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THE AIR FUEL RATIO STUDY FOR THE 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 harms the environment. This paper discusses the simulation of AFR for the Moderate or Intense Low oxygen Dilution (MILD) 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 will be 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 unwanted location. The study found that at AFR 4:1, almost zero UHC was detected in the exhaust gas pipe and Exhaust Gas Recirculation (EGR) pipe.

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

INTRODUCTION

Fuel cost for heating process is accounted up to 10 ~ 15% from total production cost (USDOE, 2001). Both fuel efficiency and lean combustion are very critical to reduce the total production cost and directly reduce the end product cost. Demand for clean and low cost energy is become a global issue due to the depletion of fossil fuel and environmental pollution concern (Shafie and Topal, 2009). A high thermal efficiency combustion technology and biogas fuel are produced from local feedstock are possible long term solutions. MILD combustion is one of the new combustion technologies to increase thermal efficiency and reduce combustion pollution emission (Cavaliere and Joannon, 2004; Dally et al., 2004, 2010). This technology is also known as Flameless Oxidation (FLOX) (Wünning, 1991, 1996). The MILD combustion is getting more attention from the scientific community (Joannon et al., 2000) and labeled as part of the dilution combustion technology (Torresi et al., 2010). It emits low nitrogen oxides (NO_x) and carbon monoxide (CO) pollutant emissions and high thermal efficiency (Dearden et al., 1993, 1996; Dally et al., 2002; Tsuji et al., 2003; Christo and Dally, 2004; Ellul et al., 2006; Noor et al., 2012a). 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% (Tsuji et al, 2003). By using biogas as a fuel (Colorado et al., 2009, 2010; Hosseini and Wahid, 2013) or Low Calorific Value (LCV) gas, CO_2 emitted by the combustion will be utilized 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 (Quinqueneau et al., 2001; Kumar et al., 2005; Noor et al., 2012b, 2012c) and hydrogen fueled internal combustion engine (Rahman et al., 2008, 2010). 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 high AFR setting which is also lean combustion. Lean combustion reduces the fuel cost and unwanted Unburned Hydrocarbons (UHC) gases that are released to atmosphere. The requirement of MILD combustion is the Oxygen dilution and the mixtures preheat. One of the economical ways to achieve this is by utilizing the exhaust gas. Exhaust Gas Recirculation (EGR) was previously used for MILD combustion (Katsuki and Hasegawa, 1998; Flamme et al., 1998; Noor et al., 2012b) and play the role to preheat the oxidiser and dilute the Oxygen. The combustion chamber needs to be enclosed in order to collect the flue gas and it is utilized as EGR. EGR flows downward to mix with incoming fresh air. The EGR ratio is determined 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% (Noor et al., 2012a). 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 the previous study using different composition of fuel.

MODELLING

The Computational Fluid Dynamics (CFD) modeling was successful in numerically solving many engineering problems (Dally et al., 1998; Davidson, 2002; Wandel et al., 2003; Hekkens, 2004; Rahimi et al., 2006; Mollica et al., 2010; Najiha et al., 2012a, 2012b). There are many researchers (Galletti et al., 2007; Parente et al., 2008; Mardani et al., 2010; Mardani and Tabejamaat, 2010; Mardani et al., 2013) are using numerical simulation method and successful to study the MILD and flameless combustion. 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 from the previous model (Noor et al., 2012c). Typical data for the burner was shown in Table 1.

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 realizable k-ε turbulence model (Shih et al., 1995) [that developed based on standard k-ε turbulence model (Launder and Spalding, 1974)] are solved. The discrete ordinate (DO) radiation model (Chui and Raithby, 1993) and absorption coefficient of weighted sum of gray gas (WSGGM) model is used in this work. Figure 2 indicates that when MILD is achieved, temperature inside the combustion chambers will be homogenous.

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 600mm, Height 860mm
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.

