Jurnal
Teknologi

Full paper

Effects of Hydrogen Addition on the Entropy Generation of Biogas Conventional Combustion

Seyed Ehsan Hosseini[a*], Ghobad Bagheri[a], Mazlan A. Wahid[a]

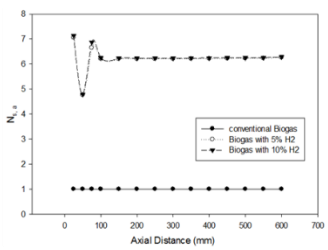
[a]*High-Speed Reacting Flow Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*

*Corresponding author: seyed.ehsan.hosseini@gmail.com

Article history

Received :15 November 2013
Received in revised form :
1 December 2013
Accepted :18 December 2013

Graphical abstract



Axial profiles of $N_{s,a}$ for various Biogas hydrogen concentrations

Abstract

Biogas has a great potential to be applied for heat and power generation throughout the world due to its availability from various resources. However, one of the most important barriers of biogas utilization development is its low calorific value. In order to increase the performance of biogas in industrial application, hydrogen enriched biogas could be substituted. In this paper a set of numerical simulations were conducted to estimate the variation of entropy generation in hydrogen enriched biogas flames due to hydrogen addition to the fuel. Reynolds Averaged Navier Stokes with a second order turbulence closure and laminar flamelet combustion model was applied to compute energy fields and flow in the flame. It was found that hydrogen enrichment resulted in an augmentation in the entropy generation rate of the biogas conventional flame. Such increase could be attributed to the increase in irreversibilities due to biogas flame temperature rise.

Keywords: Entropy; biogas; hydrogen; flame

1.0 INTRODUCTION

Energy crisis and the increasing rate of pollutant generation have encouraged scientists to find alternative fuels to guarantee the secure energy generation and peoplehealth.[1-5] Experimental studies illustrate that biogas shows its compatibility with current combustion systems and biogas could be applied as an alternative fuel to solve a part of the future fossil fuel shortage. Therefore, a comprehensive knowledge of the available technologies is needed for biogas users.[6] Moreover, general knowledge of the chemical characteristics and combustion properties of the biogas is needed for efficient combustion process. Generally, the selection of the best system for biogas conversion into thermal energy for lighting, transportation, heating and power generation is the main goal of biogas production.[7] It was pointed out that by biogas utilization the net emission of greenhouse gases such as CO_2, CH_4 and N_2O reduced drastically compared to methane.[8] The most important advantages of biogas production is collecting the organic waste materials and generating irrigation water and fertilizer concomitantly. Unlike other biomass sources, biogas does not have any geographical limitations.[9] Landfills and old waste deposits, municipal solid waste (MSW), rising main sewers, coal mining, rice paddies, anaerobic digestions, cattle ranching and agricultural products are the main sources of biogas in the world.[10-18] Furthermore, since food industries are developed due to the increasing rate of world population, animal husbandry has become one of the most important sources of biogas in the world.[19] More than 15% of global methane generation is attributed to biogas emission from ruminants, thus biogas capturing from livestock dung and energy generation from biogas have become important.[20] The sustainable strategies in the managing of waste water sources can intensify the possibility of biogas generation from waste materials.[21] Compared to natural gas by 90–95% methane, depends on feedstock the rate of methane in biogas is 40-65%. Therefore, biogas is a low calorific value (LCV) gaseous fuel. Generally, the collected biogas is cleaned and its impurities like water and sulfuric gases are eliminated. The biogas cleaning and upgrading methods and combustion improvement technologies are designed based on biogas composition. In general 55-65% of biogas is constituted by methane. The lower heating value of methane is 34,300 kJ/$m^3$and the lower heating value of biogas is about 13,720–27,440 kJ/m^3. In biogas heating value calculation, the heating value of the whole specious is considered. The heating value of non-combustible components like CO_2 is taken into consideration. Also, the impacts of water vapour on lower heating value, air–fuel ratio, biogas flammability limits and flame temperature should be taken into account. In biogas modelling, usually CO_2 and $CH_4$are considered because more than 98% of biogas is a combination of them and other specious like water vapour and hydrogen sulphide (H_2S) are eliminated. Practically removal of these corrosive gases is necessary due to their negative impact on equipment especially burner and boiler in furnace.

