Biogas production enhancement using nanocomposites and its combustion characteristics in a concentric flow slot burner

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ARTICLE INFO

Keywords:
Biogas
Partially premixed
Stability
Mixing
Mixture inhomogeneity

ABSTRACT

Biogas combustion is a very essential topic for the development of many industrial combustion systems and engines. This fuel can replace current fossil fuels used in burners, engines, and many other applications. Understanding the combustion characteristics of this fuel and its stability in highly turbulent flames of practical interest is the aim of this work. The percentage of CO2 in Biogas varies between 25% and 45%, which affects the combustion stability and flame structure. The present work shows that the generation of Biogas is improved by adding Ni-Co-Ferrite or Ni-ferrite nano-additives. In this work, we selected 25 flames of mixtures of natural gas and CO2, where the ratio of CO2 varies from 0% to 40%. The flames are generated in a concentric flow slot burner that produces planar two-dimensional flames. The stability characteristics and the flame structure were investigated. The flame structure is presented in the form of temperature profiles in some selected flames using fine wire thermocouple measurements. The stability characteristics are illustrated for two limits of lifted flames and blow out. The production rate of Biogas can be increased by almost 30% using nano-additives of Ni-Co-Ferrite or Ni-ferrite. The data show that the stability of the flames is affected significantly for the 40% CO2 mixture. Therefore, it is recommended to keep CO2 percentage up to 30% for stable turbulent Biogas flames. On the other hand, partially premixed flames are highly stable for a certain level of mixture inhomogeneity at a mixing length ratio of L/D = 16. At this level, the mixture fraction fluctuations are expected to be within the flammability limits range based on previous investigations in round jet configuration.

1. Introduction

Biogas fuel has been considered to replace conventional oil-based fuels in combustion systems; e.g. burners and engines, due to the expected scarce of oil in the future. Biogas is regarded as a renewable energy source, which can be produced through a biological degrading process called Anaerobic Digestion [1]. This is a complicated biochemical process that involves four main steps; Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis. Digestant is the decomposed substrate, which is rich in nutrients and is a suitable plant fertilizer [2,3]. Biogas composition varies according to the organic waste type and the working conditions (e.g., temperature, pressure, retention time). It mainly contains methane, carbon dioxide and small amounts of hydrogen sulfide and hydrogen.

One of the major barriers of the full utilization of Biogas in different burners and combustors is the high content of CO2 in the gas mixture, which deteriorates the Biogas flame stability and heating value. Currently, many upgrading techniques have been developed to remove the high content of CO2 in Biogas, such as water scrubbing, chemical scrubbing, pressure swing adsorption (PSA), and the use of membranes [4]. However, water scrubbing requires very complicated systems and very expensive for Biogas upgrading [5,6]. Also, chemical scrubbing exposes the neighbouring environment to dangerous levels of toxicity [7,8]. After all, Biogas purification is a sensitive process and requires complicated upgrading systems, which eventually make it a non-economic process. Therefore, researchers began to propose techniques to enhance the productivity and the quality of the Biogas during the production phase by adding inorganic additives in micro or Nano scale.
of (1) nutrients supplements like Fe, Ni, Mo, Co, and W [9], (2) ashes from waste incineration [10], and (3) chemical compound to avoid inhibition due to instability in pH. These techniques are preferable as they do not require special equipment and show significant enhancement in the production of Biogas.

The supplement of utilizing micro-nutrient is attracting more attention for the enhancement of Biogas production and the stabilization of the AD process. Micro-nutrients, like Fe, Ni, Co, W, and Mo are considered decisive cofactors for the biochemistry of methane formation [11]. Furthermore, Ni, Co, and Fe are regarded as key catalysts in the oxidation of acetate into carbon dioxide and hydrogen leading to the hydrogenotrophic methanogenesis [12]. For instance, Fe rusty scrap, when added to activated sludge waste, can increase the methane yield by 29.51% and reduce the volatile suspended solids to 48.27% [13]. Besides, Nickel and Cobalt doses of 0.6 and 0.05 mg kg⁻¹, respectively enhanced the stability of the digester and stimulated the metabolization of propionic and acetic acids at organic loading rate of 4.3 g TS L⁻¹ day⁻¹ [14]. In contrast, excessive usage of micro-nutrients can result in the inhibition of the AD process [15].

