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Hydrogen generation from biogas reforming using a gliding arc plasma-catalyst reformer

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ABSTRACT

Biogas generated from landfills, wastewater disposal plants, wastes of livestock houses, etc., causing global warming when released into the air. This study developed a GAPCR (Gliding Arc Plasma-Catalyst Reformer) which convert the biogas into higher percentage of hydrogen as low pollution recycling energy, reduced the global warming and environmental problems. This study also conducted tests for the different variables that affect the biogas reforming efficiency of the GAPCR, and presented the optimum operating conditions for high percentage of hydrogen generation.

The parametric studies were carried out according to the change of steam to carbon ratio, catalyst bed temperature, total gas flow rate, input electric power, and biogas component ratio, i.e., CH_4:CO_2. The hydrogen concentration increased up to specific limit, and then maintained almost constant values for the same steam to carbon ratio and catalyst bed temperature. Hydrogen percentage decreased with the increase in total gas flow rate but little bit increases with the increase in electric power. In terms of biogas component ratio, hydrogen concentration decreased with the increase of CO_2 amount.

The optimum operating conditions showed the concentrations of 62% H_2, 8% CO, 27% CO_2, and 0.0% CH_4 on the basis of steam to carbon ratio of 3, catalyst bed temperature of 700 °C, total gas flow rate of 16 L/min, input electric power of 2.4 kW, and biogas component ratio of 6:4 (CH_4:CO_2). At this condition, H_2 yield and H_2 selectivity were same values of 59%. Energy efficiency and specific energy requirement were 53% and 289 kJ/mol, respectively.

1. Introduction

The problem of energy insufficiency is being come due to the limitation of fossil fuel reserves from which energy utilization continuously increases. Global warming occurs due to increase of CO_2 and other gases in air that released from the burning of fossil fuels and from other working process, etc. This needs an urgent evolution in clean and environmental friendly alternative energies and their making technologies.

Now, more and more attention focused on the technology of using biogas, which released from landfills, wastewater treatment plants, wastes of livestock houses, etc., as alternative energy. Concentrations of such biogases are different from each other, depending on regional characteristics and material production methods. Generally, each biogas is composed of 55–70% methane, 27–44% carbon dioxide, 1% or less hydrogen, 3% or less H_2S, etc. It is possible to reprocess the released methane as energy for combustion, but it is difficult to provide continuous supply of heat to boiler avoiding fluctuation when using as heat. The released CO_2 from biogas plays a vital role for global warming, having an adverse influence on environment. After converting biogas into high percentage of hydrogen, it is possible to use the biogas as a more stable, energy effectiveness, and environmental friendly fuel [1–3]. The reduction in greenhouse gas encourages us using biogas as an alternative energy against the imposition of carbon tax. Today, more attention diverted in building an environmental friendly modern system for producing hydrogen-using biogas (waste gas).

Now plasma technology applied for the production of hydrogen or synthesis gas as a new method. Generally, plasma classified in two kinds: thermal plasma called equilibrium plasma and non-thermal plasma called non-equilibrium plasma [4].

For the thermal plasma, the electrical power injected in the discharge is high (higher than 1 kW) and the neutral species and the electrons have then the same temperature (around 5000–10,000 K). The temperature in the reactor and the energy consumption are very high. The cooling of the electrodes is generally useful to reduce their thermal erosion [5,6]. The use of this technology is not relevant for an efficient production of hydrogen in terms of energy consumption.

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In non-thermal plasma, the electrical power is very low (few hundred watts) and temperature of neutral species does not change whereas the temperature of electrons is very high (up to 5000 K). In this case, plasma not only provides energy to the system but also generate radical and excited species, allowing, initiating and enhancing the chemical reactions. The advantages of non-thermal plasma relate to the low temperature that will result in less energy consumption and minimum electrode erosion therefore size and weight of the non-thermal plasma reactors are relatively less and attractive for mobile applications.

There is two types of general plasma discharges and it is impossible to keep a high level of non-equilibrium, high electron temperture and high electron density simultaneously, wherease most prospective plasma-chemical applications require high power for high reactor productivity and a high degree of non-equilibrium at once to support selective chemical processes. These parmeters are somewhat practicable in gliding arc. The gliding arc occurs when the plasma is generated between two or more diverging electrodes placed in a gas flow. The gliding arc discharge has strong point of simple response control, high-energy efficiency, and environmental friendliness that developed in a new modern technology [7,8].

Three-phase gliding arc plasma-catalyst reformer (GAPCR) studied and designed. The new developed form combines a catalyst reactor with a gliding arc plasma reactor. The combined reformer has a quick starting characteristics and response time. It is open for testing of various kinds of fuel and biogas, including high molecular hydrocarbon, has a high conversion rate, and maintains optimum operating status for gas property. Therefore, GAPCR produces high percentage of hydrogen than others [9–11].

In addition, the study grasped characteristics of hydrogen generated from biogas by using the GAPCR. Lastly, tests were conducted on the changes of steam feed amount, i.e., steam to carbon ratio, catalyst bed temperature, total gas flow rate, input electric power, and biogas component ratio, i.e., CH_4:CO_2.

