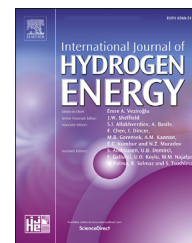


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Analysis of the effect of H₂O content on combustion behaviours of a biogas fuel

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ABSTRACT

The present work deals with the biogas in a combustor with regard to its combustion features under differing conditions of H₂O content and H₂S. The content of water (H₂O) vapour has been changed from 0% to 10% and a CFD code has been employed while implementing numerical investigations. In modelling, a combustion model (the PDF/Mixture Fraction) along with a turbulence model (the k-ε standard turbulence model) has been utilised. This study also deals with the combustion performances of the biogas by the addition of a different quantity of H₂O into the biogas. The Emissions and the flame temperature of the biogas through the combustor apparently seem to be strikingly affected by the changes in H₂O contents. It is interesting to note that the flame temperature zones change their positions and advance to the burner's downstream. The rise in flame temperatures of the biogas can be attributed to the change in H₂O content caused by a better fuel-air mixture. It is also observed that adding H₂O into the biogas lowers the axial temperature levels.

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Introduction

Today people are paying increasingly more attention to the usage of biogas. Biogas which can be obtained from effluent, public's solid waste, residuals and gasification can be conveniently employed in the generation of power, heating systems and the like. It is mainly composed of methane and carbon dioxide with a trace amount of hydrogen, sulfur, and nitrogen. The quantity of these trace components is varied according to how the gasification and production are done [1]. Methane is the main component of the biogas that contains a high level of energy while most of the other constituents are non-combustible. Thus, it is very important to examine the effect of H₂O and H₂S content in a biogas interlocking with its

temperature and emissions. Local governments can use biogas systems as an important element in regional development. Therefore, the biogas systems need to be installed and operated in the most efficient way possible. Many researchers have studied combustion of biogas in various combustion systems. Adouane et al. [2], has carried out an experimental study to investigate the reduction in NO emissions caused by fuel-bound nitrogen. The study conclude that NO_x formation heavily depends on the amount of ammonia in the fuel. It also indicates that the better the air-fuel mixture, the higher the flame temperature. Swirl number additive is robust to ensure the best air-fuel mixture. Furthermore, the emission and combustion characteristics of a producer gas, which includes the amount of nitrogen depending on equivalence ratios and thermal inputs, have been experimentally examined by Bhoi and Channiwala

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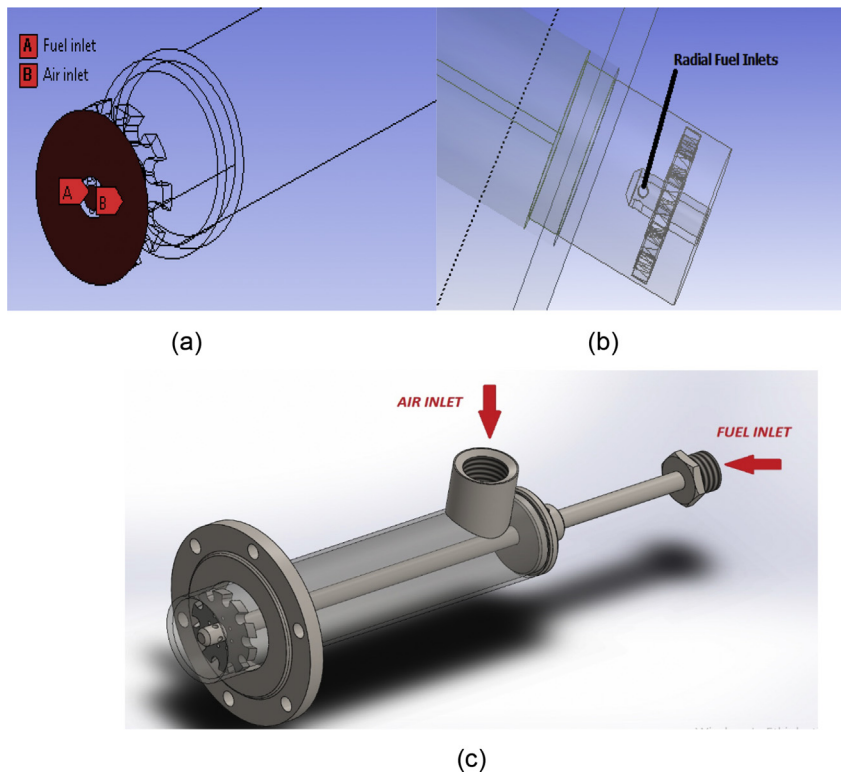


Fig. 1 – The burner; (a) The burner air and fuel inlets, (b) The burner radial fuel inlets, (c) The burner solid model view.

