DEVELOPMENT OF A TWO-STAGE BIOMASS COMBUSTION SYSTEM FOR REDUCING THE EMISSION POLLUTANT

ADI SURJOSATYO[1] & FARID NASIR ANI[2]

Abstract. One of the most popular technological processes of converting biomass to a more useful energy is through direct combustion of biomass or gasification in a two stage combustion system. This combustion system configuration comprises of gasifier, gas ejector, cyclonic chamber and swirl burner, which are enclosed by the circular chamber. A series of tests were carried out to investigate the effect of each device in contributing to the reduction of gas emission. The results show that the staged combustion method, including the installation of gas ejector, cyclone chamber and swirl burner in the current gasifier system has shown as significant device to reduce the CO concentration as well as NO_x reduction.

1.0 INTRODUCTION

There is a considerable unused potential for energy production by the use of biomass in the IEA-countries (Nussbaumer, 1997) through direct combustion, gasification and other conversion techniques, both for heat production, electricity generation and for liquid fuel production. Of the various techniques for biomass energy conversion, direct combustion is the oldest and most mature technique. However, there is still a great challenge to develop new and more efficient and environmental acceptable biomass combustion systems both in small and large scale. The driving force for development are feedstock variations since new feedstocks like straw, palm shell, grass are more utilized in the future, environmental legislations, and increased energy recovery through development of new equipment and processes.

Palm oil industry is very important for Malaysia. Biomass fuels account for about 16% of the energy consumption in the country. Palm Oil biomass waste accounts 51% of the total biomass use. Biomass waste in Palm Oil Industry are in 3 different forms: solid (fibers, shells and empty fruit bunches (EFB), liquid (palm oil mill effluents) and biogas from open ponds (Bioenergy in Malaysia, 2000; Lim, 1998). Lim reported also that the dry matter yields of shells, fruit fibers and empty fruit bunches are respectively, 2780 kg; 1853 kg and 1483 kg per 10 000 m^2 per year. The energy amounts potentially available from biomass are respectively, 10.15, 5.86 and 4.92 barrels of oil equivalent (boe) per 10 000 m^2 per year.

---

[1] Fakultas Teknik Universitas Indonesia Kampus Baru U.I. Depok 16424.
[2] Fakulti Kejuruteraan Mekanikal, Universiti Teknologi Malaysia, 81310 UTM Skudai Johor Darul Takzim, Malaysia. e-mail: farid@fkm.utm.my

Small fixed bed gasifying stoves are in very widespread use world-wide in numerous applications, either producing hot water, drying up log-wood or process heating. Typical thermal ratings (output) are in the range of few kW to around 400 kW (Grifftith et al., 1999; Unterberger et al. 1999). These systems are reasonably efficient and have many advantages in terms of capital and installation costs as the fuel is normally manually feed.

One of the major concern of the present study is the basic investigation of the combustion and emission behavior of batch-wise fed small scale wood heaters with thermal capacity of less than 150 kW in order to achieve a considerable reduction of gaseous emissions like CO and UHC. The primary function of this fixed-bed stove or gasifier is to transform and transfer the chemical energy of the solid fuel into useful heat using fixed-bed mode of gasification process. The biomass, as fuel feed used here, was the oil palm-shell waste which has the basic analysis fuel are given in Table 1.

Table 1   Fuel analysis of oil palm residues (Ani, 1992)

moisture	volatile	fixed carbon	ash	LCV (MJ/kg)	C	H	N	O
9.7%,	67%	21%,	2.1%	19. 1	47.62%	6.2%	0.7%	43.38%

2.0   EXPERIMENTAL SET-UP

The experimental work is divided into two parts, i.e., a preliminary test, as the basic of development of the present gasifier and a test for full configuration. In the first test, the gasifier system is shown on Figure 1. The purpose of this work was to study characteristic of the basic configuration of the gasifier, including the quality and quantitative of the emission level of this system, such as, CO, CO_2, NO_x, O_2, gasification and flame temperature.

As shown in Figure 1, there are two thermocouples TC1 and TC2 used for these preliminary tests. Thermocouple probe TC2 can be shifted up and down at the selected height levels. Before measurement of emissions concentration, the TC2 probe must measure the temperature distribution inside the primary chamber properly. Ejector is the ejector system that comprises of nozzle and mixer. The nozzle has the function to induce or accelerate the gas flow from the primary chamber and as the supplier the secondary air to the system.

