Converting LPG Stoves To Use Biomethane

S. Suwansri, J.C. Moran, P. Aggarangsi, N. Tippayawong, A. Bunkham, and P. Rerkkriangkrai*

ABSTRACT

This article presents a study on using portable biomethane for domestic cooking in Thailand in domestic stoves. Thailand presently uses approximately 20,000 tonnes of LPG every day. It is estimated that Thailand has the potential to produce the equivalent of 3,000 tonnes of LPG equivalent energy from compressed biomethane gas (CBG) per day. This assumes full conversion of all agricultural, industrial and municipal wastes into CBG. Since CBG is a form of renewable energy, the use of it for domestic cooking purposes will help to reduce Thailand's dependence on imported energy and have a positive impact on the environment. The difficulty arises when a cylinder of biomethane, which is processed biogas comprising of at least 85% methane, is used instead of LPG, which is comprised of propane and butane, in a cooking stove. The Wobbe index for LPG is approximately double that of biomethane indicating that they are not interchangeable gases. The density of LPG is also 2 - 3 times that of biomethane which results in incompatible calorific or heating values and flow rates, assuming constant pressure, in domestic stoves. Without modification to the stove or the supply conditions the biomethane will not properly combust. Two domestic stoves types were selected and modified to allow biomethane to be used. An experiment was setup to measure the fuel flow rates, pressure and combustion efficiency in these modified stoves. The results of these experiments point to an optimal design modifications for converting an LPG to a biomethane stove.

Keywords: Biomethane, LPG, Domestic Stove, Porous Burner, Vertical Burner, Wobbe Index

*Corresponding author: james@dome.eng.cmu.ac.th

INTRODUCTION

In 2013, Thailand has used approximately 8400 tons of LPG every day for domestic cooking. This accounts for 42% of the total LPG consumed in Thailand. Approximately 18% of Thailand's LPG came from imports in 2012 [1]. In order to provide a cheap fuel source this is subsidized by the government, which caps the wholesale price of LPG from refineries at $333 per ton [2]. If instead of using LPG as the fuel source, biomethane was used that would result in several benefits [3]. It would help increase the income of farmers who produce the biomethane from farm waste, reduce the cost of importing petroleum products, reduce the subsidy cost and ease pressure on greenhouse gas emissions [4]. Thailand has the potential to produce a lot of biogas, a raw ingredient for biomethane, from its existing stock of raw materials [5 – 7]. In 2010, biomass fuel from wood, (sugar cane) bagasse, (rice) paddy husk and other agro-residues, totaled more than 21 MTOE [8].

Biomethane is produced from biogas which is itself produced from agricultural or industrial waste. This technology is based on harnessing anaerobic biodegradation of organic matter using suitable microorganisms [9-11]. Bacteria process the waste to produce a gas containing approximately 50 – 70% methane (CH4). In order to increase the percentage of methane and reduce other impurities the biogas is purified in a water scrubbing process. This brings the final value of methane to 85% with carbon dioxide making up the bulk of the remaining gas. The heating value of this mixture is 33.7 MJ/kg. This particular ratio was selected because at this ratio biomethane is allowed to be used as an automotive substitute for natural gas grid injection in Thailand. For domestic cooking, 85% methane, was selected as it is not as critical an application as automotive power or pipeline gas quality. In other words if 85% is considered suitable for automotive use, it should also be well suited to the less demanding task of cooking. However, the removal of hydrogen sulfide from the original biogas is important as this can corrode storage tanks and connecting pipes. A review on the processes capable of purifying biogas can be found in Ryckebosch [12].

Flame stability of biomethane in reference burners has been studied by Dai et al. [13]. However, they used biomethane with a maximum methane percentage of 70% and they varied the primary air flow. For these domestic stoves under study here it is not possible to vary the primary air flow much. In order to use biomethane instead of LPG for domestic cooking then some physical changes need to be made to the stoves. For refineries in Thailand, the LPG gas mix is typically 60% propane and 40% Butane. The Wobbe Index (WI) or Wobbe number is an indicator of the interchangeability of fuel gases. It is defined as:

$$\text{Wobbe Index} = \frac{\text{GrossHeating Value}}{\sqrt{\text{Specific Gravity}}} \quad [1]$$

The WI for LPG is around 85 MJ/m^3 and for 85% biomethane, it is 36 MJ/m^3. This is less than half that of LPG meaning that these fuels are not directly interchangeable. The density of the biomethane, at standard conditions* is 0.8 kg/m^3, making it lighter than air (1.225 kg/m^3). LPG in gaseous form has a density of 1.5 – 2 times that of air giving it a higher mass flow rate for a given pressure drop. In order to get the same energy output, the biomethane volume flow rate will have to be higher. This can be done in two ways, increasing the area normal to the flow or changing the pressure.

