AIR FUEL RATIO STUDY FOR MIXTURE OF BIOGAS AND HYDROGEN ON MILD COMBUSTION

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ABSTRACT

Air fuel ratio (AFR) is an important parameter to indicate the combustion quality. Lower AFR will result in unburned hydrocarbons (UHC) that harm the environment. This paper discusses the simulation of AFR for the moderate or intense low oxygen dilution combustion using bluff-body burner. A low calorie biogas fuel of 50% methane, 20% hydrogen and 30% carbon dioxide were used in this simulation. The AFR evaluated based on the UHC produced and measured in the exhaust gas composition. Stoichiometric AFR produced zero UHC and zero excess oxygen measured in the exhaust gas. UHC in the exhaust gas is a waste of fuel and is possible to create unwanted combustion at an unwanted location. The study found that at AFR 4:1, almost zero UHC was detected in the exhaust gas pipe and exhaust gas recirculation pipe.

Keywords: Air fuel ratio; MILD combustion; biogas; hydrogen; exhaust gas recirculation.

INTRODUCTION

Demand for clean and low cost energy is become a global issue due to the depletion of fossil fuel and environmental pollution concern [1, 2]. Combustion of fossil fuel still plays a major role for today energy generations [3, 4]. Fuel cost for the heating process is accounted for up to 10~15% of total production cost [5]. Both fuel efficiency and lean combustion are very critical to reduce the total production cost and directly reduce the end product cost. There are possible long-term solutions which are high thermal efficiency combustion technology and biogas fuel produced from local feedstock. MILD combustion is one of the new combustion technologies to increase thermal efficiency and reduce combustion pollution emission [6-8]. This technology is also known as flameless oxidation (FLOX) [9, 10]. The MILD combustion is getting more attention from the scientific community [11, 12] and labelled as part of the dilution combustion technology [13]. It emits low nitrogen oxides (NO_x) and carbon monoxide (CO) pollutant emissions, and high thermal [14-16]. When using the regenerator to recycle the waste heat of flue gases, the thermal efficiency of MILD combustion can increase by 30%, while reducing

NOx emissions by 50% [15]. By using biogas as a fuel [17-20] or low calorific value (LCV) gas, CO_2 emitted by the combustion will be utilised by biomass, which is the source of biogas.

The effect of air fuel ratio (AFR) to the combustion efficiency has been studied for MILD combustion [21, 22] and hydrogen fueled internal combustion engine [23, 24]. The result shows that the performance of combustion is very much affected by AFR used. Too low or too high AFR will reduce the combustion efficiency. The industrial heating community always uses a high AFR setting, which is also lean combustion. Lean combustion reduces the fuel cost and unwanted unburned hydrocarbons (UHC) gases that are released into the atmosphere. The requirement of MILD combustion is the oxygen dilution and the mixtures preheat. One of the economical ways to achieve this is by utilising the exhaust gas. Exhaust gas recirculation (EGR) was previously used for MILD combustion [25-27] and has the role of preheating the oxidiser and diluting the oxygen. The combustion chamber needs to be enclosed in order to collect the flue gas, and it is utilised as EGR. EGR flows downward to mix with incoming fresh air. The EGR ratio is based on the dilution ratio that is required by the combustion. The EGR ratio is the volume of flue gas used as EGR over total flue gas. MILD combustion can be achieved when the oxygen level is between 3~13% [11].

The purpose of this study is to simulate and check the AFR on LCV gas mixed with hydrogen and the effect on unburned methane (CH_4) and hydrogen (H_2) for the open burner MILD combustion. A mixture of 50% methane, 20% hydrogen and 30% carbon dioxide was used to make the biogas. The result is then compared to a previous study using a different composition of fuel.

COMPUTATIONAL MODELLING

Computational fluid dynamics (CFD) modelling has been successful in numerically solving many engineering problems [28-32]. There are many researchers [33-37] who have successfully studied the MILD and flameless combustion using the numerical simulation method. The open burner MILD combustion was modelled (Figure 1) using ANSYS14.5 design modeler and simulates using FLUENT 14.5 with the size of 1.9 m height and 0.6 m width. This model is a modified version of the previous [38]. Typical data for the burner is shown in Table 1.

