

Development of Cavity Matrix Combustor for Biogas Application

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Submitted 10 July 2022

Revised 3 November 2022

Accepted 10 November 2022

Abstract. The use of conventional fossil fuels has limitations in energy resources and environmental problems such as greenhouse gas, air pollution, etc. Biogas has sustainable and renewable characteristics that can be used as an alternative energy source to alleviate these problems. In this study, we proposed a novel cavity matrix combustor that directly enables the combustion of what is produced in small and medium-sized biogas facilities without separation or purification. We also identified combustion characteristics for changes in air ratio, gas feed rate, biogas ratio, and exhaust gas recirculation rate and proposed optimal operating conditions based on this. The performance test result showed that the cavity matrix combustor is excellent for biogas combustion. The optimal operating conditions for the combustor are: the biogas ratio is 60% of CH₄ and 40% of CO₂, the air ratio is 1.1, the gas feed rate is 30L/min, and the exhaust gas recirculation rate is 100%. At this time, the combustion efficiency was 87%, and the unburned components were CO, UHCs, which are 0.01% and 0.05%, respectively, and NO_x was 1ppm.

Keywords: Super-Adiabatic Combustion, Microwave Heating, Matrix Burner, Climate Technology

INTRODUCTION

With the advancement of the industry, the use of various sustainable energies and solutions to environmental problems are actively required. From this point of view, the use of conventional fossil fuels has limitations in finite energy resources and environmental issues such as greenhouse gases (Devi, 2019).

Biogas has sustainable and renewable characteristics that can be used as an alternative energy source to alleviate these problems. Biogas is produced by microorganisms in anaerobic digesters. In this case, the feedstock may be dairy manure, municipal wastewater, organic sludge, food

waste, energy crops, and the like. If biogas produced in this way is utilized in combustion devices such as combustion furnaces, gas turbines, and kitchen stoves, it can replace a part of existing fossil fuel energy consumption (Habib, 2021; Kruczek, 2019; Roubík, 2019).

Biogas is a mixture of methane (CH₄) and carbon dioxide (CO₂). Ammonia, water, and hydrogen sulfide are the main impurities of biogas at a concentration lower than 1~2% (Fedeli, 2022).

Conventional burner combustion has a characteristic of free flame in which flame is stabilized on the surface of the burner, which is open to the air. Such a free flame burner

(FFB) has the characteristics of low energy efficiency and a large number of unburned pollutants due to a large amount of exhaust heat loss (Zhen, 2013). If this exhaust loss heat is recycled or used for preheating the incoming mixed gas, super adiabatic combustion (or excess enthalpy combustion) can be achieved in which the combustion flame temperature is higher than that of the ideal flame.

In a porous radiant burner (PRB), combustion proceeds within porous media, and high conduction and radiant heat are transferred from the combustion region to the area around the inside of the porous media to maintain a high temperature. This mechanism enables heat recirculation to the upstream region, and the mixed gas supplied to this region is preheated, and super adiabatic combustion occurs in the combustion region to form a high-temperature stable flame (Devi, 2020a). Due to these characteristics of PBRs, stable combustion is possible even when combustion of low calorific value biogas is difficult in conventional FFC, and related research is being conducted (Devi, 2020b; Suslow, 2019; Chaelek, 2019; Keramiotis, 2015; Qu, 2015). However, most of these studies have a problem: the radiant heat generated in the combustion region within the porous media with a flat porous media radiant burner is transferred and discharged to the exhaust port, causing exhaust heat loss and the preheat zone where mixed gas is introduced and heated.

Therefore, in order to minimize such exhaust heat loss and to improve combustion stability, etc., this study proposed a novel Cavity Matrix Combustor (CMC) with a 3D cavity structure that maintains the shape of a cuboid composed of porous media plates and a structure designed to center a

rectangular porous microwave receptor. Microwave heating is a dielectric heating process in which microwaves directly penetrate into the microwave receptor and vibrate material molecules to generate heat directly. For this reason, the heating efficiency and rate are more excellent than the conventional hot air heating method (Motasemi, 2013). Such microwave heating characteristics ensure the initial ignition of mixed gas and the stability of flame. In addition, a rectangular type cavity heat recuperation type burner can reduce exhaust loss due to keeping convection and radiation heat energies in the cavity compared to the existing planar porous radiant burner, maintaining excellent super adiabatic combustion flame and enabling low-pollution and high-efficiency combustion of LCVG.

