

# CO-FIRING OF COMMERCIAL FUEL OIL AND PRODUCER GAS FROM DOWNDRAFT GASIFIER FOR INDUSTRIAL APPLICATIONS

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## ABSTRACT

Biomass is one of the most promising energy resource which is expected to substitute the fossil fuel in near future. Biomass is also available in almost every part of the world. Fortunately, Malaysia is rich in its agricultural residue such as palm oil solid waste, coconut shell, rice husk and many more. These waste can be utilized as an alternate energy source rather than to be dumped. As a matter of fact, land disposal is causing serious environmental pollution to the environment. Among the various biomass wastes available in Malaysia, oil palm solid waste has tremendous potential to be utilized as a fuel to generate a combustible producer gas. In this study, co-combustion of diesel oil and producer gas, from a downdraft gasifier, was done in an experimental combustion chamber. The combustion behaviour and emissions properties of the co-combustion process were analyzed. Experimentation was done for combustion of diesel oil alone as well as combustion of producer gas alone and co-combustion of liquid fuel and producer gas. Data were recorded at different equivalence ratio and producer gas flows. It was found that that the producer gas can be co-combusted with liquid fuel. The emission data shows that the co-combustion process produces more CO, NO<sub>x</sub>, SO<sub>2</sub> and CO<sub>2</sub> compared to the combustion of diesel oil only. However, the exhaust temperature for the co-combustion process is considerable higher than the diesel combustion only which can utilized in obtaining higher boiler pressures and temperatures.

**Key words:** biomass, co-combustion, emissions, oil palm solid waste, producer gas.

## 1. INTRODUCTION

World energy consumption is increasing every year due to increased population. The rising quality of life and industrialization has also contributed to the demand for energy resources. It is estimated that current world population is 6.4 billion people living on earth today and half of it is below 25 years old. So it is expected that the

world population will rise in near future so will be the demand in energy (Donald 2000).

In Malaysia, the main energy resource is petroleum. It contributes to about 68 % of total consumption and mainly used for transportation, industry, power generation

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etc. However, these natural resources are decreasing every year because of high consumption. Nevertheless, fossil fuel utilization also creates environmental concerns.

Combustion of fossil fuel such as coal and petrol produces harmful gases like carbon monoxide (CO) and sulfur dioxide (SO<sub>2</sub>). Even the cleanest fossil fuels produce carbon dioxide when they burn. Carbon dioxide is a harmless gas but the build-up of this gas in the atmosphere may cause the greenhouse effect (Nicholas 1981).

Understandably there is a need to find another source of energy to curb oil consumption to the minimum possible level and to increase the utilization efficiency and also to minimize the pollution from energy generation. An alternative energy that can be practiced in Malaysia is energy from biomass. Some of the common biomass resources available in Malaysia are woods, agricultural residue and crops.

Most of these biomass energy resources such as agricultural residue are left abandoned without being used for other purposes. Palm oil solid waste is one of the most potential biomass resources which can be used as an energy source. The first commercial oil palm estate in Malaysia was set up in 1917. Since then the industry in Malaysia has grown by leaps and bounds and the country is now the largest producer and exporter of palm oil with 67.6 million tonnes of fresh fruit bunch received by palm oil mill in 2003. Palm oil is expected to demonstrate an annual growth of 4.57% every year. In January 2005 her production of palm oil is about 13.97 million tonnes and the total solid wastes generated by this industry has amounted to more than 3.6 million tonnes (PORIM 2005). Production is expected to reach 26.2 million tonnes by the year 2005, and anticipated to account for around 20% of the global oils and fats supply.

With this condition, it is estimated that every one million tonnes of palm oil produces 0.8 million tonnes of palm oil shell. With this large amount of palm oil shell solid waste, there is a need to find several ways to utilize this waste. Recently, there is several usage of palm oil shell waste. It

is used as a fuel for boiler in the palm oil mill (Razuki 1988).

Biomass gasification is one of the chemical processes to convert biomass solid residue into usable fuel such as producer gas. Producer gas is generated when the biomass is burned with less air to achieve complete combustion. Producer gas is mainly contained carbon monoxide (CO), hydrogen (H<sub>2</sub>), methane (CH<sub>4</sub>), water vapour, and some other inert gases. Mixed with air, producer gas can be used in the internal combustion engine with a little modification (Donald et al., 1981). Also it can be used as a co-combustion fuel with other liquid fuel to minimize the fuel consumptions. Producer gas from the gasification process can be utilized in many ways. Fig. 1 shows the various ways of utilizing producer gas and the variables involved.