Table 1. Typical data for burner and combustion chamber

Item	Data
Fuel	50% methane, 20% hydrogen and 30% carbon dioxide
Oxidiser	Atmospheric air and syntactic air at room temperature
Fuel inlet	1 x 78.5 mm^2
Air inlet	4 x 78.5 mm^2
Chamber size	Diameter 600 mm, Height 860 mm
EGR	4 EGR with 1962.5 mm^2 each inlet
Mesh method	Tetrahedrons (patch conforming method) with 111,975 nodes and 501,831elements
Radiation model	Discrete ordinate (DO) model. Absorption coefficient: Weighted sum of gray gas (WSGGM) model

The fuel and air injection nozzles were designed as a bluff body to help the mixing process. The fuel nozzle was in the middle with the diameter of 1 mm, and annulus air nozzle around the fuel nozzle with the opening size of 1,570 mm^2. The combustion chamber consists of four EGR pipe with inner diameter of 1962.5 mm^2 each. The MILD combustion simulation involved the solution of the chemical reactions, turbulent flows, heat transfer and species transport. Non-premixed combustion with chemical equilibrium and non-adiabatic energy treatment was used. In this work, the Reynolds-Averaged Navier-Stokes (RANS) equations, together with a realisable k-ε turbulence model [39] (that was developed based on standard k-ε turbulence model [40] are solved. The discrete ordinate (DO) radiation model [41] and the absorption coefficient of the weighted sum of gray gas (WSGGM) model is used in this work.
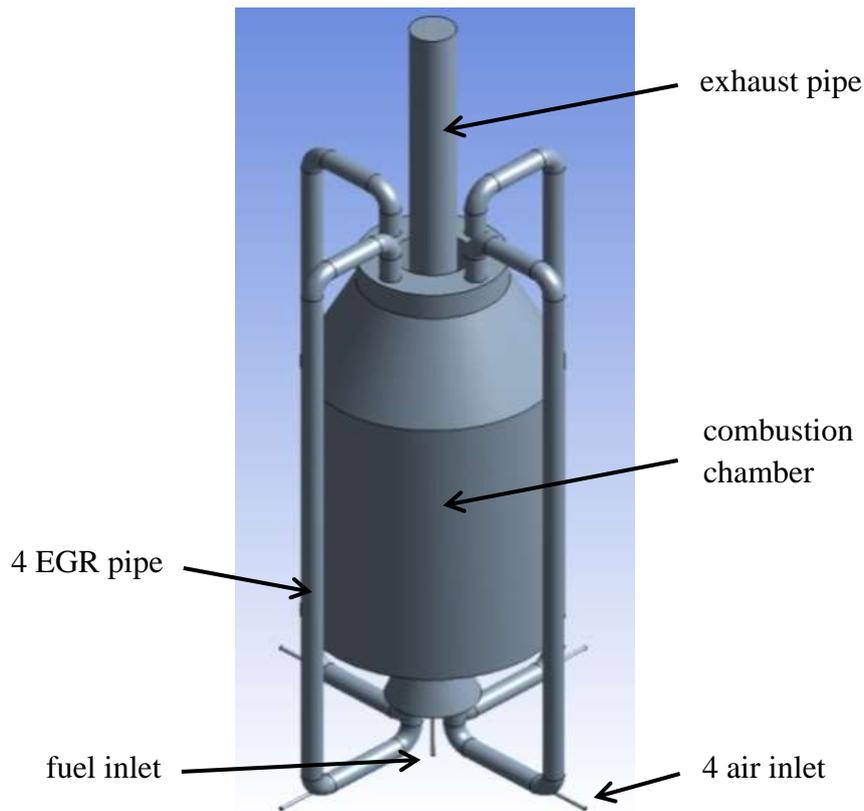