The second test was designed for investigations in the full configuration of fixed-bed (combustion) stove systems as shown in Figure 2. The difference configuration compared with the previous test is the additional of cyclonic chamber (10) and swirl burner (11).
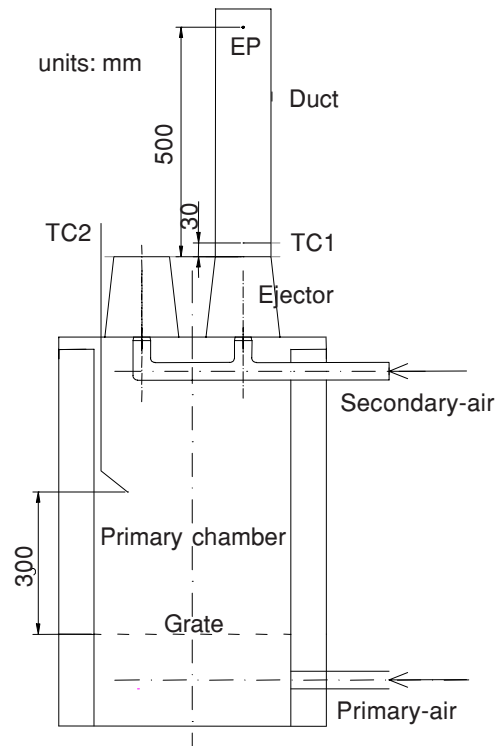
Figure 1 The schematic of primary chamber and gas ejector before the installation of cyclonic chamber (TC1 and TC2: thermocouple probes; EP: exhaust probe)

The gasifier test facility was operated at atmospheric pressure and temperature. The fuel feeding system is a supporting system of the gasifier consist of screw feeder, pulleys, belt, feeding-speed controller and electric drive-motor. An air blower with the capacity of 1360 lpm supply both the primary an secondary air.

The present primary chamber as the main chamber, where the original palm shell fuel is loaded through the feeding system, has a height of 0.6 m and overall diameter (including the refractory lining) of 0.58 m. The thickness of the refractory line is 0.08 m and direct attached to mildsteel plate of the primary chamber. Based on experimental experience, this thickness can prevent heat loss to a maximum of 5%.

The bottom of primary chamber attached the fixed-grate which has round shape to follow the shape of cylinder primary chamber. The fixed-grate must sustain a high temperature since the combustion zone occurred on this gate. With of combination of mild steel plate grill and stainless-steel screen, the fixed-grate can sustain against a maximum combustion-temperature of 1300°C. The screen grid has an average size of 0.005 m (5 mm).

Between the primary chamber and cyclonic chamber exist two (2) tubes of ejector. There are two (2) nozzles for each ejector which have two main functions, first, to
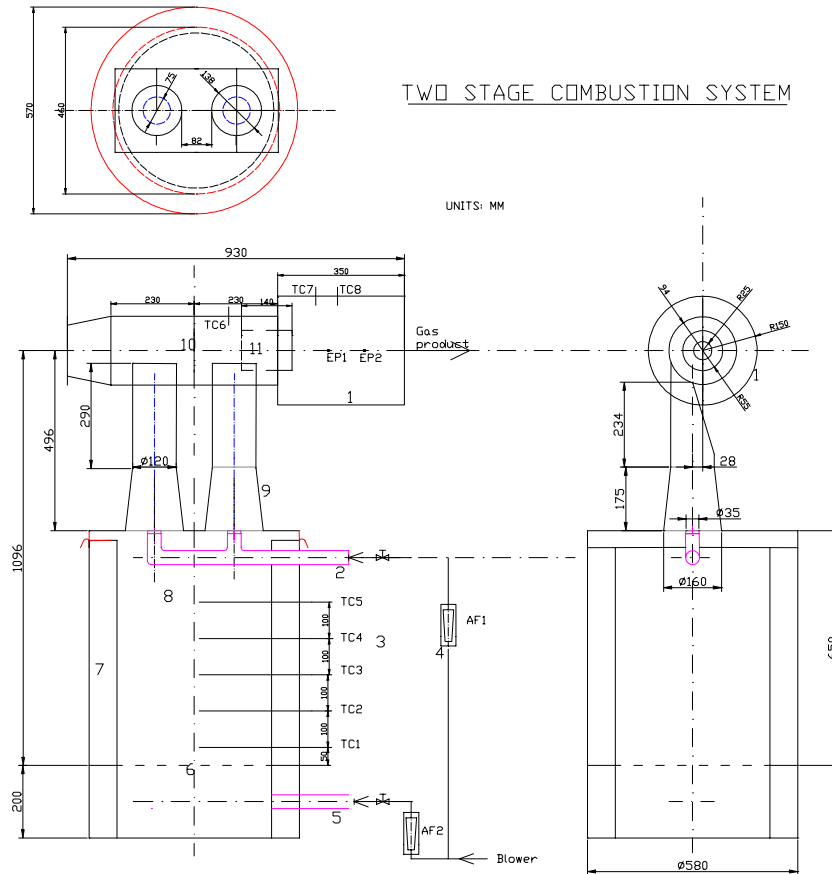
Figure 2	Schematic of fixed-bed combustion test facility

