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Performance Analysis of Mixed Fuel Biogas and LPG in Domestic Cook Stove Burner

[1] Dhananjay Singh Yadav,[2] Ansab Khan, [3]Bireswar Paul, [4]Akshoy Ranjan Paul

[1] Research Scholar, [2] M. Tech. Student, [3]Assistant Professor,[4] Associate Professor
[1,3] Mechanical Engineering Department, [2,4]Applied Mechanics Department
Motilal Nehru National Institute of Technology Allahabad, Prayagraj-211004, Uttar Pradesh, India

Abstract:
Numerical investigation of interchangeability of Biogas - Liquefied Petroleum Gas (LPG) mixed fuels in domestic cook stove burners has been performed. ANSYS Fluent software is used to simulate the 3-D steady state gaseous flow, combustion and heat transfer to the vessel wall for LPG, Piped Natural Gas (PNG) and Biogas-LPG mixed fuel in domestic cook-stove burner. The combustion of Biogas - LPG mixed fuel above the burner head were simulated with equivalence ratio of air-fuel mixture is 1.4 (maximum efficiency) to the inlet of domestic cook-stove burner. For this study, a vessel is placed above the burner head and only 15° sector of this setup were simulated due periodic symmetry of setup. The performances of burner were also studied by velocity and temperature field around the vessel wall which is placed just above the burner head. By calculating the thermal efficiency, this study confirms the Biogas - LPG mixed fuel is interchangeable with PNG for domestic cook-stove burner.

***Index Terms* – Domestic cook stove; Gas interchangeability; Partially premixed combustion; Biogas; Liquefied Petroleum Gas (LPG).**

I. INTRODUCTION

The reduction of energy sources and environment pollution are the serious problem in world. The choice to decrease the current energy problem and improve the situations of environment is the use of renewable source of energy as much as possible. Biogas is the one the best option for future and alternative fuels in place of traditional conventional fossil fuels. It is a clean and renewable energy resource which is produced by biological breakdown of organic matter in the absence of oxygen (anaerobic decomposition) from biodegradable materials such as municipal solid waste, biomass, agricultural wastes and residues, manure, plants and green waste and etc. The biogas is primarilyconstituting of methane (CH_4) and carbon dioxide (CO_2) with smaller amount of oxygen (O_2), nitrogen (N_2), hydrogen sulfide (H_2S), moisture and other volatile compounds. The high concentration of carbon dioxide (40 -60%) in biogas, which is depending upon the source of biogas so its calorific value of fuel is too low as comparison to other conventional fuels [Balat et al., 2009]. Due to the higher percentage of carbon dioxide in biogas, the combustion characteristics of biogas are poorer than the other conventional fuels. The quality of biogas increases as the percentage of methane increseses and, its depend on the source, method of production, method of purification and etc. Generally, the heating value of biogas from 14 - 20 MJ/m^3, it is just sufficient for heating and cooking purposes [Bond et al., 2011]. The utilization of biogas may vary according to the quality of biogas which may be similar to the other conventional fuels.

The higher concentration of methane in biogas can be utilized as a fuel in application of transportation, electric generation. From the literature survey, the fundamental studies were carried out the effects of CO_2 on the combustion characteristics of biogas flame such as flame lengths [Yadav et al., 2016], flame temperature [Yadav et al., 2018], flame speed, extinction and flammability limits and pollutant emissions [Yadav et al., 2016; Lee et al., 2008 and 2013]. The another approach for the utilization of low quality of biogas, is to raise or improve its heating value of biogas through mixed the higher graded fuels such as LPG or PNG [Lee et al., 2008]. Lee et al., 2002 found the relationship of burning velocity of Landfill Gas (LFG) and LFG-LPG mixed fuels; it is depending on the equivalence ratio of different fuels. They found that the CO_2 fraction in LFG leads to increases radiation heat losses and at low strain rate of the flames and decreases the thermal NO and Prompt NO. Lee and Hwang, 2007 investigated the flame stability of a LFG-LPG mixed fuel for a domestic appliances using premixed combustion and swirl combustor using non-premixed combustion. LFG55 (methane percentage of 55%) can be interchangeable with Liquefied Natural Gas (LNG) fuel using a strong swirl conditions. The quality of LFG can vary significantly according to number of factors such as production site, lapse of filled time, pretreatment method and optimum parameters like as temperature, pH and so on.