In addition, to understand the performance of the newly proposed CMC during biogas combustion, we identified the combustion and exhaust gas characteristics according to air ratio, gas feed rate, biogas ratio, and exhaust gas recirculation rate. In addition, the optimal operating conditions of the CMC were presented based on the results of the study for each variable.

MATERIALS AND METHODS

Experimental Apparatus and Method

Figure 1 shows a schematic diagram of the experimental setup to investigate the performance characteristics of CMC developed to burn low calorific value biogas. The experimental apparatus was composed of CMC, Gas-Air Feed Line, Power Supply Equipment, and Measuring-Analysis Line.

The CMC has a structure in which the porous media matrix forms a rectangle

(excluding the front and back sides of the chamber) in a rectangular steel chamber, and rectangular porous media, as a microwave receptor, was installed at the center. Both porous media were silicon carbide (SiC). The magnetron irradiated with microwaves was fixed on the chamber window to coincide with the center plane of the microwave receptor. The recirculation pipe through which combustion gas at the top of the matrix burner was re-supplied to the CMC inlet was installed, and the amount of exhaust gas recirculation was controlled by the coke valve.

In the Gas-Air Feed Line, CH₄ and CO₂, which are simulated biogas, and combustion air, were supplied, respectively, mixed in a venturi mixer and then supplied to the CMC. The discharge pressure of CH₄ and CO₂ cylinders was 2 kgf/cm². The pressure of the combustion air from the compressor was 7 kgf/cm². The feed rates of simulated biogas gas and combustion air were controlled by the MFC (Mass flow controller), respectively.

The Power Supply Equipment consisted

of a power supply that supplies electricity to the magnetron (Model LUP1200Q, Korea). The electrical characteristics of the power were measured by a voltage probe (Model P6015, Tektronix, USA), a current probe (Model: A6303, Tektronix, USA), and an oscilloscope (Model TDS-3052, Tektronix, USA).

In the Measuring-Analysis Line, sampling ports (Si, So) were installed at the inlet and outlet of the CMC to collect combustion gas, respectively. The combustion gas burned in the CMC goes through glass wool to remove soot, and then the cooler (Model: JELO TECH HC-30, USA) operated at -20°C to cool the gas and condense moisture and was sampled by a suction pump (Model: N-820.3FT 18 KNF, Switzerland). For the sampled gas, CH₄, CO₂, H₂, CO, and unburned hydrocarbon gases (UHCs; C₂H₂, C₂H₄, C₂H₆) were analyzed by GC-TCD (Model: CP-4900, Varian, Netherland). For nitrogen oxides (NO_x), NO and NO₂ were measured by Flue Gas Analyzer