Figure 1. 3D burner geometry with boundary conditions

The method of meshing is tetrahedrons (patch conforming) with advanced sizing function of proximity and curvature and detail setting, as in Table 2. The mesh inflation for the near the wall was five layers with a growth rate of 20%. The nozzle mesh element refinement was used for air, fuel inlet, air fuel nozzle and EGR inlet and outlet. Figure 2 shows the meshing elements of 1,477,322 and nodes count of 490,406. The maximum skewness is 0.904, which is below the allowable limit of 0.98. The maximum skewness must be below 0.98 or the solution will easily become divergence error and will not converge as desired [42]. Fuel enters the burner fuel inlet at the bottom of the burner with 10 mm diameter and 78.5 mm^2 inlet area. If the velocity of the fuel injected is 1 m/s, the volume flow rate for the fuel is 7.85×10^{-5} m^3/s. Air is injected through four inlets at the side of EGR with 10 mm diameter each. Total air inlet diameter is 314 mm^2. If the

air is injected at 1 m/s, the air volume flow rate is 3.14×10^{-3} m^3/s. The ratio of air and fuel nozzle in this study is 5.0. This ratio was based on the previous study that gave AFR of 5.0 to achieve almost zero UHC and unburned hydrogen in the EGR pipe [43]. The initial air and fuel nozzle ratio in the previous study was based on the methane air mass fraction ratio which 9.5:1.

Table 2. Mesh setting details.

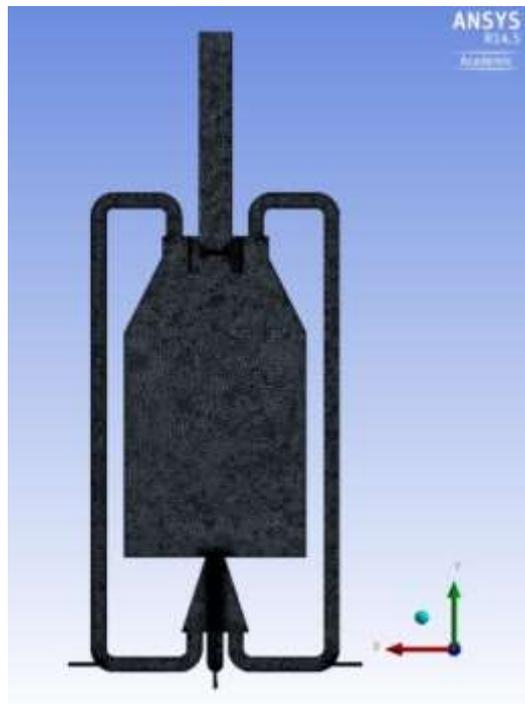| Sizing	Setting
Advance Size Function	On: Proximity and Curvature
Relevance Center	Fine
Initial Size Seed	Active Assembly
Smoothing	High
Transition	Slow
Span Angle Center	Fine

Figure 2. Model after meshing in 2D.

This burner was fuelled by the mixture of methane with hydrogen and carbon dioxide. The fuel mole fraction for this work to produce LCV is given in Table 3. The air mole fraction is 21.008% O_2 and 78.992% N_2. In the author's earlier paper, the different LCV composition was used with an amount of ethane, propane and butane. In the laboratory for the experimental work, it is not practical to use seven types of gas (Table 3), as the supply and mixing process becomes too complicated and not economical. Thus, three types of gases are analysed in this paper: methane, hydrogen and carbon dioxide. The difference is that the previous study used 86.64% of hydrocarbon mixed with 13.36% CO_2, and this paper used 70% of hydrocarbon and 30% of CO_2.

Table 3. LCV gas composition

| Gas	This paper	Previous study [38]
Methane (CH_4)	0.50	0.5344
Hydrogen (H_2)	0.20	0.3000
Carbon dioxide (CO_2)	0.30	0.1336
Nitrogen (N_2)	0.00	0.0130
Ethane (C_2H_6)	0.00	0.0170
Propane (C_3H_8)	0.00	0.0010
Butane (C_4H_{10})	0.00	0.0010

The oxygen in the oxidiser stream will be diluted by EGR to the required level. The AFR was calculated based on the air and fuel velocity injected to the burner. Due to the different size of the inlet diameter between air and fuel, AFR is calculated on volume flow rate of air divided by fuel volume flow rate. The AFR and air velocity used in this study ranges from 1.0 to 6.5 m/s and 20 to 120 m/s. The total injected volume flow rate into a burner is between 0.0057 m^3/s and 0.0176 m^3/s. The details of AFR and volume flow rate are shown in Table 4.