DOMESTIC STOVE USE IN THAILAND

Burner efficiencies have been studied and methods suggested to increase their efficiency [13, 14]. However, these studies were only with LPG. This study will focus on two types of stoves that are commonly used in Thailand for domestic cooking purposes. They are shown in Figure 1. The air and fuel are premixed in both before reaching the burner head. The porous burner (PB) has a porous ceramic surface that combusts the air fuel mixture at the head surface. The vertical burner (VB) has 5 distinct heads with separate flow lines leading to each head. They both have a small inner flame for when the stove is set to the low setting and a larger outer ring for when the setting is medium or high. Both are designed for use with LPG.

The operating principle of each stove is similar. The LPG fuel, which is normally stored in a small portable cylindrical tank, is passed through a regulator which limits the gauge pressure to 0.05 bar (5 kPa).

*The International Standard Metric Conditions for natural gas and similar fluids are 288.15 K (15.00 °C; 59.00 °F) and 101.325 kPa. *Natural gas – Standard reference conditions (ISO 13443).* Geneva, Switzerland: International Organization for Standardization. 1996.

The fuel then flows through a hose which is connected to the stove. Once the fuel reaches the stove it is forced through one or two small nozzles depending on whether the flow setting is low or medium/high. The gaseous fuel passes through a small nozzle resulting in a jet that entrains air, similar to the operation of a jet pump. These nozzles and gates can are shown in Figure 2. The porous burner has a secondary outer ring fed by a second nozzle assembly. When the setting is low, no fuel flows in the outer ring. When the setting is medium or high, fuel flows through the outer ring. The vertical burner has a nozzle assembly for each burner, 5 in total. At a low setting only the middle one is used, at medium/high settings all 5 burners are in use.

Once leaving the nozzle assembly, the fuel and air then flow together through a pipe with an increasing area. This causes the mixture to slow down and promotes fuel air mixing. The pipe then undergoes a 90o turn before directing the mixture into the burn head. The mixture exits the head and combusts.

BIOMETHANE SUBSTITUTION FOR LPG

To combust biomethane in these two stoves some of the hardware must be modified. The less hardware changes the better from the point of view of manufacturing cost and commercial stove vendors. The first question is why it is necessary to make any hardware changes to the stove? Can we simply flow biomethane through the inlet hose pipe and burn

Figure 1a. Porous Burner.

Figure 1b. Vertical Burner.

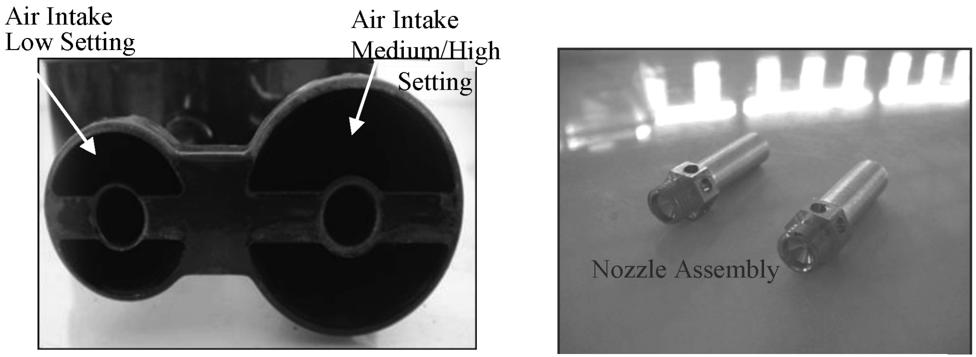
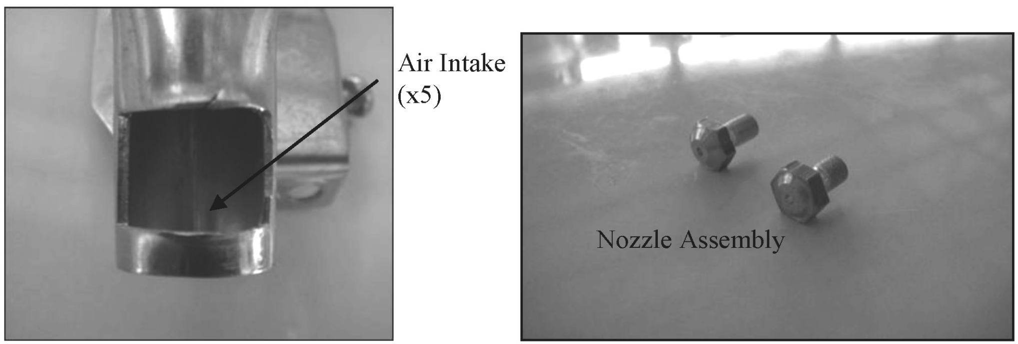


Figure 2a. Porous Burner Nozzle and Air Inlet Assembly.



Figures 2b. Vertical Burner Nozzle and Air Inlet Assembly.

the combustion mixture? Unfortunately, this doesn't work. The different densities and WI for both gases limit their interchangeability. If biomethane was connected to any of the LPG stoves under the same conditions of temperature and pressure, then the ratio of molar to volume flow rate of the biomethane would be the same as that of the LPG. Since the biomethane molecular weight (20.2 kg/kmol) is less than half the molecular weight of LPG (47.6 kg/kmol) coupled with its lower heating value means that per unit volume, less than one third of the LPG energy content would reach the burner head. This results in a very weak, unstable or just no flame. This is also confirmed by preliminary experimental results.