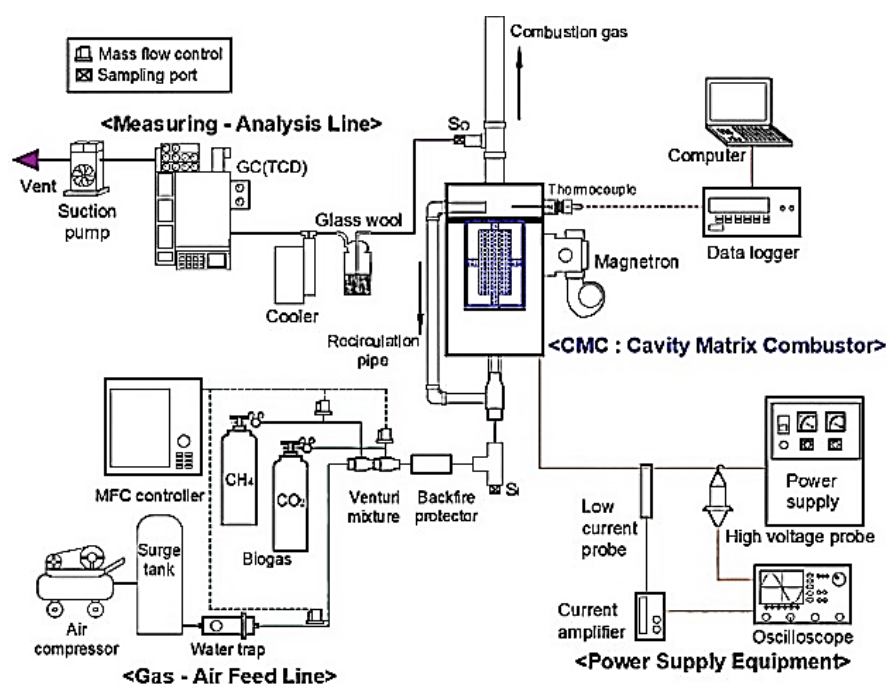


Fig. 1: Schematic diagram of an experimental setup for cavity matrix combustor

Table 1. Experimental conditions and ranges of experiment parameters

Variables	Air ratio	Gas flow rate (L/min)	Biogas ratio (CH ₄ :CO ₂)(%)	Recirculation rate (%)
Test ranges	0.8~1.3	10~50	75:25, 60:40, 25:75	0, 50, 100
Reference conditions	1.1	30	60:40	100

(Model: MK 4000, ECOM, Germany). The gas temperature was measured by a thermocouple (k-type, diameter 0.3mm) and a data logger (Model: FLUKE 2625A HYDRA, Japan).

In order to develop CMC for biogas combustion, which is LCVG, a microwave heating regenerative CMC was newly proposed and manufactured, and an experimental study was conducted on the parameters affecting the combustion performance characteristics. The experimental range for each variable is shown in Table 1, and the reference conditions are the conditions that are the standard for each experimental variable.

Combustion Efficiency (CE) is done by determining the conversion ratio of carbon from the input form (HC) to the desired output form (CO₂). CO, being an intermediate oxidation form, is weighted at 0.5 to indicate that its carbon is 50% oxidized.

$$CE(\%) = \frac{[CO_2] + ([CO] \times 0.5)}{[CO_2] + [CO] + (n \times [HC])} \times 100 \quad (1)$$

where, [XX] is gas concentration in percent V/V; 0.5 is oxidation weight of CO; n is 1 for CH₄, 2 for UHCs (= C₂H₂, C₂H₄, C₂H₆).

Principle of Cavity Matrix Combustor

A CMC has a structure in which a closed cavity burner composed of a rectangular porous media matrix is located in a combustion chamber, and a microwave receptor is located in the cavity (See Figure 2(a)). Mixed gas for

combustion is preheated while passing through the bottom and side of the matrix burner, and then a flat flame is formed in the high-temperature combustion region, and the heat generated at this time is transferred to the preheating part and the cavity inside.

Unlike the existing flat porous media radiant burner, the CMC has a structure in which the radiant heat of porous media is stored inside the cavity burner without loss by the upper cover surface.

Strong convective and radiative heat exchanges proceed from the flame side to the matrix surface, and the temperature of gas produced by combustion is reduced, and the inner surface of the matrix is heated to preheat the incoming mixed gas, and the temperature is almost equal to the surface temperature. Since there is no radiation loss from the flame, it is regarded as ideal combustion, and due to high heat recuperation, the so-called super adiabatic mode occurs in which the flame side temperature exceeds the adiabatic flame temperature. Due to these characteristics, low concentrations of NO_x and CO can be achieved as the combustion limit range is expanded and the flame is stable at low temperatures. In addition, the closed-type CMC has a relatively superior combustion of gas produced by combustion compared to the conventional flat matrix radiant burner (PRB) or free flame combustion burner (FFB) because there is no recuperation of

combustion gas heat and loss of radiant heat.

In microwave heating, dielectric heating, in which microwaves directly penetrate into the microwave receptor and vibrate the material to generate heat directly, increases the heating rate and improves initial start-up characteristics and combustion stability. In addition, the microwave receptor increases the reaction rate during combustion due to the direct heating of the receptor due to the presence of a hot spot in which microplasma is generated when microwaves are irradiated, thereby improving combustibility and achieving the reduction of unburned components (Zhang, 2003; Will, 2004).

Figure 2(b) shows the velocity vector when the optimal shape is derived by performing computational fluid dynamics (CFD) numerical calculation to install a distributor at the inlet to uniformly supply the mixed gas to a closed cavity matrix burner.

