JOURNAL OF FACULTY OF MECHANICAL ENGINEERING

Emission Characteristics of Palm Oil Shell in a Cascading Hearth Staged Combustor

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Abstract

Palm oil shells are biomass fuels with 47.62% carbon and 0.7% nitrogen content, and a higher heating value of 20.7 MJ/kg. This paper investigates the emission characteristics of CO and NO_x from the thermal processing of palm oil shells in a cascading hearth staged combustor. The cascading hearths in primary staged combustion offers higher solids burnout rate by the action of fuel movement and distribution. Secondary stage applies swirl flow combustion to enhance efficiency in pollution control. The experimental is conducted at 0.2 kg/min fuel feed, and primary stage air is supplied at starved and excess conditions. Comparative analysis is conducted in understanding the combustion and emission characteristics under both conditions. Starved air is found to lower primary combustion temperatures (400°C – 900°C), and gasification is promoted which leads to high carbon monoxide levels (1800 – 3400ppm). Secondary stage combustion furthers the oxidation of CO to CO_2 at an approximated oxidation efficiency of 70%, with flue gas CO measured at 600 – 800ppm. NO_x levels were successfully controlled below 100ppm due to moderate combustion temperatures achieved in both combustion stages (300°C to 700°C).

Keywords: *Cascading hearth, swirl combustor, Carbon Monoxide, Oxides of Nitrogen, palm shells, starved air.*

INTRODUCTION

Palm oil shells are carbonaceous solids, produced from the processing of palm oil fruit. Carbonaceous solids contain high volume percentage of carbon element and may be converted as a heat energy source by thermal reaction of the carbon content. Thermal reaction via combustion occurs at microscopic levels, in which a conversion process of chemical energy from a mixture of fuel, heat and oxygen occurs. These reactions are mainly exothermic, occurring first in solid phase then continuing in gas phase. The derived heat can then be utilized for producing work. However, the same chemical reactions form a wide range of substances and these are emitted to the environment as flue gases. The pollutants of main concern from palm oil shells combustion are carbon monoxide (CO) and oxides of nitrogen (NO_x).

Complete combustion of carbonaceous wastes produces carbon dioxide (CO_2). However, formation of CO can be found when incomplete combustion of the fuel occurs. CO is part of a class of pollutants in the carbon-hydrogen-oxygen compounds. These compounds are often associated with odorous emissions.

Incomplete combustion can be caused by low levels of combustion air, providing an inadequate oxygen environment for complete oxidation of the fuel. Apart from insufficient air supply, lack of adequate fuel-air mixing and short residence time to complete combustion reactions are also main factors in CO formation. The exposure of CO at higher than 4000ppm is particularly hazardous to the heart and blood vessels because it reduces the ability of blood to bring oxygen to body cells and tissues [1]. Damaged lungs and breathing difficulties can result from inhaling excessive CO.

Oxides of nitrogen are referred collectively as NO_x and reported as NO_2. Nitric oxide (NO) is produced from its elements at high temperature levels attained in combustion systems. Although only a small portion of the NO further oxidizes to nitrogen dioxide (NO_2) within the furnace, oxidation does take place slowly at ambient atmosphere. The air quality impact arises from their participation in atmospheric chemical reactions, especially when stimulated by solar ultraviolet light, producing ozone and a variety of oxygenated compounds associated with smog. Human respiratory system is also affected, causing illness in breathing passages and lungs.

In combustion systems, NO_x arise through fixation of nitrogen from the combustion air with oxygen (thermal generation). Also, NO_x is formed by oxidation of nitrogen entering the system bound in the fuel (fuel nitrogen generation). At very high temperatures, the dominant source of NO_x is thermal generation but at lower temperatures fuel nitrogen mechanism dominates. However, nitrogen has the potential to yield a totally non-polluting and readily disposable residue. The main principal during combustion is to minimize the O_2 supply for as long as possible. In practice this means reducing oxygen availability during devolatilization and the accompanying homogeneous combustion of the volatiles [2]. Some other methods suggested by Breen and Sotter [3] are low excess air operations, burner improvements, and staged combustion.

In this modern era, environmental concerns with strict regulations have become a governance factor in combustion technology development. Flue gas treatment facilities located at the end of the combustion flow process are compulsory in minimizing the levels of emission released to the environment. These facilities increase the capital and operating costs of the plant. Therefore, enhances in the combustion process itself is required to reduce the initial emission of hazardous substances. The combustion technology selected must be efficient and capable to reduce the volume of solid wastes without producing, or minimizing, harmful flue gases to the environment. Staged combustion meets these requirements and can be adapted to burn a wide variety of solid wastes. The existing technology can achieve complete destruction of even the most hazardous materials while effectively controlling emissions to the atmosphere for minimal environmental impacts [4].