1.	Secondary chamber;	
2.	Secondary air port;	
3.	TC1..TC8: K-type Thermocouples;	
4.	Air flowmeters;	
5.	Primary air port;	
6.	Grate or screen;	
7.	Refractory;	
8.	Primary combustion chamber;	
9.	Ejector tubes;	
10	Cyclonic chamber;	
11.	Burner tube.	

induce or accelerate the gas flow from the primary chamber to cyclone chamber, second, to supply the secondary air into cyclonic chamber. While the secondary air injected into mixer-ejector, the gas induced and immediately mixed in the same mixer. Then both of the gas and secondary air expected to mix perfectly in the cyclonic chamber.

2.1 Instrumentation Set-Up

Figure 2.1 shows the location of some important instrumentation such as Air-Flowmeter and Thermocouple probe. The flowmeter used was ventury type and before utilized for the air flowrate measurement (primary and secondary air supply), it was calibrated with the standard flowmeter. For adjusting the air supply consumption, two air valves were mounted on each air-supply pipes. Measuring the air flowrate can be done directly through reading the differentiation of water level in the U-tube.

Temperature distribution were detected by Chromel- Alumel Thermocouple K-type assembly. There are 6 (six) thermocouple-probes located inside the primary-chamber. They are placed inside the reactor in such away that their tip remains along the axis of the chamber. The distance between the thermocouples was determined to ensure the best description of the temperature field along the axis and to allow for an accurate determination of the propagation velocity of the combustion front. Another thermocouple-probe in the cyclonic chamber and 2 (two) probes in the secondary chamber. All these thermocouple-probes connected with a system data-logger from Data Taker 605 and all the data by the computer displayed online.

2.2 Testing Procedure

Both tests have the same operating procedure to generate gasification process. The early step was creating the combustion zone by feeding 2 kg the palm shell into the primary chamber through the screw-feeder. Then, a small amount of kerosene is mixed with the palm shell inside this chamber. After igniting the mixing of kerosene and palm shell, a thin white smoke appears. With the correct gasification temperatures, the white smoke-gas is ready to ignite with a gas-torch. Based on experience, the best condition to produce the flame is when the combustion zone reaches the temperature, T1 between 950–1200°C.

The smoke ignition occurs close to the burner-tube. Before ignition the thick smoke, the air mass flowrate from both primary and secondary air, is adjusted in proportional ratio so that, the mixed gas can be ignite easily and a sustainable flame occurs at outside the cyclone chamber. The sustainable flame can be maintained at the primary air flowrate of 125 lpm and the minimum secondary air flowrate of 438 lpm and maximum of 622 lpm.

The scope of measurement activity during combustion process are collecting the temperature at combustion zone (TC1), reduction zone (TC2), pyrolysis zone, drying zone (TC3, TC4 and TC5), cyclonic chamber (TC6), existing flame (TC7 and TC8), emission level at EP1 and EP2, primary and secondary air flowrate (AF1 and AF2), solid fuel flowrate (Q_f). To achieve a reliable results on measurements, all instrumentation are periodically calibrated, such as thermocouple, gas analyzer and air flowmeter. All measurements will be conducted in a steady state condition. The measurements should be started when the flame in sustainable and stable condition. The

solid feeding occurs every 30 minutes and each time fuel feeding, it needed 6 minutes long at the constant flowrate of 0.339 kg/min. This interval of solid feeding was chosen to ensure the gasification process in primary chamber can support the gas burner to produce the flame continuously.