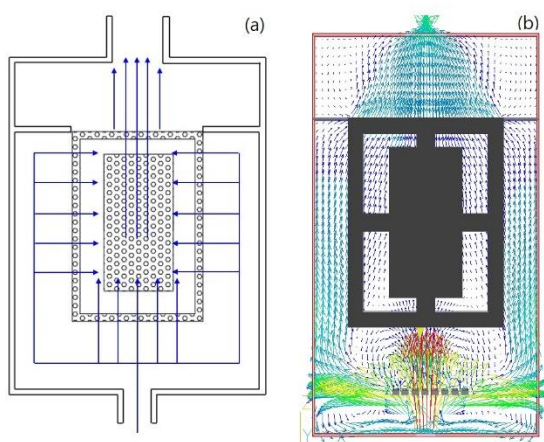


Fig. 2: Cavity matrix combustor

RESULTS AND DISCUSSION

Air Ratio Effect

Figure 3 shows the results when the air ratio is changed to 0.8~1.3 when the biogas ratio ($\text{CH}_4:\text{CO}_2$) is 60:40 and the gas flow rate is 30 L/min in the state of exhaust gas recirculation.

Figure 3(a) shows the combustion efficiency, gas temperature, and NO_x concentration. Combustion efficiency, which shows combustibility, had the smallest value at an air ratio of 0.8 and gradually increased, reaching the maximum value of 84% when the air ratio was 1.1, and then decreased. The gas temperature was measured at the rear side of the cavity burner porous media and showed a pattern similar to the result of combustion efficiency. When the air ratio was 1.1, the temperature of the combustion region present inside the porous media might be maximized, and thus a lot of conduction and radiation heat was transferred to the preheat zone, making it possible to maintain a higher temperature compared to other air ratios. This increased the gas temperature in the cavity burner, improving the overall combustibility.

The NO_x concentration showed the minimum value, unlike the free flame combustion burner (FFB), which has a maximum value at an air ratio of 1.1 where maximum combustion occurs. This is because, although air is supplied in excess of the theoretical amount, combustion proceeded in an oxidizing atmosphere of the front matrix combustion region, and then a reducing atmosphere of lean air was formed in the rear flow, and the reduction reaction occurred. This was also found from the fact that the O_2 concentration of the outlet combustion gas is 17.06% at the air ratio of 0.8, showing the maximum NO_x value, and rather 9.24% when the air ratio is 1.1. And then, NO_x increased with increasing O_2 concentration, showing 3ppm of NO_x .

Figure 3(b) shows the concentration of combustion gas, CH_4 and CO_2 , the biogas components, and H_2 , CO , intermediate products, and unburned hydrocarbons (UHCs: C_2H_2 , C_2H_4 , C_2H_6). At an air ratio of 1.1,

which has the maximum combustibility, CH₄, a combustible component, showed a minimum value among biogas components, and CO₂, a non-combustible component, increased more than the supply amount. This is because CH₄ is consumed by combustion and completely burned to be converted to CO₂ or to remain unburned as CO and UHCs. H₂ showed the maximum value as the hydrogen component in CH₄ is decomposed and remains without being converted to H₂O by oxidation reaction with oxygen.

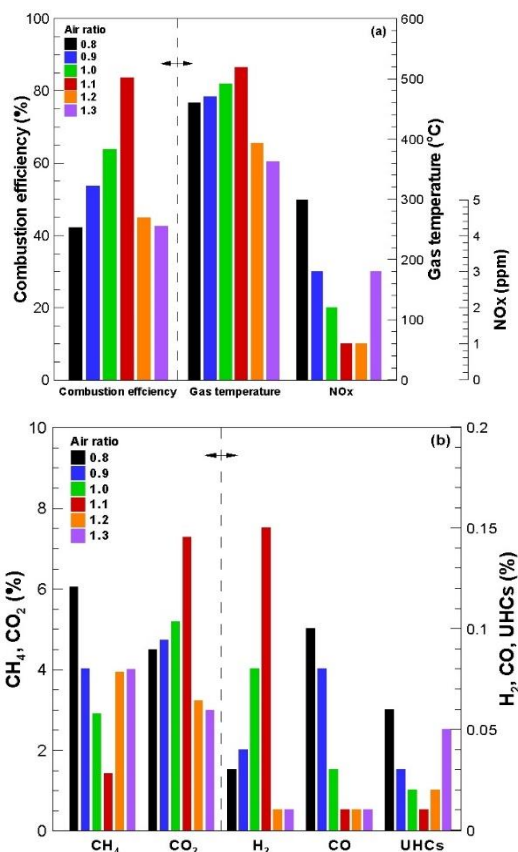


Fig. 3: Combustion characteristics and gas concentration according to changes in air ratio

Effect of Total Gas Supply

Figure 4 shows the results when the gas flow rate is changed to 10~50 L/min while the biogas ratio is 60:40 and the air ratio is fixed to 1.1. An increase in the gas feed rate means an increase in the amount of biogas and, thus,

an increase in the amount of CH₄, which is a combustible component.