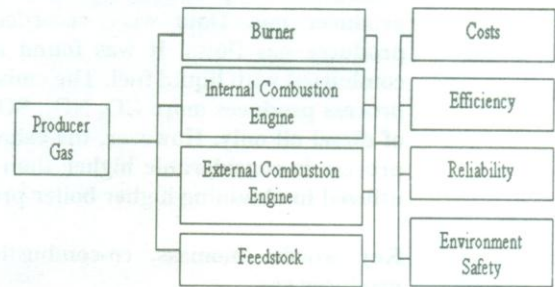


Figure 1. Various ways of producer gas utilization

Gasification offers the cleanest, most efficient method available to produce synthesis gas from low or negative-value carbon-based feed stocks such as coal, petroleum coke, high sulphur fuel oil or materials that would otherwise be disposed as waste. Gasification adds value to low- or negative-value feed stocks by converting them to marketable fuels and products. Gasification technologies differ in many aspects but share certain general production characteristics. Different types of fixed bed gasifiers are shown in Fig. 2.



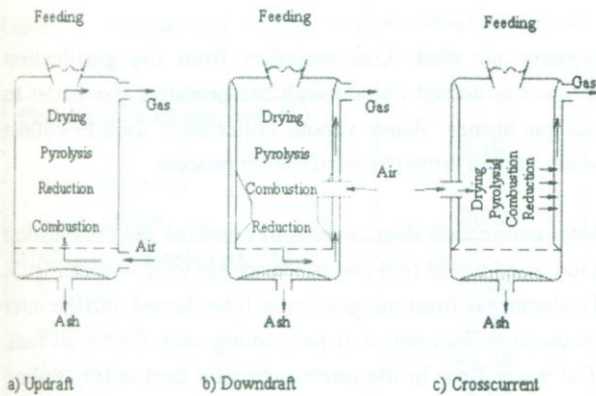


Figure 2. Types of fixed bed gasifiers

The high temperature in the gasifier converts the inorganic materials in the feedstock (such as ash and metals) into a vitrified material resembling coarse sand. Fixed bed gasification is an important commercial gasification process. A recent survey of gasifier manufacturers were found that 75% of the gasifiers were downdraft, 20% were fluid beds and only 2.51% were updraft and 2.5% were other types.

For this study, a downdraft gasifier is used to produce the producer gas. In the downdraft gasifier the tar have to pass through the hot combustion and reduction zones. A schematic diagram of the downdraft gasifier is shown in Fig. 3.

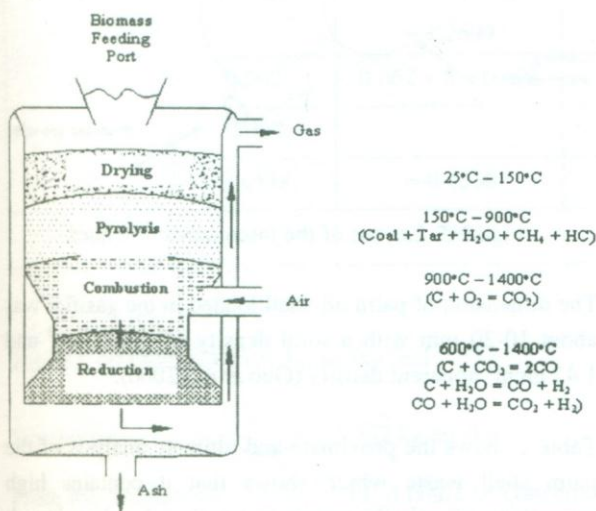


Figure 3. Downdraft gasifier used for experimentation

If the gasifier is properly designed, it will lead to sufficient combustion and cracking of the tar to make the gas useful with minimal cleaning process.

## 2. CO-COMBUSTION OF BIOMASS

Co-combustion of biomass is to burn biomass fuel with other type of fuel simultaneously. The fuel can be any type of fuel such as fossil fuel. Recently, there have been several designs that use producer gas as fuel for co-combustion. This concept has been applied to the internal combustion engine and burner. It sometimes called dual fuel engine or dual fuel burner.

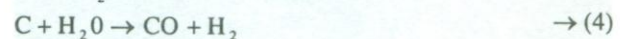
Gasification process generally uses reactants such as oxygen or steam to increase gas yields while consuming char. In systems where solid fuels are gasified in the presence of sub stoichiometric air, several chemical reactions occur. Gasification reaction and temperature zone are shown in Fig. 3.

In this case, there is a surplus of solid fuel, carbon dioxide and water vapor from the combustible zone can be passed through the glowing layer of charcoal and are reduced to carbon monoxide (CO) and hydrogen (H<sub>2</sub>) in the region known as the reduction zone (Naksite 1989).