[3]. The study revealed that the maximum energy was formed in its flame front. The combustion characteristics of biogas have been observed by Hosseini et al. [4]. They have investigated the combustion characteristics of biogas flameless mode focus on clean technology development strategies. Biogas with a uniform combustion temperature compared to the traditional combustion has also been analysed. According to their results, when the combustion was without flame, it would not be suitable to use in some combustion systems. In this study, the amount of O_2 in the air is also increased to eliminate this problem. The biogas in micro gas turbines has been studied with respect to the fuel flexibility and performance by Somehsaraei et al. [5]. They argued that with some adjustments in fuel valves and compressor, it is possible to operate engines

with simulated biogas composition. Furthermore, İlbaş and Karyeyen's experiment [6] has confirmed that how the swirl number influences the combustion features of fuels having hydrogen in their content through modelling. The study also indicated that the swirl number providing better air-fuel mixture, thus emission values give better results. H_2S and H_2O mixture was activated to activate the oxygen with an electrical discharge to ensure very low energy cost in H_2 production [7]. Due to the high H_2/CO production capacities under large H_2O/CO_2 flow rates, the promising perovskites are not very efficient in the system, especially because of their low temperature resistance [8]. It is true that some studies mentioned above have dealt with biogas or the blend of fuel combustion. However, there has not been any research conducted so far to examine

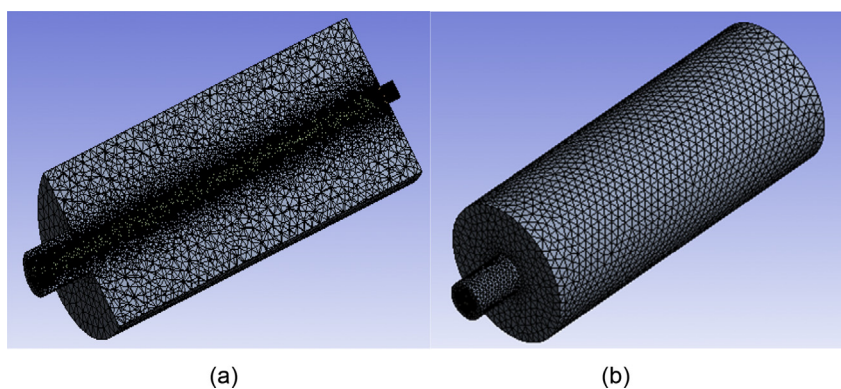


Fig. 2 – The mesh structure; (a) Cross-sectional view of the mesh (b) General view of the mesh.

Table 1 – The composition of Biogas.

Contents	Volume (%)
CO ₂	43,1
CH ₄	55
N ₂	1,53
H ₂ S	10 ppm
O ₂	0,3

the effect of H₂O on combustion features of biogas. Therefore, the current study aims to examine the H₂O influences on biogas fuel combustion features numerically.

Modelling

In this work, to examine the effect of H₂O on combustion features of a biogas fuel, 3D CFD technique has been employed to develop a model through a newly generated diffusion flame of the burner. Fig. 1a shows the burner employed in the current study. The fuel and air inlets are represented by A and B, respectively in Fig. 1a. What is more, this burner fuel outlet contains radial inlets in order to mix fuel with air better as is seen in Fig. 1b. Air and fuel inlets hydraulic diameters are 32 mm and 6 mm respectively. On the other hand, the combustor outlet has a hydraulic diameter of 110 mm. While inlet and fuel temperatures are stabilised at a temperature of 283 K, and combustion gauge pressures are at 21 mbar. It is also important to note that the outlet of the combustor is

indirect contact with the atmospheric air. Fig. 1c shows the solid modelling of the burner.

In Fig. 2a and Fig. 2b are the combustor and burner mesh structure employed in this work. The combustor used is of sudden enlargement type and is 100 cm in length and 40 cm in diameter.

Governing equations

The momentum, 3D continuity, steady-state condition, species equations and energy are employed for the gas mixture combustion mathematical modelling. Below, they can be seen in the transport equation's general form [9]:

$$\frac{\partial(\rho\Phi)}{\partial x} + \text{div}(\rho\Phi u) = \text{div}(\Gamma \text{grad}\Phi) + S_{\Phi} \quad (1)$$

here Φ stands for the dependent variables, while Γ and S_{Φ} symbolizes the transport coefficient and the transport equation's source term for Φ respectively.