Staged combustion is a concept utilized to enhance combustion efficiency. Control of pollutant emission by complete combustion is the direct objective of a staged combustion system. Basically, a two-stage combustion system is applied. It consists of a two-stage combustion process using a primary furnace chamber and a secondary gas afterburner chamber. This method of combustion is used in several hundred large boilers in the United States, mainly as a NO_x emission control technology [5].

The first or primary stage combustion is mainly a reduction of solid fuel particles to finer particles by chemical reaction, and the same combustion chemistry forms the emission gases that are mostly dangerous to human health. The products of incomplete combustion in the primary stage are then channeled into a secondary combustion chamber. Secondary stage combustion consists of solid-gas phase combustion of particulate matters, as well as gas-gas phase combustion of the combustible gases, such as CO and methane (CH_4), rising from primary stage combustion.

Palm Oil Shells

Palm shells are obtained from palm oil processing. Malaysia is the largest palm-oil producer in the world, producing 51% of world palm oil production and 62% of the total world export. In 1999, the country produced 10.55 million tones of crude palm oil from a total plantation area of 3.31 million hectares, with a total export revenue of RM19.21 billion [6]. Palm-oil mills produce a large amount of solid wastes, such as oil palm fibers, palm kernel shells, and empty fruit bunches.

Palm kernel shells are oval in shape and have a maximum dimension that varies between 10-20 mm. It is hard physically, with good resistance to breaking in handling. For the purpose of combustion, several analyses should be considered such as physical properties, proximate as well as ultimate analysis. These properties are shown in Table 1.

Table 1: Properties of oil palm shell [7]

Analysis	Oil Palm shell
Proximate analysis (wt %)	
Ash	2.3
Volatile matter	68.8
Fixed carbon	20.3
Ultimate analysis (wt %)	
(dry ash free)	
C	47.62
H	6.27
O	43.38
N	0.70
Moisture (wt % air day)	8.4
Gross CV (HHV)	
(MJ/kg)	20.7
Average bulk density (kg/m^3) <18 mm	440

STAGED COMBUSTOR SET-UP

The cascading hearth staged combustor consists of the primary combustion chamber (PCC), secondary combustion chamber (SCC), fuel feeder mechanism, pneumatic actuator circuits, Programmable Logic Controller (PLC) unit, and the air supply lines. It is designed with the capability to handle bulk solids, particularly palm oil shells. Batch feeding is accomplished by the movement of the charging rams, which are pneumatically driven and automatically controlled by the PLC unit. Two cascading hearths with underfire air supply are applied to improve primary stage solids combustion efficiency. The secondary stage combustion takes place in a swirl combustor, where gas phase combustion occurs to complete the combustion of combustible gases and particulate matters. The combustor system is designed to closely comply with British Standards BS3813: Part 1 [8], with a maximum operating temperature of 1200°C for the PCC, and 1000°C for the SCC. Table 2 and 3 lists the important design parameters of both chambers. Design drawing of the SCC is shown in Figure 1, while Figure 2 is the schematic of the cascading hearth staged combustor assembly.

Table 2: Summary of primary combustion chamber design parameters

	PRIMARY COMBUSTION CHAMBER	
	PARAMETER	**VALUE**
1	Fuel feed maximum capacity	40 kg/hour
2	Combustion heart area	0.14 m²
3	Usable capacity for combustion	0.264 m³
4	Ram charging force	40 N to 130 N
5	PLC unit type	Siemens S7-200 Micro

Table 3: Summary of secondary combustion chamber design parameter

	SECONDARY COMBUSTION CHAMBER	
	PARAMETER	**VALUE**
1	Operating combustion volume	0.00628 m³
2	Geometrical swirl number	1,57
3	No. of tangential air inlets	2
4	Burner and fuel type	Torch burner; LPG