As shown in Figure 4(a), as the gas flow rate increased, the combustion efficiency increased and showed a maximum value when the gas flow rate was 30 L/min and then decreased. An increase in the gas flow rate means an increase in the total gas supply, which increases the velocity of the inflow gas and increases the amount of CH₄, a combustible component in biogas. When the gas flow rate has the maximum combustion efficiency, it can be said that the fuel supply is sufficient to maintain the optimal combustion of the cavity burner and is the optimal gas flow rate to maintain the combustion region in the matrix, which is also confirmed by the fact that the gas temperature also has a maximum value. In the case of the gas flow rate above the optimum condition, it was difficult to maintain the combustion flame surface in the matrix like a kind of blow-off flame; rather than improving the combustibility for the increase of CH₄, the combustible gas, so combustion efficiency and gas temperature were reduced. NOx, which is nitrogen oxide, generally showed a small value in the region where the gas flow rate was low, probably because the mixture of biogas and air is relatively small and a reducing atmosphere is formed locally.

Figure 4(b) shows the combustion gas concentration of CH₄, CO₂, H₂, CO, unburned hydrocarbon UHCs, and intermediate products. CH₄, a combustible component of biogas, showed a minimum value of 30 L/min, which is the optimal combustion condition, and CO₂, a non-combustible component, showed a maximum value. And the unburned component CO showed the minimum value, UHCs also showed a small value, and the intermediate product H₂ showed the maximum value.

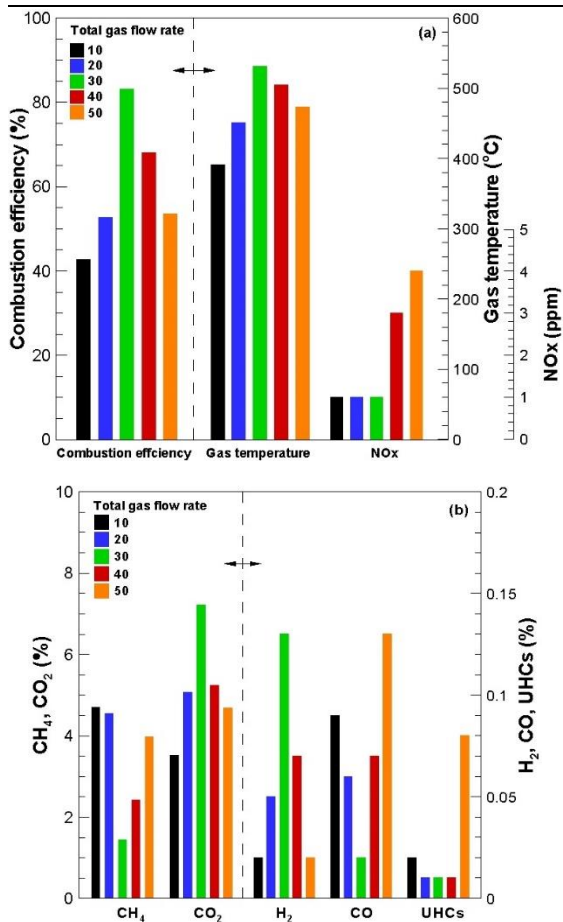


Fig. 4: Combustion characteristics and gas concentration according to changes in total gas supply

Effect of Biogas Components

Figure 5 shows the results when the air ratio is set to 1.1, the gas flow rate is constant at 30 L/min, and the biogas ratio, which is the ratio of CH₄ to CO₂, which are biogas components, is changed.

