Biogas Combustion in a Crater Bed

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ABSTRACT

The application of crater bed for simulated biogas (mixture of methane and carbon dioxide) combustion was studied. The effects of biogas composition, biogas to air ratio, bed particle size, and the height of burner tube on the circulation of bed particles and lower flammability limit (LFL) were experimentally examined. It was found that the circulation amount and height of bed particles increase when high flow rate of fuel-air mixture and/or small bed particle size were used. An increase in burner tube height caused a decrease in circulation height, while the amount of circulated particles increased. Under the study conditions, the values of LFL obtained for simulated biogas were 35% to 60% lower than those of standard conditions reported in the literature. With the preheating effect obtained from both hot gas and particle circulation, biogas containing CH_4 *as low as 7% vol (93%* CO_2*) can be burned with stabilized flame in this crater bed.*

1. INTRODUCTION

Biogas, which is the by-product of anaerobic digestion in wastewater treatment systems or fermentation of municipal waste in landfill systems, can be used as a fuel source for both heat and power generation [1, 2]. Its composition depends significantly on the characteristics of the substrate to be digested. For example, biogas at a constant concentration of 60% CH_4 and 40% CO_2 is flammable when its concentration in air is between 8.83% and 20% vol. and it will not burn using a conventional combustor if its CO_2 concentration is more than 75% [2]. To overcome this limitation, new techniques involving heat-recirculating particulate beds such as fluidized bed, spouted bed, and crater bed have been introduced [3]. This will enable the low-methane content biogas to burn without supplemented fuel, and the generated heat, with proper design of combustion chamber, can be recovered and utilized.

Both fluidized and spouted beds, which are unique for various specific applications, show some technical problems when they are applied for heat recirculation. For example, the fluidized-bed burners are characterized by a uniform temperature due to their high rate of heat transfer but do not generally recirculate heat from beyond the zone of maximum temperature to the cold reactants [3]. Malik, et al. [4] pointed out that the spouted bed, which provides the obvious geometry for a recirculating particle burner, has high starting pressure and its pressure drop hysteresis makes it difficult to scale up by way of multiple spouts. The crater bed, therefore, was proposed by this research group as an alternative that can overcome the scale up limitation of the spouted bed for heat recirculation [4].

The crater bed employs the impingement of a high velocity jet of gas from a downward-facing nozzle located at some distance above the bed of particles to form a crater and create particle circulation on and above the bed surface. The preliminary study of hydrodynamic and combustion characteristics of the crater bed has been reported elsewhere [3, 4]. As a combustor, the system recirculates heat between products and reactants by the circulating particles and by heat transfer to the inlet tube in the same manner of counter-current heat exchanger. Tests performed by Malik, et al. [4] showed that the crater bed can be used either with gaseous reactants entering through the nozzle or with only oxidant introduced in that way, solid or liquid fuel being incorporated with the bed material. The leaner burning capability of the crater bed against that achieved in spouted and fluidized beds has also been reported [4]. Figure 1 [4] presents the crater formed which is a well defined cylindrical shape with a round base and is surmounted by a hollow cone of particles descending its walls which continually replace those rising in the ascending fountain. The momentum flux of the gas jet and particle type, size and shape have significant effects on the mass flow of displaced particles and hence the size of the crater and the height of the cone. However, little attention has been given to the application of this technique as recognized from currently limited publications.

This paper reports on the application of crater bed for simulated biogas combustion. The study emphasized on how the bed can improve the flammability limit of low calorific gaseous fuel (biogas) by heat recirculation. The effects of particle size as well as the height of inlet tube on the flame stability were examined. Also reported are the experimental results of LFL of simulated biogas containing various concentrations of CO_2 burning in a crater bed.