Enhancing the production rate and Biogas quality is an important topic of research and is considered in this work based on the use of nanocomposites. On the other hand, the combustion stability is one of the main concerns for the application of Biogas in many practical combustion systems. The stability characteristics and flame structure of Hydrogen-Biogas was investigated by some research groups in open flames [16,17] and combustion bomb [18]. The stability is improved by adding Hydrogen to Biogas in premixed flames. However, flash back caused some problems. Biogas combustion was also investigated in mild combustion or flameless oxidation mode [19] and a map of operating conditions was generated.

The combustion characteristics and flames stability are affected by the mode of combustion. Mansour et al. [20] and Meares and Masri [21] showed that partially premixed flames with inhomogeneous jet are more stable than premixed and non-premixed flames. In addition, partially premixed combustion was reported to reduce NOx and soot emissions by Belgiorno et al. [22] and Tang et al. [23]. Partially premixed combustion has attracted the attention of many researchers [24–32] due to its wide application in many practical systems. Accordingly, investigating the combustion and stability characteristics of Biogas in partially premixed combustion system is one of our main objectives of this work. Masri [26] provided an extensive review of partially premixed combustion and discussed several burners and their practical application. Turbulent flames with inhomogeneous mixture can be investigated in special burners when the mixing process is well controlled. Mansour [25] designed a new burner with mixing technique that can generate wide range of mixing field structure from fully premixed to non-premixed. The burner provides round jet with a simple control mechanism. However, the burner diameter affects the stability characteristics of the burner where large diameter leads to more stable flames [33]. The turbulent flames in the round jet burner can be further stabilized by a pilot flame [21,26,34] or a conical nozzle [20,25,32,33] at the burner exit. The first technique provides a source of stabilizing heat at the exit of the nozzle while the second technique changes the aerodynamics and pressure to the nozzle exit. The improvement of the flames stability of using the second technique is an attractive method to solve the decreased stability limit of Biogas flames. Accordingly, another new burner was developed by Mansour et al. [35] to create 2D planar turbulent flames with inhomogeneous rectangular jet using the same mixing technique of Mansour [25]. Recently, more researches were devoted to utilize slot burners in experimental combustion analysis. Nourmai et al. [36] and Kiani et al. [37] investigated the combustion operation conditions and temperature fields of syngas and landfill gas respectively in a slot burner using advanced Mach-Zehnder interferometry. A slot burner was also adopted by Yousefi-Asli et al. [38] in presenting the temperature field and heat transfer of methane-air flame between the slot burner and an impingement surface.

It is clear from the review that several researchers investigated the flame stabilization privilege of partial premixing combustion with different types of fossil and renewable fuels. However, the research work that deals with low heating values like Biogas while applying partial premixed mode of combustion is limited. Therefore, enhancing the stability of Biogas flames in slot burner and studying the effects of jet inhomogeneity of Biogas are the main goals of our research study. In this work, our focus is the study of the effect of jet inhomogeneity for different percentage of CO₂ in Biogas. The Concentric Flow Slot Burner (CFSB) [35] was selected for the current study in order to generate 2D turbulent flames. The flame stability was investigated at different mixing field inhomogeneity and percentages of CO₂ in the Biogas mixture. Yet, to define the actual carbon dioxide percentage in raw Biogas, a 35 days Biogas-production experiment was conducted with the aid of two types of nanocomposites: Ni-Ferrite and Ni-Co-Ferrite. These nanocomposites work as biocatalysts to enhance the Biogas production process. Accordingly, the aim of this work is two folds; studying the enhancing rate of generation of Biogas using nanocomposites and studying the stability limits, the combustion characteristics, and temperature profile for Biogas mixtures with different percentages of CO₂.

2. Experimental setup

The setup of the burner was established in the engines’ laboratory at the American University in Cairo. The setup managed to facilitate the process of controlling the flowrates of air, CO₂, and CH₄. For safety aspects, ball valves were added to the gases lines to provide quick shut-off access. The air-line used in this experiment was supplied from an air header at 6 bar. Air regulator (0–10 bar) was also added to the air-line to damp the variations in the air flowrate. CO₂ regulator (with heater) was also connected to the CO₂ cylinder to smooth the CO₂ output and overcome the throttling cooling effect consequently supply CO₂ at constant temperature. In addition, needle valves were installed in the gases lines to provide precise flowrate adjustment. The valves were coupled to Poly-Urethane tubing with inner diameter of 8 mm. The flow rates adjustment of the needle valves was afterwards detected by a group of mass flowmeters. The sensors have I2C connections ports and the signals were sent to an Arduino-uno chip for processing before delivering them to a laptop. The exhaust gases were drawn from the burner through the confinement installed above the burner. The results were previewed using Microsoft Excel Sheet 2016.
2.1. The concentric flow slot burner (CFSB)