3.0   RESULTS AND DISCUSSIONS

3.1   Effect of Cyclonic-Chamber on the Flame Stabilization

The first configuration of the combustion system as the first test is shown in Figure 1. During the operation the average combustion temperature near the grate is around of 1100 K. At 100 mm from the grate, the temperature reduces to between 700 and 800 K and at 300 mm from the grate between 383 to 400 K. In this condition the smoke appears in gray and black colors, and it is easy to be ignited. The smoke color has such tend to gray and some locations dominated by black color. Because, the exit gas contains a lot of char or carbon entrainment that is not well mixed with the secondary air. After igniting the gas-smoke, the flame is smokeless and anchored inside the ejector close to the end of ejector-tube. It can be noticed that the flame source occurs after the equivalence ratio, ϕ, reaches of 1.7. Flame temperature fluctuated between 627 to 1080°C at 0.03 m above the ejector outlet as shown on Figure 3. This indicated that the flame quality is not stabile or flame stabilization was poor enough. It could be the fuel mixing was not homogenize against the flow. There was not enough time to produce an intimate mixing between gas fuel and (secondary) air. Therefore, soot production can be detected through the appearance yellow color.
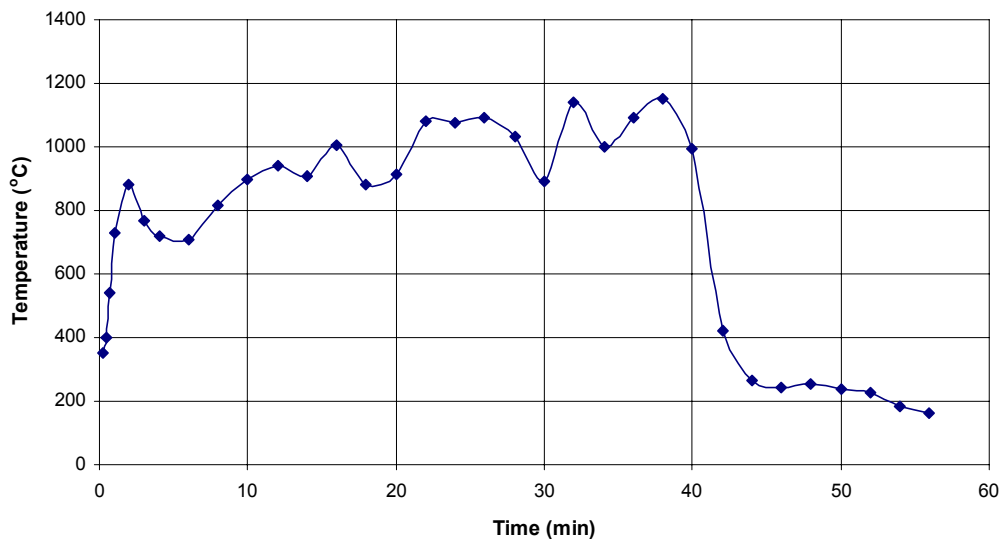

Figure 3   Temperature variation of flame against the time in preliminary configuration (first test condition)

To improve the flame stabilization, a cyclonic chamber and a simple gas burner is then attached on the upper section of the ejector as shown on Figure 2 (legend no 10 and 11). The combustion result produces a different smoke color, i.e a better premixing process of air/gas fuel in the cyclonic chamber causes the appearance of smoke change from gray and dark color to white color. Cyclonic chamber has the following main characteristics features of interest:

a. Long residence time of the air and smoke gas particles.
b. The particles which with heavier mass can be separated or suspended for very long periods by centrifugal force field, generated by the swirling motion of the fluid.
c. In the exhaust region (gas burner on the central axis), large toroidal recirculation zones, high levels of turbulence intensity and the precessing vortex core (PVC) are usually formed.
d. As entering the cyclone, there was an increasing of the air and gas-particle velocity (acceleration) by the pressure differential existing across the inlet orifice. This effected to create a strong vortical (swirling) flow field, and therefore could possess pressure gradients that accelerate the fluid in both and axial directions.