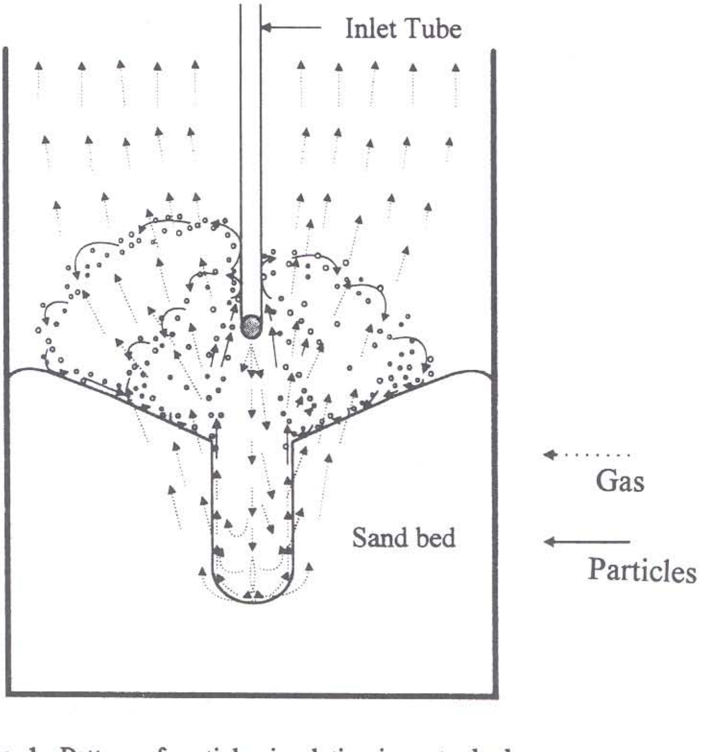

Fig. 1. Pattern of particle circulation in crater bed.

2. APPARATUS AND PROCEDURE

The crater bed and gas flow system are illustrated in Fig. 2. A cylindrical quartz tube with 0.095 m *i.d.* and 1.5 m length was used as the combustor. From the top of this quartz tube a 0.5 m long heat recirculation zone was provided, in which the vertically moveable inlet tube having *i.d.* of 0.009 m was held at the axis of the combustor and facing downward. A ceramic fiber sheet (0.03 m thick) was wrapped on the outer surface of the combustor.

Methane (99.99%) and carbon dioxide (99.99%) gases from standard gas cylinders were mixed to form simulated biogas in the first mixing chamber and then mixed with air from a compressor in the second chamber before feeding to the combustor. The flow rates of both gases and air were measured by three individual calibrated orifices and manometers. A K-type thermocouple connected to a digital thermometer was installed at the same level as the inlet tube nozzle and 0.03 m apart from its outer surface. Sand was used as the bed material.

The crater bed, having desired sand size and inlet tube height was pre-heated by using LPG until the chamber temperature reached 900°C to 950°C. The LPG was then changed to simulated biogas in which the concentration of both CH_4 and CO_2 could be adjusted for specific composition by controlling their flow rates. In the experiment, the biogas flow rate was fixed while the air flow rate was slowly increased starting from stoichiometric ratio until the extinction of flame was observed. Following this, the air flow rate at extinction condition was then fixed and the biogas flow rate with constant composition was increased. At each total gas flow rate, the bed temperature and flow rate of all gases were recorded after the steady state, constant bed temperature, was reached. Data were recorded in triplicate to confirm the reproduction. It should be noted that the minimum total gas flow must be sufficient for crater formation and this can be roughly predetermined from cold bed experiment. The effects of sand size, inlet tube height and total gas flow rate on both particle circulation and biogas combustion were visually observed by taking out the insulator from the quartz tube.

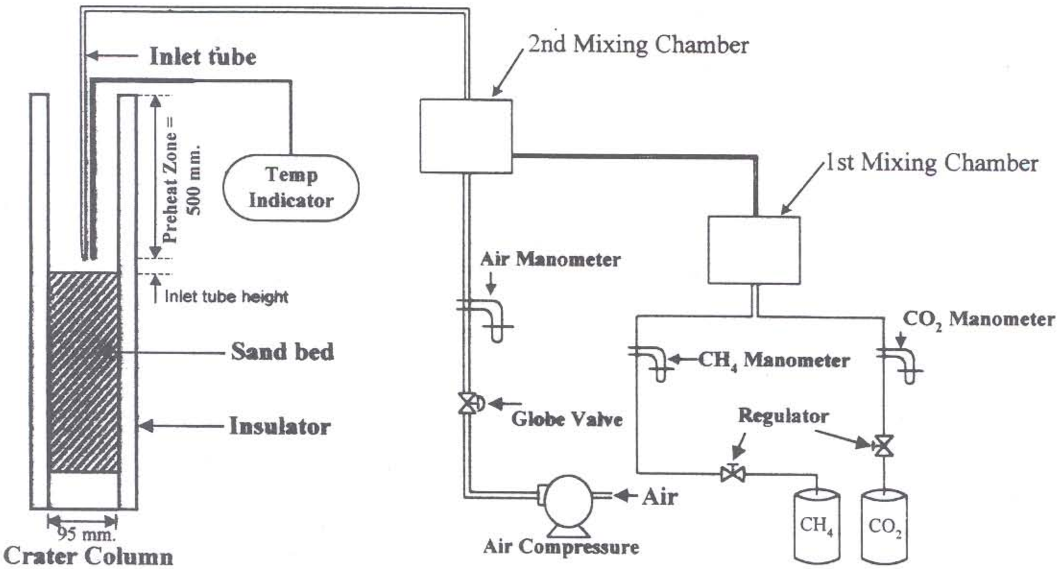

Fig. 2. Crater bed and flow system.