As discussed above, the concentric flow slot burner (CFSB) [35] was selected for the current study of turbulent partially premixed and inhomogeneous mixture Biogas flames. In fact, this slot burner was inspired by the Wolfhard-Parker slot burner which was designed for 2-D laminar flames [39]. Fig. 1 shows the top of the CFSB. It was designed to overcome the curvature effect on the flame structure and stability [39]. The nozzle of the burner includes three main rectangular ducts; two-outer ducts for pure Biogas and the middle duct for pure Air. The Air duct dimensions are 2 mm × 100 mm while the fuel duct dimensions are 4 mm × 100 mm. The mixing between the air and fuel occurs upstream the nozzle exit within the mixing length L. The level of partial premixing and mixture inhomogeneity is controlled by varying the length L. Five different mixing lengths were used in the current work; L/D = 3, 5, 7, 10, and 16, where D is the nozzle exit hydraulic diameter, defined as 4A/P, where A is the slot area and P its perimeter. The fuel inlets direct Biogas into a serpentine-path homogenizing chambers. The purpose of these champers is to generate a homogeneous inlet flow of the fuel [35].

2.2. Temperature measurements instrumentation and correction

A bare-wire thermocouple of B-type thermocouple (Omega-SP30RH-008) was used in this work. It was manufactured from Platinum 6% Rhodium (−) and Platinum 30% Rhodium (+) wires of 200 µm diameter. It had a hot junction of approximately 300 µm diameter which was formed by electric welding. The thermocouple wires were carried in twin bore recrystallized pure alumina ceramic tube containing over 99.8% Al₂O₃ (Omega-TRX-13218). It is non-reactive and recommended for use with platinum thermocouple alloys and can stand a maximum temperature of 1900 °C. The twin bore ceramic tube has inner diameters of 0.794 mm and outer diameter of 3.175 mm and a length of 152.4 mm. The thermocouple is mounted on a 3-D transverse mechanism to scan the flame temperature along the length and width of the burner slot at different heights. The temperature of the flame was scanned at 3 levels in the z direction normal to the burner slot plane.

A thermocouple/voltage input data acquisition module (OM-DAQ-USB-2401) was used to store and display the temperature of the flame with 500 V isolation between input and PC for safe and noise-free measurements. The data acquisition module has a maximum sampling rate of 1 kHz with an accuracy of ± 3.3 °C for B-type thermocouples and 24-bit resolution. A bare thermocouple immersed in flame gives a temperature less than the actual flame temperature because of the radiation losses to the surroundings [40,41]. In addition, the conduction losses from the hot junction to the main leads cause a measurement error, but the conduction loss can be reduced to be negligible by

![Fig. 1. View of the top of the burner illustrating the air and Biogas flow paths.](image-url)

![Fig. 2. The effect of Nano-additives on the production of Biogas and Methane. The dotted lines with open symbols represent the Ni-Co-Ferrite (NCF) Nano-additives while the solid lines with closed symbols represent the Ni-Ferrite (NF) Nano-additives.](image-url)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Biogas designation for the selected operating conditions of premixing ratio (L/D) and Carbon Dioxide percentage.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L/D = 3</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>NG0003</td>
</tr>
<tr>
<td>10%CO₂</td>
<td>BG1003</td>
</tr>
<tr>
<td>30%CO₂</td>
<td>BG3003</td>
</tr>
<tr>
<td>40%CO₂</td>
<td>BG4003</td>
</tr>
</tbody>
</table>
Fig. 3. The effect of Biogas (BG) mixtures on the Lift-off limit at different L/D.

Fig. 4. The effect of L/D on the Lift-off limit at different mixtures of Biogas (BG).
Fig. 5. The effect of L/D on the Blow-out limit of different mixtures of Biogas (BG).