2.0 HYDROGEN ADDITION TO BIOGAS

Hydrogen which is considered as a clean fuel due to low emission formation has a great potential to be applied as a major fuel in the future.[23, 24] However, due to high diffusivity and flammability of hydrogen, safety in storage and transport of hydrogen is encountered some problems.[25] The effects of hydrogen addition on the combustion of gaseous fuel are radical because the combustion properties of these flames depend heavily on the characteristics of the gaseous fuel and flame circumstances. Hydrogen enrichment of various gaseous fuels such as CH_4, propane (C_3H_8) and natural gas was investigated during the last decade. Ignition of hydrogen-enriched fuel mixtures under the lean flammability limits causes the fuel saving goals. In hydrogen-enriched fuel the Arrhenius reaction rate is intensifies due to augmentation of the flame temperature, therefore high reaction rate of hydrogen is recorded and the rate of required oxygen in the lean mixture rises. Due to the low computational cost fast chemistry models are superior in the simulation of hydrogen-enriched fuel combustion.[26] The conserved scalar model was applied to model a non-premixed turbulent combustion of mixture of methane and hydrogen by Ilbas.[27] An unacceptable accuracy was reported by Mardani when similar flame with eddy dissipation concept (EDC) was modeled.[28] It was reported that for simulation of hydrogen-enriched methane combustion, the steady laminar flamelet model has better prediction in terms of minor species.[29,30] Yilmaz compared the results of flamelet method with equilibrium model when Probability Density Function (PDF) was calculated for mass fraction of species.[31] It was reported that mixture fraction and temperature illustrate better results within the reaction zone could be achieved. Hossain pointed out that just major species could be predictable by flame sheet model.[29] Although accurate results for water vapor mass fraction and flame temperature could be obtained by flame sheet model, unaccepted prediction of CO_2 is one of the weak points of this method. Various chemical reaction mechanisms were applied by different researchers in their modeling method and it was reported that chemical reaction mechanism modeling method is very important in laminar flamelet model. For example in simulation was done by Ilbas only seven species were used.[27] Yilmaz applied GRI mechanism with 18 species.[31] Ravikanti used GRI2.11 and reported that the results are in good agreement with the reduced DRM-22 mechanism results.[30] In the combustion modeling was done by Frassoldati, 600 reactions were applied and 48 species were taken into account.[32]

3.0 ENTROPY GENERATION

Hydrogen enrichment is one of the potential methods which were introduced for improving biogas combustion for heat and power generation. Hydrogen addition to the biogas enables the combustion system to work at very lean circumstances which improves the efficiency of combustion system.[33-35] However, the temperature of hydrogen-enriched biogas flame increases significantly in some regions.[36] This condition causes a mitigation in the reversibility work of combustion system which could expunge the fuel economy achievements. For a given thermodynamic system, the lost work can be calculated by formula (1).

$$\dot{W}_{rev} - \dot{W} = T_0 \dot{S}_{gen} \tag{1}$$

$\dot{W}_{rev}$ is the reversible work, $\dot{W}$ is the actual work and $\dot{S}_{gen}$ is the total entropygenerated in the combustion system. Generally, entropy is produced due to various factors depending on the characteristics of combustion system such as chemical reactions, heat transfer and viscous dissipation. In formula (2) illustrates the local entropy generation in a two dimensional radial axisymmetric domain when the heat and mass irreversibilities is considered in the thermodynamic system.[37,38]

$$\dot{S}_{gen} = \frac{K}{T^2}\left[\left(\frac{\partial T}{\partial x}\right) + \left(\frac{\partial T}{\partial r^2}\right)\right] + \frac{\mu}{T}\Psi \tag{2}$$

The first and second terms on the right side of formula refer to heat transfer entropy generation ($\dot{S}_{ht}$) and viscous dissipation entropy generation ($\dot{S}_v$) respectively and Ψ is viscous dissipation parameter defined by formula (3).

$$\Psi = 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial r}\right)^2 + \left(\frac{v}{r}\right)^2\right] + \left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial r} - \frac{w}{r}\right)^2 \tag{3}$$

The axial, radial and swirl velocity of various components is demonstrated by u, v and w respectively.