In the combustion zone, the reactions which are exothermic are:



The reaction in the reduction zone which are endothermic, will decrease the temperature during the reduction process are :



Producer gas is therefore a mixture of the gaseous such as hydrogen (H<sub>2</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), nitrogen (N<sub>2</sub>), methane (CH<sub>4</sub>), and small amount of other hydrocarbons. The combustible components of the gas are CO, H<sub>2</sub>, CH<sub>4</sub> and C<sub>x</sub>H<sub>x</sub>, the percentages of which should be made as high as possible. The quantity of CO in the gas depends on the temperature in the reduction zone. To achieve complete reduction, the temperature in the reduction zone must be at least 1100°C (Henry 1981).

If water vapor is present, reaction (4) play an important role to enrich the gas with H<sub>2</sub> and thus enhance its heating value. However, if too much water is present, CO may react with H<sub>2</sub>O to form CO<sub>2</sub> and H<sub>2</sub>, as indicated by reaction (8) and the quantity of CO may be reduced.

### 3. MATERIALS AND METHOD

For this experiment, downdraft gasifier is used for the gasification process. Fig. 4 shows the picture of the experimental setup and it component.

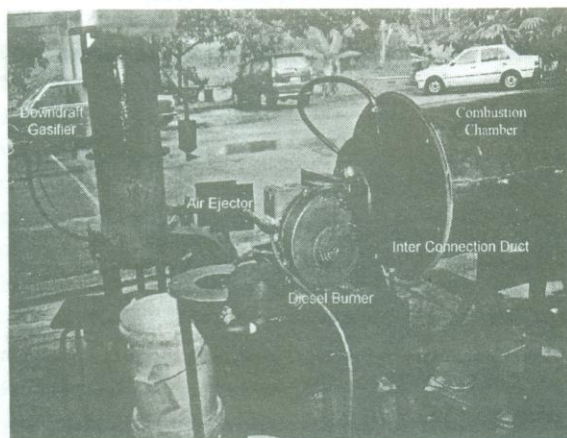


Figure 4. Picture of the experimental setup

The setup consisted of downdraft gasifier, air ejector, Inter connection duct, oil burner, gas analyzer and air blower. A small quantity of air is needed for combustion process, and the air is blown using a blower through the

primary air duct. Gas emission from the gasification process is ducted out through the producer gas outlet to the gas burner. Water vapour collector is used to collect water vapour from the gasification process.

Inter connection duct is used to combine the combustion process of liquid fuel and producer gas as shown in Fig. 5. Producer gas from the gasifier will be ducted into the inter connection duct and will burn along with the liquid fuel. The water flow in the interconnection duct is for cooling the interconnection duct during the experiment. This is to prevent any hazard during the experiment because without coolant it will become very hot and it is really dangerous. It is also used as an energy converter to burn the producer gas.

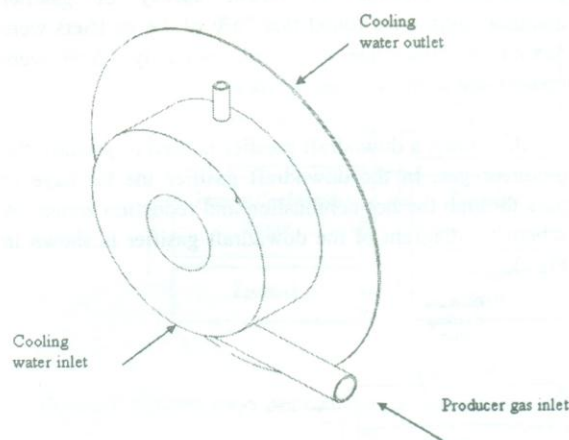


Figure 5. Layout of the interconnection duct

The dimension of palm oil shell loaded in the gasifier was about 10-20 mm with a solid density of 1.53 g/cm<sup>3</sup> and 1.47 g/cm<sup>3</sup> apparent density (Guo *et al.*, 2000).

Table 1 shows the proximate and ultimate analysis of the palm shell waste which shows that it contains high percentage of volatile matter and carbon but low in ash (Ani 1992).



Table 1. Proximate and ultimate analysis of oil palm shell waste

<b>Proximate analysis (wt. %)</b>	
Ash	2.10
Volatile matter	67.0
Fixed carbon	20.3
<b>Ultimate analysis (wt. %)</b>	
Carbon	47.62
Hydrogen	6.20
Oxygen	43.38
Nitrogen	0.70
Moisture (wt. % air dry)	9.70
Low Calorific Value (MJ/kg)	19.10

Using the ultimate analysis of the palm shell waste, calculations were done for the stoichiometric air requirement for the gasifier. The sample calculation procedure is outlined in Table 2.