In this paper, numerically investigate the gas interchangeability of mixed fuels such as Biogas-LPG in the traditional LPG cook stove burner for the application of domestic heating and cooking. The main objective of the present work is to replace the PNG fuels by the mixed fuel Biogas and LPG. The biogas-LPG mixed fuels were produced to have same Wobbe index to PNG fuels.

II. Interchangeability of gases:

Gas interchangeability is not a new concept; it began in 1930s and 1940s. Gas interchangeability is simply defined as "the ability to substitute one gaseous fuel for another in combustion application without changing the performance parameters and emissions" [Guide book, 2011; Hunag et al., 2014]. When natural gas began to replace manufactured gas which is derived from coal and oil sources in the application of street lighting and other applications [Guide book, 2011]. Combining biogas with LPG gas can increase the use of biogas, reduce carbon intensity and promote renewable energy resources.

The utilization and promotion of biogas as a renewable energy resources mixing into LPG gas which can also reduce emissions of carbon [Hunag et al., 2014; Dai et al., 2011]. Woobe Index (WI) is the most important method for theoretical prediction of biogas interchangeability, but this is not sufficient for interchangeability of gas so another methods such as Combustion Potential (CP), American Gas Association (AGA) interchangeable index, Weaver index to use the burning velocity and for stability of flames. [Yadav et al., 2018]. When the composition of a gaseous fuel changes, its combustion characteristics, heating value and density change. This will lead to variation in many factors, such as heat load, combustion stability, flame structure, CO emission, etc. Wobbe index (WI) and (Combustion Potential) CP are used as the national standards to identify the gas interchangeability. However, in order to provide a more comprehensive analysis on interchangeability requirements, American Gas Association (AGA) indices are also calculated. AGA indices include lifting, flash-back and yellow indices in order to decide interchangeability. The Wobbe Index of fuel is defined as the ratio of heating value of fuel to the square root of specific gravity (relative density) at the constant pressure of burner nozzle. The Wobbe Index is defined as:

$$Wobbe\ Index\,(WI) = \frac{Higher\ Heating\ Value\,(H)}{\sqrt{Specific\ Gravity\,(d)}} \tag{1}$$

The typical composition and properties of Biogas, LPG and PNG used in this study are shown in Table1. The composition and properties of fuel gasses used in this study are the gasses generally used in India [GOI, 2019]. The composition of biogas is considered as 60% methane and 40% carbon dioxide and composition of LPG is considered as 60% butane and 40% propane and PNG fuels is considered as purely methane.

Interchangeability is the criteria to find the percentage of mixture of Biogas-LPG mixed fuel for this study. For the fuel interchangeability, Wobbe Index of Biogas-LPG mixed fuels must be nearly equivalent to Wobbe Index of piped natural gas (PNG). Consider, 'x' is the percentage of biogas in Biogas-LPG mixture.

WI of PNG = WI of BG-LPG

$$50.73 = x\,(24.39) + (1-x)\,82$$

$$x = 0.55$$

From above the calculation we get, minimum and maximum percentage of biogas fuel mixed in to LPG fuels such as 55 to 71% respectively. That means the allowable minimum and maximum percentage of biogas mixed into LPG fuels which is nearly equivalent to Wobbe index of PNG fuels. In this paper the Biogas-LPG mixed fuels is considered for the numerical analysis is 55% Biogas and rest 45% LPG fuel.

Table.1. Composition and properties of Biogas, LPG and PNG [Gattei, 2008]

Fuels	Composition	Heating value (MJ/Nm^3)	Density (kg/m^3)	Relative density	Wobbe Index (MJ/Nm^3)
Biogas	60% CH_4 + 40% CO_2	23.08	1.1	0.9	24.39
LPG	60% C_3H_8 + 40% C_4H_{10}	113.98	2.3	1.876	82
PNG	100% CH_4	37.77	0.68	0.555	50.73