4.0 SIMULATION

In this simulation, pure biogas is considered as a combination of 40% CO_2 and 60% methane and the effects of 5% and 10% hydrogen addition to this combination when the rate of CO_2 is constant are investigated. Based on Shih investigation, [39] realizable k–ε simulation yields more acceptable results for shear flows. Therefore, the standard k–ε model is applied to model combustion with the laminar flamelet combustion model in present study. Furthermore, the main reason for this decision is that the turbulence kinetic energy dissipation is computed differently in realizable and standard k–ε model and the flamelet model employs dissipation to count for deviation from equilibrium this difference in dissipation formulation affects the modeling of combustion differently. Therefore, performance of realizable k–ε model with flamelet model could be investigated biogas-enriched conventional flames. Following transportation equations are modeled k and ε in the standard k–ε model. For turbulent kinetic energy k:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\varepsilon - Y_M + S_k \tag{4}$$

For dissipation ε:

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(P_k + C_{3\varepsilon}P_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{5}$$

The laminar flamelet turbulent combustion is applied to model the interaction turbulence and chemical reaction. The GRI3.0 chemical reaction mechanisms were employed to calculate the chemical species.[40] In this study attention is given to the variations of the local entropy generation rates due to hydrogen enrichment of biogas conventional flame. ANSYS Fluent 14 is applied to carry on the simulation and computational work.[42] CFD model of the chamber for this numerical study is based on the geometry of the experimental flameless combustion carried out by SE Hosseini.[6] The inside diameter and the length of the chamber are 150 mm and 600 mm respectively. The 5 mm central inlet of the burner is considered for the inlet of the hydrogen enriched biogas mixture and the other inlets are considered for the oxidizer entrances. The emissions are exhausted through a central hole with 50 mm diameter. Convergence rate and scalar properties can be modified by mesh refinement and grid resolution. The chamber geometry is not very complicated, therefore calculations speed increase due to lower meshing nodes and elements. The quantity of mesh grids directly impacts on the solution duration. Since the chamber model is symmetrical, just an eighth part of the model is solved. Figure 1 shows the schematic of the furnace and a part of the furnace which has been meshed.