The obvious solution is to increase the pressure, thereby forcing a larger mass flow rate of biomethane into the burner head. This results in a higher volume flow rate and more energy being available for combustion. This potential solution does not work. Increasing the volume flow rate the fuel exit jet velocity increases. The entrained air is related to this velocity. A higher jet velocity means more air for combustion is entrained with the fuel. Too much air at the burner head results in flame lift off, an unstable or no flame. This is also confirmed in the experimental results.

Therefore the approach taken for this project was to enlarge the nozzle diameters. This will reduce the fuel exit velocity and therefore reduce the entrained air. At the same time, the fuel supply pressure will be increased to allow more energy to reach the burner head. It is hoped that a combination of these two relatively minor changes will be enough to produce a stable flame at all stove power settings.

EXPERIMENTAL SETUP

Equipment

An experiment was setup to measure the pressure, flow rate and temperature of the gaseous fuel before entering each stove. Measuring the airflow rate was not possible without interfering with the airflow. The nozzle diameter was modified, usually by enlarging it for each set of tests. The experimental setup is shown in Figure 3.

Specific elements of the test apparatus are shown in Figure 4. For baseline tests using LPG a commercial regulator was used. The output pressure was fixed. The baseline LPG tests were used as a guide to see how an optimal flame looks like. For the biomethane testing, a general regulator was used to control the output pressure. Therefore, it was

Figure 3. Experimental Setup.

possible to change the pressure. In all tests the fuel tank was placed on a weigh scales and the weights before and after testing were recorded. The fuel mass flow rate was calculated in this manner.

Experimental Procedure

The first tests were to determine if biomethane could be combusted safely and cleanly with a combination of pressure and/or nozzle changes. The stoves were always initially tested with their existing nozzle and standard LPG pressure. The biomethane fuel was introduced to the stove with the flow setting set to the lowest point. Later tests were carried out at the medium and high settings. If the flames at all settings were completely stable and similar in structure to an equivalent LPG flame, then the pressure and nozzle size were recorded. Determining an 'equivalent LPG flame' is a subjective interpretation, especially when a flame displays only tiny flickers of instability. Not enough air in the combustion mixture will result in flames having a yellow tip. Too much air in the mixture and the flames will not anchor to the burner head but will try and lift off. If there was any yellow tipping or lift off on any of the burner settings then that particular combination of pressure and nozzle diameter was considered non-performing or outside the working range. After one pressure set was analyzed the pressure was increased and the process repeated. The next step was to replace the nozzles with larger diameters and the process of increasing the pressure and examining the flame at all low/medium/

Figure 4a. Compressed Biomethane 100 Liter Tank.

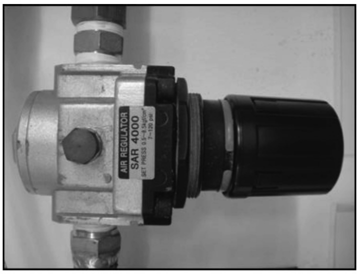


Figure 4b. Air Regulator Model SAR 4000.

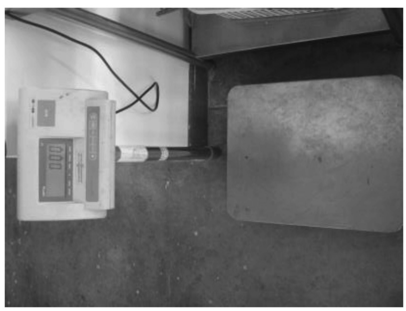


Figure 4c. Scale for Weight Measurement.

Figure 4d. LPG Pressure Regulator: Model L-326.

high settings was repeated. The set of nozzle diameters and pressures that produced stable flames at all settings were recorded.

Once suitable combinations were discovered a map was built, displaying the combinations that worked and those that did not. The mass flow rates, from the acceptable combination pairs, were measured and compared to LPG flow rates. The heating values entering the burner head were calculated. Similar heating values will provide a similar length of time to cook food, assuming the stove efficiency stays constant. Of all the suitable sets (nozzles/pressure) that worked, some of the promising combinations were selected to run efficiency tests. These tests are based on the standard DIN EN 203-2. The efficiency test involved heating 7.8 kg of water by 70˚C and measuring the time and quantity of fuel to do so. The efficiency can be obtained from:

$$\eta = \frac{M_{water} C_{water} \Delta T}{Q_{fuel} x HV} \qquad [2]$$

where: m_{water} is the initial mass of water (kg), C_{water} is the specific heat capacity of water (J/kgK), ΔT is the temperature increase in the water (˚C), Q_{furl} is the volume of fuel used (m^3), and HV is the fuel heating value per unit volume (J/m^3).