Table 2. Stoichiometric air requirement using oil palm shell waste as fuel

Constituent	Mass constituent kg/kg fuel	O <sub>2</sub> required kg/kg fuel	Product of combustion kg/kg fuel		
			CO <sub>2</sub>	H <sub>2</sub> O	N <sub>2</sub>
C	0.4762	$0.4762 \times 2 \frac{2}{3}$ = 1.2699	$0.4762 \times 3 \frac{2}{3}$ = 1.7461		$0.4762 \times 8.84 = 4.21$
H <sub>2</sub>	0.062	$0.062 \times 8 = 0.496$		$0.062 \times 9 = 0.558$	$0.062 \times 26.5 = 1.643$
N <sub>2</sub>	0.007				= 0.007
O <sub>2</sub>	0.4338	= -0.4338			$-0.4338 \times 0.768 = -0.3332$
Total		1.3321	1.7461	0.558	5.5268

Total O<sub>2</sub> required = 1.3321 kg air /kg fuel

$$\text{Stoichiometric air} = \frac{1.3321}{0.232} = 5.742 \text{ kg air /kg fuel}$$

From the stoichiometric mass of air, it could be converted to volume flow rate and for gasification the amount of air

required is less than stoichiometric i.e. less than 50% required.

The experimental work comprised of three distinct experiments. These were done to compare and analyse the emission properties of combustion with different fuel condition and properties. The experiments were as follows:

- i) Combustion of diesel oil
- ii) Combustion of producer gas
- iii) Co-combustion of diesel oil and producer gas

The mass flow rate of the diesel oil used in the burner was 0.001195 kg/s.

### Combustion of diesel fuel

The diesel fuel burner was used for this experiment. Before starting the experiment, the cooling water circulation is regulated to assist the cooling process in the combustion chamber and in the interconnection duct. The

combustion chamber is preheated using the diesel burner for fifteen minute to prevent heat losses during the experiment.

The diesel burner was set with different baffle air opening to get a different equivalent ratio setting. Data was recorded for equivalence ratio ( $\Phi$ ) ranging from 0.9-1.2. The emission data was analyzed using the TELEGAN gas analyzer.

### **Combustion of producer gas**

After the experiment of diesel fuel combustion was completed, the diesel fuel burner was turn off to allow the combustion of producer gas to proceed. Before the experiment, producer gas was needed to be generated using the downdraft gasifier. Before starting the experiment, all connection in the gasifier was checked to prevent any gas leakage. Gasifier is start up by filling the bottom of the bed with charcoal to assist for reduction process to generate producer gas. Then, the gasifier is filling up with palm oil shell until 1/2 of the gasifier bed. Then it was ignited by adding a little petrol. After it is ignited, it is left for 15 minute until it was fully ignited. Primary air supply valve is open to full and the windowpane is left opened (Lukeman 2004).

After that, the feeding process is continued by filling the gasifier with palm oil shell until it is full to about three quarter. Then the windowpane is closed and properly tightens. The primary air valve is reduced to 1/4 valve opening. This is to generate the producer gas because producer gas is generated when solids burn with less air supply. Secondary air valve is opened to 1/4 valve opening. After a few minute one can see white thick smoke flow to the interconnection duct and then to the combustion chamber. The producer gas is then ignited using burning paper through the burner port in the interconnection duct.

The burning process if left for a few minute to wait it to become stable before data is recorded. After the burning

process is stable, data is recorded for 1/4 and 1/2 secondary valve opening.

### **Co-combustion of diesel oil and producer gas**

After the experiment on combustion of producer gas, the experiment is proceeded to the co-combustion of diesel oil and producer gas experiment. Before starting the experiment, the gasifier must feed with palm oil shell. It is because during the experiment of producer gas, it is burned and turn into ash. This will reduce the amount of palm oil shell in the gasifier and also reduce the producer gas generation. After that, the feeding process is continued by filling the gasifier with palm oil shell until 3/4 full.

The windowpane is closed, and diesel burner is turn on. It is left for a few minute before data is recorded. Data is recorded for 1/4 and 1/2 secondary air valve opening and equivalent ratio ( $\Phi$ ) equal to 0.9, 1.0 (stoichiometric), 1.1 and 1.2. Graph for value of gas emission, combustion temperature versus equivalent ratio is plotted.

## **4. RESULT AND DISCUSSION**

Equivalence ratio ( $\Phi$ ) is used to indicate quantitatively whether a fuel oxidizer mixture is fuel rich, lean or stoichiometric. For  $\Phi > 1$  the mixture is fuel rich,  $\Phi < 1$  the fuel is fuel lean, and  $\Phi = 1$  the fuel mixture is stoichiometric (Stephen 2000). The emissions were plotted as a function of equivalence ratio for diesel combustion only as shown in Fig. 6. Also  $O_2$  and  $CO_2$  graph were also plotted as function of equivalence ratio. It was found that by increasing the equivalence ratio, the  $NO_x$ ,  $SO_2$  and  $CO_2$  formation was increased during the diesel combustion process. Fig. 7 shows that the  $O_2$  percentage decreased with the increase of equivalent ratio. Fig. 8, shows that with the increase in equivalence ratio the exhaust temperature also increased. At stoichiometric condition the exhaust temperature was 680 °C.