NOTES:
1. Drawing not to scale.
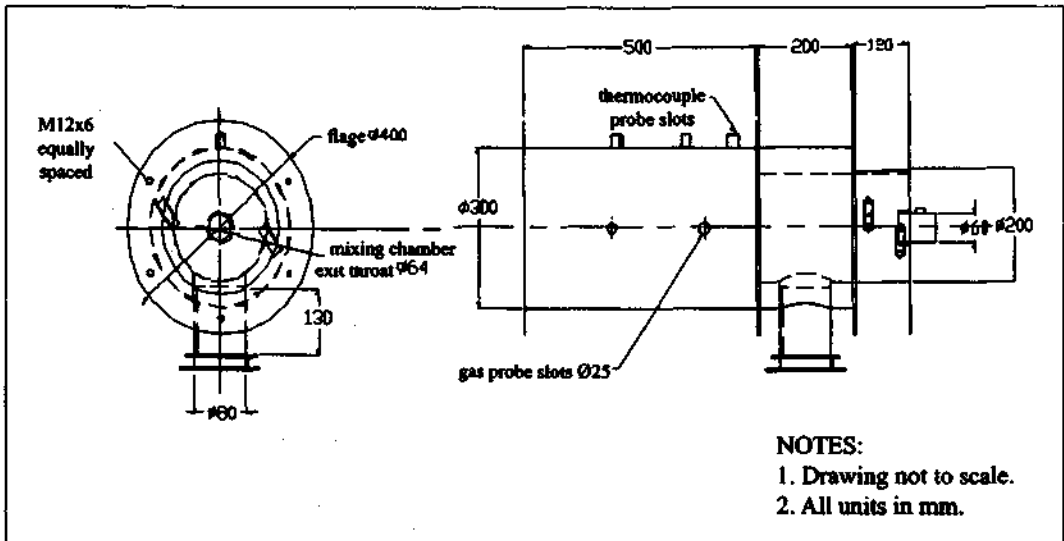2. All units in mm.

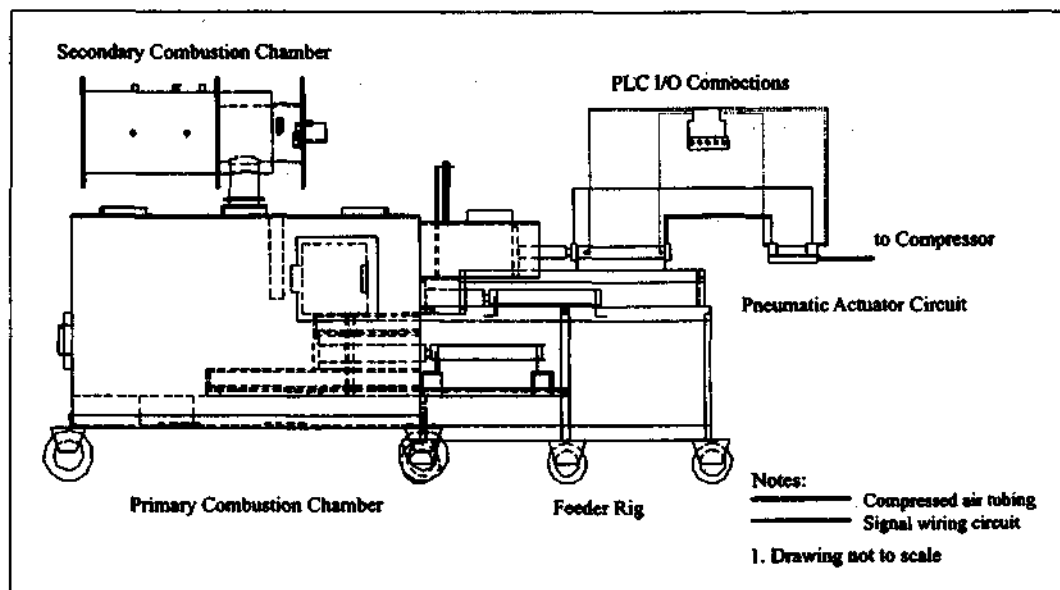**Figure 1: Secondary stage swirl combustion chamber**

Figure 2: Schematic of cascading hearth staged combustor

Operationg Principles

The solid fuel is discharged to the first cascading hearth by the action of the charging ram, and is ignited. Underfire air through the combustion bed allows the spreading of an even flow of combustion air supply to the core of the fuel bed, with the capability to penetrate and reach the outer layers sufficiently [9]. More solid fuels are added periodically in batches. The flow of high temperature gases rising from the oxidation of fuel on the combustion bed naturally drafts towards low temperature regions in the chamber. The traveling distance from the combustion bed to the exhaust, as well as factors of gas flow patterns and combustor temperatures, determines whether the residence time is adequate for gas phase reactions to occur inside the PCC. The burning fuels are then discharged to the second cascading hearth. This action promotes breaking, redistribution and fuel mixing, therefore increasing combustion efficiency as a more complete burnout of the solid fuel is achieved.