Thus with the above advantage the current cyclonic chamber exhibits a high intimate mixing between gas particle and air, further more in this chamber the premix fuel will expect a flame stabilization as shown in Figure 4.

Figure 4 shows the graph of flame temperature variation against the test time. Since the premixing of gas particle and air was in homogeneous condition, the temperature fluctuation is in relative small. Phase a-b is the phase of starting the early combustion of palm shell as fuel waste using some amount of kerosene. A successfully burning of this fuel can be achieved by control of the temperature of the primary chamber by certain air blower flowrate. After 33 minutes slowly the combustion zone indicates a temperature rising and intensify of thick smoke from secondary chamber exit. Phase b-c is the phase where it occurs fast rising of temperature in combustion zone without any assisting of kerosene. On the same time indication of the formation of reduction, pyrolysis and drying zone can be acknowledged by temperature differentiation in side the primary chamber. Phase c-d is a phase where the gas flame existed and in a stabile condition. The thick-smoke is distinguished as long as the flame exists.

Phase d-f is the phase where the gas flame extinguished through closing the secondary air and primary air. Temperature in the secondary chamber drops suddenly and the thermocouple probes just measure the heat radiation in the secondary chamber.
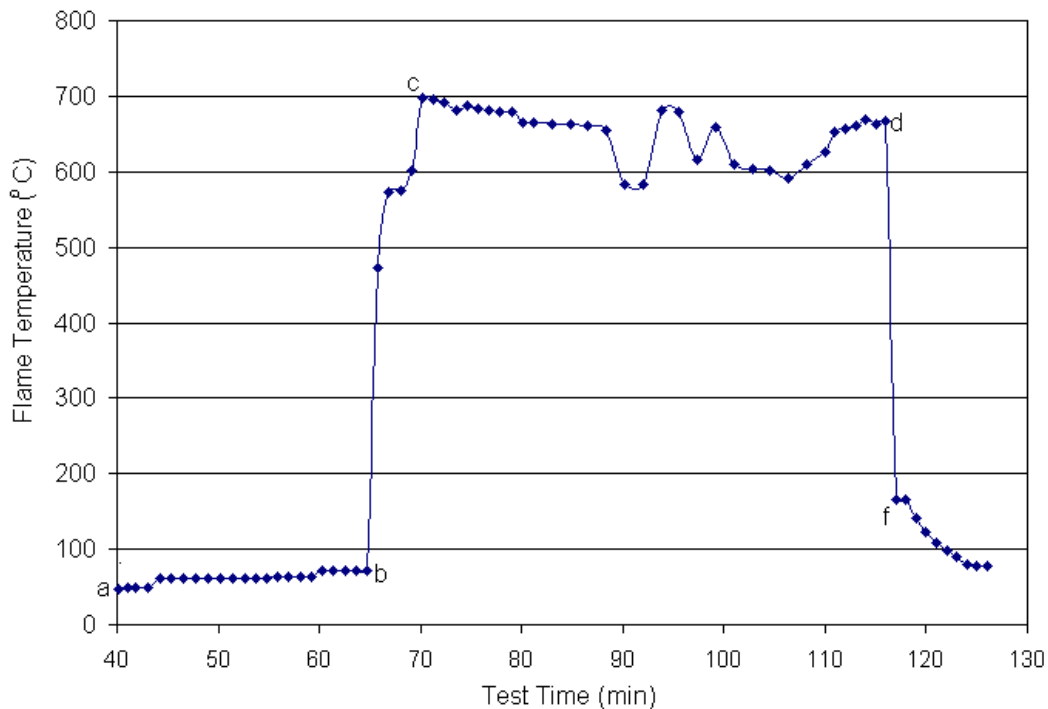
Figure 4   Temperature variation of flame against the time in full configuration rig test

3.2   Effect of Cyclonic-Chamber on Emissions

The gas analyzer measures of the flame emission level at the preliminary test at 0.5 m from the ejector outlet as shown in Figure 1. The measurement result of O_2, Excess Air (EA), CO_2, CO, NO_x, Combustion Efficiency (CE) give an average of 10%, 132.4%, 9%, 2784.6 ppm, 150 ppm, 49%, respectively with the equivalence ratio, ϕ, of 1.7. This means, this gasifier operates under rich mixture. Results of the above emission measurements indicate that the combustion system has a poor performance. This can be indicated with as following conditions:

    i.   measurement CO emission level is far beyond the recommended value i.e. max 250 ppm,

    ii.   measurement of EA is too lower compared to the recommended value, i.e. min 150%,

    iii.   measurement of CE is too lower compared to the recommended value, i.e. min 80%.