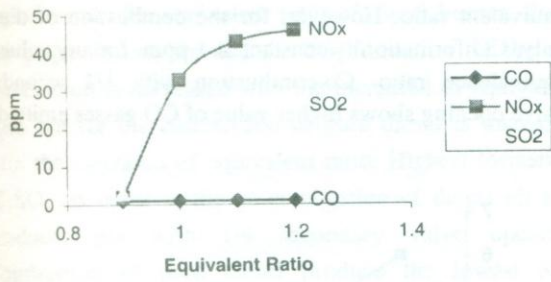


Figure 6. Emissions profile for diesel combustion

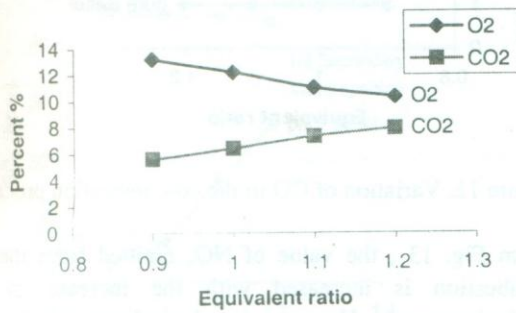


Figure 7. Variation of O<sub>2</sub> and CO<sub>2</sub> for diesel combustion

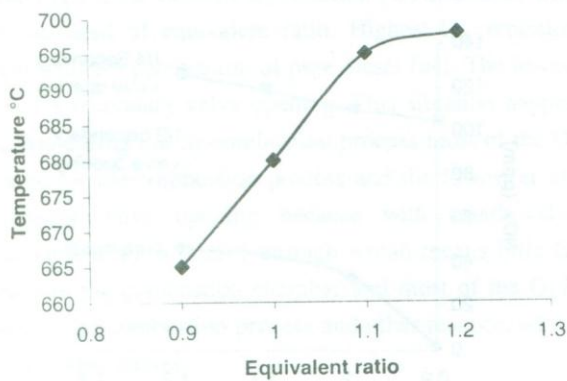


Figure 8. Temperature profile for the diesel combustion

For the combustion experiment for producer gas combustion only, the data was collected based on two secondary air valve opening, 1/4 and 1/2. The secondary air valve is used to control the amount of producer gas flow to the interconnection duct for burn in the combustion chamber and also as an air supply for the combustion of producer gas.

The formation of CO, NO<sub>x</sub> and SO<sub>2</sub> increased with bigger valve opening as shown in Fig. 9. For O<sub>2</sub> and CO<sub>2</sub> it shows a very little reduction with the increase of valve opening as reported in Fig. 10. Compared with CO and SO<sub>2</sub>, NO<sub>x</sub> shows the highest production with 1/4 valve opening but it shows the lowest with 1/2 valve opening. This situation may cause of with bigger valve opening, more air and producer gas is ducted to the combustion chamber and this mean that more producer gas is burn and produces more CO, SO<sub>2</sub> and NO<sub>x</sub>.

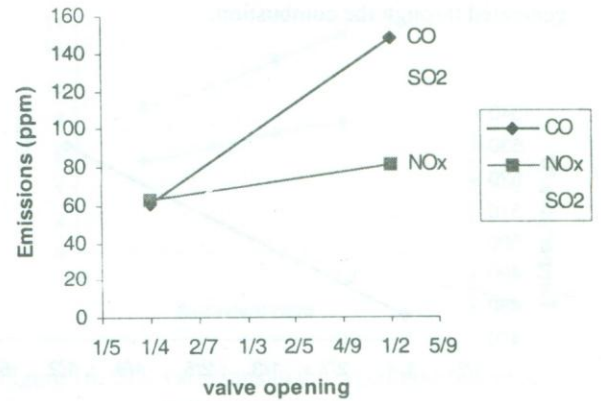


Figure 9. Emissions profile for the combustion of producer gas from downdraft gasifier

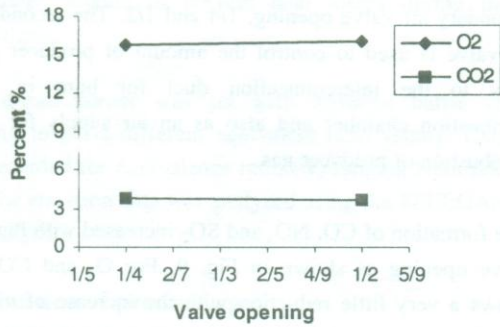


Figure 10 . Variation of O<sub>2</sub> and CO<sub>2</sub> for the producer gas combustion

From Fig. 11 it can be seen that the combustion temperature is increased with the increased of secondary valve opening. It is because with bigger valve opening more air is ducted through and also more producer gas flow to the combustion chamber and more heat are generated through the combustion.