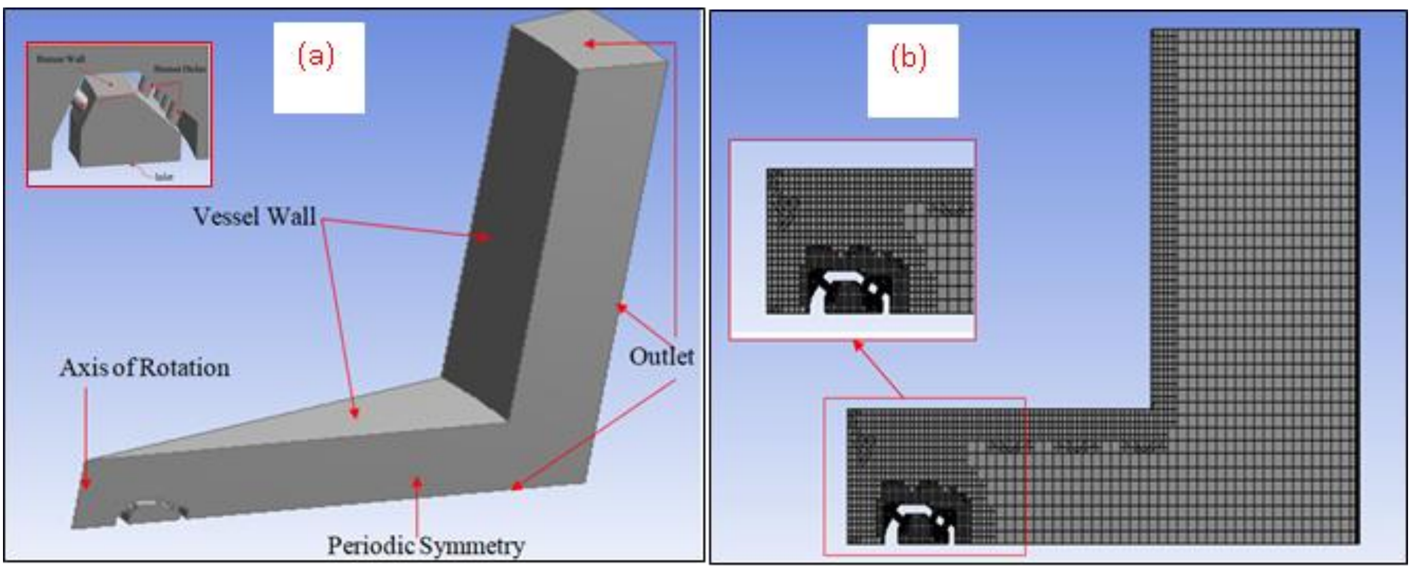

Figure1 (a) Computational domain with boundary conditions, and (b) grid generation of computational domain

III. Computational Methodology:

a) Physical geometry and grid generation:

The 15° sector of burner and computational domain were modeled using ANSYS Design Modeler and simulated the gaseous fluid flow, combustion and heat transfer using ANSYS - FLUENT 16.0. The computational domain is considered for the study, the portion of burner cap and flat bottomed and lateral surface of vessel. The physical model (**Fig.** 1 (a)) refers to flame impinges to cylindrical surface of flat bottomed vessel as well as lateral surface of vessel of the domestic cook stove burner, which is placed over a certain distance is called loading height. It is defined as the distance between the top surfaces of the burner cap to bottom surface of the vessel. In the 15° sector of the physical model have two parts: one is burner cap and other part is vessel above it with periodic symmetric on the either side. The part of the conventional burner cap has three concentric circular ports each having the 1.9 mm diameter and outer diameter and inner diameter of burner cap is 39 mm and 14.95 mm respectively. As per Indian Standard, the bottom of the vessel should be flat and its size (285 mm diameter and 151 mm height) is specified on the fuel flow rate. The performance of domestic cook stove burner is evaluated in the form of thermal efficiency. In India, the thermal efficiency of a cook stove burner is calculated according to Indian Standard (IS 42426:2002). The efficiency of cook stove burner is defined as the rate of the heat transfer to the water in the loading vessel to the heat input of the fuel.