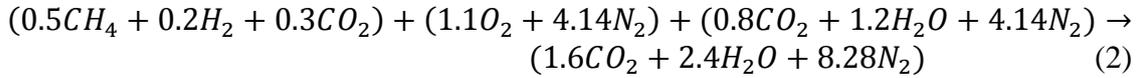Table 4. Air and fuel volume flow rate and AFR

Air velocity (m/s)	Fuel velocity (m/s)	Air volume flow rate (m^3/s)	Fuel volume flow rate (m^3/s)	Total volume flow rate (m^3/s)	AFR
20	100	0.0028	0.0028	0.0057	1.0
30	100	0.0043	0.0028	0.0071	1.5
40	100	0.0057	0.0028	0.0085	2.0
50	100	0.0071	0.0028	0.0099	2.5
60	100	0.0085	0.0028	0.0114	3.0
65	100	0.0092	0.0028	0.0121	3.3
70	100	0.0099	0.0028	0.0128	3.5
75	100	0.0107	0.0028	0.0135	3.8
80	100	0.0114	0.0028	0.0142	4.0
100	125	0.0142	0.0035	0.0177	4.0
100	120	0.0142	0.0034	0.0176	4.2
90	100	0.0128	0.0028	0.0156	4.5
100	100	0.0142	0.0028	0.0170	5.0
90	82	0.0128	0.0023	0.0151	5.5
120	100	0.0170	0.0028	0.0199	6.0
100	77	0.0142	0.0022	0.0164	6.5

RESULTS AND DISCUSSION

The effect of AFR on the concentration of the unburned CH_4 and H_2 was evaluated using a modelled open burner (Figure 1). The simulated results in Figure 3 show that the AFR of 1.0 gives the highest unburned CH_4 at the stoichiometric value 4.17. The initial value of mole fraction for CH_4 and H_2 is 0.5 and 0.20, respectively. The combustion process can be written in a general hydrocarbon stoichiometric combustion equation:

$$C_n H_m + \left(n + \frac{m}{4}\right)(O_2 + 3.76N_2) \rightarrow nCO_2 + \frac{m}{2}H_2O + 3.76\left(n + \frac{m}{4}\right)N_2 \qquad (1)$$
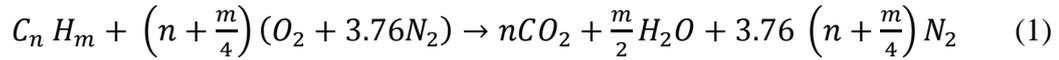
The stoichiometric combustion equation (Eq. (1)) with 50% EGR for low calorific value gas consists of mole fraction of 50% methane, 20% hydrogen and 30% carbon dioxide. From total flue gas, 50% will flow back to the chamber and lower the oxygen level in the oxidiser stream.

$$(0.5CH_4 + 0.2H_2 + 0.3CO_2) + (1.1O_2 + 4.14N_2) + (0.8CO_2 + 1.2H_2O + 4.14N_2) \rightarrow$$
$$(1.6CO_2 + 2.4H_2O + 8.28N_2) \qquad (2)$$