Fig. 6. The effect of Biogas (BG) mixtures on the Blow-out limit at different L/D.
heating the thermocouple wires or increasing the thermocouple wire-flame contacting length [41, 42]. Several temperature correction methods [43, 44] based on multiple thermocouples with different diameters have been developed based on the fundamental heat transfer theory. Thermocouples of different types especially Platinum and iridium thermocouples have been developed to measure the flame temperature because of their ability to withstand and measure high temperatures. The suction pyrometer also has been used in flame temperature measurement [40, 45] for reducing the radiation error, but with a significant low spatial resolution. Krishnan et al. [46] designed a rotating thermocouple to achieve accurate flame temperature measurements and with better spatial resolution than that of the suction pyrometer, but it had a complicated structure. However, the bare thermocouple is used widely to measure the flame temperature because of its good spatial resolution and simplicity [40–43].

### 2.3. Biogas production setup

One of the objectives of this work is to study the effect of nano-composites on the rate of Biogas generation through the anaerobic digestion process. Two types of Nano-composites (Ni-Ferrite and Ni-Co-Ferrite) were used for the enhancement of Biogas production rate. A one liter autoclave bottle was utilized to host the anaerobic digestion process of animal substrate as adopted from Abdallah et al. [47]. Two ports were connected to bottle with two pneumatic ball valves to ease the purging procedure of the air in the headspace. The valves are coupled with quick connections to the tubes of the Biogas analyser (Biogas 5000, Geotech, UK) to determine the percentage composition of the Biogas constituents. The analyser uses dual wavelength infrared sensor coupled with reference channel to detect Methane (0–100%) and Carbon dioxide (0–100%). The analyser was also used to determine the oxygen percentage (0–25%) in the Biogas composition by internal electrochemical cell. Monitoring of oxygen percentage is vital to maintain full anaerobic conditions inside the bio-digester which affects directly the methanogenesis bacteria. Another pneumatic ball valve was also installed in the cap of the bottle for digestate sampling. The Biogas volume was monitored daily by recording the change in the pressure of the biodigester. Therefore, a digital pressure transducer (ZSE40AF, SMC, Japan) was utilized to measure the headspace pressure of the biodigester. The pressure sensor possessed an operating range of −100 kpa to 100 kpa. The sensor was then connected to a Programmable Logic Controller (PLC, Siemens, Germany) to collect the data from the transducer.

A series of 21 pressure-based Biogas reactors were designed and implemented to carry out a 35-days batch-mode experiment. For each Biogas reactor, a single 1L Autoclave bottle (Schott, Germany) was used to host the anaerobic digestion of the 400 ml animal substrate. Besides, simple modifications took place for each bottle to ease the analysis procedures for Biogas and substrate. All the reactors were maintained at 38 °C using 3 water baths. Three doses (20, 70, & 130 mg/l) of the two types of Nano-additives were tested. The Nano-additives worked as a biocatalyst to enhance the Biogas production process in 35 days experiment. The percentage of Methane in Biogas will determine the biocatalyst to enhance the Biogas production process in 35 days experiment. The results showed that the Nano-additives have a stimulating effect regarding the total volume of the produced Biogas, however, the Nano-additives have less significant effect on methane content in Biogas.

### 3. Results and discussion

#### 3.1. Biogas production enhancement

The results showed that the methane percentage in Biogas ranged between 53.31% and 54.72% upon the use of Ni-Ferrite Nano additives. The total amount of produced methane from Biogas reactors was enhanced due to the addition of Ni-Ferrite Nano additives, as shown in Fig. 2 by the solid lines. The utmost enhancement in methane production from Ni-Ferrite reactors was noticed at the concentration of 20 mg/l to increase by about 32.4% (from 1331.35 ml to 1762.52 ml). At this concentration, the utmost enhancement in Biogas production is 30.78%. Also, the methane content was ranging between 52.64% and 55.08% in Biogas reactors with Ni-Co-Ferrite Nano additives, as shown in Fig. 2 by the dotted lines. Ni-Co-Ferrite Nano additives induced the methane production; however, the optimum dose was 130 mg/l which led to a total volume of 1746.58 ml. At this concentration, the utmost enhancement in Biogas production is 32.87%. These results encourage the use of nanocomposites during the production of Biogas using the anaerobic digestion process.

Wang et al. [48] investigated the effect of various types of NPs (Ag, Fe2O3, MgO) on Biogas production. Their study concluded that no significant enhancement on methane production, except for 10 mg/g TSS, which promoted methane production by 20%. Herein, 130 mg/l (1.326 mg/g TS) of Ni-Ferrite and Ni-Co-Ferrite stimulated methane by

### Table 2

The operating conditions of the selected flames for temperature at L/D = 10.