In this numerical work, a specified model (Mixture Fraction/PDF Model) is utilised for combustion modelling. In this model, transport equations are solved for a particular conserved scalar. This model does not come up with a solution to equations for individual species. It does not solve transport equations for individual species, either. Rather, the predicted mixture fraction distribution is employed to obtain every single component concentrations for species. The probability density function (PDF) [10] allows explaining the interaction of turbulence and chemistry.

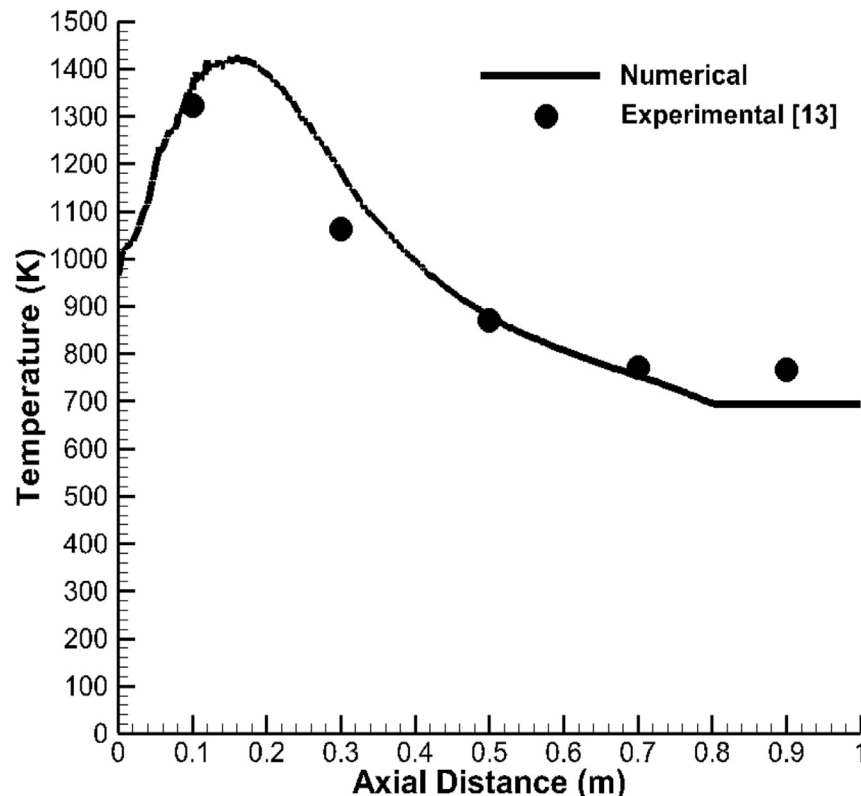


Fig. 3 – The predicted and measured axial temperature profiles in comparison.

In order to simulate turbulent diffusion flames, the PDF modelling approach was specially established. It is possible to express the mixture fraction for a fuel/oxidant system as follows:

$$f = \frac{m_F}{m_F + m_O} \quad (2)$$

here m_O and m_F represent mass fraction of oxidant and fuel, as in the given order.

Interestingly, the fraction of a mixture, f is a conserved quantity with values being computed at the flow domain's each point through the conservation equations below for the averaged value of time in the turbulent flow field [10]:

$$\frac{\partial(\rho \bar{f})}{\partial t} + \frac{\partial(\rho u_i \bar{f})}{\partial x_i} = \frac{\partial}{\partial t} \left(\frac{\mu_t}{\sigma_t} \frac{\partial \bar{f}}{\partial x_i} \right) + S_m \quad (3)$$

here S_m represents the source term whose only function is to transfer mass from liquid fuel droplets into the gas phase.