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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 5 layer with 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 be easy to become divergence error and will not converge as desired (Noor et al., 2013). 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 $7.85x10^{-5}$ m^3/s. Air is injected through 4 inlets at the side of EGR with 10 mm diameter each. Total air inlet diameter is 314 mm^2. If the air injected at 1 m/s, the air volume flow rate is $3.14x10^{-3}$ 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 was given AFR of 5.0 to achieve almost zero UHC and unburned hydrogen in EGR pipe (Noor et al., 2012a). The initial air and fuel nozzle ratio in previous study was based on the methane air mass fraction ratio which 9.5:1.

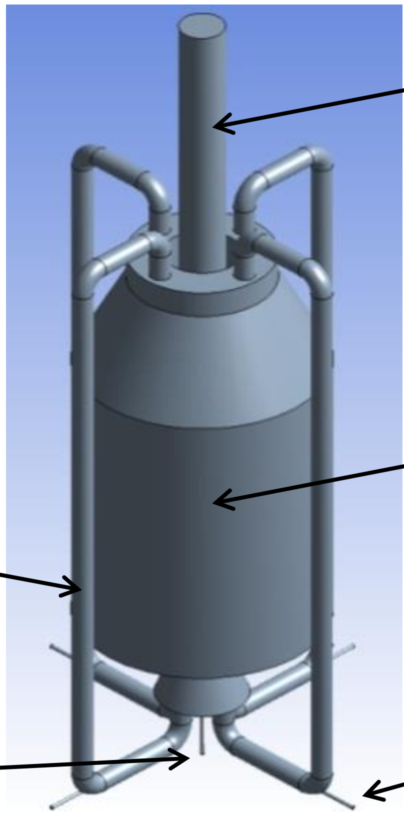


Figure 1. 3D burner geometry with boundary conditions

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

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 author earlier paper, the different LCV composition was used with some amount of ethane, propane and butane. In the laboratory for the experimental work, it is not practical to use 7 types of gas (Table 3) as supply and mixing process becoming too complicated and not economical. Thus, three types of gases are analysed in this paper; methane, hydrogen and carbon dioxide. The difference is; 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. 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 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 that 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 to 0.0176 m^3/s. The details of AFR and volume flow rate are shown in Table 4.

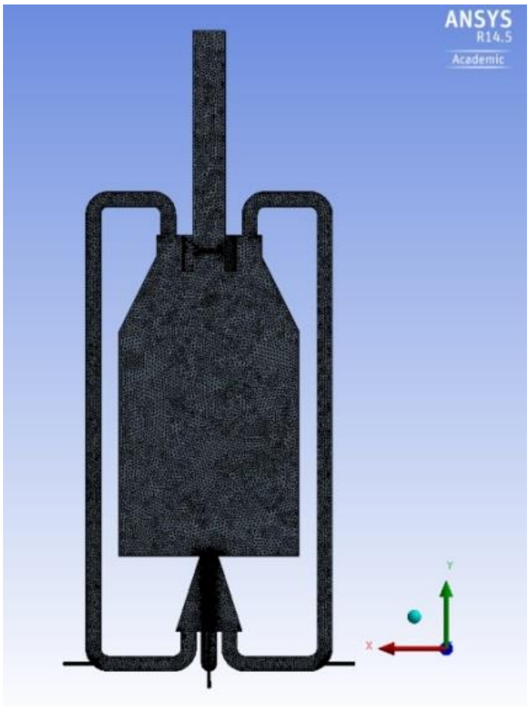


Figure 2. Model after meshing in 2D.

Table 3. LCV gas composition.