In the SCC, swirl is used to induce intense recirculation patterns along the cylindrical walls. The generation of swirl in a flowing medium can be achieved by the impartation of a tangential velocity component to the medium [10]. The mixture of combustion air and combustible gases travels back towards the burner bringing heat energy and reactive species, leading to increased combustion rates and a more intense, shorter and stable flame due to increased residence time [11].

In secondary stage combustion, the products of primary stage are supplied with additional heat and oxygen to further its combustion reactions. In the aspect of emission, CO is further oxidized to CO_2 in excess air conditions. The capability for this chemical reactions to take place fully will be dependant on adequate residence time, combustion temperatures to speed reactions, availability of excess oxygen compared to incoming rate of CO, and turbulence for intimate mixing with oxygen. However, high temperature environment with excess air conditions may promote NO_x formation via thermal mechanism reactions. Therefore, conditions within primary stage combustion must be capable

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to minimize the generation of nitrogen-based compounds before it goes through secondary stage combustion. Particulate matters and volatiles are also burned further to completion in secondary stage, where its reduced level may be indicated by the thickness of the final smoke emission.

EXPERIMENTAL

The stoichiometric air/fuel mixture ratio for palm oil shell is calculated at 5.37 kg air/kg fuel (as fired). For an experimental fuel feed rate of 0.2 kg/min, the theoretical airflow rates for complete combustion is 0.737 m^3/min (26 cfm). The objective of the experiments conducted is to collect emission data for analytical comparison on two different primary stage combustion processes of palm oil shell in a cascading hearth staged combustor. The first process is based on the concept of starved air combustion, and the second is in excess air mode. Fuel temperatures, combustion efficiency, $\%O_2$, $\%CO_2$, %excess air, secondary combustion temperatures and flue gas temperatures are the parameters that will be further analyzed in relation to the emission levels.

Starved air combustion is the combustion of fuels in a fuel rich condition, where the combustion air is supplied below stoichiometric. For the experiment, the supplied air is 0.3 – 0.5 of the stoichiometric it has the advantage of attaining reasonably low primary chamber temperatures while still capable of removing the organic materials from the ash [12]. Sub-stoichiometric oxygen concentration in a combustion process promotes gasification of the fuels rather than complete combustion. Gasification of solid matters involves thermal decomposition of organic compounds present to produce combustible gases. When heated at high temperatures, the volatile compounds are thermally cracked to produce gases having H_2, CO_2, CO, and CH_4 as the combustible constituents. In a combustion zone, the oxygen is rapidly consumed near the air inlets to form CO_2 and CO (oxidation zone). At positions further from the air inlet, the concentrations of CO_2 increases and reaches a peak value at a point in the bed just before all the oxygen disappears. Subsequent to this, the concentration of CO_2 decreases since it is reduced to CO by the excess carbon present (reduction zone).

Excess air combustion is the opposite of starved air combustion. Supplied air is higher than stoichiometric for complete combustion. This condition may promote faster combustion rates, higher flame and combustor temperatures, as well as better efficiency in the incineration of the solid fuel to ash [13]. The supplied air is in the range of 1.2 – 1.4 of the stoichiometric (20% to 40% excess air).

Primary combustion stage is divided into two phases – fuel feed for initial phase (ignition) and combustion phase. The major differences of the two phases are the new fuel feed intervals and number of discharges. For the initial phase, new solid fuels are fed at 5 minutes intervals, ending as approximately 4 to 5 kg of fuel has been loaded to the first hearth. This signals the start of the combustion phase at faster feed rates. The 2nd ram fully advances to discharge the burning fuels onto the second hearth below. During combustion phase, fuels on the first hearth are discharged to the second hearth at approximately 4 to 5 minute intervals.

Pre-calibrated thermocouple wires of type-K, 0.65 mm in diameter placed inside a stainless steel tube of 5 mm outer diameter to form a thermocouple probe, was used to measure bed temperature. For this experimental objective, two points of temperature measurements are of importance; the fuel core temperature on the second hearth during starved/excess air combustion, and secondary stage combustion temperature in the swirl combustor. The probe to measure the fuel core temperature is positioned on the center of the second hearth surface, while the probe for measuring secondary stage

combustion temperature is positioned at the exit throat of the main combustion chamber of the swirl combustor.