The grid generation of the 15° sector computational domain is done using the ANSYS Fluent 16.0 software (Fig. 1(b)). The geometrical domain is very complicated shape so the cut-cell method [ANSYS 16.0 user guide] utilized for generation of the grids. The fine meshes or higher gradients are generated at very close to the head of burner and the boundary of vessel wall whereas the coarser meshes are employed to other rest boundaries. The tetrahedral grids have been used for meshing complicated geometry and structured grids are generated at simple geometry [Das et al., 2020].

b) Boundary conditions:

In the domestic cook stove burner, at the inlet boundary conditions the rich premixed mixture of fuel and air given associated with the mass flow rate of fuels and their mass fraction of species at the equivalence ratio 1.4 (Table 2). Both sides the 15° sector of computational domain is considered as periodic symmetric boundary conditions. The boundaries exposed to atmospheric air are treated as pressure outlet and walls of burner cap as no slip for velocity and constant wall temperature 300 K. The vessel wall shall be treated as similar to water boiling temperature which is maintained at 403 K, assumed to be approximately 30 K higher temperature than nucleate boiling of water [Das et al., 2020].

c) Numerical solution techniques:

In this simulation, the Reynolds-averaged conservation equations of mass, momentum, energy, are solved along with k-ϵ model turbulence model of turbulence kinetic energy and its dissipation rate of equations [ANSYS User guide 16.0]. The variation in concentrations and temperature causes the gas flow throughout the vessel wall due to effects of buoyancy. To account the flow due to buoyancy, the force of gravity is considered in the conservation equation of momentum. The premixed laminar flame above the burner causes the turbulent flow of hot gases at the corner of vessel. The k–ϵ turbulence model with standard wall function is used in the present simulation for the turbulence closure and solid walls. The use and selection of the models used in this simulation are depends on the nature of problems to be solved. Due to fluid flowing through the system, the viscous model is activated. The turbulent kinetic energy (k) equation and turbulent dissipation rate (ϵ) equation are the two equations composed the viscous model. The pressure based solver is used to simulate the problem due to incompressible nature of flow. The radiation model is used in this simulation for considering the high temperature in the system. To consider the radiation effects, the radiation model of discrete ordinates is used in this simulation. In this simulation, the volumetric reaction model is activated for the species transport solution of the problem. The STIFF chemistry solver is enabled in ANSYS FLUENT to solve the solution. The numerical solution of gaseous fuel combustion model is solved in the two step procedure: firstly, solver solved the numerical problem without reaction of gaseous species for developed the flow phenomena in the whole computational domain and in the second step solver solves with volumetric reaction with ignition sources near to burner wall in the combustion zone. The solution has been considered as the converged when the heat transfer to vessel walls is almost constant [Anetor et al., 2011].

d) Reaction kinetics:

In this study, the numerical simulation is conducted for the evaluation of the performance of domestic cook-stove burner for three types of fuel such as LPG, PNG and mixed fuel Biogas-LPG. The chemical reaction kinetics employed in this study is based on the works reported by (Boggavarapu et al., 2014; and Das et al., 2020). In order to solve for species transport and chemical reactions of LPG-air partial premixed combustion a combination of two step propane-air global reaction model and single step butane-air global reaction model is considered for the purpose [Ansys 16.0 user guide, 2016]. This simplified global reaction kinetics consist of four chemical reactions and seven species, namely as C_3H_8, C_4H_{10}, O_2, CO_2, CO, H_2O and N_2. In order to solve for species transport and chemical reactions of PNG-air partial premixed combustion of two-step methane-air global reaction model, it consists of 5 reactions and 6 species. When solve for mixed fuel Biogas-LPG, using the combination of the chemical reaction of LPG and PNG fuels [Ansys 16.0 user guide, 2016]. The laminar finite rate reaction model computes the chemical source terms using Arrhenius expressions for constant rate of reactions, and ignores the effects of the turbulent fluctuations. The laminar finite rate models are exactly adopted for laminar flames and relatively slow turbulence-chemistry interaction of flames.