   To improve the performance of this combustion system, a cyclonic combustion chamber was installed and this is the full configuration of the current combustion

system. Using the latest configuration, experiments are conducted into two kind of tests:

i.   The first is gasification test i.e *without igniting* the smoke gas.
ii. The second is flame test i.e *igniting* the smoke gas at the secondary chamber.

The *first* test has the purpose as following:

i.   to observe the temperature distribution inside the whole combustion system in a certain period of time,
ii. to measure the gas composition during gasification test.

Figure 5 shows the temperature distribution on each Thermocouple-probes location in a selected operation time. This figure shows the temperature reduction from TC-probe 1 to TC-probe 3. Beyond TC-probe 3, the temperatures is almost constant. The temperature distribution shows the typical of gasification zones as following: combustion, reduction, pyrolysis and drying zone respectively. Based on the time-duration of experimental, it indicates that between TC-probe1 and –2 occurred the combustion process in which the temperature increases gradually until reaches close to 1000°C. In the same time period, beyond TC-probe 3 the gasification process occurs. In these zones the increasing of temperature is not significant.
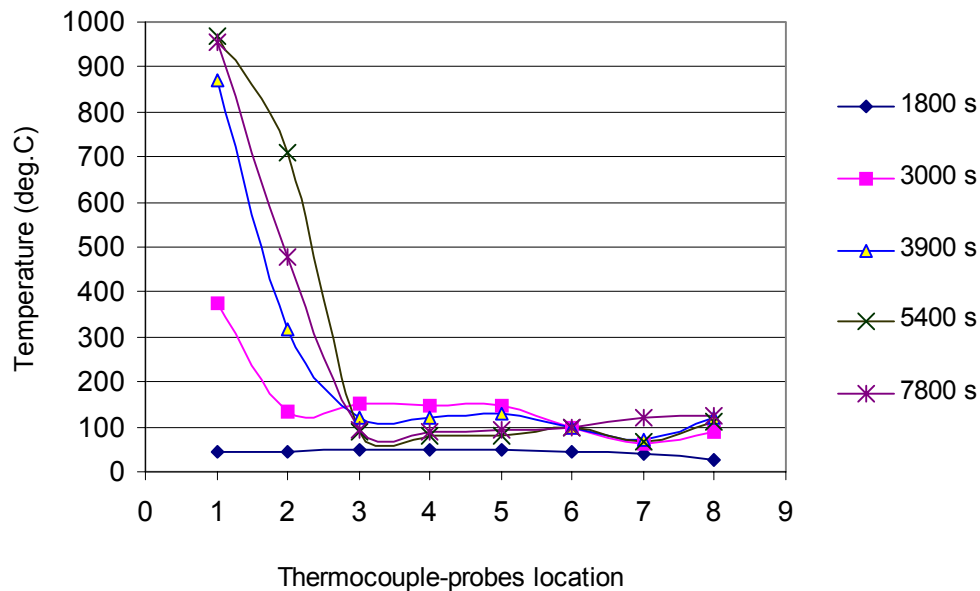

Figure 5   The transient of temperature on TC1 to TC8 in a selected time during gasification test

Results of the measurement in the secondary chamber for O_2, Excess Air (EA), CO_2, CO, NO_x, Combustion Efficiency (CE) were the average of 18.6%, 75%, 5.5%, 3337.3 ppm, 56 ppm, 65% respectively.