This equation is for the equivalent ratio of 1.0. If the equivalent ratio is reduced, the fuel is reduced and AFR increases. In this study, when AFR is equal to 4.0, unburned CH_4 and H_2 mole fraction in the EGR pipe is almost zero. The stoichiometric AFR for this fuel composition is 4.17. Compared to the previous study [38] with different burner design and different LCV mixing (Table 3), UHC and unburned hydrogen reaches almost zero when AFR is 5.0. The stoichiometric AFR for this fuel composition is 3.61. Figure 3 shows the comparison of these results and shows that when AFR = 4.0 and 5.0, the CH_4 and H_2 mole fraction in EGR were almost zero.
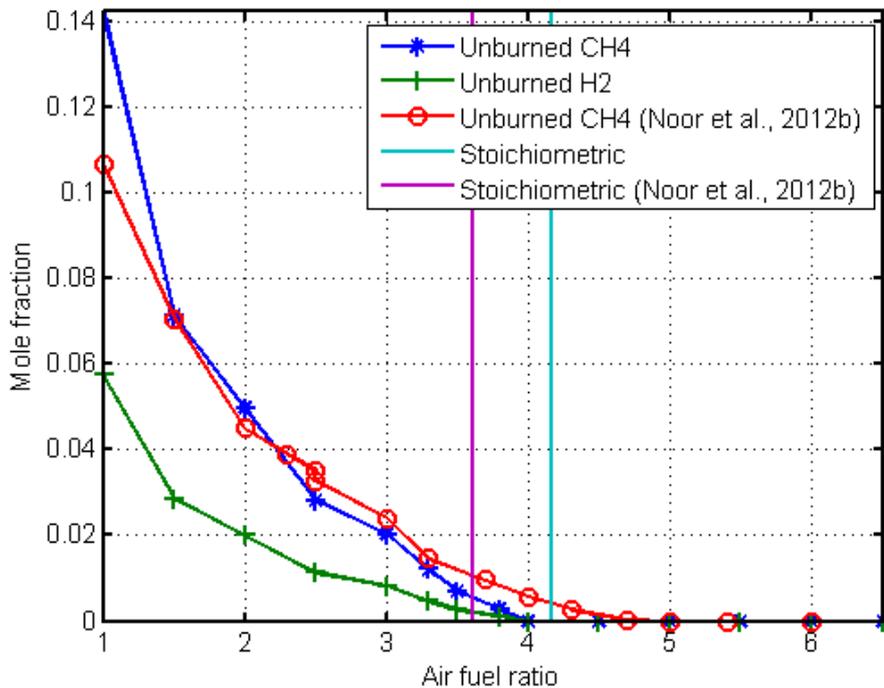

Figure 3. Unburned of CH_4 and H_2 for AFR.

The result in Figure 4 shows that the UHC in flue gas flows through an exhaust opening and EGR pipe. Figure 4 shows a reaction from the mixing of the hot UHC and O_2—which is supplied from the fresh air—that happens outside of the combustion chamber such as in the EGR pipe. The reaction is unfavourable. Figure 5 shows a desired combustion with 100% methane and oxygen consumed by the combustion process, which achieves MILD combustion state. Figures 6 and 7 shows the mole fraction of methane and oxygen respectively. Both methane and oxygen were 0% in the

combustion chamber and EGR pipe. For oxygen mole fraction in the Figure 7, there is a small amount of oxygen on the top of the exhaust pipe. This condition occurred due to the back flow of the exhaust pipe. A small back flow does not have a significant effect on the combustion process since the exhaust pipe is long enough to avoid back flow of fresh air into the combustion chamber.
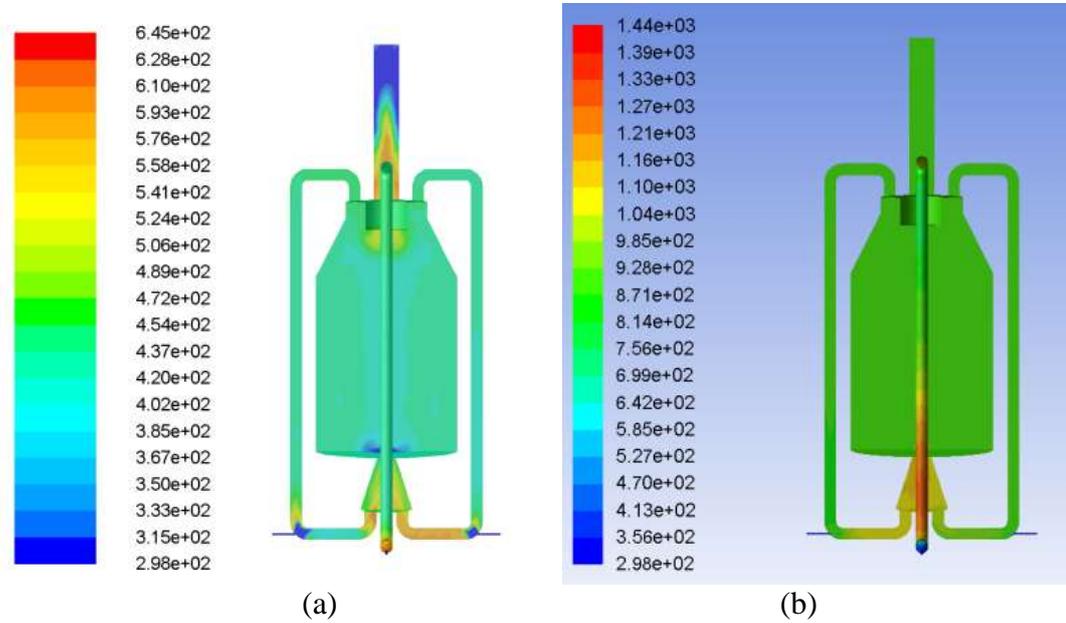