2. Experimental apparatus and methods

2.1. Experimental apparatus

Fig. 1 shows an experimental setup used for plasma reforming tests. The setup was consists of a plasma-catalyst reformer, power supply, gas/steam supply line, measurement/analysis line, and control/monitoring system.

The plasma-catalyst reformer combined with a gliding arc plasma reformer and a catalyst reformer. The gliding arc plasma reformer had three fan-shape electrodes located at 120° in a quartz tube and fixed on the opposite side at a gap of 4 mm on a ceramic ring part. The quartz tube is used for the purpose of insulation and internal inspection of the plasma reactor. The jet nozzle for gas installed with a diameter of 3 mm at the upper part of electrodes. The catalyst reformer designed in a triple co-axial tube to heat catalysts evenly in the reactor.

The manufactured Ni/γ-Al_2O_3 catalyst (Sűd-chemie, FCR-4, Japan) using the impregnation method. The catalyst consist of 12% Nickel oxide (NiO) with gray spherical γ-Al_2O_3 as catalyst supports. Bulk density and diameter are 1.22 kg/L and 2 mm, respectively.

The power supply (Unicorn Tech, UAP-15KIA, Korea) used to stabilize plasma within the plasma reactor, and has maximum capacity of 15 kW (voltage: 15 kV; AC: 1 A). The gas/steam supply line supplied gases into the plasma reactor precisely using the methane and CO_2 mass flow controllers (LINETECH, M3030V, Korea) and (BRONKHOST, F201AC-FAC-22-V, Netherlands), respectively. The quantitative pump (KNF, STEPDOS 03, Switzerland) supplied water into the steam generator.

The measurement/analysis line was operational for temperature and gas analysis. Temperature measured by K-type thermocouple while H_2, CO and hydrocarbon (C_nH_m) gases were sampled and analyzed at the same time using two gas chromatographs (SHIMADZU, GC-14B, Japan; VARIAN, CP-4900, Netherlands). The LabVIEW instrument (National Instrument, LabVIEW 8.6, USA) control flow of gases, water pump and records the change of temperature and other conditions automatically.

2.2. Experimental methods

The plasma-catalyst reformer kept the temperatures of 580 °C in the gliding arc reactor and 700 °C in the catalyst reactor. Since steam-reforming reaction of Eq. (10) is highly endothermic, an external heat source (gas burner) is required. For the complete conversion of methane, high temperature in the catalyst reformer is critical. Therefore, the catalyst reformer provided gas burner to maintain 700 °C for the best activation of Ni catalyst.

Tests at optimum conditions conducted after injecting steam of 12 L/min, methane of 2.4 L/min and CO_2 of 1.6 L/min in a stable state at which plasma discharge power was 2.4 kW. CH_4 and CO_2 injected with controlled amount through mass flow controller and the steam entered from the steam generator together with these

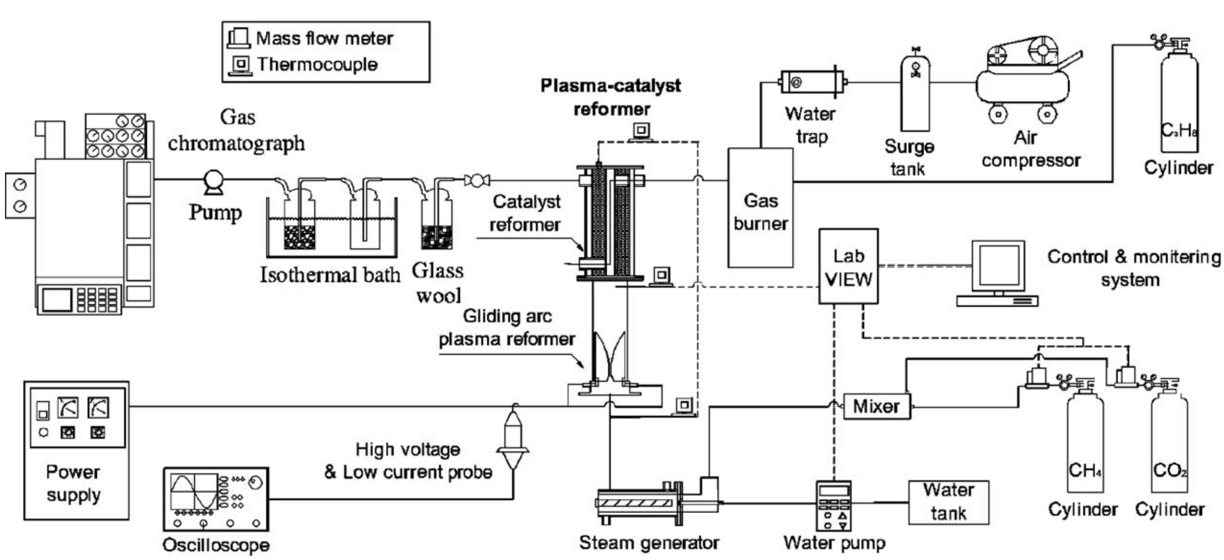

Fig. 1. Schematic of the GAPCR setup.