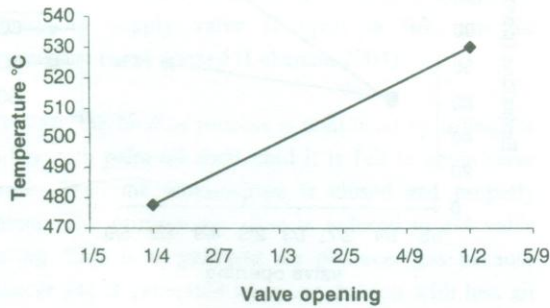


Figure 11. Temperature (°C) profile for the combustion of producer gas

Co-combustion of diesel and producer gas was done for different secondary valve opening and equivalent ratio of diesel fuel burner. Emission data has been plotted and is compared with of the combustion of diesel. Fig. 12 shows that the value of CO is decreased with the increase of

equivalent ratio. However, for the combustion of diesel only, CO formation is constant at 1 ppm for any value of equivalence ratio. Co-combustion with 1/4 secondary valve opening shows higher value of CO gasses emitted.

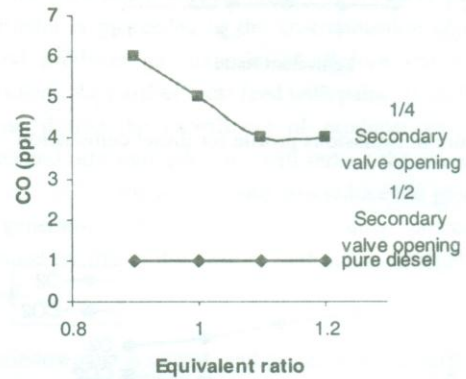


Figure 12. Variation of CO in the co-combustion process

From Fig. 13 , the value of NO<sub>x</sub> emitted from the co-combustion is increased with the increase of the equivalence ratio. However diesel combustion it shows a rapid increase from the equivalent ratio of 0.9 to the stoichiometric condition. When  $\Phi > 1$  NO<sub>x</sub> emission show a little increase. Co-combustion with 1/4 secondary valve opening shows the highest of NO<sub>x</sub> emission of and the lowest is pure diesel combustion.

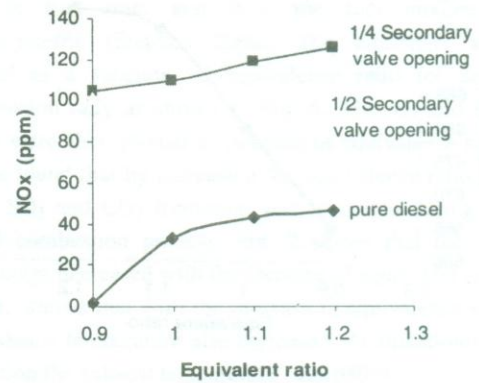


Figure 13. NO<sub>x</sub> emission behaviour in the co-combustion process.



Fig. 14 show the graph for the emission value of SO<sub>2</sub> (ppm) versus the equivalent ratio of diesel burner. From the graph we can see that the SO<sub>2</sub> formation for the co-combustion is decreased with the increased of equivalent ratio but for the combustion of pure diesel is increased with the increased of equivalent ratio. Highest formation of SO<sub>2</sub> is occur at the co-combustion of diesel oil and producer gas with 1/4 secondary valve opening. Combustion of pure diesel produce the lowest SO<sub>2</sub> emission compared to the combustion of the fuel combination.

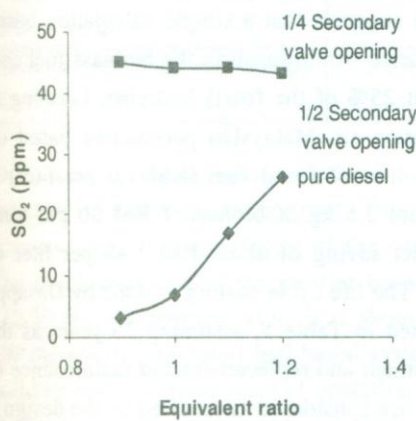


Figure 14. Variation of SO<sub>2</sub> in the co-combustion process

From Fig.15, the value of O<sub>2</sub> emission (%) decreased with the increased of equivalent ratio. Highest O<sub>2</sub> emission occur with the combustion of pure diesel fuel. The lowest is at 1/4 secondary valve opening. This situation happen because during the co-combustion process most of the O<sub>2</sub> is used for the combustion process and the lowest at 1/4 secondary valve opening because with small valve opening less air is ducted through which means little O<sub>2</sub> flow into the combustion chamber and most of the O<sub>2</sub> is used for the combustion process and other reaction which formed other gasses.