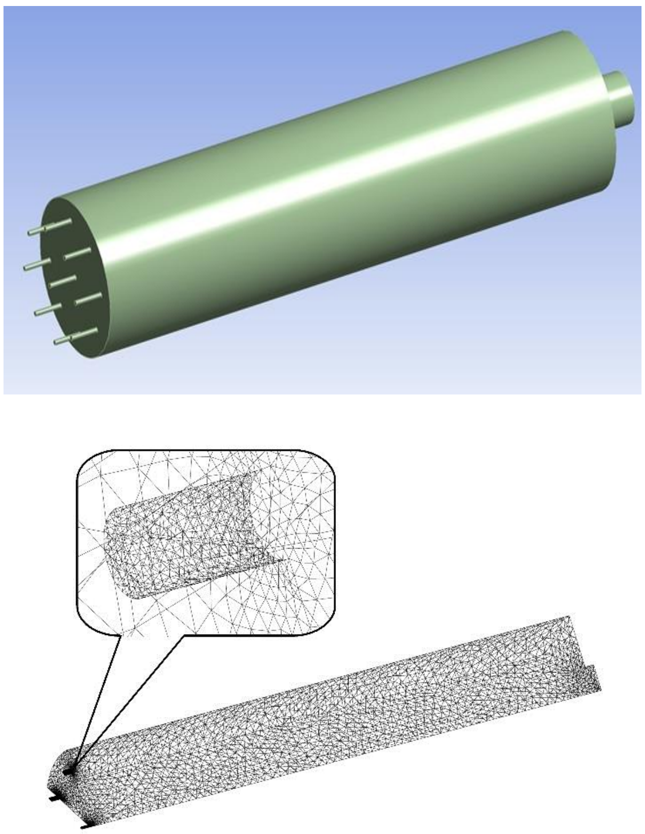


Figure 1 Schematic of the furnace and its mesh

For validation, comparisons between this numerical solution of the reacting flow and experimental measurements presented by Hosseini are compared.[6] Figure 2 demonstrates numerical and experimental results of the temperature distribution along the furnace. This figure confirms that the numerical results are in good agreement whit experimental records and the simulation settings are reliable. Indeed Figure 3 depicts the radial distribution of temperature in four various sections of the chamber.

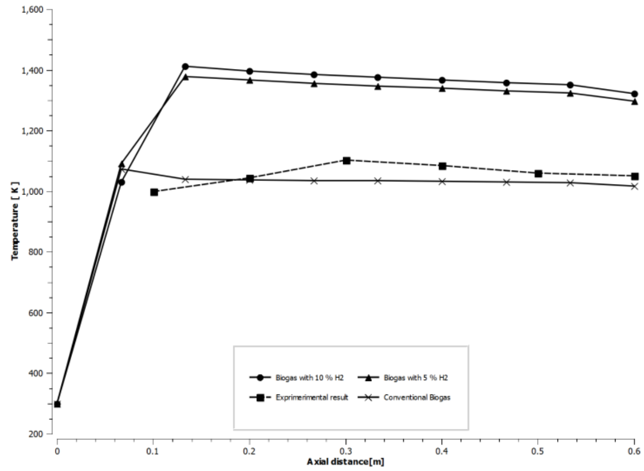


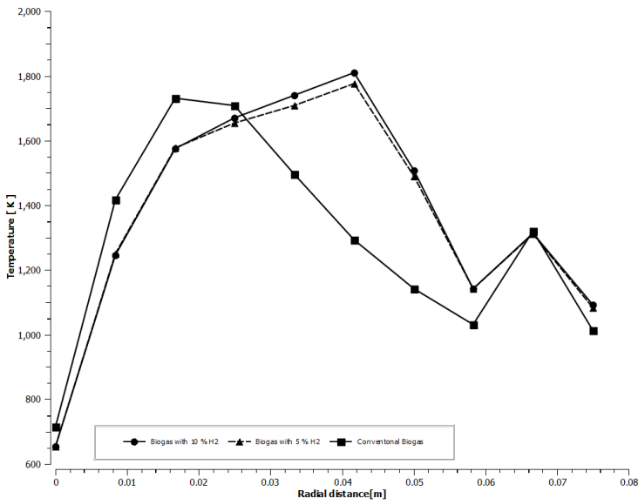
Figure 2 Numerical and experimental results of the temperature distribution along the furnace

5.0 ENTROPY GENERATION

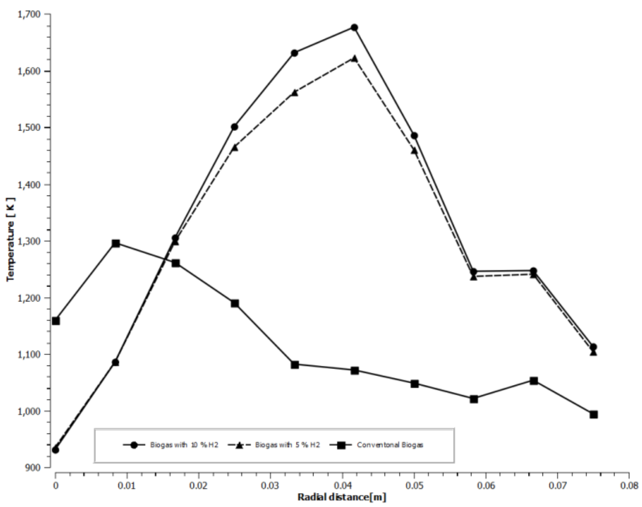
Figure 4 demonstrates the entropy generation in the chamber in biogas conventional combustion and hydrogen-enriched biogas traditional combustion when 5% and 10% hydrogen is added respectively. Since high entropy generation intensifies irreversibility, exergy loss is higher in traditional combustion of hydrogen-enriched biogas when 10% hydrogen is added. SK Som stipulated that the most irreversibility in a conventional combustion system is related to the internal heat transfer within the combustor between the products and reactants.[43] Entropy generation in hydrogen-enriched biogas with 10% could be attributed to higher temperature inside the chamber.