3. RESULTS AND DISCUSSION

The combustion of biogas in a crater bed at various conditions as visually observed from the experiment is shown in Fig. 3 and Fig. 4. The size and depth of crater formed and the height of ascending fountain of particles increases with total gas flow rate or its momentum flux (Fig. 3), but decreases as sand size increases due to its gravity effect. The increase in inlet tube height caused the larger radial profile of gas jet, and hence increase in crater size and amount of ascending sand (Fig. 4).

The typical plot of experimental results for LFL determination of a crater bed with different inlet tube height and 324 μm of sand size are presented in Fig. 5 and Fig. 6 for biogas containing 60% and 9% by volume of methane, respectively. For the case of biogas with 60% methane, Constant, et al. [2] reported that the standard LFL is 8.83% or 4.98% vol. based on biogas or methane in air, respectively. It is clearly seen that the heat recirculation effect obtained from the crater bed can reduce LFL to 4.98% vol. of biogas or 2.98% vol. of methane, and it is expected that the effect of heat recirculation can be enhanced through better insulation. The simulated biogas with methane as low as 9% vol., which is much lower than the minimum flammable composition of methane obtained from conventional firing as reported above (25% vol. of methane in biogas), can be burned steadily with stabilized flame in this crater bed. The corresponding LFL obtained from the experiment is 4.24% vol. of methane in air which is also lower than the standard LFL of pure methane (5% vol. in air).

The LFL of biogas at various methane concentrations with 0.02 m and 0.03 m of inlet tube heights and 324 μm and 730 μm of sand sizes is depicted in Fig. 7. It can be observed that the crater bed used in this study resulted in about 35% to 60% lower LFL when compared to that obtained from the standard method. When the sand size was fixed at 324 μm, the LFL values from the case of inlet tube height of 0.03 m is gradually lower than those of 0.02 m with CO_2/CH_4 ratio higher than 1.5. This is because the total flow rate of gas mixture and the ascending height of sand particles at the condition of LFL are nearly the same for both inlet tube heights, while the amount of ascending sand is more for the 0.03 m inlet tube height compared to that of 0.02 m. Therefore it can be presumed that the bed will recirculate more heat by circulating particles, and thus decrease in LFL. Increasing the sand size from 324 μm to 730 μm with the constant inlet tube height of 0.03 m, showed a significant decrease in LFL. The reason is not clear, however it is believed that at the condition of LFL the larger sand size would contribute more heat recirculation through radiation as well as thermal mass. With this sand size and inlet tube height, the crater bed used in this study can burn biogas containing methane as low as 7% vol. (CO_2/CH_4 = 13.2, adiabatic flame temperature = 371°C at lean limit) with stabilized flame.

At LFL condition, the combustor temperature at the same level of inlet tube nozzle and 0.03 m apart from its outer surface as a function of CO_2/CH_4 ratio is presented in Fig. 8. As reported above, the simulated biogas with CO_2/CH_4 ratio above 3 up to 10 will never burn by using a conventional burner due to the amount of heat release being too small to heat the inert gas (N_2 and CO_2), and hence resulting in a relatively low furnace temperature to sustain the flame. In contrast, the crater bed recirculates heat between reactants and combustion product by the circulating particles and by heat transfer through the inlet tube. As a result, the temperature inside the combustor obtained from the experiment is nearly constant at about 620°C to 650°C which is, of course, high enough to sustain the combustion.