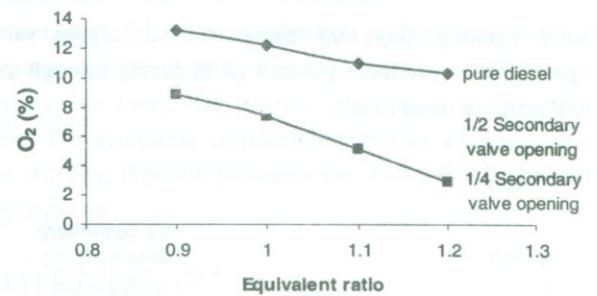


Figure 15. Variation of O<sub>2</sub> in the co-combustion process

According to Fig. 16, it shows that the amount of CO<sub>2</sub> emitted is increased with the increased of equivalent ratio value. Equivalent ratio  $\Phi > 1$  means that the fuel burn with less air which cause incomplete combustion. Incomplete combustion will produce more CO<sub>2</sub>. The highest CO<sub>2</sub> emission is at 1/4 secondary valve opening and the lowest is during the combustion of pure diesel.

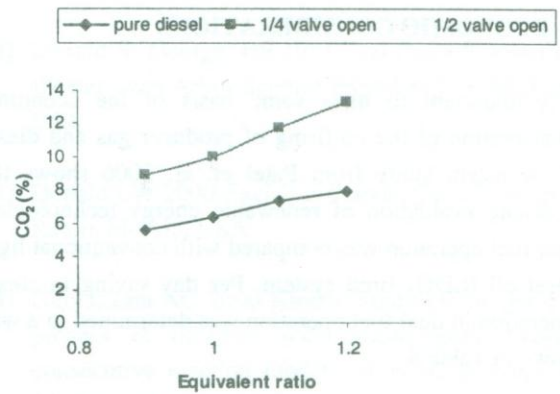


Figure 16. CO<sub>2</sub> variations in the co-combustion process

Fig.17 show the graph of combustion temperature for pure diesel combustion and the fuel combination versus the equivalent ratio. From the graph it shows that the temperature is increased with the increased of equivalent ratio. Temperature from the co-combustion with producer gas is higher compared to the temperature for pure diesel fuel combustion. Highest temperature is 1/2 secondary

valve opening, this may cause of with bigger valve opening more producer gas and air is ducted through and will produce more heat.

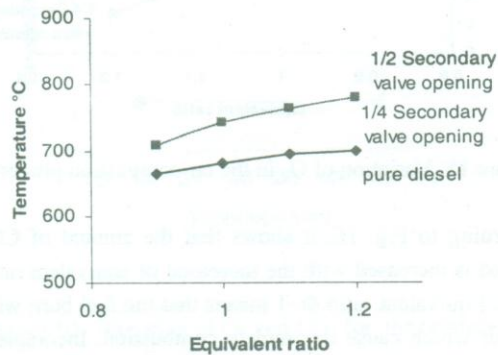


Figure 17. Temperature (°C) profile for the co-combustion process

### 5. ECONOMIC CONSIDERATIONS

It is important to have some basis of the economic consideration of the co-firing of producer gas and diesel oil. A recent study from Patel et. al. 2006 shows the economic evaluation of renewable energy technologies. Dual fuel operation was compared with conventional light diesel oil (LDO) fired system. Per day saving in steam generation in dual fuel operation was determined in a way shown in Table 4.

Table 4. Comparison of fuel cost: net LDO and dual fuel mode operation (adopted from Patel *et al.* 2006)

Fuel used	LDO consumption liter/hr	Biomass consumption Kg/hr	Total cost of fuel per hr (RM)	Saving (RM./hr)	Saving per day (15 hr of operation per day) RM
LDO (100%)	50	-	80	-	-
LDO(60%) + producer gas (40%)	30	78.8	48.8	31.4	471

Cost of LDO = RM 1.6 per liter, Cost of palm shell waste = RM 30/ton, 1 US \$ = 3.70 Ringgit

Economic analysis of the gasifier system showed that user could save about RM 31.40 per hour (about 39 % cost saving) by using dual fuel (60% LDO + 40% producer gas) for steam generation. This proves the economic economic viability of the gasifier-based operation. The pay back period for the gasifier system can be around 1000 h of operation or using the system for about 67 days (15 hr/day operation).