The experiments were carried out at 0.2 kg/minute fuel feed rate. For a feed interval of 5 minutes per discharge, this amount is equal to 1.0 kg/feed. Phase one of primary stage combustion (ignition) takes about 40 minutes. Phase two (starved air/excess air) then commences until a final experimental amount of 12 kg palm oil shells has been loaded.

Secondary stage combustion in the swirl chamber is conducted at excess air conditions for both processes. The tangential airflow is set between 43 liters/min (1.5 cfm) to 57 liters/min (2.0 cfm). From experimental experiences, lower airflow rates were found unsuitable in achieving satisfactory burnout of the particulate matters rising with the flue gas. Airflow at higher rates than 57 liter/min (2.0 cfm) induces faster swirl velocities within the chamber, which in turn creates a high resistance condition at the inlet of the swirl chamber due to back pressure. Consequently, flow of gaseous products from primary chamber was found restricted.

RESULTS AND ANALYSIS

Figures 3 and 4 show the comparison of NO_x and CO, respectively, at excess air and starved air conditions. At starved air, the emission measurements before (primary stage) and after secondary stage combustion are plotted, with the objective to analyze the capability of the swirl combustor in minimizing pollutant gases. Figures 5 and 6 are plotted to further analyze the characteristics and factors influencing CO emission, in relation to flue gas composition and combustion temperatures.
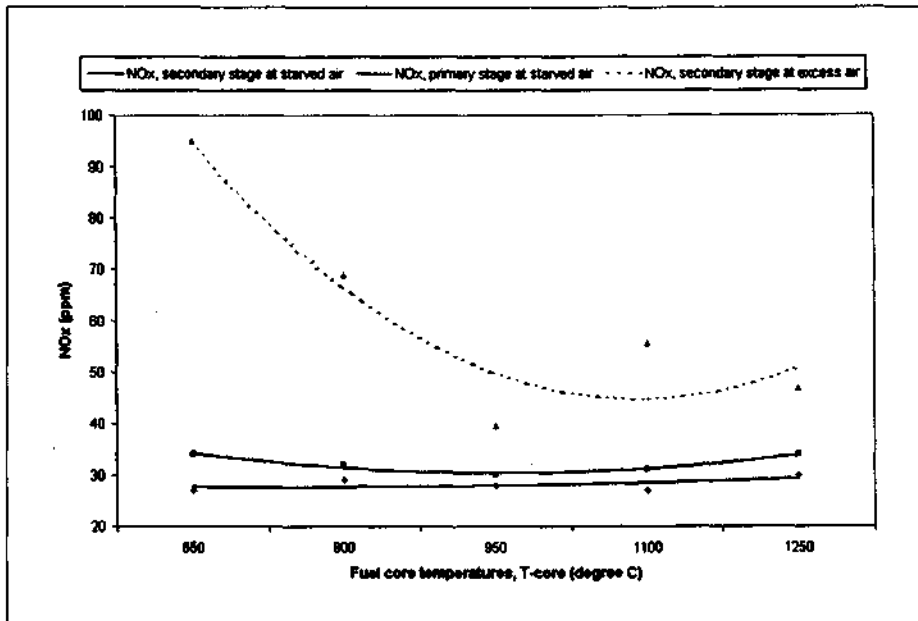

Figure 3: NO_x emission pattern at excess air and starved air conditions

Two methods of NO_x formation mechanism takes place during combustion- *thermal NO_x* at elevated temperatures above 950°C from air-bound nitrogen, and *fuel NO_x* formation occurring at lower temperatures from the nitrogen contained in the fuel. Low amount of nitrogen element in palm shells (0.7%) suggests that limiting thermal NO_x from occurring throughout the combustion region can minimize NO_x formation during combustion. The limit set by Best Available Control Technology (BACT) for NO_x emission from incinerators is 100ppm [14].

Figure 3 indicates a difference of NO_x emission at excess and starved air conditions. At excess air condition, the range is between 40-95ppm measured at 150% - 400% excess air. It shows a decreasing trend because the reading taken at 650°C fuel core temperature is influenced by high flame intensities (flame temperatures 800°C – 900°C) occurring on the fuel bed during the measurement period. A degree of thermal NO_x formation is suspected to increase the NO_x measurement, compared to readings at other periods where flame intensity was lower (flame temperature range 350°C – 500°C). Low excess air (20% to 40%) supplied to primary stage solids combustion, combined with low flame temperatures (below 500°C) manages to maintain NO_x emission within the limit of BACT.