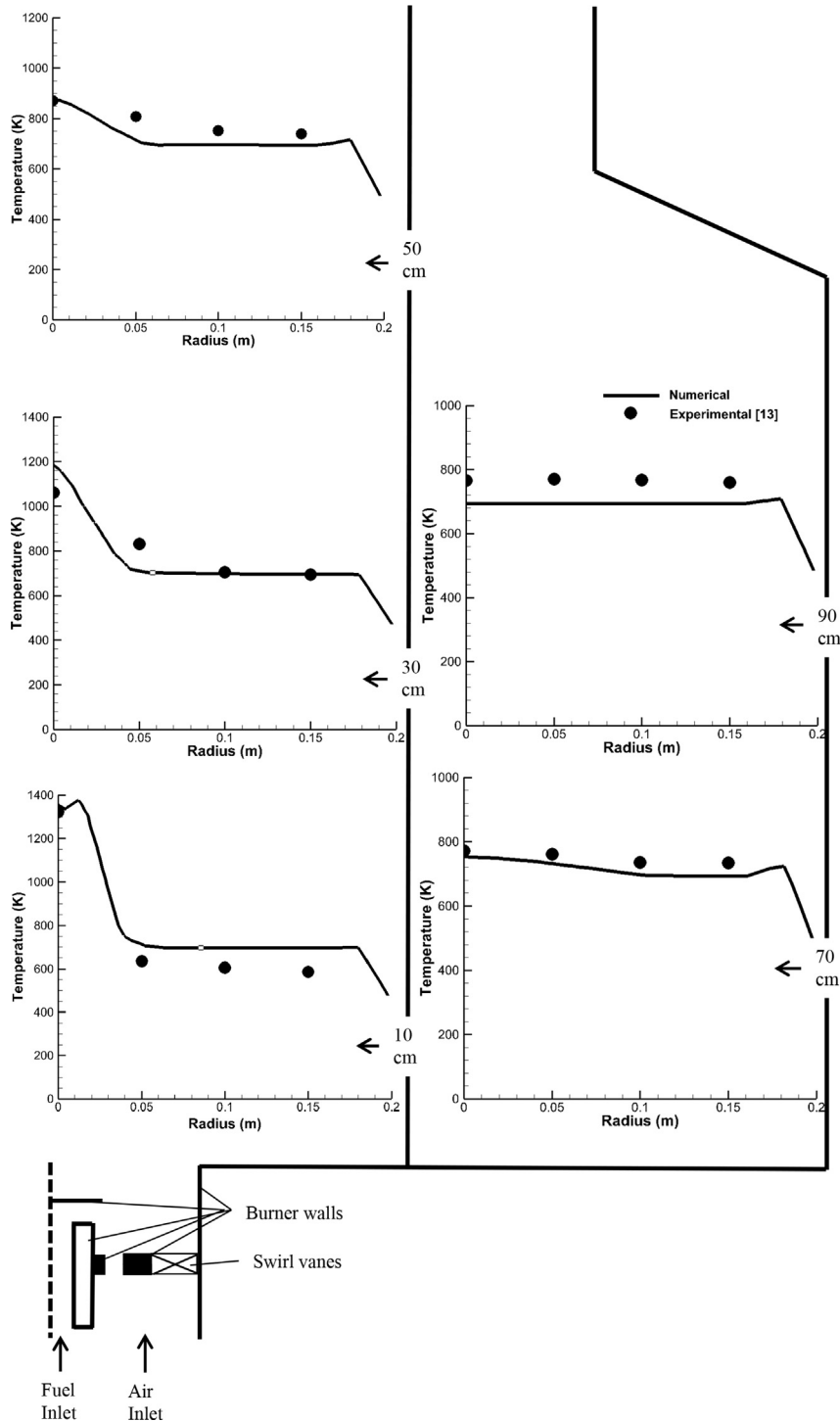


Fig. 4 – The predicted and measured radial temperature profiles.

Apart from the solution of the mean mixture fraction, the mixture fraction variance, \bar{f}^2 a conservation equation is also solved and this is utilised in the closure model defining turbulence-chemistry interactions [10]:

$$\frac{\partial(\rho\bar{f}^2)}{\partial t} + \frac{\partial(\rho u_i \bar{f}^2)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\mu_t}{\sigma_f} \frac{\partial \bar{f}^2}{\partial x_i} \right) + C_g \mu_t \left(\frac{\partial \bar{f}^2}{\partial x_i} \right)^2 - C_d \rho \frac{\epsilon}{k} \bar{f}^2 \quad (4)$$

here σ_f , C_g and C_d represent constants employed in the equation.

The radiative heat transfer occurs when temperatures are high. It is calculated that the flame temperature is usually in value of (1000–1600 °C) in combustors, particularly with regard to near stoichiometric combustion conditions. That's why, there is a considerable heat transfer from swirl combustors. Accordingly, in combustors radiation should be taken into account to make a better estimation of temperature distributions [10]. The simplest form of the P–N model, which is more general, is the P-1 model. The pluses of the P-1 model outweigh those of other radiation models in some ways. For example, because this model comprises the influence of scattering, it makes the solution of it possible with little CPU demand. When it comes to combustion applications with a large optical thickness, it is also seen that this model operates very successfully. It is also possible to conveniently apply this model to intricate geometries with curvilinear coordinates [11]. That is why, in this study, the P-1 radiation model was preferred to predict the biogas combustion more accurately.

The study utilised the FLUENT code for conducting a simulation of the biogas reacting flow in the developed burner and combustor. The finite volume method is employed in this code. The competence to employ diverse physical models including viscous or inviscid, laminar or turbulent flows and so on [12] can be obtained. In order to obtain the pressure–velocity coupling, the Simple algorithm was employed.

The biogas constituents used in this study are given in Table 1 below.