5.1 Entropy Augmentation Number

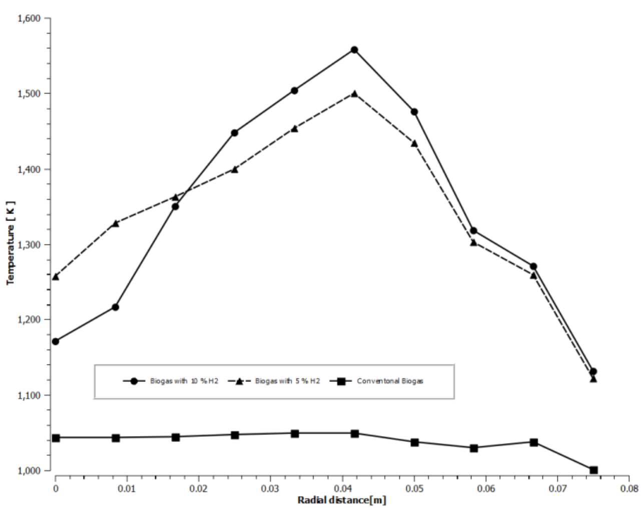
The entropy augmentation number $N_{s,a}$ is the dimensionless ratio of local entropy generation in two specific cases ($\frac{\dot{S}_{gen,i}}{\dot{S}_{gen,1}}$) which $\dot{S}_{gen,1}$ and $\dot{S}_{gen,i}$ are the local entropy generation in biogas conventional flame (without hydrogen enrichment) and in hydrogen-enriched biogas flame (with hydrogen enrichment), respectively. When $N_{s,a}$ is less than unity, it can be concluded that the addition of hydrogen resulted in a reduction of entropy, hence an enhancement of the system exergy. Figure 5 displays axial profiles of $N_{s,a}$ for various biogas hydrogen concentrations. From this figure it can be seen that the hydrogen addition causes substantial increase of $N_{s,a}$ in some whole of the chamber.



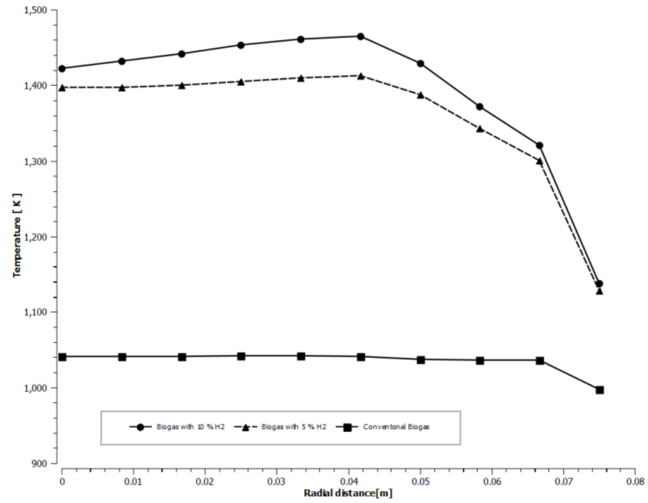
(a) Radial distribution of temperature x=25 mm