(a)   (b)

Figure 4. Temperature contour (Kelvin) when unwanted burning in EGR pipe due to unburned CH_4 and H_2 (a) in exhaust pipe (b) in EGR pipe
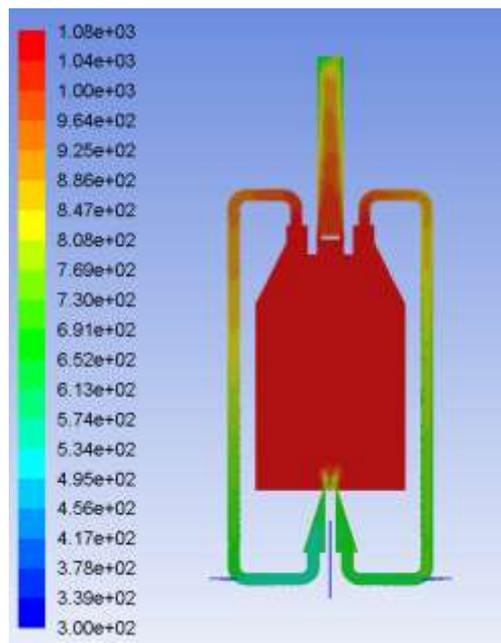

Figure 5. Cross section on temperature contour (Kelvin) when proper MILD combustion with fuel 100% consumed
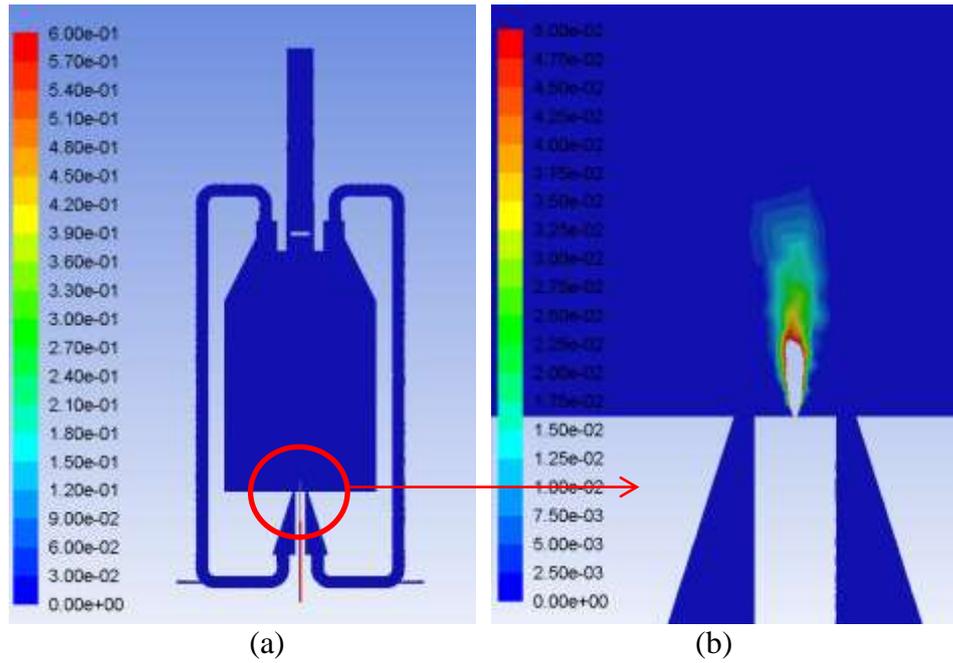
(a)   (b)

Figure 6. The mole fraction of methane in the combustion chamber and EGR pipe; (a) is for the full domain (with a mole fraction range between 0 and 0.6), (b) for a zoomed-in region (with a mole fraction range between 0 and 0.05)