Results and discussions

The model validation

A comparison of the existing measurements [13] is made with obtained predicted results to validate the model. The measurements of the biogas axial and radial temperature values are found to be at axial distances from one end of the combustor to the other. So as to obtain better predictions, combustion conditions were specially designated. Thermal power was set as 10 kW and excess air ratio was set as 1.2. As Fig. 3 plainly demonstrates, the axial temperature profiles correspond to the experimental data to a large extent. Only a very insignificant divergence exists between the forecasts made and the measurements obtained along the combustor.

A comparison of the measurements and predictions has also been made with regard to the biogas combustion at radial positions. As can be seen in Fig. 4, the temperature distributions of biogas combustion are clearly seen that the predictions are to a large extent consistent with the

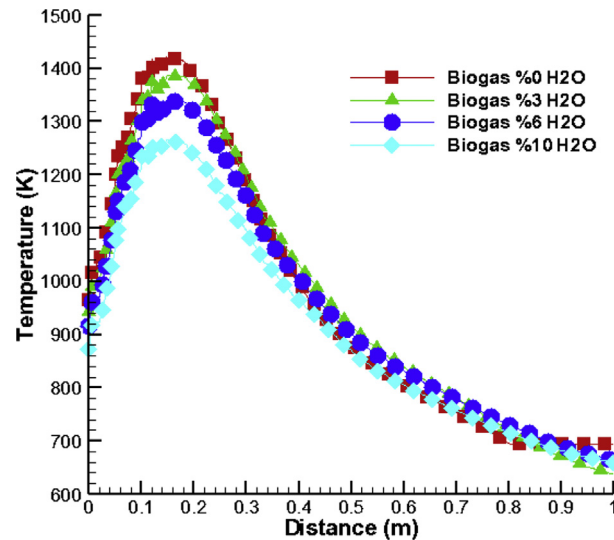


Fig. 5 – The predicted axial temperature profiles for different H₂O contents.

measurements taken in the biogas combustion. Hence, this is showing that combustion modelling can be suitably used for further modelling.

The impact of the H₂O contents on temperature distributions

Fig. 5 reveals the influence of the H₂O content on axial temperature distributions. It may be concluded that the more rises H₂O is in the biogas fuel, the more decreases the temperature of biogas flame. This can be because of dilution of the air-fuel mixture.

In general, it is observed that the flame positionally advances to the burner downstream. This may be explained with the tangential air velocity by means of turbulator. In all cases, because of convective and radiative heat transfers, a progressive decline in temperature levels is observed close to the combustor outlet. The highest temperatures obtained during the combustion of the biogas is from 0.1 to 0.2 m in the combustion chamber.

Fig. 6 demonstrates the impact of the H₂O on the biogas combustion radial temperature distributions. It can be seen from Fig. 6 that there is a rise in temperature of the biogas flame when the amount of H₂O is decreased in axial distances from 10 cm to 90 cm in 20 cm intervals. It is interesting to note that the temperature levels vary significantly depending on the amount of H₂O. Yet, there is not any noteworthy alteration in radial temperature levels from one end of the combustor to the other whatever the amount of H₂O is.

Fig. 7 demonstrates CO releases of the biogas combustion at axial positions. It can be concluded from Fig. 7 that CO emission distributions are significantly affected by any change in H₂O content. As the H₂O content is augmented in the biogas composition, the CO resulting from the combustion is decreased in the flame zone due to the oxidation of CO by means of H₂O in the biogas fuel. Connected with this, as the amount of CO decreases, it is observed that the complete