RESULTS

Tests with LPG

Testing with LPG established a baseline case with which to compare the biomethane. Getting the biomethane flame that looks closest to the LPG flame is the goal of this project. Tests were run with LPG on both types of domestic stoves. The pressure of the fuel was measured before it entered the stove and the mass flow rate was recorded at all stove settings. The results are displayed in Table 1.

At each setting, pictures were taken with both an ordinary and an infrared camera. Selecting the highest setting or the maximum flow rate, Figure 5 shows a snapshot of these flames for both different stoves.

Tests with Biomethane

The purpose is to find an optimal nozzle/pressure ratio that will allow biomethane to cleanly and stably combust in each stove. The test-

Table 1. Baseline Test Results with LPG

	Inlet Pressure (bar)	Nozzle Inner Diameter (mm)	Nozzle Outer Diameter (mm)	LPG Flow Rate (Low Setting) (kg/hr)	LPG Flow Rate (Medium Setting) (kg/hr)	LPG Flow Rate (High Setting) (kg/hr)
Porous Burner	0.05	0.5	0.7	0.06	0.16	0.19
Vertical Burner	0.05	0.5	0.55 (x4)	0.05	0.16	0.33

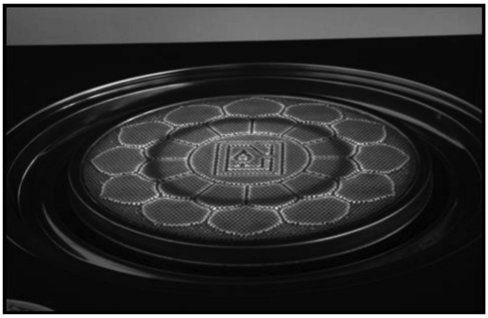


Figure 5a. Porous Burner LPG Flame.

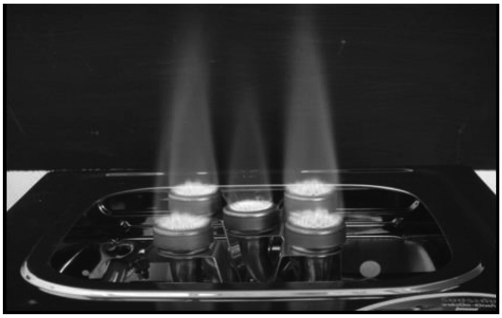


Figure 5b. Vertical Burner LPG Flame.

ing procedure was carried out as described in Experimental Procedure section. The result was a 'map' of particular pressure and nozzle combinations that worked and those that did not. These maps are shown for each stove in Figure 6.

Figure 6a is for the porous burner and Figure 6b is the vertical burner. The x-axis is the pressure in bar. The y-axis is the diameter of

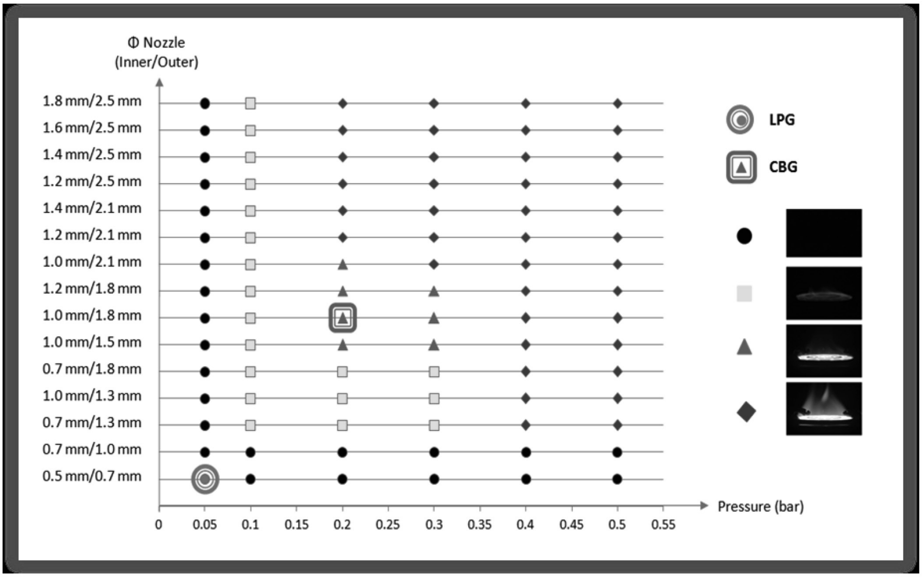


Figure 6a. Porous Burner Optimal Nozzle/Pressure for Biomethane.

both nozzles used. A circle marker (●) means that it was not possible to get a flame at those conditions. For example in figure 6a, we see that at standard LPG conditions (three concentric circles), 0.05 bar and a 0.5 mm inner nozzle and 0.7 mm outer nozzle diameter, no flame was possible. This validates the theoretical arguments above that it should not be possible to directly substitute biomethane for LPG. For convenience the LPG condition is shown on each figure for comparison.