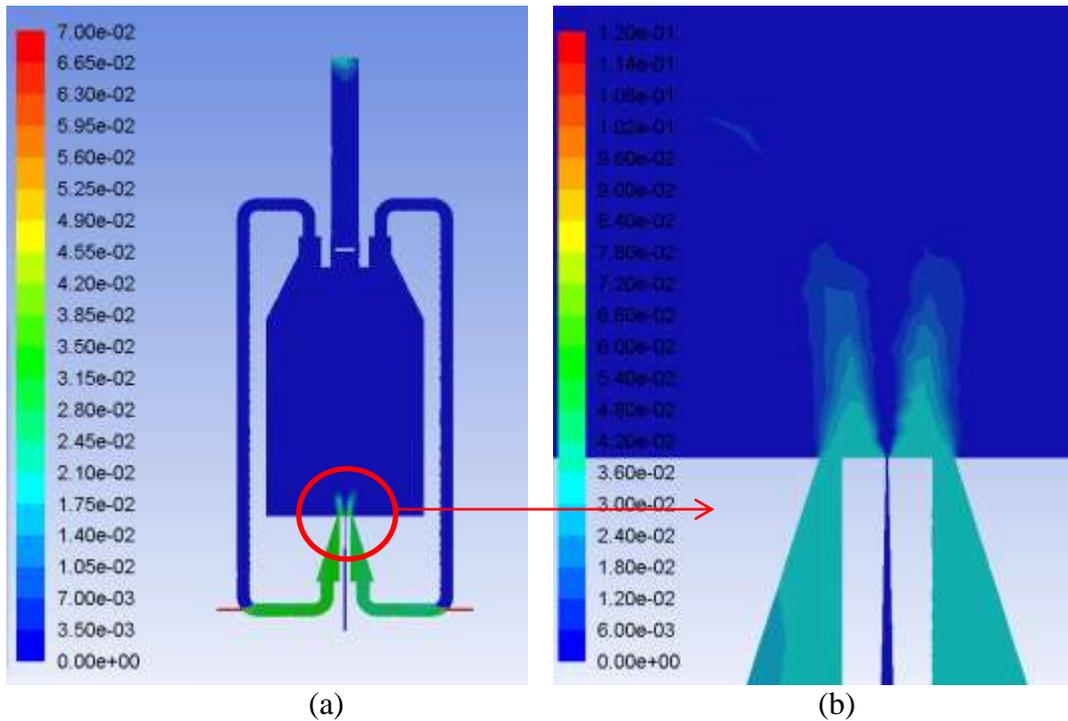(a)   (b)

Figure 7. The mole fraction of oxygen in the combustion chamber and EGR pipe; (a) is for the full domain (with a mole fraction range between 0 and 0.07), (b) for a zoomed-in region (with a mole fraction range between 0 and 0.012)

The MILD combustion regime can be achieved either fuelled by natural gas or biogas, and the performance of a burner remaining constant. In both cases, pollution

emissions are very low, NO_x emissions are below 3 ppm and CO emissions are below 16 ppm [17]. Dally et al. [44] was successful in achieving MILD combustion by using sawdust as a fuel. Biogas gives 2% lower efficiencies compared to natural gas. This condition should be compensated by the reduction of greenhouse gases when using biogas as a fuel. These results indicate that the flameless combustion regime can be achieved with different fuels compositions [17].

CONCLUSIONS

The present paper concludes that AFR for biogas mixed with 20% hydrogen gives lower AFR than the 30% hydrogen. For biogas mixed with 20% hydrogen, the achieved AFR is 5:1; and for biogas mixed with 30% hydrogen, the achieved AFR is 4:1. The simulation results deduce that unburned fuel or UHC will be in the exhaust gas when not enough oxygen is supplied to the combustion chamber. Air and fuel plays an important role to complete the combustion process. In the combustion process, to consume all the fuel, AFR must be higher than 4:1. Otherwise, the combustion process will produce unburned methane and hydrogen. This condition is called rich fuel combustion. UHC is a waste of fuel, and it is part of environmental pollution.

ACKNOWLEDGMENTS

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