The *second* test is igniting the smoke gas or flame test of the tube burner. The flame emission of the tube burner is studied in the current test. Figures 6 and 7 show the variation of the measurement emission against the increasing of the equivalence ratio-EQR (ϕ). In general, this shows the direct effect of the rising of the ϕ to the decreasing both of oxygen level of 30% and the excess air of 38.8%. But the rising of ϕ is responsible of a slightly imcrease of combustion efficiency of 4.11% and given a lower of the flame-temperature of 10.6%. When ϕ decreases, a clear reduction of CO and NO_x concentration of 40.041% and 43.52% respectively are also indicated.

Table 2 presents the summary of the emission result of the three tests at the exit of secondary chamber. If it compared with the test result of the preliminary configuration, there are indicating of some significant improvements, such as the rise of CE from 49% to the average of 76%, reducing CO concentration from 2784.6 ppm to 223.3 and slightly reducing on NO_x level from 150 ppm to 136.6 ppm.

4.0 CONCLUSIONS

A two-stage biomass-combustion system was developed and investigated experimentally. The producer gas that was generated from the gasification process of the palm shell waste was burned in a secondary chamber with a non- swirl gas burner. There
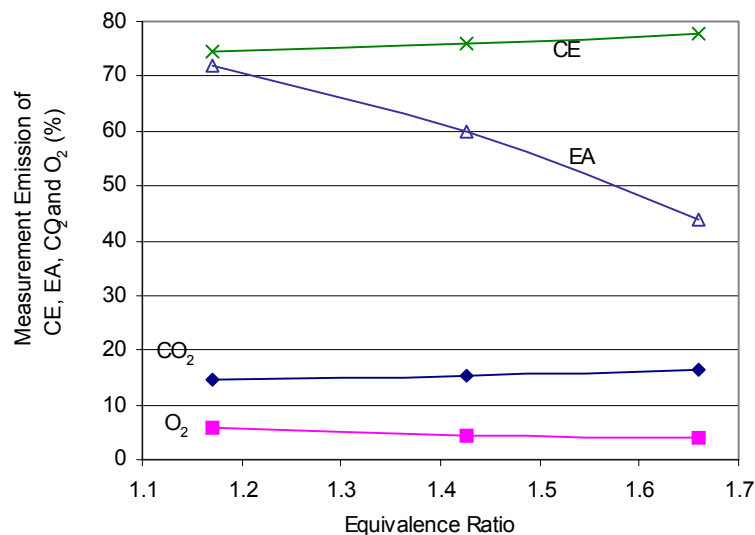

Figure 6   Effect of the increasing equivalent ratio to CO_2, O_2, EA-Excess Air and CE-Combustion Efficiency

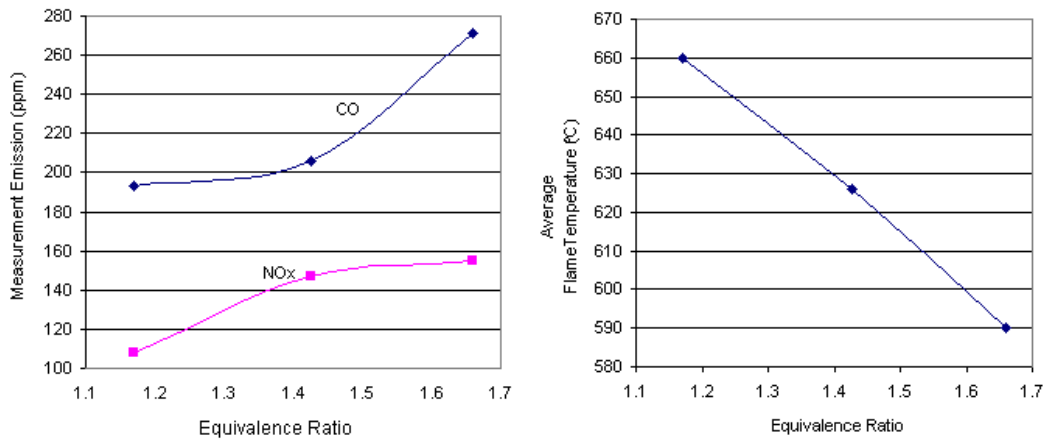**Figure 7** Effect of the increasing equivalent ratio to CO, NO_x and Flame Temperature (tube burner)

Table 2 Summary of the emission result at the secondary chamber exit of the three tests on the combustion system at $\phi = 1.66$