Scale up to relatively large bed can be made by using multiple inlet tube. When burning landfill biogas which composed of certain amount of high molecular weight or aromatic hydrocarbon,

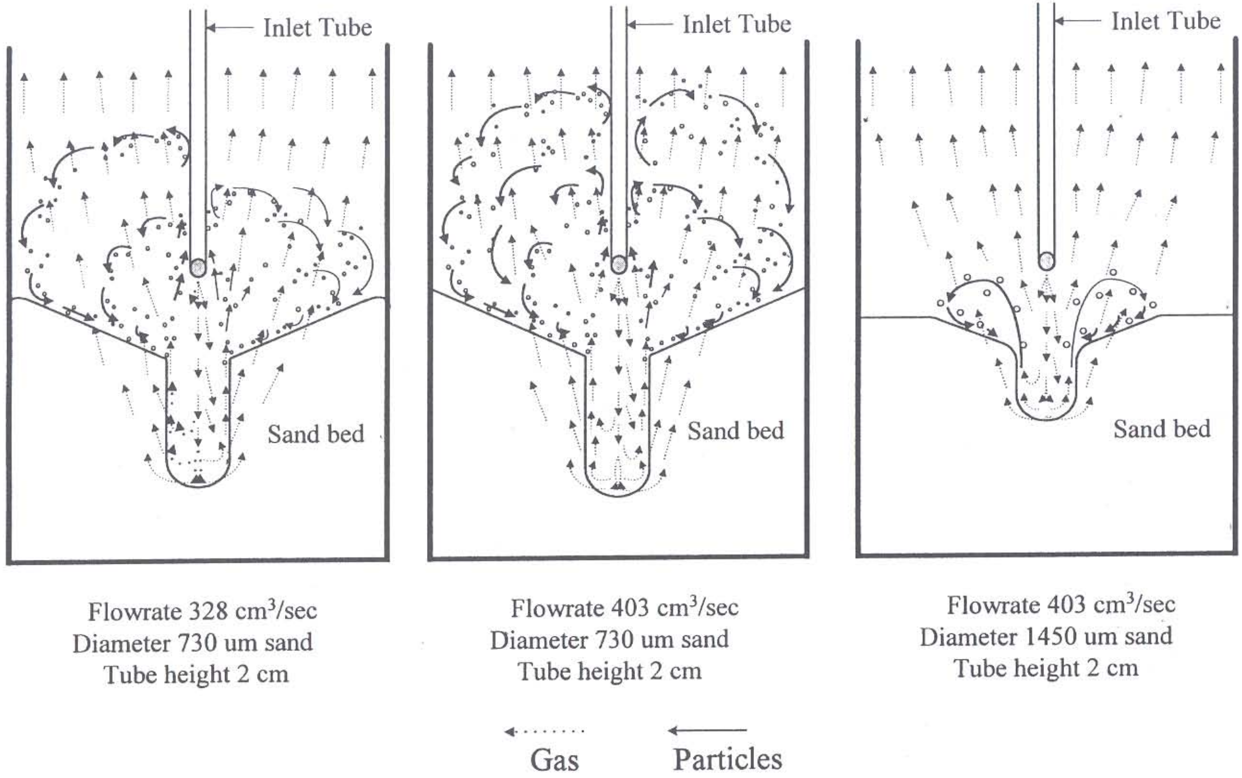

Fig. 3. Effect of gas flow rate and sand size on the crater size, and height and amount of ascending sand particles.

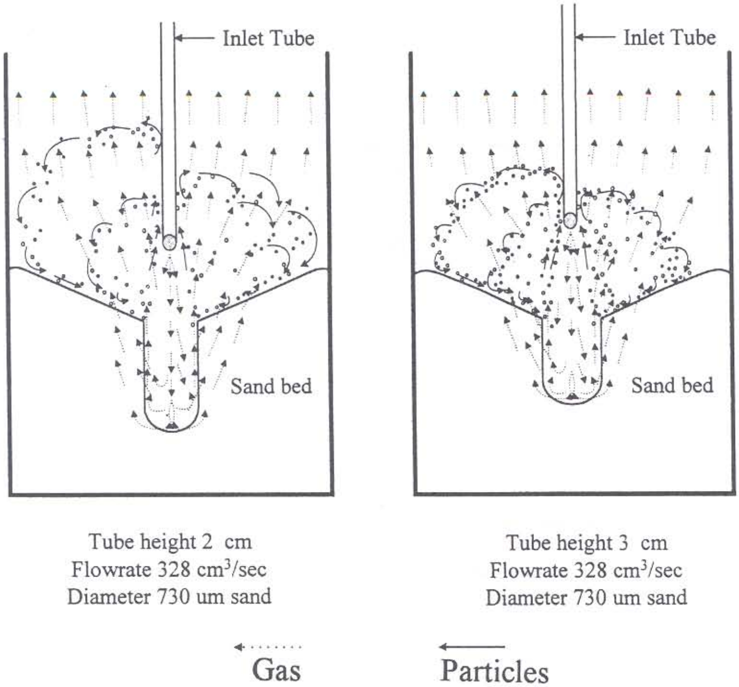

Fig 4. Effect of gas flow rate and inlet tube height on the crater size, and height and amount of ascending sand particles.