A square marker (□) means that there was a flame but it was very low. At the lower setting it was liable to extinguish. There was too little fuel relative to air entering the stove head and the flame was liable to lift off. A diamond marker (◊) means that the flame is high and potentially dangerous. It was decided that for the vertical stove a 5″ flame was considered to be too high and 2″ was too high for the porous stove. A high flame indicated too much fuel relative to air entering the stove. A triangle marker (Δ) was the optimal condition where the flame at all stove settings most closely resembles a LPG flame. Figure 6b for the vertical burner, contains no triangle markers as optimal conditions were not found for this burner. A star (*) marker was used, indicating that a stable flame was possible at the medium and high settings but not at the low setting. This means that biomethane was not usable in a vertical burner,

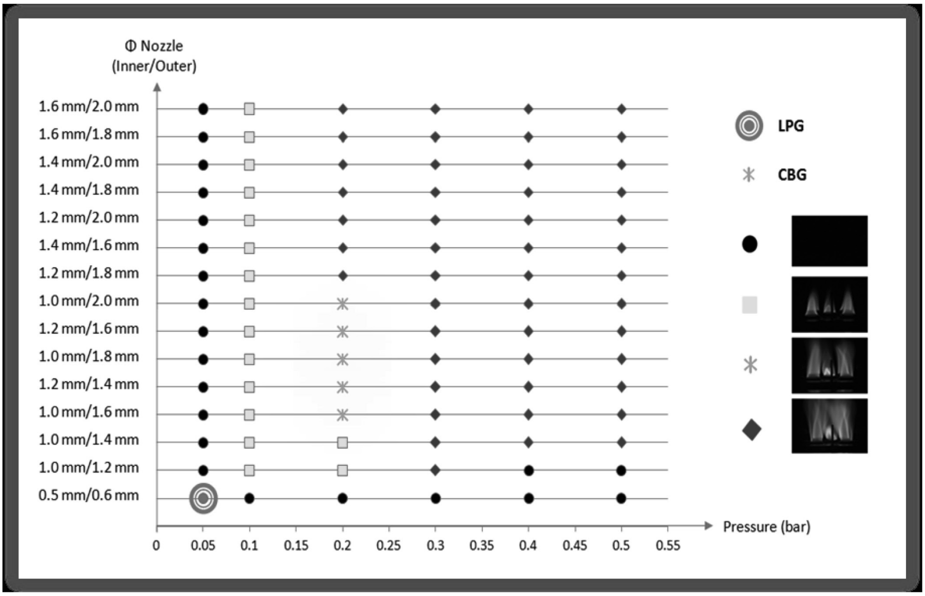


Figure 6b. Vertical Burner Optimal Nozzle/Pressure for Biomethane.

without a major redesign of the burner. Changing nozzle diameter and fuel supply pressure is not sufficient to get a stable performance map.

Therefore the remaining tests were only performed on the porous stove. From figure 6a there are several available triangle markers which provide a stable flame. It was decided to select the point at the center of the nozzle range. This allowed for stability, as the nozzle sizes above and below it are also stable points. The most suitable pressure was selected at the lowest functioning value. A low pressure was preferred as the risks of gas leaks inside the porous stove, decrease.

Pictures of some of the biomethane flames at different settings are shown in Figure 7. A summary of the optimal conditions for the porous stove can be found in Table 2.

As can be seen for the porous stove the optimal fuel supply pressure is 0.2 bar and the optimal inner and outer nozzle diameters are 1.0 mm and 1.8 mm, respectively. These diameters represent an increase in nozzle area of 300 and 560%, respectively. For the vertical burner an optimal condition was not found. At 0.2 bar and nozzle diameters of 1.0 mm and 1.8 mm, a stable flame was found at the medium and high settings but at the low setting the flame was unstable, as can be seen in Figure 8.

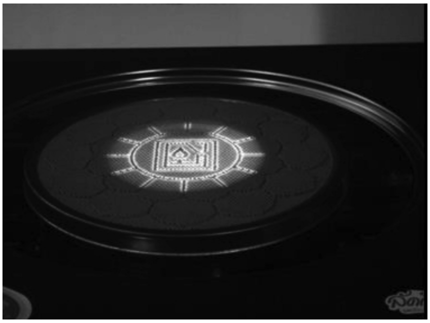


Figure 7a.
PB, Low Setting, Biomethane.

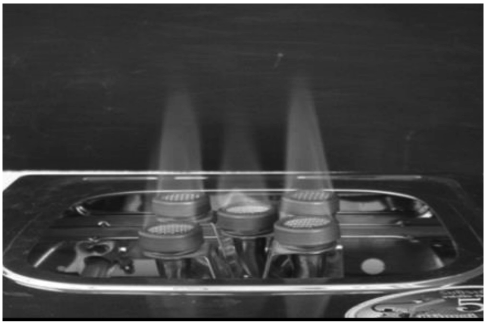


Figure 7b.
VB, Medium Setting, Biomethane.