Table 2. Mass flow rate and mass fraction of different fuels and their species

Fuels	Mass flow rates and Mass fraction of species
LPG	Mass flow rate of mixture = 1.66×10^{-5} kg/s Mass fraction of C_3H_8 = 0.0332 Mass fraction of C_4H_{10} = 0.0498 Mass fraction of air = 0.917
PNG	Mass flow rate of mixture = 4.98×10^{-5} kg/s Mass fraction of methane = 0.075 Mass fraction of air = 0.925
Biogas-LPG mixed fuel	Mass flow rate of mixture = 2.42×10^{-5} kg/s Mass fraction of C_3H_8= 0.018 Mass fraction of C_4H_{10} = 0.027 Mass fraction of CH_4 = 0.033 Mass fraction of CO_2 = 0.022 Mass fraction of air = 0.90

e) Grid independency test and Validation:

In the grid independency test (GIT), the optimum or minimal grid size or element size of computational domain which gives the optimum results in the optimum computational times. In GIT of the present study, the thermal performance of cook stove burner for LPG fuel is computed for five different mesh structures from M_1 to M_5. The number of elements selected for each mesh structures is based on the edge size of elements. The mesh structure of less number of elements (M_1) shows slightly less thermal efficiency whereas the efficiency of M_2 and other mesh structures of larger number of elements are fairly close to each other. It is observed from GIT, the mesh structure corresponding to the M_3 is considered for the computational analysis.

The present numerical work is validated against the similar work by Boggavarapu et al., 2014. The present numerical calculation of temperature and velocity distribution of flame is quite similar to it is numerical results of Boggavarapu et al., 2014.

IV. Results and Discussion:

a) Temperature and velocity distribution of flames:

Figure 2 a-b illustrates the temperature distribution of flames at the mid plane of the computational domain of PNG and mixed fuel of Biogas-LPG. A naturally aspirated cook stove burner works on the principle of Bunsen burner. The high momentum of gaseous fuel comes from fuel injector nozzle in the mixing tube and attains a local minimum pressure at the throat section of mixing and primary air entrained from the atmosphere through the adjustable holes. Finally, the rich reactant mixture of gaseous fuel and air leaves from burner port holes into the combustion zone.

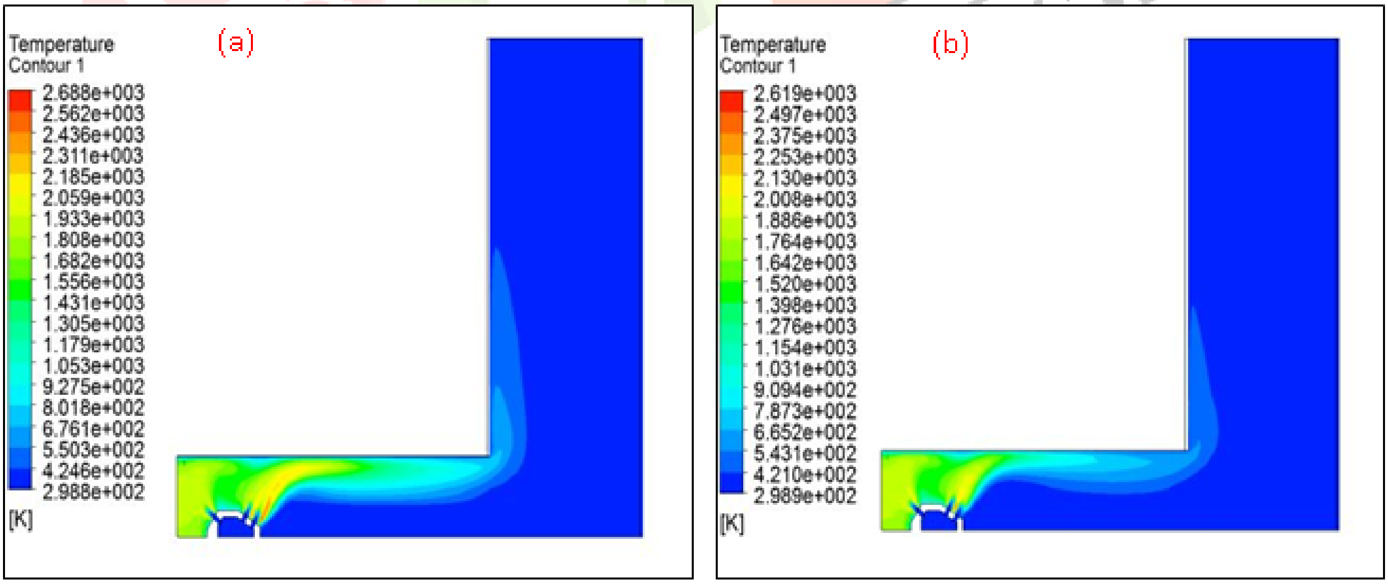

Figure 2. The temperature distribution of flames at the vertical mid plane of compuattaional domain for (a) PNG and (b) BG-LPG