(b) Radial distribution of temperature x=50 mm



(c) Radial distribution of temperature x=75 mm



(d) Radial distribution of temperature x=100 mm

Figure 3 Radial temperature distribution along the furnace in various sections

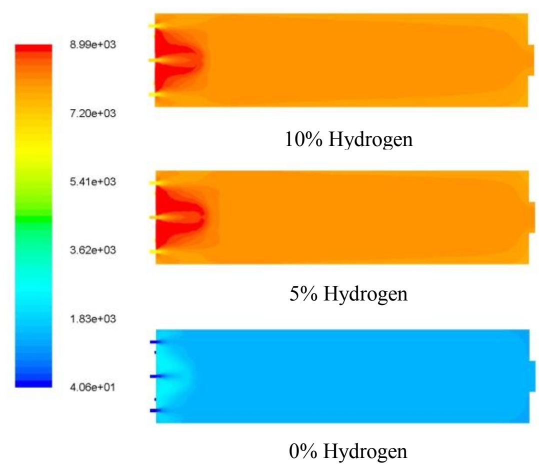


Figure 4 Entropy generation in the chamber in hydrogen-enriched biogas traditional combustion

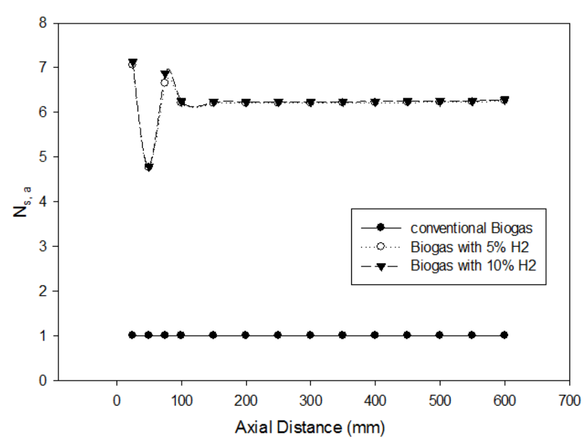


Figure 5 Axial profiles of $N_{s,a}$ for various biogas hydrogen concentrations

6.0 CONCLUSION

Numerical simulations of the entropy generation in turbulent hydrogen-enriched biogas flame have been conducted. Pure biogas and biogas consist of 5% and 10% hydrogen were modeled. It was found that the entropy generation rate increases due to hydrogen enrichment. Such increase was attributed as rises in the entropy augmentation number. Future investigations should prepare more detailed insights on the characteristics of entropy generation patterns and extend the analysis to cover a wider range of hydrogen concentration.

Acknowledgement

The authors would like to thank Universiti Teknologi Malaysia for supporting this research activity under Research University Grant No.08J60 and Ministry of Science, Technology and Innovation of Malaysia for the EScience Grant No. 4S080.

References

[1] Hosseini, S. E., Andwari, A. M., Wahid, M. A., &Bagheri, G. 2013. A Review on Green Energy Potentials in Iran. *Renewable and Sustainable Energy Reviews*. 27: 533–545.

[2] Hosseini, Seyed Ehsan, Mazlan Abdul Wahid, Saber Salehirad, and Mohsin M. Seis. 2013. Evaluation of Palm Oil Combustion Characteristics by Using the Chemical Equilibrium with Application (CEA) Software. *Applied Mechanics and Materials*. 388: 268–272.

[3] Hosseini, Seyed Ehsan, and Mazlan Abdul Wahid. 2012. Necessity of Biodiesel Utilization as a Source of Renewable Energy in Malaysia. *Renewable and Sustainable Energy Reviews*. 16(8): 5732–5740.

[4] Hosseini, Seyed Ehsan, Mazlan A. Wahid, and Abuelnuor Abdeen Ali Abuelnuor. 2013. Biogas Flameless Combustion: A Review. *Applied Mechanics and Materials*. 388: 273–279.

[5] Hosseini, Seyed Ehsan, Mazlan Abdul Wahid, and NasimAghili. "The scenario of greenhouse gases reduction in Malaysia." *Renewable and Sustainable Energy Reviews* 28 (2013): 400-409.

[6] Hosseini, Seyed Ehsan, and Mazlan Abdul Wahid. 2013. Biogas Utilization: Experimental Investigation on Biogas Flameless Combustion in Lab-scale Furnace. *Energy Conversion and Management* 74: 426–432.

[7] Hosseini, Seyed Ehsan, and Mazlan Abdul Wahid. 2013. Feasibility Study of Biogas Production and Utilization as a Source of Renewable Energy in Malaysia. *Renewable and Sustainable Energy Reviews*. 19: 454–462.