Table 2. Optimal Parameters for Biomethane Combustion

	Optimal Inlet Pressure (bar)	Optimal Nozzle Inner Diameter (mm)	Optimal Nozzle Outer Diameter (mm)
Porous Burner	0.2	1.0	1.8
Vertical Burner	none	none	none

Energy Output

Of concern to the end user is how much energy is delivered by the biomethane in comparison with the LPG. This directly affects the cooking time. Too much, the food may burn and too little, the cooking time increases.

The biomethane flow rate was measured under the conditions shown in Table 2. Each point will have two different flow rates, for the high and medium settings. It was decided to leave out the lower setting as measuring the low flow rates was not possible with the resolution of the scale balance. The energy content of the 85/15 biomethane is 33.7MJ/kg. The energy content for the porous stove, at each setting is shown in Table 3. The vertical burner is left out of the results because an optimal condition was not found for it.

Comparing both energy contents, it is seen that the biomethane outputs 22% more energy than the LPG resulting from its higher mass flow at the chosen settings. This should mean that the cooking time will be faster with biomethane. However, it is not quite a linear relationship; the heating time also depends on the flame temperature since a higher

Table 3: Energy Content at Optimal Conditions

	Biomethane	LPG	Biomethane	LPG
	Medium Setting (kW)		**High Setting (kW)**	
Porous Burner	2.5	2.04	2.94	2.42

Figure 8. Vertical Burner Flame, 0.2 bar, 1.0mm Nozzle, Low Setting.

flame temperature can lead to higher heat losses. The stove efficiency may also change with different fuels. To estimate the flame temperatures, a FLIR T200 infrared camera was used. This is a general IR camera that measures temperatures on the surface of objects. It does not have the capability to measure the hottest temperature at the center of the flame. Therefore, this camera will only allow for a relative temperature difference to the estimated, it will not record the absolute temperature. Some selected thermal images are shown in Figure 9 to compare surface temperatures of both biomethane and LPG.

The maximum measured flame temperature difference between biomethane and LPG is 18°C for the vertical burner and it is equivalent in the case of the porous burner. In order to determine the cooking efficiency of one fuel over another, experiments were carried out according to the standard DIN EN 203-2. This has been explained in section 4.2. A 7.8 kg mass of water is heated by 70°C and the mass of fuel used is measured. The efficiency is calculated from Eq. 2. Efficiency testing was only carried out on the porous burner.

As can be seen in Table 4, the biomethane operates 4% less efficiently at the medium setting but heats the water 5 min quicker. At the high settling the biomethane efficiency is 6% more efficient and the heating time is 9 min faster. The small differences in efficiencies are unlikely to matter greatly but the faster cooking times are an advantage. The faster cooking times can be explained from the 22% more energy entering the burner. The increased energy does not seem to lead to higher flame temperatures meaning that losses are similar and the heating efficiencies are also similar. Since 7.8 kg is a large quantity, it is suspected that in day-to-day cooking the time difference and efficiency between both fuels would be barely noticeable.

DISCUSSION

Biomethane can be used in a porous burner domestic stove in Thailand with just two operational modifications. The first is that a higher

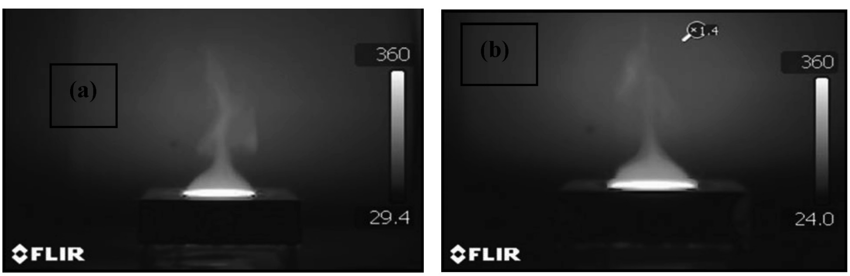


Figure 9a. Porous Burner IR Picture of (a) Biomethane and (b) LPG.

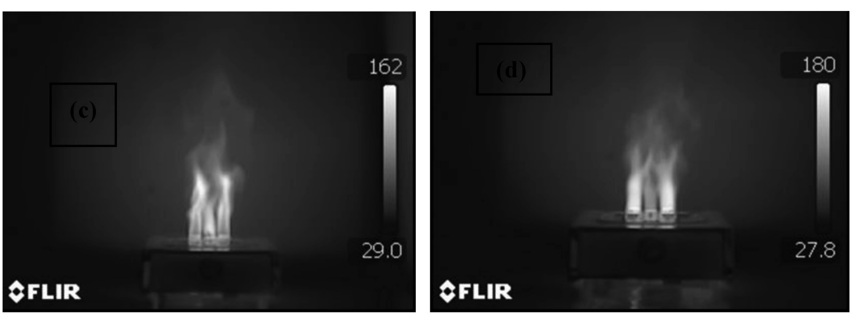
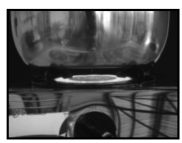
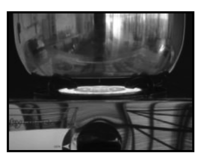