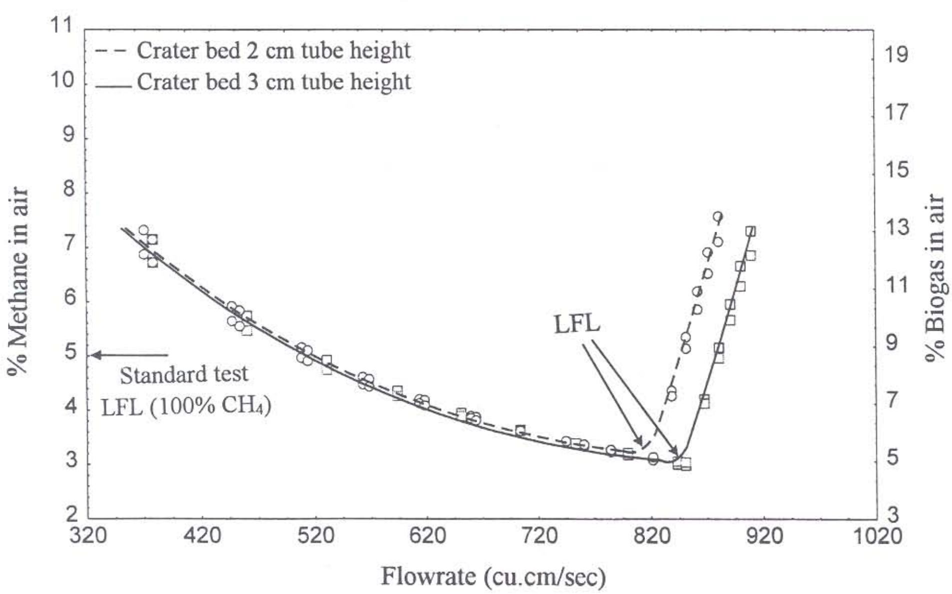

Fig. 5. Stability limits for combustion of simulated biogas containing 60% vol. of methane in crater bed.

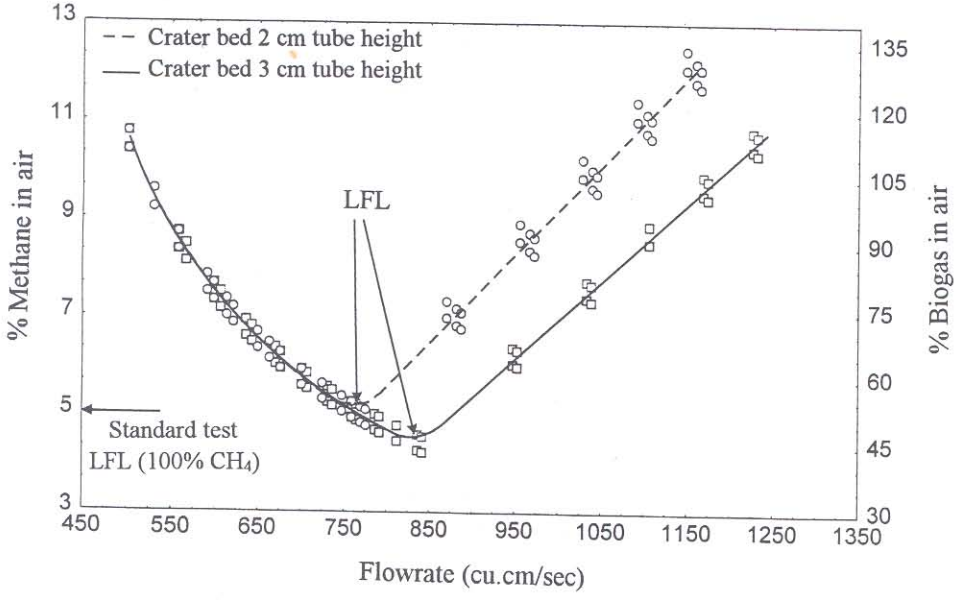

Fig. 6. Stability limits for combustion of simulated biogas containing 9% vol. methane in crater bed.