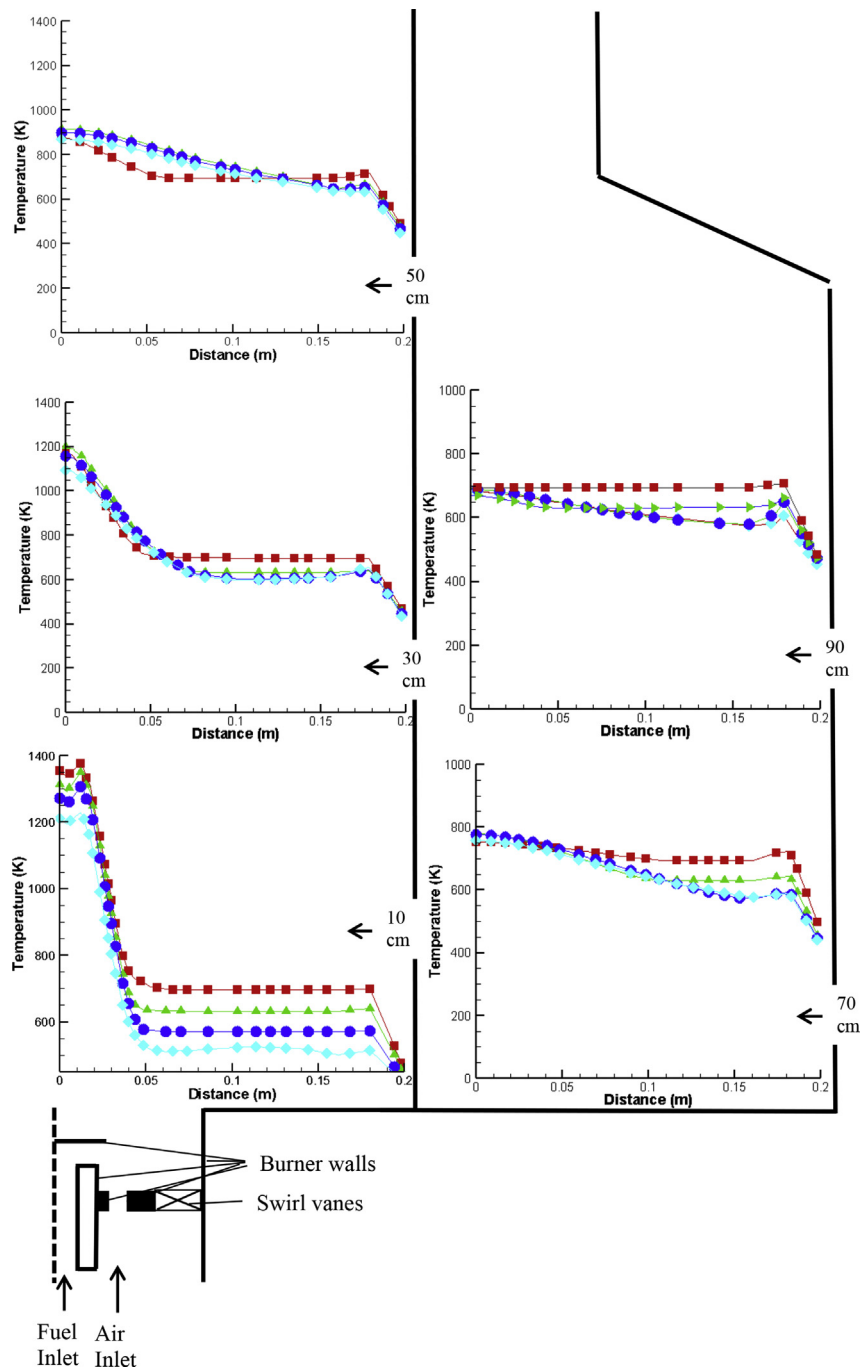


Fig. 6 – The predicted radial temperature profiles for different H_2O contents.

combustion is approached. Besides, when the amount of H_2O in the biogas content is 10%, the amount of CO obtained by the combustion is least in the flame zone, while CO emission levels have almost the same level at the combustor exit.

Fig. 8 revealed the releases of CO_2 in biogas combustion at axial positions. As the H_2O in the biogas content increases, the change in the CO_2 content of the combustion is shown in Fig. 8. It can be easily concluded from Fig. 8 that CO_2 emissions decreased with any increase in the amount of H_2O , which may be attributed to the dilution of the fuel-air mixture by

decreasing the methane and CO_2 ratio in the biogas. Further, it is observed that the amount of CO_2 becomes a maximum into the downstream due to the completion of combustion process. However, there is almost no change in CO_2 emission levels in all cases after an axial distance of 0.5 m up to the outlet.

Fig. 9 demonstrates distributions of axial SO_2 emissions. H_2S , in the amount of 10 ppm, is found in the biogas content. There are SO_2 emissions from the combustor because of H_2S in the biogas. It is predicted that SO_2 distributions are affected by

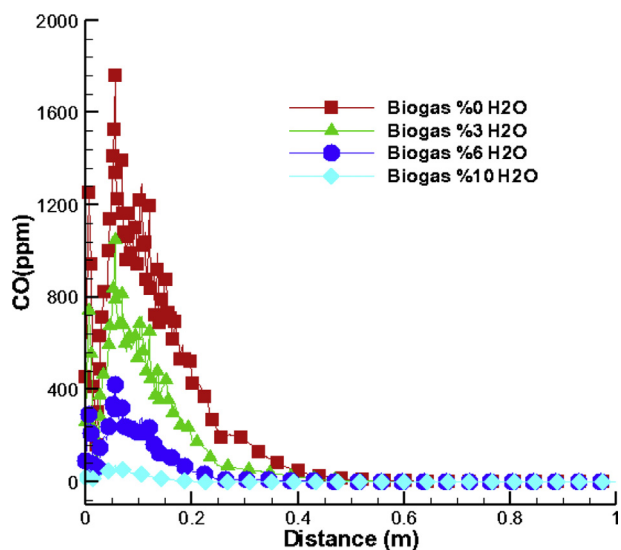


Fig. 7 – Axial CO (ppm) distributions.