Gas	This paper	Previous study (Noor et al., 2012b)
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

RESULTS AND DISCUSSION

The effect of AFR on the concentration of the unburned CH_4 and H_2 was evaluated using modeled 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 general hydrocarbon stoichiometric combustion equation:

$$C_n H_m + \left(n + \frac{m}{4}\right)(O_2 + 3.76N_2) \rightarrow nCO_2 + \frac{m}{2}H_2O + 3.76\left(n + \frac{m}{4}\right)N_2 \quad (1)$$

Stoichiometric combustion equation (Eq. (1)) with 50% EGR for low calorific value gas consist mole fraction of 50% methane, 20% hydrogen and 30% carbon dioxide by mole fractions. From total flue gas, 50% will flow back to the chamber and lower the Oxygen level in the oxidiser stream.

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

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

This equation is for the equivalent ratio of 1.0. If equivalent ratio reduces, the fuel reduces and AFR increases. In this study when AFR is equal to 4.0, unburned CH_4 and H_2 mole fraction in EGR pipe is almost zero. The stoichiometric AFR for this fuel composition is 4.17. Comparing to previous study (Noor et al., 2012b) 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 showed when AFR = 4.0 and 5.0, the CH_4 and H_2 mole fraction in EGR were almost zero.

The result in Figure 4 shows that the UHC in flue gas flows through 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, is happened 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 combustion process with achieves MILD combustion state. Figure 6 and 7shows 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. Small back flow does not give significant effect the combustion process since the exhaust pipe is long enough to avoid back flow of fresh air into the combustion chamber. The MILD combustion regime can be achieved either fuelled by natural gas or biogas and the performance of a burner remained constant. In both cases, pollution emissions are very low, NO_x emissions are below 3 ppm and CO emissions are below 16 ppm (Colorado et al., 2010). Dally et al., (2010) was successful in achieving MILD combustion by using sawdust as a fuel. Biogas giving 2 % lower efficiencies compare to natural gas. This condition should be compensating 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 (Colorado et al., 2010).

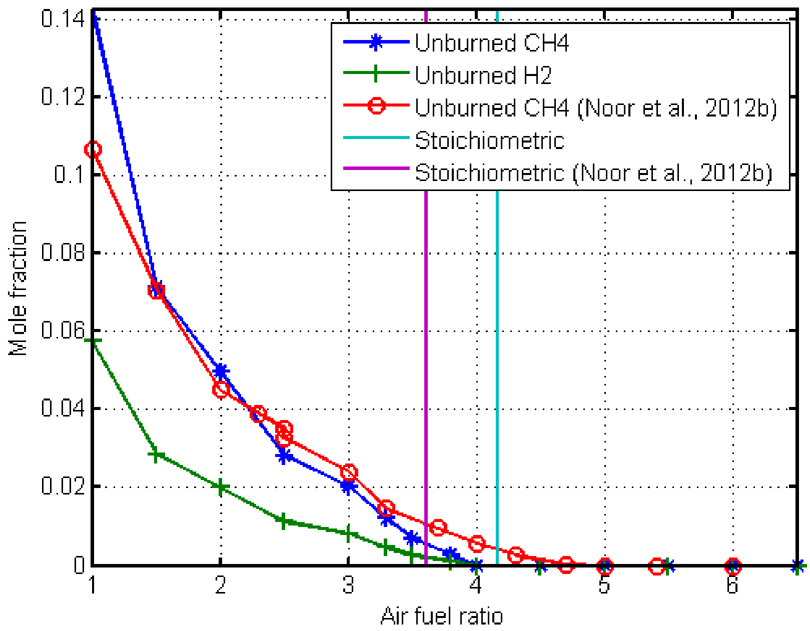
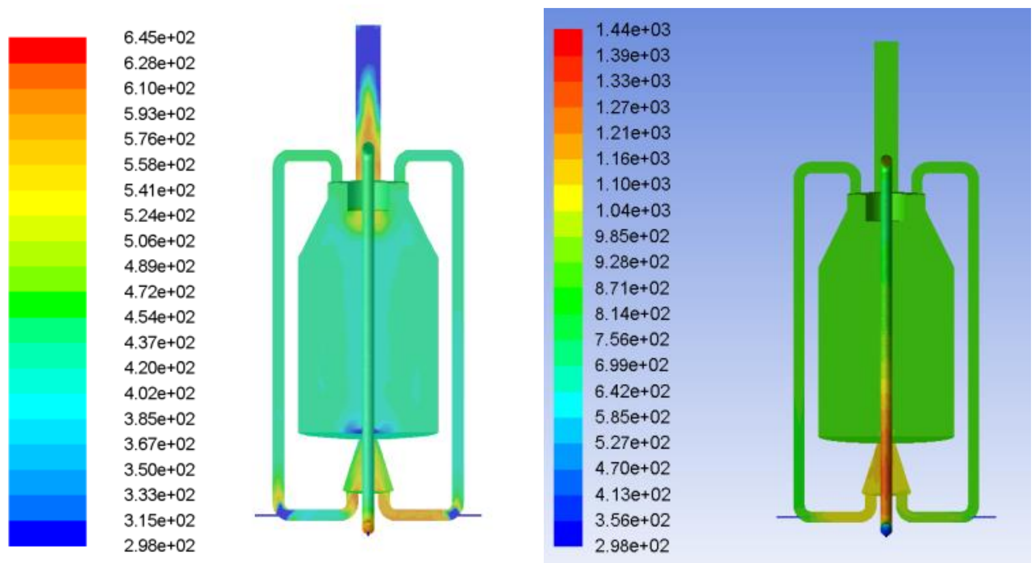