As shown in Figure 5(a), the combustion efficiency showed the maximum value when the biogas ratio was 60:40, and the gas temperature and NOx also showed the same pattern. This is because, when the biogas ratio is 60:40, combustion of the cavity burner is relatively well performed, showing excellent combustibility. Due to this, the concentrations of CO, UHCs, and H₂, which are unburnt components, showed the minimum values. And when the biogas ratio is 25:75, the amount of CH₄, which is a

combustible component, was relatively decreased, and the combustibility was lowered, so the combustion efficiency was relatively decreased, and unburnt components were also increased. When the biogas ratio is 75:25, however, it is initially burned under an excess air condition with an air ratio of 1.1, but a dry reforming reaction (Seo, 2002) proceeds as the oxygen concentration in the cavity decreases. Therefore, some seem to be converted to H₂ and CO, as shown in Figure 5(b).

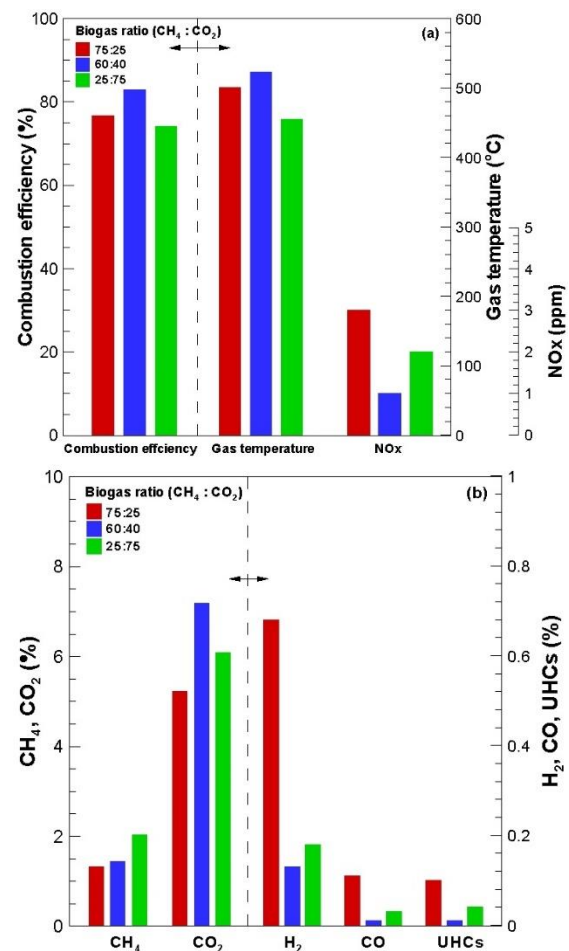


Fig. 5: Combustion characteristics and gas concentration according to changes in biogas composition ratio

Effect of Exhaust Gas Recirculation

Figure 6 shows the results of comparing the exhaust gas recirculation under the standard conditions in Table 1: biogas ratio of

60:40, air ratio of 1.1, and total gas supply amount of 30 L/min. The exhaust gas recirculation rate shows the ratio of the flow rate when the valve installed in the recirculation pipe is fully opened to the flow rate, which is actually recirculated.

As shown in Figure 6(a), the combustion efficiency and gas temperature were increased when the recirculation proceeded compared to the case where the exhaust gas recirculation rate was 0% without recirculation, and the values were further increased when the exhaust gas recirculation rate was 100%. This is because, as the recirculation rate increases, a portion of the high-temperature combustion gas is mixed with the supply gas, which was supplied to the cavity burner, so the supply enthalpy is increased, and the combustibility is improved. In addition, NO_x is also increased as the recirculation rate is increased, which seems to be because the temperature effect is relatively larger than the effect of the reducing atmosphere caused by the recirculation.

Figure 6(b) shows the concentration of

combustion gas. As the exhaust gas recirculation rate increased, CH₄ decreased, and CO₂ increased due to the increase in combustibility. However, CO, an unburnt component, was slightly decreased, but UHCs was slightly increased, and H₂ was also increased.

Through the above-mentioned parametric screening studies, the optimal operating conditions and the results during the biogas combustion of the newly proposed cavity matrix combustor were obtained and are shown in Table 2 below. The optimal operating conditions are 100% of the exhaust gas recirculation ratio, 60:40 of the biogas ratio, an air ratio of 1.1, and 30 L/min of total gas supply. At this time, the combustion efficiency was 84%, the gas temperature was 536°C, the unburned gas CO was 0.01%, and the nitrogen oxide, NO_x, was 1ppm, fully satisfying the combustor emission gas limit. And when exhaust gas recirculation was not performed, the combustion efficiency was 81%, and CO was 0.01%.