<table>
<thead>
<tr>
<th>Flame</th>
<th>Re</th>
<th>ϕ</th>
<th>%CO₂ Departure from blow-out limit, δ , %</th>
<th>Laminar flame speed m/s</th>
<th>Burner Load kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG0010-I</td>
<td>2400</td>
<td>3.3</td>
<td>61.01</td>
<td>0.38</td>
<td>19.33</td>
</tr>
<tr>
<td>BG1010-I</td>
<td>2400</td>
<td>3.3</td>
<td>52.08</td>
<td>0.175</td>
<td>18.31</td>
</tr>
<tr>
<td>BG2010-I</td>
<td>2400</td>
<td>3.3</td>
<td>47.55</td>
<td>0.09</td>
<td>17.18</td>
</tr>
<tr>
<td>BG3010-I</td>
<td>2400</td>
<td>3.3</td>
<td>6.74</td>
<td>15.92</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7. Temperature profiles at four positions, Y, along the slot for Biogas flame BG1010-II at Re = 4034, and ϕ = 3.57 at (a) Z = 1 mm (b) Z = 40 mm and (c) Z = 80 mm.
19.49% and 31.19% respectively. Also, Zitomer et al. [49] increased methane production between 12% and 17% upon the use of 25 mg/l of Ni, Co and Fe salts. Yet, in this study, 20 mg/l of Ni-Ferrite NPs managed to stimulate methane 32.39%.

3.2. The stability characteristics of the Biogas in the CFSB

The second objective of this work is to study the stability characteristics of Biogas turbulent flames in the CFSB with inhomogeneous jet of Biogas-air. Five ratios of CO₂: 0%, 10%, 20%, 30% and 40% in a mixture with natural gas are used. The level of mixture inhomogeneity is controlled, as described above, by varying the mixing length, L. As listed above, five ratios were selected for the current work, at L/D = 3, 5, 7, 10 and 16. Table 1 illustrates the designations for the tested Biogas with different premixing ratios (L/D) and Carbon Dioxide percentage. The effects of the level of inhomogeneity and percentage of CO₂ on the stability characteristics are investigated and presented in this section. The lift-off and blow-out limits were identified and illustrated in Figs. 3–6 below.

Fig. 3 illustrates the effect of the percentage of CO₂ in the mixture on the lift-off limit for the different L/D ratios. For all mixing lengths, the data show that the lift-off limit is higher for the pure natural gas mixture and decreases gradually by increasing the CO₂ percentage. This indicates that the flames are lifted at lower Reynolds number with more...
CO₂ percentage in the Biogas. At L/D = 3, as shown in Fig. 3, there was no lift-off limit recorded for pure natural gas, NG00, where the flames reached blow-off limit without lift. The lifted flames are usually stabilized at the lift-off height due to expected triple flame propagation towards the jet [50]. The addition of CO₂ to natural gas should affect the flame propagation speed and hence the stabilization of the Biogas should be different than pure natural gas.

Fig. 4 illustrates the effect of the mixing length on the lift-off limit for the different CO₂ percentages in the fuel mixture. For all cases of pure NG and BG the lift-off limit is increased by the increasing the mixing length, i.e. moving towards more premixed conditions. This indicates that the flames are lifted at lower Reynolds number with less premixing between the fuel and air. At higher percentage of CO₂, 40%, as shown in Fig. 4, the flames are lifted near the laminar conditions. Fig. 4 suggests that partially premixed flames with mixture inhomogeneity affects the flame stability for the same Re and this is purely due to the mixing field that affect the generation of triple flames at the lift-off height. Fig. 5 illustrates the effect of the mixing length on the blow-out limit for the different CO₂ ratios in the fuel mixture. The data show that the trend between the flame stability improvement and the mixing length varies for each percentage of the CO₂. This indicates that the mixing field is affected by the CO₂ and varies with the mixing length. In most cases, the optimum L/D is 16 for better flame stability.