[8] Jahangirian, Saeed, Engeda, Abraham, Wichman, Indrek S. 2009. Thermal and Chemical Structure of Biogas Counterflow Diffusion Flames. *Energy Fuels*. 23(11): 5312–21.

[9] Taleghani G, Shabani Kia A. 2005. Technical–economical Analysis of the Saveh Biogaspower Plant. *Renewable Energy*. 30(3): 441–6.

[10] Rasi S, Läntelä J, Rintala J. Trace. 2011. Compounds Affecting Biogas Energy Utilization A Review. *Energy Conversion and Management*. 52(12): 3369–75.

[11] Lastella G, Testa C, Cornacchia G, Notornicola M, Voltasio F, Sharma Vinod Kumar. 2002. Anaerobic Digestion of Semi-solid Organic Waste: Biogas Production and Its Purification. *Energy Conversion and Management*. 43(1): 63–75.

[12] Machado, Sandro L, Carvalho Miriam F, Gourc Jean-Pierre, VilarOrencio M, do Nascimento Julio CF. Methane Generation in Tropical Landfills: Simplified Methods and Field Results. *Waste Manage*. 29(1): 153–61.

[13] DongkunLuo, Youjin Dai. 2009. Economic Evaluation of Coal Bed Methane Productionin China. *Energy Policy*. 37(10): 3883–9.

[14] FatihDemirbas M, Balat Mustafa, BalatHavva. 2011. Biowastes-to-biofuels. *Energy Conversion and Management*. 52(4): 1815–28.

[15] Demirbas Ayhan. 2011. Waste Management, Waste Resource Facilities and Waste Conversion Processes. *Energy Conversion and Management*. 52(2): 1280–7.

[16] Albert Guisasola, Sharma Keshab R, Keller Jurg, Yuan Zhiguo. 2009. Development of Amodel for Assessing Methane Formation in Rising Main Sewers. *Water Res*. 43(11): 2874–84.

[17] CigdemYangin-Gomec, OzturkIzzet. 2013. Effect of Maize Silage Addition on Biomethane Recovery from Mesophilic Co-digestion of Chicken and Cattle Manure to Suppress Ammonia Inhibition. *Energy Conversion and Management*. 71: 92–100.

[18] Yang Shang-Shyng, Liu Chung-Ming, Lai Chao-Ming, Liu Yen-Lan. 2003. Estimation of Methane and Nitrous Oxide Emission from Paddy Fields and Uplands During 1990–2000 in Taiwan. *Chemosphere*. 52(8): 1295–305.

[19] Nusbaum, Neil J. 2010. Dairy Livestock Methane Remediation and Global Warming. *J Commun Health*. 35(5): 500–2.

[20] Astals S, Ariso M, Galí A, Mata-Alvarez J. 2011. Co-digestion of Pig Manure and Glycerine: Experimental and Modelling Study. *Journal of Environmental Management*. 92(4): 1091–6.

[21] Takahashi J. 2011. Some Prophylactic Options to Mitigate Methane Emission Fromanimal Agriculture in Japan. *Asian–Aust J AnimSci*. 24: 285–94.

[22] Balat M, Balat H. 2009. Biogas as a Renewable Energy Source—A Review. *Energy Sources, Part A*. 31(14): 1280–93.

[23] W. Peschka. 1992. *Liquid Hydrogen: Fuel of the Future*. Springer-Verlag, Wien and NewYork.

[24] A. A. Burbano HJ, J. M. Garcıa. 2008. Effects of Hydrogen Addition to Methane on the Flame Structure and CO Emissions in Atmospheric Burners. *International Journal of Hydrogen Energy*. 33: 3410–3415.

[25] S. A. 1997. Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation, Safety Standard for Hydrogen and Hydrogen Systems.

[26] W. P. a. Jones, J. H. 1982. Calculations Method for Reacting Turbulent Flows: A Review. *Combustion and Flame*. 48: 1–26.