At starved air conditions, the measurements after secondary stage combustion is in the range of 32-38ppm at 100% - 260% excess air in the flue gas. The initial NO_x emission after primary stage combustion was 27-30ppm. The average difference of emission levels between the two stages is approximately 5ppm, meaning that secondary stage combustion promotes an increase of 5ppm NO_x. The increase is attributed to the reaction of nitrogen volatiles when burned in an excess air condition in the swirl combustor. N_2, and NH react with available oxygen atoms to form nitric oxide (NO). The small increase of about 18% is due to the small fraction of nitrogen substance in the fuel, as well as low temperatures of secondary combustion (registered maximum 490°C) that limits thermal NO_x reactions at secondary stage. However, the graph of NO_x at primary stage combustion shows a tendency to increase higher than 30ppm as fuel core temperatures reaches 1250°C, due to the increasing influence of *thermal NO_x* formation to the final emission.

Figure 3 also shows a significant difference in final NO_x emission at excess and starved air conditions. Excess air conditions gives higher NO_x readings due to the higher availability of air-bound nitrogen, combined with higher volatisation rates of the shell particles, and subsequently higher flame temperatures that promotes NO_x formation, especially in gas phase reactions above the fuel bed.

Research works on NO_x formation mechanism is well established, and the NO_x emission obtained is comparable to other published data n palm shell combustion. Abdul Halim [15] reported the NO_x emission from palm shell combustion has a value between 20 – 120ppm with excess air at 300% to 800%. The values obtained from this research (30 – 90ppm at 200% to 400% excess air) is within that range and confirms with BACT limit of 100ppm. The analysis also conforms with various results and observations reported by Breen and Sotter [3] and McRee [9] on the capability of staged combustion to reduce NO_x emissions from solid fuel combustion.
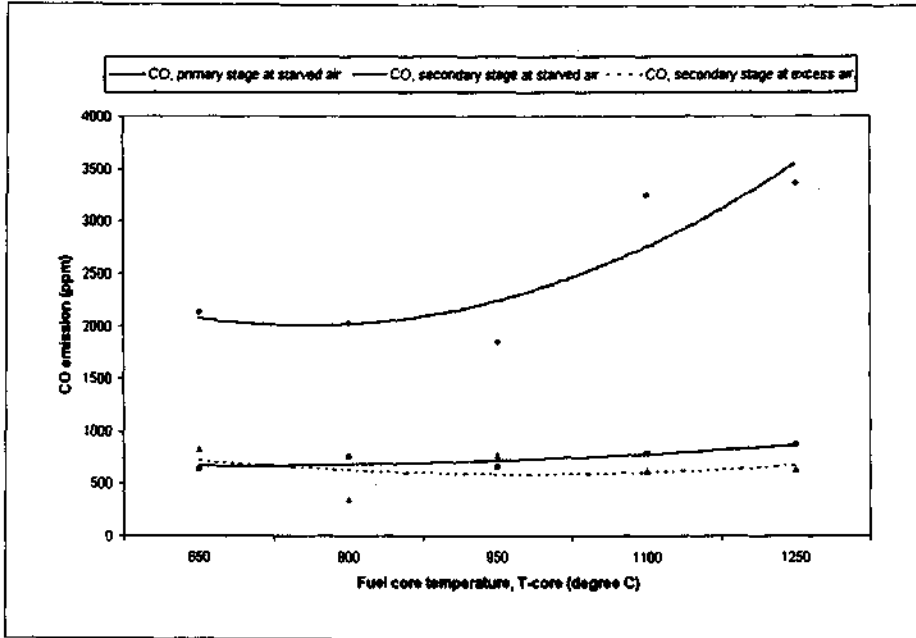
Figure 4: CO emission pattern at excess air and starved air conditions

CO formation is largely dependant on air availability and distribution, as well as the kinetic rates of carbon based substances during solid and gas phase combustion. From Figure 4, the emission of CO at starved air condition is reduced as the process shifts from primary stage to secondary stage. In the primary stage, the range is between 1800-3400ppm at $3.4\%O_2 - 5.3\%O_2$, while the level after secondary stage combustion is reduced to 600-800ppm at $11.6\%O_2 - 16.1\%O_2$. Primary stage CO emission registers a rapid increase as fuel core temperature increases as a result of faster reactions of pyrolysis, volatisation, and char oxidation of the solid fuel particle, as well as the increase in kgmol of available carbon coming in with new fuel feeds. Further oxidation of CO to CO_2 occurs in the swirl combustor, reducing the emission significantly. The presence of additional supply of combustion air, heat, with good mixing and residence time, promotes oxidation reactions of CO. In average, 1800ppm of CO is oxidized after secondary stage, at an oxidation efficiency of approximately 70%.