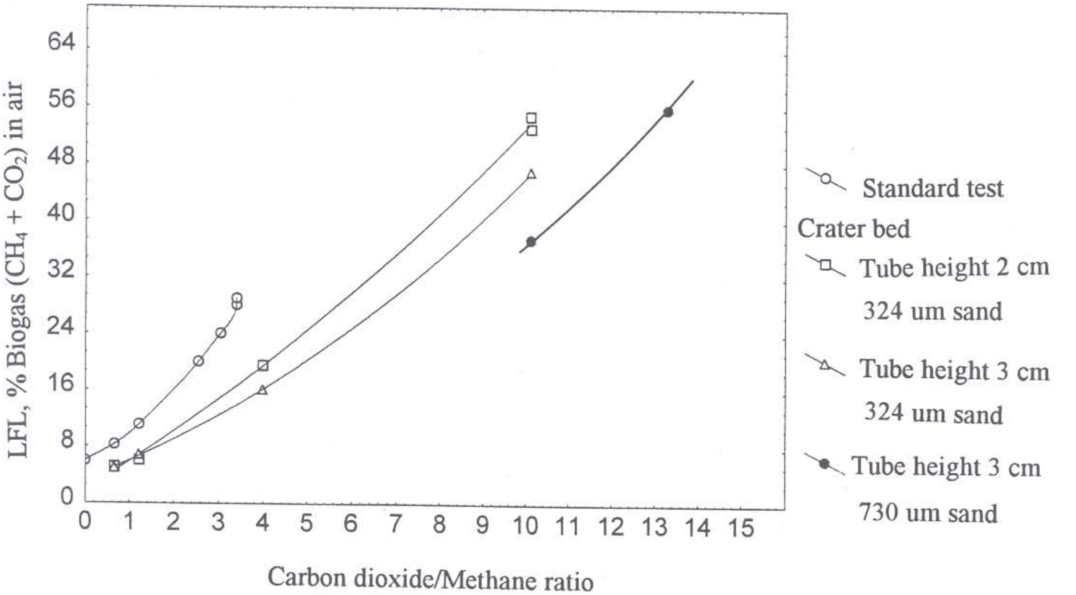

Fig. 7. Comparison of LFL of simulated biogas in air obtained from standard method and crater bed used in this study.

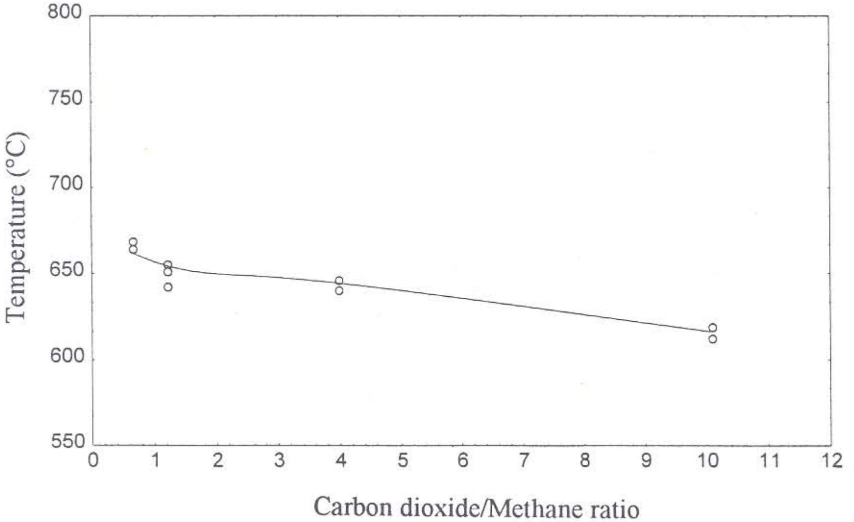

Fig. 8. Typical inside temperature of combustor for simulated biogas-air at LFL as a function of CO_2/CH_4 ratio.

some inlet tubes can be fed with air only in order to provide enough secondary air for complete combustion. Further research required for both single and multiple inlet tube are the hydrodynamic and heat transfer mechanism between crater bed and inlet tube as well as the combustion and emission characteristics for each specific gaseous fuel.

4. CONCLUSION

This study showed that the crater bed can be well applied as a recirculating particle burner. The size and depth of crater form, as well as the ascending height of solid particles, increase with flow rate of impinging gas jet. The amount of particle ascending depends markedly on the inlet tube height. The lower flammability limit (LFL) obtained from crater bed experiment was 35% to 60% lower as compared to those obtained from the standard method. In this study, biogas containing methane lower than 25% down to 7% vol. can be steadily burned with stabilized flame in the crater bed due to its good heat circulation characteristics.

5. REFERENCES

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