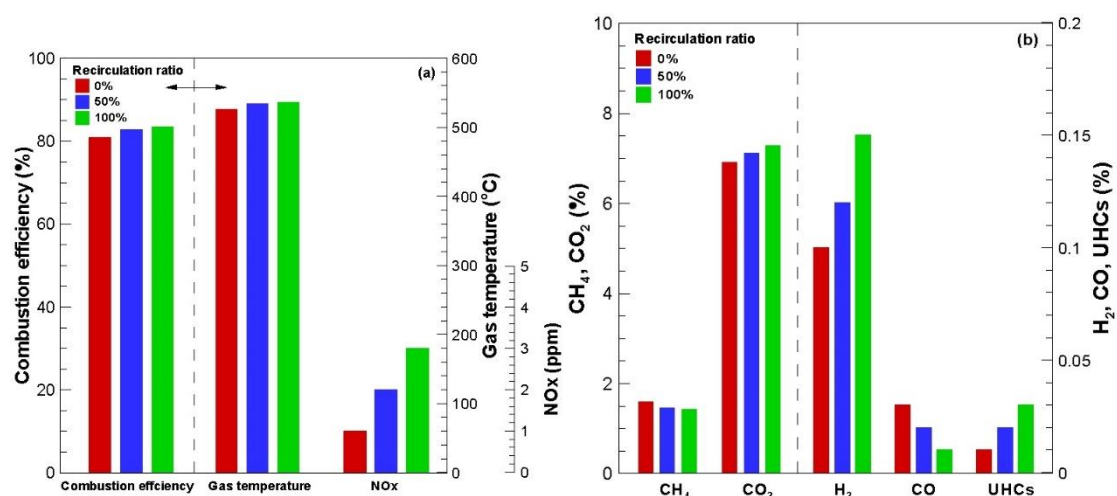


Fig. 6: Combustion characteristics and gas concentration according to changes in recirculation supply.

Table 2. Optimal operating conditions and their results

Standard Conditions	Air ratio	Total Gas Feed Rate				Biogas Ratio (CH ₄ :CO ₂)	Recirculation Rate (=RR) ¹⁾	Input microwave Power
		CH ₄	CO ₂	H ₂	CO			
Values	1.1	30 L/min				60:40	0%, 100%	1 kW
Combustion Gas (%)					UHCs ²⁾	Combustion Efficiency(%)	Gas Temperature (°C)	
WR ¹⁾	nR ¹⁾	CH ₄	CO ₂	H ₂				CO
		1.42	7.29	0.15	0.01	0.01	84	536
		1.60	6.91	0.10	0.01	0.01	81	526

¹⁾ WR: with recirculation (RR=100%), nR: no recirculation (RR=0%); ²⁾ UHCs: C₂H₂, C₂H₄, C₂H₆

Currently, medium and large-scale biogas plants are used as bio-natural gas(BNG) by separating carbon dioxide or being converted to gray hydrogen or blue hydrogen through reformation and used as a fuel for fuel cell power generation. However, small biogas production facilities such as barns and anaerobic food digesters should be used directly because the method mentioned above is not reasonable due to cost problems, but combustion in existing combustors is difficult due to low calorific value. Therefore, this study showed that a new type of CMC to which the super adiabatic combustion flame concept is applied could be effectively used.

CONCLUSION

In this study, a new type of CMC was proposed, and combustion characteristics were identified for changes in air ratio, total gas supply, biogas component ratio, and exhaust gas recirculation for biogas combustion. In addition, the optimal operating conditions for each case were presented based on the combustion and exhaust gas characteristics for each variable.

A CMC maintains the conditions that there is a combustion region in the matrix in order to ensure combustibility, a preheating zone where heat is accumulated at the front end, and heat is conserved inside the 3D

volumetric cavity to minimize exhaust loss. In addition, microwave heating was effectively applied to maintain stable combustion of inconsistent low-grade biogas components and to improve initial start-up characteristics.

The optimal operating conditions of CMCs whose above-mentioned differentiated characteristics have been verified are when the exhaust gas recirculation rate is 100%, and the biogas component ratio is CH₄ 60%, CO₂ 40%, the air ratio is 1.1, the total gas flow rate is 30 L/min. At this time, the combustion efficiency was 89%, CO and UHCs were 0.01% and 0.05%, respectively, and NO_x was 1ppm.

ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF), funded by the Ministry of Education (2018R1D1A1B07040326).

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