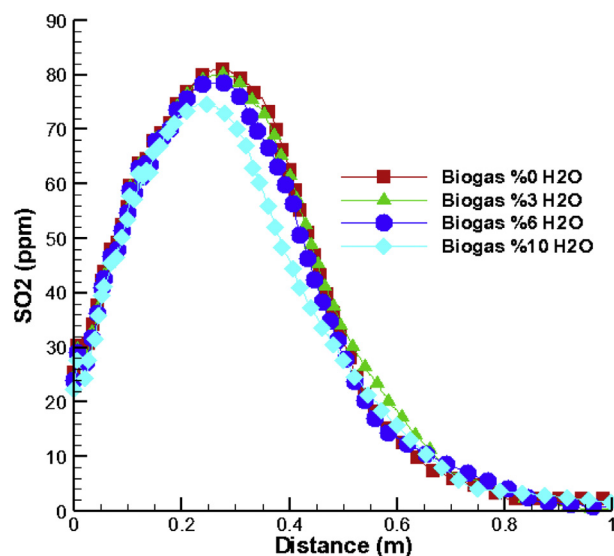


Fig. 9 – The predicted axial SO₂ (ppm) profiles for different H₂O contents.

the change of H₂O content in the fuel. The maximum SO₂ regions changed their positions with the change of the H₂O content. According to the H₂O change in the biogas content, the maximum value of SO₂ emissions as a result of combustion is between 0.2 and 0.4 m in the combustion chamber. It can be stated that the increase in H₂O content gradually decreases the SO₂ emissions in the flame zone by means of SO₂ reacted with H₂O in the biogas fuel.

The axial H₂O emission distributions and its emission values when H₂O content is changed from 0% to 10% in the biogas content during the combustion are shown in Fig. 10. H₂O distributions in the combustor are considerably influenced by any change in H₂O. In the event of a change in the H₂O amount, a move to other positions can be observed in the maximum H₂O zones. As the H₂O in the biogas content increases, it is possible to easily say that the amount of H₂O obtained by the combustion increases.

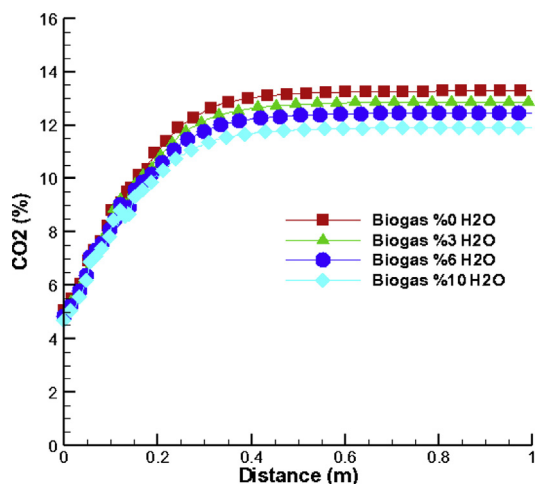


Fig. 8 – The predicted axial CO₂(%) profiles for different H₂O contents.

Fig. 11 illustrates temperature distributions for different N₂ and O₂ contents in the air. It is shown that, as the amount of O₂ in the air increases, the temperature in the axial distance in the combustion chamber increases. Temperature distributions in the combustor is significantly influenced by changes in the amount of N₂ and O₂. As the O₂ content of the air increases, it is advisable to burn the biogas with O₂ due to the temperatures resulting from the combustion. In the case of a change in O₂, the maximum O₂ zones advance to other positions. The maximum temperatures obtained from the combustion of the biogas at 0.2 m in the combustion chamber. It

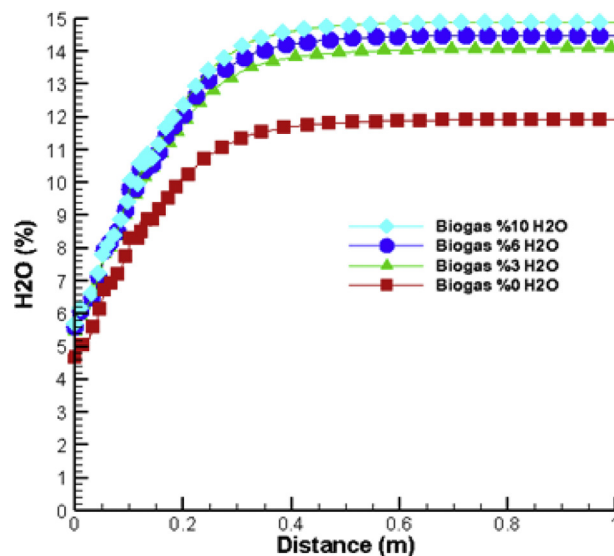


Fig. 10 – The predicted axial H₂O (%) profiles for different H₂O contents.