Measurements of CO after secondary stage at excess air condition are in the range of 400-800ppm at $5.7\%O_2 - 8.1\%O_2$. In excess air combustion, high flame intensities and high temperatures increases the rate of gas phase reactions of CO to CO_2 as the gases travels from the combustion hearths to the primary chamber exit, resulting in lower levels of CO concentration entering the secondary stage swirl chamber. Fuel lean conditions in the primary chamber may also increase the tendency of oxidation and complete combustion of fuel to CO_2 rather then producing CO.

The graph of CO at starved air shows a higher increase rate, mainly due to the increasing formation of CO in primary stage combustion. The permissible level for incinerators set by EPA (USA) is 700ppm [14], and the CO emission in the experiments fails to confirm with the limit, especially at starved air conditions. This failure may be attributed to the inadequate time for gas mixing and combustion to occur effectively in the swirl combustor, requiring adjustments to the dimensional

parameters of the swirl combustor (increase in swirl number). From starved air experimental, a CO level that conforms to the 700ppm limit (600ppm at 12.8%O_2) can be achieved at approximately 1800ppm primary stage emission (Figure 4, at 950°C fuel core temperature). This suggests that the maximum level of CO formed at primary stage, for the designed combustor with 1.57 swirl number, should not exceed a maximum of 1900-2000ppm for achieving final emissions within the EPA (USA) limit.
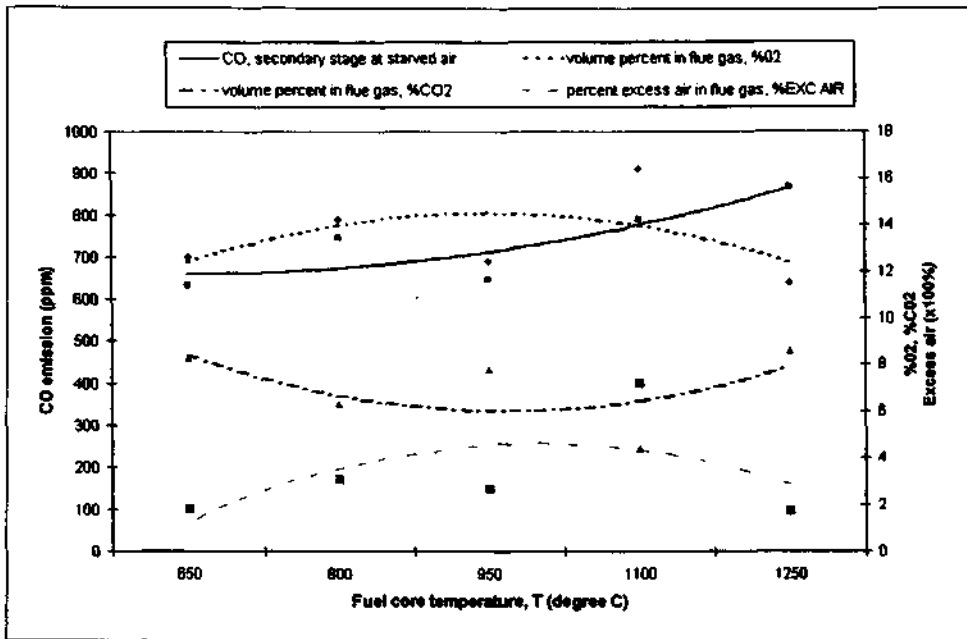

Figure 5: Fuel gas composition in relation to CO emission at starved air condition