A similar study from Dasappa et al., 2003 shows that about 3 kg of biomass replaces about 1 liter of diesel. Patel et al 2003 suggests that a simple calculation based on the mass balance would result in the biomass fuel cost amount to about 25% of the fossil fuel cost. Looking at the said calculation sin Malaysian perspective based on the fuel cost, 1 liter of fossil fuel (RM 1.6 per liter) is replaced by about 3.5 kg of biomass ( RM 30 per ton); resulting in a net saving of about RM 1.49 per liter of diesel replaced. The life cycle costing as done by Dasappa (ibid) is presented in Table 5, assuming 25 years as the life of the equipment and replacement and maintenance of the components are considered as required by the design.



Table 5. Economic of the gasifier based operation for thermal applications (adopted from Dasappa et al. 2003).

Life cycle cost estimates	Gasifier based systems	Diesel based systems
Initial capital cost (RM per kW thermal)	445.31	37.50
Life cycle O&M cost (RM per kW thermal)	141.82	56.73
Life cycle fuel cost (RM per kW thermal)	709.16	4538.50
Total life cycle cost (RM per kW thermal)	1296.3	4648.12
Overall unit cost of energy (cents per kW thermal)	3.63	12.82

In presenting the economic analysis, various costs are indicated as the input energy cost. This approach would eliminate the efficiency factor of the conversion device. The investment cost of the gasifier based system is RM 412.50 per kW thermal while it is about RM 37.50 per kW thermal for the fossil fuel based system including the building cost, the economics of operation are as presented in Table 4. The economics are fairly attractive even without the CO<sub>2</sub> cost benefits. The entire investment is realized in about 2 years. This proves a strong basis for utilizing biomass producer gas with LDO in thermal applications.

## 6. CONCLUSION

The producer gas generated from the downdraft gasifier can be used as an alternative fuel for combustion.. It can be used for power generation such as gas turbine, gas burner, heating process etc. Experimental results shows that co-combustion of diesel oil and producer gas emitted more CO, NO<sub>x</sub>, SO<sub>2</sub>, and CO<sub>2</sub>. For CO, NO<sub>x</sub>, SO<sub>2</sub>, and CO<sub>2</sub> gasses, the highest gas emitted is with 1/4 secondary valve opening. Combustion of pure diesel oil has the highest level of O<sub>2</sub> gasses compared to the combustion of fuel combination. The lowest O<sub>2</sub> emitted is with co-

combustion with 1/4 secondary valve opening. Temperature for the co-combustion process is higher than the combustion of pure diesel oil as the co-combustion process has more fuel to burn and thus generates more heat. The economic consideration proves a strong basis for utilizing biomass producer gas with LDO in thermal applications.

## REFERENCES

- [1] Ani F N 1992 Thermal characteristics of oil palm fruit shells. In: *Proceedings of the second international energy conference- Energy from biomass residues*, Kuala Lumpur, Malaysia, November 3-5, 1994.
- [2] Dasappa, S., Sridhar, H.V., Sridhar, G., Paul, P.J. and Mukunda, H.S. (2003) Biomass gasification - a substitute to fossil fuel for heat application. *Biomass and Bioenergy* 25: 637-649.
- [3] Donald K, George HE 1981 *Fuel From Biomass and Wastes*, Ann Arbor Science Publisher Inc., Michigan, USA.
- [4] Donald LW 2000 *Fuel Gas System*, ORC Press, Boca Raton, Florida, USA.
- [5] Guo J, Lua AC 2000 Kinetic Study on the pyrolytic process of oil-palm solid waste using two-step consecutive reaction model. *Biomass & Bioenergy* 20, 223-233.
- [6] Henry KB 1981 *Energy the Biomass Option*, John Wiley and Son Inc, New York, USA.
- [7] Lukeman Y 2004 Pressurized induced flow on downdraft gasifier system with low emission burner, MS thesis, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia.

- [8] Naksite C 1989 *Biomass Gasification Research and Field Development*, Prince of Songkhla University, Thailand.
- [9] Nicholas P C 1980 *Biomass Application, Technology and Production*, Marcell Dekker Inc, New York, USA.
- [10] Patel, S.R., Bhoi, P.R. and Sharma, A.M. (2006) Field-testing of SPRERI's open core gasifier for thermal application. *Biomass and Bioenergy* 30: 580–583.
- [11] PORIM 2005 *A summary of the performance of the Malaysian Oil Palm Industry – A weekly update*. Palm Oil Research Institute of Malaysia, Kuala Lumpur, Malaysia, (<http://www.mpob.gov.my>).
- [12] Razuki I 1988 Gasification of Biomass, MS Thesis, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia.
- [13] Stephen RT 2000 *An Introduction To Combustion Process*, McGraw Hill, Singapore.