Emission Item	Test types		
	Gas flame on ejector exit (Preliminary test)	Complete Configuration	
		Gasification test (test 1)	Flame test on burner (test 2)
O_2 (%)	10	18.6	4.8
CO_2 (%)	9	5.5	15.4
Excess Air (%)	32.4	75	58.6
CO (ppm)	2784.6	3337.3	223.33
NO_x (ppm)	150	56	136.66
Combust. Eff. (CE) (%)	49	65	76.06
Flame Temp. (°C)	839.8	98.77	601.4

are two concerns in this experimental study, i.e the first, to investigate the performance of the proposed combustion system and the second, to develop a basic non-swirl gas burner for the combustion system.

The important result can be summarized as following:

i. The producer gas, which is generated in the primary chamber through the gasification process, in full premixed condition is burned at the gas burner in the secondary chamber.

ii.   The staged combustion method of the current combustion system, through the enhancement of mixing process in the cyclone chamber, has shown as significant device to reduce the CO concentration as well as NO_x reduction.

iii. The flame temperature of the gas burner reached a range of 590 to 677°C. This low temperature has the advantage to prevent increasing of NO_x ormation.

iv.   However, the combustion efficiency of the flame is still low between 74 to 77.5%.

v.   Based on experimental study, burning rate of the primary chamber is 0.0472 kg/min of solid palm shell waste and therefore the maximum heat capacity of combustion system reaches 15.02 kW.

vi.   The maximum heat release of the gas burner is 5.8 kW at equivalence ratio of 1.21 with the gas flowrate of 1.04 g/hr.

ACKNOWLEDGEMENTS

REFERENCES

[1]   Ani, F. N. 1992. *Thermal Characteristics of oil Palm fruit Shells*. The second International Energy Conference, Energy from Biomass residue, Kuala Lumpur.

[1]   Arshad, A. S., A. J. Griffiths, C. S. Avenell, and N. Syred. 1995. *Design, Development and Testing of 200 kW Prototype Batch Type Biomass Pyrolyser*. Cardiff University.

[2]   Bette, M., W. Schaefers, and H. Kirschener. 1994. *The Achievement of "Good Combustion" by Improvement of Secondary air Injection at The Montgomery County Waste to Energy Facility*. National Waste Processing Conference Proceeding ASME.

[3]   Bioenergy in Malaysia, Potential for Finnish Energy Industry. FINPRO-report 56 p. 2000.

[4]   Bridgwater, A. V. 1995. *The technical and economic feasibility of biomass gasification for power generation*. Fuel. 74, No. 5, 631 – 653.

[5]   Corey, R. C. 1969. *Principles and Practices of Incineration*. Willey Interscience.

[6]   Griffiths, A. J., D. Beedie, N. Syred, and T. O'Doherty. 1999. *Experimental and computational investigations of Biomass Combustion in a secondary gasification chamber*. Cardiff University.

[7]   Hassler, P., and T. Nussbaumer. 1999. *Gas cleaning for IC engine applications from fixed bed biomass gasification*. Journal of Biomass and Bioenergy. 16: 385 – 395.

[8]   Kuo, K. K. 1986. *Principles of Combustion*. A Willey-Interscience Publication, Canada & USA.

[9]   Lim, K. O. 1998. *Oil Palm Plantations – A Plausible Renewable Source of Energy*. RERIC International Energy Journal, 20, 2, 107 – 116.

[10] Nussbaumer, T., and J. E. Hustad. 1997. *Developments in Thermochemical Biomass Conversion*. Blackie Academic and Professional, Vol. 2, 1229 – 1243.

[11] Spliethoff, H., U. Greul, H. Maier, and K. R. G. Hein. 1995. *A comparison of Air Staging and Reburning*, Proc. Of The Institute of energy Conference, 61 – 70.

[12] Unterberger, S., H. Maier, and K. R. G. Hein. *In-furnace measurements in discontinuously wood fired small scale heating systems*. Proc. of the 2nd Oll Lindstrom Symposium on Renewable Energy-Bio Energy, Sweden, (June 1999), 14 – 20.

[13] Warnecke, R. June. 2000. *Gasification of Biomass- comparison of fixed bed and fluidized bed gasifier*. Journal of Biomass and Bioenergy, 18, 6, 1 – 16.