivalence ratios ϕ_m in the combustion chamber (calculated value) are indicated by the broken lines. As the engine speed Ne increases, the air flow rate increases and the averaged equivalence ratio ϕ_m in the combustion chamber falls.

4. 1. 1 Equivalence ratio in sensor gap

As shown in Fig. 6(a), the equivalence ratio rises approximately 0.2 seconds after the instant at which the fuel shutoff valve opens. It reaches a maximum value of 3 approximately 1 second after the valve opens. The equivalence ratio ϕ at this instant is equal to the averaged equivalence ratio ϕ_m in the combustion chamber. Subsequently, the equivalence ratio falls as the engine speed increases. As shown in Fig. 6 (b), in the case of combination (diffusion: premix = 20%: 80%), the equivalence ratio increases slightly after a delay of about 1 second. The peak value reaches a maximum value of 0.7 2.2 seconds later. This is rather low in comparison with the maximum value of 3, as shown in Fig. 6(a). This is attributable to two reasons. First, the amount of fuel and the injection velocity fall from 100% to 20% for diffusion. Second, the injection velocity of the fuel for premix is lower because it coincides with the velocity of the fuel-air mixture. In the case of premix, the result is equal to that for combination, or slightly less.



(a) In the case of one line for diffusion



(b) In the case of combination of two lines (diffusion20%:premix80%)

Fig. 6 Measurement of equivalence ratio and engine speed.

4. 1. 2 Relationship between the equivalence ratio in the sensor gap and ignitability

As shown in Fig. 6(a), in the case of diffusion, the mixture is easily ignited when the engine speed is between 5,200 and 5,500 rpm. In the case of combination, as shown in Fig. 6(b), the mixture is normally ignited at engine speeds of between 8,000 and 12,000 rpm. Considering these results, it seems that light-up is achieved in the range of approximately 0.5 to 1.4.

4. 2 Affect of initial equivalence ratio

The results for diffusion are shown in **Fig. 7**, when the initial equivalence ratio ϕ_i varies with different fuel flow rates. The mixture is ignited reliably when the engine speed is between 5,200 and 5,500 rpm, regardless of the initial equivalence ratio. The

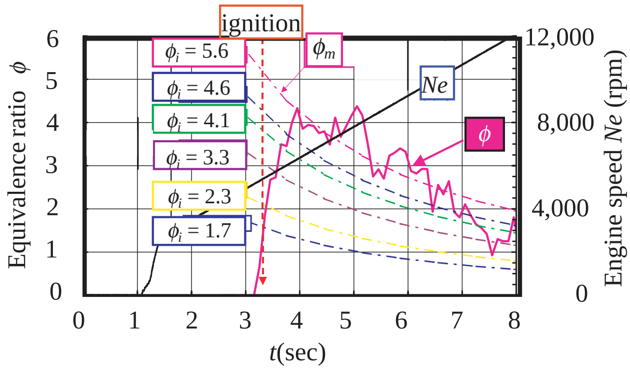


Fig. 7 Measurement of equivalence ratio and engine speed (diffusion).
- Affection of initial equivalence ratio -

differences between equivalence ratio ϕ of the sensor gap and the averaged equivalence ratio ϕ_m are smaller if the initial equivalence ratios ϕ_i are higher. These results show that it is easier to deliver the required amount of fuel to the sensor gap, because the flow rate of the injected fuel is higher.

4. 3 Influence of sensor position

We considered the effect of the sensor position, setting the initial equivalence ratio ϕ_i to 4.2. The equivalence ratio ϕ_i changes little, even if the sensor position L_s is set to 0, 1, or 2 mm in the case of diffusion. In the case of combination (diffusion: premix = 30%: 70%), the equivalence ratio under the conditions of $L_s = 0$ is zero. However, the equivalence ratio under the conditions of $L_s = 2$ mm reaches the maximum value of 2. We found that, in the case of combination, the distribution of the equivalence ratio across the diameter had a large slope in the vicinity of the liner wall of the TLP combustor, relative to the case of diffusion.

4. 4 Ignition limits in constant-volume chamber

We obtained the ignition limit for the lean or rich side through experiment with a constant-volume chamber. The mixture is ignited provided the equivalence ratio has settled within a range of approximately 0.5 to 1.4. This result agrees with that obtained with the engine experiments.

5. Conclusion

To investigate the local equivalence ratio in the spark plug gap for a premixed combustor burning city gas, we developed an instrument to measure the equivalence ratio by infrared absorption by the CH-bond. The relationship between the equivalence ratio and ignitability was considered. As a result, we clarified that the mixture could be ignited provided the equivalence ratio has settled within the range of approximately 0.5 to 1.4. In the case of combination, the equivalence ratio was found to be lower than in the case of diffusion a few seconds later.

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