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Biogas utilization: Experimental investigation on biogas flameless combustion in lab-scale furnace

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ABSTRACT

Biogas generated in the anaerobic digestion of biomass and organic wastes by micro-organisms can be applied for heating, transportation and power generation as a renewable energy source. However, low calorific value (LCV) of biogas is one the most important bottlenecks of biogas conversion into electrical or thermal energy. Indeed, the presence of corrosive gases such as H_2S and water vapor in biogas components makes some dilemmas in biogas purification and utilization. In order to obtain the efficient biogas utilization method, different biogas resources, physical and chemical properties of biogas and biogas combustion characteristics should be considered. In this paper biogas was utilized in lab-scale flameless combustion furnace and the performance of flameless combustion chamber fueled by biogas has been presented. Results demonstrated that flameless combustion is one of the best feasible strategies for biogas utilization. Uniformity of temperature in the flameless furnace increases the durability of refractory and related equipment. Simplicity of the flameless burner, pollutant formation reduction and fuel consumption decreases are the main causes of biogas flameless combustion supremacy.

1. Introduction

Fossil fuel depletion and the increasing rate of pollutant formation have encouraged scientists to find environmentally friendly alternative fuels to guarantee the secure energy provision and people health. Besides, clean development strategies have conducted combustion technologies to fuel consumption reduction and low pollutant formation to attain sustainable purposes. Experimental investigations confirm that biomass has shown its compatibility with current combustion systems and biomass has promised to be applied as an alternative fuel to solve the future fossil fuel shortage. Biogas utilization and production technology offered in biomass category to meet a portion of energy demand of the world. Therefore, biogas users must have comprehensive knowledge of the available technological options for biogas utilization. Indeed, general knowledge of the physical and chemical properties and combustion characteristics of the biogas is needed to have efficient combustion. Also, the required systems for biogas storage, transportation and clean up comparison are selected based on all of this information [1,2]. Totally, the best system selection for biogas conversion into thermal energy for transportation, gas turbine, heating, lighting and small-scale power generation is the main target of biogas production and utilization steps [3]. Among various environmentally friendly combustion technologies emerged in recent decade, flameless combustion has been attracted more attentions due to its excellence such as fuel consumption reduction, stability of combustion, temperature uniformity and low pollutant formation [4]. Generally, preheating the diluted oxidizer over the self-ignition of the fuel is the main key of flameless combustion achievement [5]. Thermal and chemical structures of diluted biogas by nitrogen in counter-flow diffusion flames were investigated by Jahangirian et al. [6]. It was found that by biogas utilization the net emission of three greenhouse gases CO_2, CH_4 and N_2O decreased drastically in comparison with pure methane [6]. Performance evaluation of flameless combustion furnace fueled by natural gas and biogas was investigated by Colorado et al. [7]. It has been stated that flameless combustion technology has great capability to apply LCV fuels like biogas as a fuel [7]. Biogas flameless combustion has great capability to reduce pollutant constitution especially soot formation [8]. Since biogas purification is very expensive and its conventional combustion in industrial boilers is not feasible, flameless combustion as the best method for biogas utilization has been investigated in this paper.

1.1. Biogas main resources

The distinction point of biogas production system from other biofuels is its power point in collecting the organic waste materials and producing irrigation water and fertilizer simultaneously. Biogas production is not complicated process and unlike other alternative fuel forms does not have any geographical limitations [9]. Municipal solid waste (MSW), coal mining, rice paddies, rising main sewers, landfills and old waste deposits, anaerobic digestions,

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cattle ranching and agricultural products are the main sources of biogas in the world [10–18]. Moreover, the increasing rate of world population is the main cause of food industries and especially animal husbandry development and one of the most important sources of CH_4 in the world is animal husbandry [19]. It has been proven that more than 15% of global methane generation is related to CH_4 emission from ruminants and biogas capturing from livestock dung and energy generation from waste gases have become routine process in many countries [20]. The appropriate strategies in waste water recirculation can increase the possibility of biogas generation as a renewable fuel from these waste materials [21]. Around 90–95% of natural gas is methane, but in biogas the rate of methane depends on feedstock decreases to the values of 55–65%. Therefore, biogas is a low calorific value (LCV) gas or low grade natural gas. Generally, the collected biogas is purified and its impurities like water and sulfuric gases removed. The biogas purification method and combustion improvement strategies are designed based on composition of biogas. The general composition of biogas has been shown in Table 1 [22].