3.3. The temperature profiles in the CFSB

The third objective of this work is to study the effect of the CO₂ percentage on the flame structure. The temperature profiles were measured at different locations in four selected flames, as listed in Table 2, using fine wire thermocouple, as described above. Initially, we examined the similarity of the temperature profiles, in X-direction, in four locations along the slot length, Y-direction, in order to prove that the burner provides 2-dimensional flame structure. The selected flame is at Re = 4034, and ϕ = 3.57, with 10% CO₂ (BG1010-II) in the fuel mixture at L/D = 10. Fig. 7 illustrates the temperature profiles at the four locations along the slot length, Y-direction, near the nozzle, at Z = 1 mm, and at two positions further downstream, Z = 40 and 80 mm. This is clear from the profiles in Fig. 7 and thus the CFSB burner produces 2-dimensional planar flames.

Four flames are selected at the same level of mixture inhomogeneity, L/D = 10, Reynolds number, Re = 2400, and average jet equivalence ratio, ϕ = 3.3, at different percentage of CO₂ in the fuel mixture, by volume. The flames departure from the blow-out limit, δ, is defined as δ = (Re − Re_{blow-out})/ Re_{blow-out}, where Re_{blow-out} is the blow-out Re. The data show that the flames approach blow-out limit by increasing the CO₂ percentage. Thus, the natural gas flame, NG0010, is more stable than Biogas flames. This is consistent with the stability characteristics presented above. The burner load is reduced from the natural gas flame NG0010-I to the rest of the three flames, BG1010-I, BG2010-I, and BG3010-I, to 95%, 89%, and 82%, respectively. The laminar flame speed was measured and calculated, using the GRIMech 3.0 with PREMIX computations, for different percentages of CO₂ in a mixture with methane [51] and the data are listed in Table 2. Fig. 8 shows the relations between the departure from blow-out limit, δ, and the laminar flame speed, S₀, and the burner load. There is a strong linear relation between δ and S₀. At L/D = 10, the mixing is more towards fully premixed conditions and thus the flames are likely to be more affected by the flame speed. This should also affect the flame stability, as illustrated above.

Fig. 9 illustrates the temperature profiles for the four selected flames at three different heights above the burner, at Z = 1 mm, 40 mm, and
80 mm. There is a clear change of the flame structure by increasing the percentage of CO₂ in the mixture especially at 30% CO₂. At 40% CO₂, turbulent flames were difficult to stabilize and could not presented in these profiles. This indicates that beyond 30% turbulent flame cannot be stabilized at this mixing length, L/D = 10, while at L/D = 16, turbulent flames of 40% CO₂ can be stabilized, as shown in Fig. 5 above.

The effect of both CO₂ percentages on the mean temperature and rms of the temperature fluctuations profiles at three vertical locations above the burner is illustrated in Fig. 10. The temperature drop is clear by adding more CO₂ in the mixture, except at Z = 1 mm where the temperature of 10% CO₂ (BG10) is slightly higher than that in pure natural gas (NG00). The temperature drop is expected due to the drop of the fuel heating value and the flame load, as listed in Table 2. The drop is more significant in the 20% (BG20) and 30% (BG30) flames. In addition, the flame size is also reduced by increasing the CO₂ percentages. The rms of the temperature fluctuations are higher at the shear layer and it also increases by increasing the CO₂ percentage. So, smaller flames with lower temperature and higher temperature fluctuations are produced by increasing the percentages of CO₂ in the mixture.

4. Conclusions

The production rate enhancement of Biogas has been investigated in this work using nanocomposites of Ni-Ferrite and Ni-Co-Ferrite through the anaerobic digestion process. The material used to enhance the production rate showed an increase of about 32.87% for a concentration 20 mg/l of Ni-Ferrite nanocomposites. These large production rates should be attractive for the implementation of nanocomposites in the anaerobic digestion process of Biogas.

On the other hand, the stability limits of mixtures of natural gas and CO₂, similar to Biogas mixture, were investigated at different levels of mixture inhomogeneity, in turbulent partially premixed burner, and at different percentages of CO₂. In general, the stability limits are lower in all Biogas mixtures for all operating conditions as compared to natural gas in the same burner. In addition, beyond 30% of CO₂ in the mixture the flames suffer from a large drop of the stability limits. Thus, it is recommended to reduce the CO₂ percentage in the Biogas to be within 30% or less.

The structure of the flames, based on the temperature measurements, shows a reduction of the flame size and temperature levels by increasing the percentage of CO₂. This is expected in low heating value flames. The 30% CO₂ flame also shows very low temperature levels.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was financially supported by the American University in Cairo - Egypt research grant to the first author and Misr El-Khir Foundation - Egypt.

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