Figure 9b. Vertical Burner IR Picture of (c) Biomethane and (d) LPG.

pressure is needed. Experiments have shown that a gauge pressure of 0.2 bar is the most suitable. This is four times the pressure of LPG and therefore the same pressure regulator cannot be used. The second change is that the nozzle diameters through which the fuel enters the stove must be enlarged. The optimal inner diameter was 1.0 mm and the outer diameter was 1.8 mm as shown in Table 2. For comparison the inner and outer nozzle diameters for LPG combustion were 0.5 mm and 0.7 mm. These conditions were established experimentally by producing a map of all operating conditions that produced stable flames and those that did not, as shown in Figure 6. In the case of the vertical burner, a stable flame was never found for all settings. The geometry of this stove was a little different as it had four outer nozzles instead of a single one. Any conditions that resulted in a stable outer flame in each of the burner heads, resulted in too much fuel flow to the inner head at the low setting.

Once the optimal conditions were established the performance of the porous burner was measured. The energy output, flame temperature

Table 4. Results from Efficiency Tests of Porous Burner

	Porous Burner	Porous Burner
Biomethane: Medium Setting		
Efficiency	42%	
Heating Time	33 min	
LPG: Medium Setting		
Efficiency	46%	
Heating Time	38 min	
Biomethane: High Setting		
Efficiency	51%	
Heating Time	23 min	
LPG: High Setting		
Efficiency	45%	
Heating Time	32 min	

and efficiency was measured and compared to the LPG case as shown in Table 3, Figure 9 and Table 4, respectively. The conclusion for the biomethane is that the heating times are faster and the efficiencies are broadly similar. Any differences observed are probably not perceptible enough to be distinguished in typical daily use. The next stage of the research will focus on different domestic and commercial stoves and obtaining a biomethane performance map for them.

CHALLENGES AND FUTURE OPPORTUNITIES

There are two unsolved problems remaining with the current setup. The first is that after some of the testing, some melting was observed on the inlet to the porous stove as shown in Figure 10. This was more than likely caused by gas leaking and burning while the stove was operating. These particular stoves are designed to operate at 0.05 bar. The required biomethane pressures are four times greater than the pressures the stoves are normally subjected to. It was observed that this leakage and combustion only happened at pressures of 0.4 bar and higher. However careful monitoring of the situation is needed to ensure that at the chosen pressure of 0.2 bar, no leakage occurs.

The second problem was that of ignition. The biomethane was more difficult to ignite than the LPG. Often the inbuilt igniter was not sufficient to begin combustion. An external ignition source was needed.

Figure 10. Combustion Outside the Main Head.

It is not clear what the appropriate solution to this problem should be.

All testing was only carried out on one grade of biomethane. The grade used was 85% methane and 15% carbon dioxide which resulted from processing biogas, from agricultural waste, using a water scrubbing process. This particular grade was selected as it can be used in NGV vehicles as a direct substitute from natural gas. However, different grades of biomethane may result in different optimal stove settings.

In the future, high powered commercial or single wok, stoves will also be examined for convertibility as well as two additional domestic stoves. It is hoped that a similar process will yield an optimal set of conditions there too. The combustion and performance map will be modeled.

CONCLUSIONS

In order for biomethane to be used on a large scale for domestic cooking in Thailand, several infrastructural issues must be addressed. These include, designing a portable gas storage tank, its associated pressure regulator, having a biogas infrastructure for selling the gas and having stoves capable of safe and clean combustion. This article focused on the last item. It was shown that for two domestic stoves, the porous and vertical burners, only the porous can be used to burn biomethane. The vertical one cannot be used with the fuel unless a significant redesign is done of this stove. Simply altering the pressure and nozzle diameters is not sufficient to provide stable flames at all high, medium and low settings. The porous burner does stably burn biomethane with two small modifications; increases of the fuel supply pressure and the nozzle diameters. Results show that a clean, stable flame exits under low, medium and high flow settings. Under these conditions the energy from the biomethane is around 22% higher than the energy from LPG. The flame temperature is similar and the heating efficiency is also similar. The heating time is between 13 – 28% less for the biomethane fuel.

Acknowledgments

The authors would like to express their thanks to the Energy Policy and Planning office of Thailand (EPPO) and the Center of Excellence for Renewable Energy at Chiang Mai University for supporting this research.