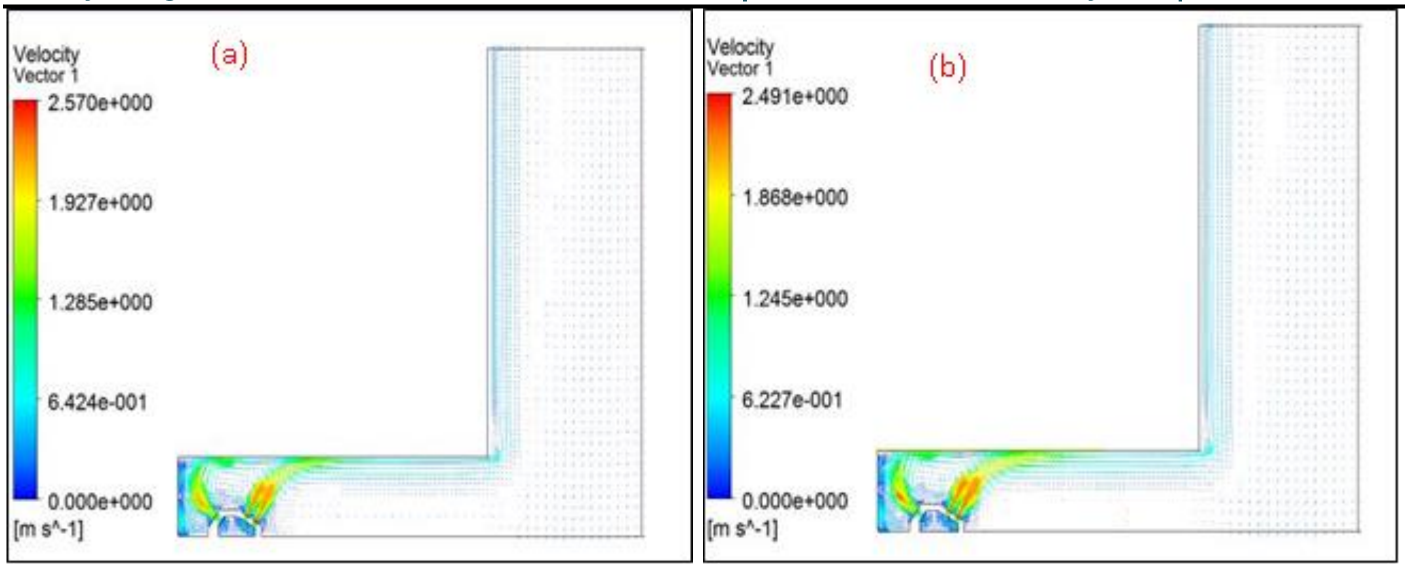

Figure 3. The velocity distribution of flames at the vertical mid plane of compuattaional domain for (a) PNG and (b) BG-LPG

The distribution of the velocity and temperature of flames of PNG and Biogas-LPG mixed fuel along the vertical mid plane of 15° sector of computational domain which is shown in fig 3. In the velocity distribution diagram shows the velocity is maximum occurs near about the burner ports where the fuel and air mixture of comes out in the combustion zone. The mixture velocity is depending on the gaseous fuel flow rate and working pressure of gaseous fuel. In the combustion zone, two flame zones are stabilized at each and every port of burner and the maximum velocity appears from rich mixture of fuel and air at the ports. The secondary air entrained from atmosphere which can only help for stability of flames.

b) Thermal efficiency of cook stove burner:

The performance of the domestic cook stove is evaluated in terms of the thermal efficiency, the thermal efficiency (η) of cook stove burner is calculated as the ratio of total heat transfer rate of the vessel to total heat input of fuel [Das et al., 2020]. Fig 4 (a) shows the heat flux distribution along the bottom of vessel at an 18 cm distance from top surface of the burner cap (loading height). With increasing radial distance from the centre of burner or axis of rotation, the total heat flux from bottom vessel wall firstly decreases then increases reach a peak value then continuously decreases. The high temperature flame impinges to bottom surface of vessel wall centrally and then outer rows of the burner respectively. The total heat transfer rate is calculated in terms of conduction and convection heat transfer from bottom as well as lateral surface of vessel and total heat input of fuel is calculated in terms of the total fuel flow rate and its calorific value of fuel. The total heat transfer rate (conduction and convection heat transfer) is similar in the both case of flames in PNG and mixed fuel Biogas-LPG. The thermal efficiency of cook stove burner approximately 60% in the both fuels (fig. 4(b)).

$$\eta = \frac{Total\ heat\ transfer\ to\ vessel\ walls}{Total\ heat\ at\ the\ inlet}$$

$$\eta = \frac{70.75}{118.72} = 0.596\ or\ 59.6\%$$

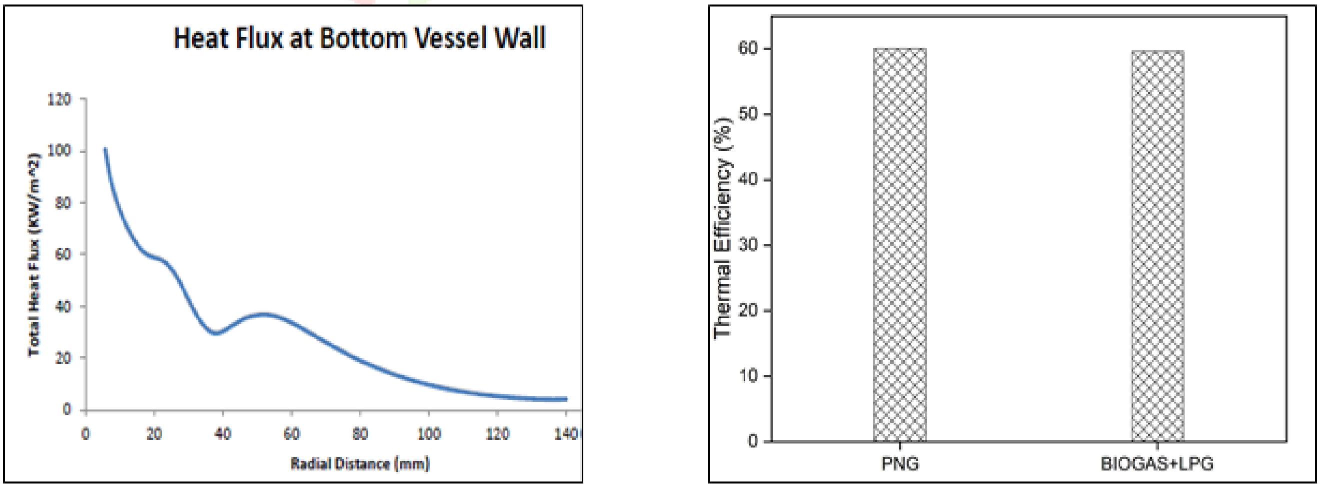

Figure 4: (a) Total heat flux through the bottom vessel wall for BG-LPG mixed fuel, (b) Comparison of thermal efficiency for PNG and BG-LPG fuel

V. Conclusion:

A numerical study was carried out here to investigate, the gas interchangeability of mixed fuel Biogas-LPG by replacing PNG fuel at same Wobbe index. The following observations can be made from the present study.

- The heat transfers to the vessel from Biogas - LPG mixed fuel is nearly equivalent to PNG which is due to the same Wobbe Index of PNG and BG-LPG mixed fuel. Hence the thermal efficiency of burner for Biogas - LPG mixed fuel is nearly equivalent to PNG.
- The maximum flame temperature and maximum velocity of air-fuel mixture above the burner head for Biogas - LPG mixed fuel less than the PNG fuel. It is due to mass flow rate of Biogas - LPG mixed fuel is less than PNG fuel as the burner is simulated for the same heat input. It has been also observe that the maximum temperature of flame and maximum velocity of air-fuel mixture of Biogas - LPG mixed fuel is slightly less than PNG fuel.

The Biogas can be mixed in LPG according to American Gas Association (AGA) indices to interchange the PNG fuel as the thermal efficiency of Biogas - LPG mixed fuel is nearly equivalent to PNG fuel.

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