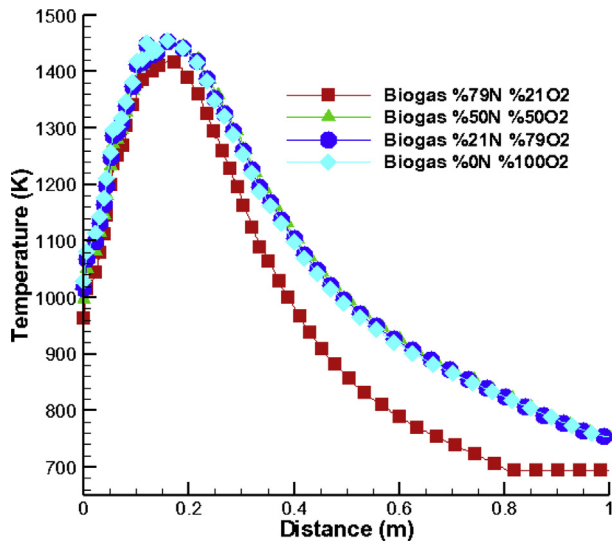


Fig. 11 – The predicted temperature profiles for different N_2 and O_2 contents.

can be concluded that as the O_2 content in the air is increasing, temperature levels are also increasing gradually.

Conclusions

This is a numerical study conducted to examine the effects of varying H_2O contents in the biogas on biogas combustion characteristics. In the case of different proportions of H_2O in biogas, SO_2 values resulting from the combustion of H_2S in biogas content were also investigated. In order to pave way for further modelling, a comparison has been made between the numerical predictions and the existing temperature measurements. The biogas content is calculated volumetrically and mathematically modelled using the CFD program. The present study enables us to make the following conclusions;

- It can be concluded that an increase in the H_2O content of biogas leads to a decrease in the biogas flame temperature in the combustor due to the dilution of the mixture.
- When there is an increase in H_2O content, the flame zone position is moved to the burner downstream.
- CO and CO_2 emissions are observed in significant variation with an increase in H_2O contents. It is interesting to note that a decline in CO_2 emission occurs when H_2O rises due to account of a better fuel-air mixture.
- As the H_2O content is augmented in the biogas composition, the CO resulting from the combustion is decreased in the flame zone due to the oxidation of CO by means of H_2O in the biogas fuel.
- H_2S in the biogas causes considerable SO_2 emissions. The change in H_2O content also influences the combustor SO_2 distributions. The maximum SO_2 zones advance to the other positions in the event of a change in the H_2O content.

- The increase in H_2O content gradually decreases the SO_2 emissions in the flame zone by means of SO_2 reacted with H_2O in the biogas fuel.
- As the O_2 content in the air increases, the combustion temperature of the biogas increases at the axial distance of the combustion chamber.

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Nomenclature

A	Convection heat transfer surface area
C	Experimental constant
CH_4	Methane
CFD	Computational fluid Dynamics
CO	Carbon monoxide
CO_2	Carbon dioxide
c_p	Specific heat
f	Mixing ratio
J	Flux
h	Heat transfer coefficient
H_2	Hydrogen
H_2O	Water vapour
H_2S	Hydrogen sulfide
k	Heat conduction coefficient
K	Kelvin
m	Meter
m^3	Cube meter
m_j	Mass rate
N_2	Nitrogen
NO_x	Nitrogen oxide
NO	Nitrogen monoxide
O_2	Oxygen
Q	Heat transfer
R	Universal gas constant
SO_x	Sulfur Oxide
SO_2	Sulfur dioxide
Sj	Mass ratio of occurrence
T	Temperature
u	Velocity
ppm	Parts per million
$^{\circ}C$	Celcius
ρ	Density
τ	Viscous shear stress
Γ	Coefficient of laminar change
μ	Viscosity
δ	Kronecker delta tensor
ε	Rronec Propagation rate
Pr	Prandtl number
\bar{F}^2	Mixing ratio change
σ	Stefan-Boltzman's constant
α	Absorption and scattering coefficient
\emptyset	Equivalence ratio

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