References

1. Energy Policy and Planning Office, Ministry of Energy, 2011. http://www.eppo.go.th/info/2petroleum_stat.htm [accessed 2013-03-11]
2. Energy Policy and Planning Office, Ministry of Energy, 2011. "Report on Policies of the LPG price structure," http://www.escctcc.com/upload/Page/default_knowledge_information/general_lpg.pdf [in Thai, accessed 2013-06-28]
3. Thailand Greenhouse Gas Management Organization, 2012. "Status of CDM projects in Thailand" http://www.tgo.or.th [accessed 2013-04-01]
4. Aggarangsi, P., Tippayawong, N., Moran, J. C., Rerkkriangkrai, P., 2013. "Overview of livestock biogas technology development and implementation in Thailand" Energy for Sustainable Development, DOI:10.1016/j.esd.2013.03.004
5. Prasertsant, S., Sajjakulnukit, B. 2006. "Biomass and biogas energy in Thailand: potential, opportunity and barriers" Renewable Energy, 31, 599-610.
6. Chaiprasert, P., 2011. "Biogas production from agricultural wastes in Thailand" Journal of Sustainable Energy and Environment, special issue: 63-65.
7. Ali, G., Nitivattananon, V., Abbas, A., Sabir, M., 2012. "Green waste to biogas: renewable energy possibilities for Thailand's green markets" Renewable and Sustainable Energy Reviews, 16: 5423-5429.
8. Yokoyama, S., Ogi, T., Nalampoon, A., 2000. "Biomass energy potential in Thailand" Biomass and Bioenergy, 18: 405-410.
9. Gunaseelan, V. N., 1997. "Anaerobic digestion of biomass for methane production: a review" Biomass and Bioenergy, 13: 83-114.
10. Sakar, S., Yetilmezsoy, K., Kocak, E., 2009. "Anaerobic digestion technology in poultry and livestock waste treatment for biogas production: a literature review" Waste Management and Research, 27: 3-18.
11. Nasir, I. M., Ghazi, T. I. M., Omar, R., 2012, "Anaerobic digestion technology in livestock manure treatment for biogas production: a review" Engineering in Life Sciences, 12: 258-269.
12. Ryckebosch, E., Drouillon, M., Vervaeren, H., 2011. "Techniques for transformation of biogas to biomethane" Biomass and Bioenergy, 35: 1633 – 1645.
13. Dai, W., Qin, C., Chen, Z., Tong, C., Liu, P., 2012. "Experimental studies of flame stability limits of biogas flame" Energy Conversion and Management, 63: 157–161.
14. Tanatvanit, S., 1998. "The relationship between performance and emission of LPG cooking stove" M.Sc. thesis (Environment Management), King Mongkut University of Technology Thonburi, Thailand.
15. Jugjai, S., Tia, S., Trewetasksorn, W., 2001. "Thermal efficiency improvement of an LPG gas cooker by a swirling central flame" International Journal of Energy Research, 25: 657-674.
16. PTT Transport Department, 2008. "Natural gas vehicles," PTT Standard, p.23 [in Thai].
17. Martchamadol, J., Kumar, S., 2012. "Thailand's energy security indicators" Renewable and Sustainable Energy Reviews, 16: 6103-6122.
18. Udomsri, S., Petrov, M. P., Martin, A. R., Fransson, T. H., 2011. "Clean energy conversion from municipal solid waste and climate change mitigation in Thailand: waste management and thermodynamic evaluation" Energy for Sustainable Development, 15: 355-364.

ABOUT THE AUTHORS

Mr. Suriyun Suwansri obtained his Master's degree from Chiang Mai University, specializing in the field of design and development of domestic burners. He now works as a research engineer in burner development at the Lucky Flame Company which develops and produces stoves for the market in Thailand. His research focuses on thermal efficiency and emissions characteristics of these burners.

Dr. James Moran, the corresponding author, received his Ph.D. degree in Mechanical Engineering from the Massachusetts Institute of Technology in 2001. He is currently an Assistant Professor at the Department of Mechanical Engineering in Chiang Mai University, Thailand. His research interests include low friction surfaces, meso scale combustion, sustainability and sources of bioenergy. Email: james@dome.eng.cmu.ac.th

Dr. Pruk Aggarangsi is an assistant professor in mechanical engineering at Chiang Mai University where he moved after receiving his doctorate from Carnegie Mellon University. He is also the deputy director of the Energy Research and Development Institute-Nakorping which is well known for decades of biogas developments in Thailand and South-East Asia. Dr. Pruk specializes in the fields of anaerobic digestion technology, design and development of biogas system in tropical areas as well as mathematical modeling in many engineering applications. E-mail: pruk@gmail.com

Dr. Nakorn Tippayawong received his B.Eng. degree in Mechanical Engineering and Ph.D. degree in Internal Combustion Engines from Imperial College London, UK in 1996 and 2000, respectively. He is currently an Associate Professor at Chiang Mai University, Department of Mechanical Engineering. His research interests include biomass utilization, energy efficiency improvement, and aerosol analysis. So far, he has published more than 100 papers in peer reviewed international journals.

Dr. Prasert Rerkkriangkrai received his B.Eng. (Mechanical Engineering) from Chiang Mai University, Thailand, and M.Eng. (Energy Technology) from the Asian Institute of Technology in 1986 and 1988, respectively. He is currently an Associate Professor at Chiang Mai University in the Department of Mechanical Engineering. He is also the Director of the Energy Research and Development Institute - Nakornping, Chiang Mai which for decades has developed biogas projects throughout Thailand and South-East Asia.