Figure 3. Unburned of CH_4 and H_2 for AFR



(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 .

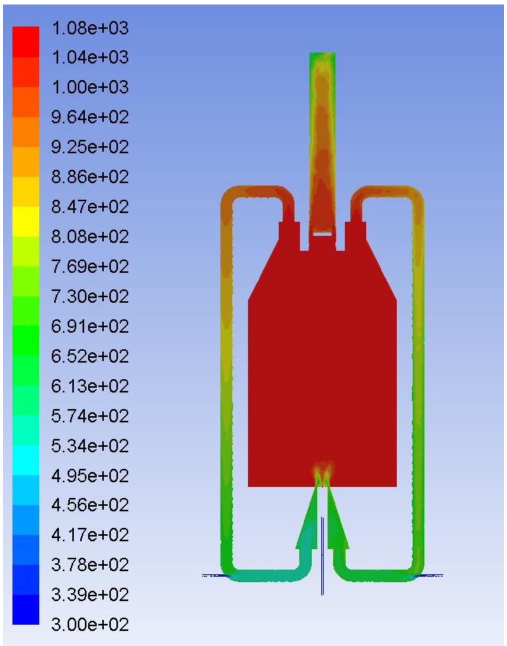
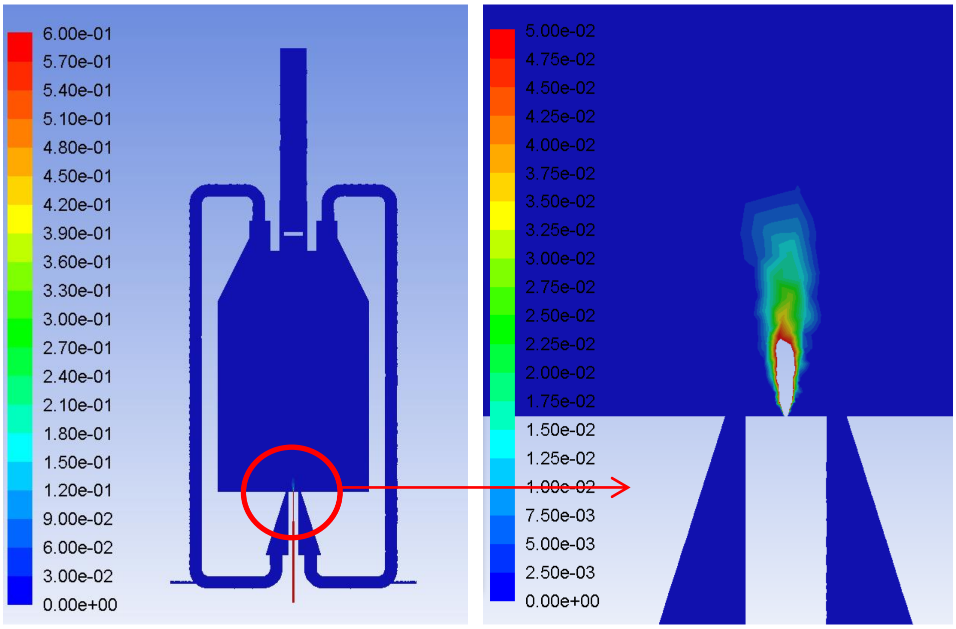
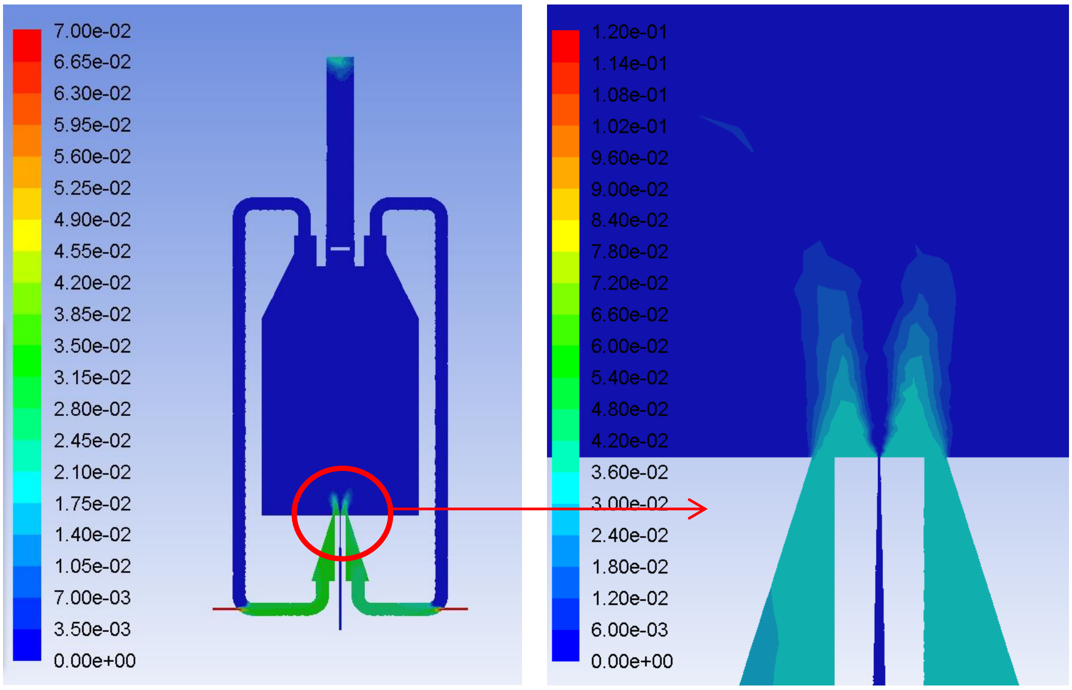


Figure 5. Cross section on temperature contour (Kelvin) when proper MILD combustion with fuel 100% consumed .



(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 to 0.6) (b) for a zoomed-in region (with a mole fraction range between 0 to 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 to 0.07) (b) for a zoomed-in region (with a mole fraction range between 0 to 0.012)

CONCLUSIONS

The present paper concludes that AFR for the biogas mixed with 20% hydrogen is giving lower AFR than the 30% hydrogen. For biogas mixed with 20% hydrogen, the achieved ARF is 5:1 and 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 the 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 produced unburned methane and hydrogen. This condition is called rich fuel combustion. UHC is a waste of fuel and it is part of the environmental pollution.

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