[27] M. Ilbas, I. Yilmaz, Y. Kaplan. 2005. Investigations of Hydrogen and Hydrogen–Hydrocarbon Composite Fuel Combustion and NO Emission Characteristics in a Model Combustor. *International Journal of Hydrogen Energy*. 30(10): 1139–1147.

[28] S. T. Amir Mardani. 2010. Effect of Hydrogen on Hydrogen–Methane Turbulent Nonpremixed Flame Under MILD Condition. *International Journal of Hydrogen Energy*. 35: 11324–11331.

[29] W. M. M. Hossain. 2007. A Combustion Model Sensitivity Study for CH4/H2 Bluff-bodystabilized Flame. Proceedings of the Institution of Mechanical Engineers. *Part C: Journal of Mechanical Engineering Science*. 221: 1377.

[30] M. H. M. Ravikanti, W. Malalasekera. 2009. Laminar flamelet Model Prediction of NO Formation in a Turbulent Bluff-body Combustor. Proceedings of the Institution of Mechanical Engineers. *Part A: Journal of Power and Energy*. 223: 241.

[31] D. Yilmas, S. U. 2005. Onbasioglu, Computational Modeling of Hydrogen Enriched Nonpremixed Turbulent Methane Air Flames. Proceedings of European Combustion Meeting.

[32] P.s. Alessio Frassoldati, Alberto Cuoci, Tiziano Faravelli, Eliseo Ranzi. 2010. Kinetic and Fluid Dynamic Modeling of Methane/Hydrogen Jet Flames in Diluted Coflow. *Applied Thermal Engineering*. 30: 376–383.

[33] D. M. Wicksall, A. K. Agrawal. 2007. Acoustics Measurements in a Lean Premixed Combustor Operated on Hydrogen/Hydrocarbon Fuel Mixtures. *International Journal of Hydrogen Energy*. 32(8): 1103–1112.

[34] O. Tuncer, S. Acharya, U. H. Jong. 2006. Effects of Hydrogen Enrichment on Confined Methane Flame Behavior. In: American Society of Mechanical Engineers, Power Division (Publication) PWR,Atlanta, GA, 2006.

[35] S. Vijaykant, A. K. Agrawal, 2005. Numerical Investigation of Swirl Stabilized Combustion of Lean Premixed Methane and Hydrogen Enriched Methane. In: 43rd AIAA Aerospace Sciences Meeting and Exhibit - Meeting Papers, Reno, NV, 2005. 11577–11585.

[36] F. Cozzi, A. Coghe. 2006. Behavior of Hydrogen-enriched Non-premixed Swirled Natural Gas Flames. *International Journal of Hydrogen Energy*. 31(6): 669–677.

[37] S. Chen, Z. Liu, J. Liu, J. Li, L. Wang, C. Zheng. 2010. Analysis of Entropy Generation in Hydrogen Enriched Ultra-lean Counter-flow Methane-air Non-premixed Combustion. *International Journal of Hydrogen Energy*. 35(22): 12491–12501.

[38] B. S. Yilbas, S. Z. Shuja, M. O. Budair. 1999. Second Law Analysis of A Swirling Flow in a Circular Duct with Restriction. *International Journal of Heat and Mass Transfer*. 42(21): 4027–4041.

[39] W. W. L. T.-H. Shih, A. Shabbir, Z. Yang, J. Zhu. 1995. A New K-epsilon Eddy Viscosity Model for High Reynolds Number Turbulent Flows—Model Development and Validation. *Computers Fluids*. 24(3): 227–238.

[40] G. P. Smith, D. M. Golden, M. Frenklach, N. W. Moriarty, B. Eiteneer, M. Goldenberg, C.T.

[41] Bowman, R. K. Hanson, S. Song, W. C. Gardiner, V. V. L. Jr., Z. Qin, GRI-Mech 3.0, The Gas Research Institute : http://www.me.berkeley.edu/gri_mech.

[42] Fluent, Ansys, 14.0 Theory Guide, AnsysInc 5. 2012.

[43] Som, S. K., and A. Datta. 2008. Thermodynamic Irreversibilities and Exergy Balance in Combustion Processes. Progress in Energy and Combustion Science. 34(3): 351–376.