The final level of CO influences the volume percentage of O_2 and CO_2 in the fuel gas. From the experimental, an increase of CO from 650-850ppm results in a subsequent decrease of O_2 (minimum 11.6%O_2) and increase in CO_2 (maximum 9.4%CO_2). The excess air level recorded in this period was normally in the range of 200% to 300%. The mixing efficiency of combustion air and combustible gases in the swirl combustor seems to be unsatisfactory in improving oxidation rates of CO. This can be assumed due to high volume percentage of unreacted oxygen in the fuel gas, and shown by the increase in CO emission when fuel core temperature increases. Apart from increasing the geometrical swirl number, the combustion air should also be increased proportionally as fuel core temperature increases so that adequate contact of CO to oxygen is accomplished.
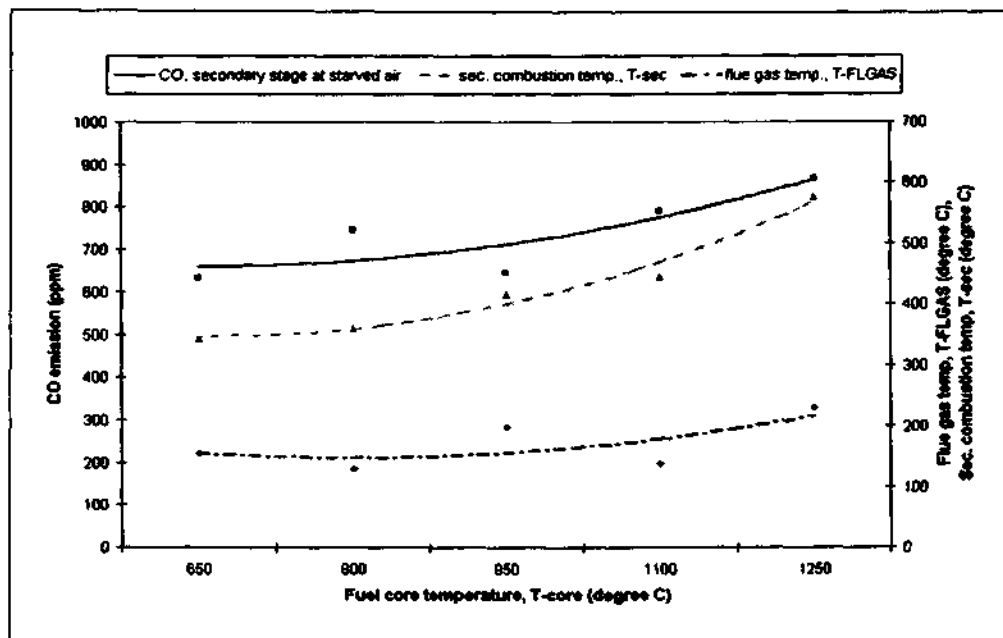
Figure 6: Relation of CO emission and fuel core temperature to fuel gas temperature and secondary combustion temperature

Figure 6 shows an increase in CO emission (650-850ppm) as fuel core temperature rises from approximately 650°C to 1250°C, pointing to an increasing rate of CO formation rate at high fuel core temperatures. Secondary combustion temperature also increases, from 350°C to 580°C, as a result of exothermic reactions of CO oxidation. The temperature of the fuel gas leaving the combustor also increases but is significantly lower, from a range of 140°C to 230°C. This condition is due to the cooling effect of excess air present in the flue gas. Further analysis shows that at 200% to 300% excess air, the fuel gas temperature can be estimated to be at approximately 40% of the secondary combustion temperature.

Formation of CO is caused by the oxidation of char and volatiles, as well as reduction of CO_2 in gas phase reactions above the fuel bed. Oxidation rates of carbon in the char increases as fuel temperature increases due to higher diffusion rates. Further oxidation of CO in the swirl combustor to CO_2 releases heat energy that influences the secondary combustion temperatures and flue gas temperatures. Basically, higher CO volume formed in primary stage combustion is a main factor in increasing the temperature of secondary stage combustion. The capability of the swirl combustor to efficiently increase the rate of CO oxidation is an important factor in optimizing the heat energy recovery of the combustion process.

CONCLUSIONS

Combustion characteristics of palm kernel shells in a cascading hearth staged combustor varies with the process conditions applied. Introducing excess air during primary stage combustion promotes a higher

concentration of NO_x pollutant to be formed (40-95ppm measured at 150% to 400% excess air) compared to starved air conditions (32-38ppm at 100% to 260% excess air). High flame intensities were achieved due to the abundance of air available in excess air mode, which leads to higher costs in and setting-up of cooling systems for safe operating conditions. Service life of the combustion system may also be reduced. Starved air combustion conditions during primary stage combustion offers an advantage in reducing combustion temperatures and lowering NO_x emission, thus savings can be made to the operating costs. However, CO formation is highly promoted in starved air conditions, therefore requiring that the secondary stage combustor operates with high efficiency to further oxidize the monoxides into dioxides. The analysis from the experiments conducted shows that the swirl combustor efficiency must be increased.

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ACKNOWLEDGEMENTS