1.2. Biogas general characteristics

In ideal conditions 40–80% of biogas is constituted by CH_4 and at the standard pressure and temperature the lower heating value of CH_4 is about 34,300 kJ/m^3. Therefore, the lower heating value of biogas is approximately 13,720–27,440 kJ/m^3. However, in biogas heating value determination, the heating value of the whole components should be taken into consideration. It means that the heating value of non-combustible specious like CO_2 should be taken into account. Also, the noticeable effects of water vapor on lower heating value, air–fuel ratio, biogas flammability limits and flame temperature should not be neglected. The physical characteristics of biogas are usually modeled by CO_2 and CH_4 because more than 98% of biogas is a combination of these two gases. However, hydrogen sulfide (H_2S) and water vapor removal process are vital in biogas production process due to their crucial role in equipment corrosion especially burner and boiler in conventional combustion chambers. Chemical and physical characteristics of CH_4 and CO_2 as the main components of biogas have been presented in Table 2.

In order to achieve an effective biogas conventional combustion some pretreatments should be done in biogas production step. H_2S and water as biogas corrosive constituents and other useless components of biogas such as CO_2, N_2 and hydrocarbons should be removed to obtain better traditional combustion. A summary of biogas pretreatments for elimination of detrimental components are presented in Table 3 [23].

2. Biogas combustion

2.1. Biogas flame velocity and temperature

The velocity of flame plays crucial role in the burner design in conventional combustion. The rate of injected fuel and air to the burner should be matched to flame velocity to prevent blowing out the flame. Compared to the natural gas the biogas flame velocity decreases due to lower concentration of CH_4 in biogas. Therefore, in biogas conventional combustion the flow rates of air and fuel injected to the burner should be decreased to prevent flame blow out. The maximum velocity of the flame is occurred at the stoichiometric air to fuel ratio. The other important parameter in the performance of combustion systems is the flame temperature. The design of refractory, insulation and other heat recovery equipment of combustion systems are done based on the flame temperature of the fuel because the rates of heat transfer from combustion system and flame temperature of combustible mixture have a direct proportion. In traditional combustion condition the flame temperature of biogas is lower than natural gas due to presents of non-combustible components such as CO_2 and water vapor [24].

2.2. Biogas flameless combustion

Biogas direct combustion in the furnace named conventional combustion is the simplest method of biogas utilization. Since biogas characteristics compared to natural gas are totally different, some substantial modification in control system, fuel delivery system, burner and orifice should be done to upgrade the combustion system for biogas utilization. In the other hand, low calorific value of biogas is the great obstacle for biogas conventional combustion. Furthermore, biogas upgrading for CO_2 elimination from biogas components is very expensive process. All of aforementioned disadvantages can be removed by biogas flameless combustion because flameless method can work well with extremely small LCV fuels and CO_2 removal from biogases is not necessary because CO_2 is applied to dilute the oxidizer. Indeed, ceramic which is applied in the burner and refractory of flameless furnace is a resistant in front of corrosive components of biogas like water vapor and H_2S. In natural gas flameless combustion the reactants are natural gas and highly diluted air. Also, the inside temperature of the flameless furnace should be above the self-ignition temperature of the natural gas. In these conditions traditional flame is not stable and the flame lifts. In the other word, due to low oxygen concentration and high Reynolds number for oxidizer, the flame structure is changed and the conventional flame is disappeared [25]. In order to achieve flameless combustion, combustion system should be run in traditional mode at the first step. This preheating step prevents reaction from quenching and increases the flameless chamber temperature above the self-ignition temperature of the fuels (normally more than 1000 K). When the temperature inside the furnace raises adequately, the reactance jet velocity increased, therefore the flame is disappeared and the furnace average temperature declines, this zone also is named as instability zone. Visible and audible flame is eliminated and the reaction region spreads to the downstream zone of the chamber. Therefore, temperature distribution is uniform along the flameless chamber, hot spots are eliminated and thermal NO_x formation suppressed [26].

3. Methodology

3.1. Experimental set up

Carbon steel pipe with 264 mm diameter and 600 mm length applied as the flameless furnace. An especial ceramic made by local factories used as refractory inside the chamber to maintain the inside temperature. The real diameter of the chamber is 150 mm after installation of refractory. Five holes have been set at the top of the chamber in specific distances from burner for K-type thermocouples installation. Fig. 1 shows the furnace before equipment installation and Fig. 2 is a picture of the combustion system during installation.

Table 1
Biogas general composition.

Biogas components	Typical analysis (% by volume)
Methane (CH_4)	55–65
Carbon dioxide (CO_2)	35–45
Hydrogen sulfide (H_2S)	0–1
Nitrogen (N_2)	0–3
Hydrogen (H_2)	0–1
Oxygen (O_2)	0–2
Ammonia (NH_3)	0–1