

THE EFFECT OF FUEL FEED RATE ON TEMPERATURE PROFILES OF A CASCADING HEARTH WITH SECONDARY SWIRL COMBUSTOR

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ABSTRACT

The abundant availability of biomass solid wastes in Malaysia such as palm shells from the oil palm industry promotes diversified research fields for its utilization. This paper investigates the application of a cascading hearth staged combustor to palm shells combustion in terms of fuel feed rate effect on temperature profiles. The application of a two-step hearth setup at primary stage combustion offers wider alternatives for solid phase combustion processes. Initial combustion studies of palm shells by controlled air combustion conditions using these set-ups show promising results for further development. Controlled air conditions promote gasification of the solid fuel and significantly lower combustor temperatures below 500°C. Varying the fuel feed at 0.1, 0.15 and 0.2 kg/min with constant air supply of 227 liters/min (8 CFM) and good fuel distribution on the hearth leads to fuel core temperatures exceeding 1000°C. As a result of high core temperatures, release rates of volatiles and combustible gases increases which influences attainable secondary combustion temperatures. The maximum secondary stage combustion exhaust temperature recorded was 490°C at 0.2 kg/min fuel feed, a secondary air supply of 42.5 liters/min (1.5 CFM) and a corresponding fuel core temperature of 1225°C.

Keywords: Cascading hearth, swirl combustor, solid waste, fuel feed rate, temperature distribution.

1.0 INTRODUCTION

The technology of combustion has gone through sophisticated contemporary research and continuously improved to satisfy strict modern regulations and efficiency requirements. As concern on the depletion of oil and gas reserves rises, solid fuels are certainly regarded as an alternative source of energy for the future. Carbonaceous solid wastes from the agricultural sector have been identified as a promising prospect for this purpose.

The objective of this paper is to investigate the application of a staged combustion system to biomass solid waste combustion in Malaysia. The concept of two-stage combustion with cascading hearths and secondary swirl combustion is studied, and a laboratory scale combustion system is developed. Experimental

combustion tests are conducted using palm oil shells as fuel, and the temperature profiles are analyzed to study the combustion characteristics of palm oil shells and combustor performance.

1.1 Two-Stage Combustion

Staged combustion is a concept utilized to enhance combustion efficiency of solid fuels combustion products burnout. 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 [1]. 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 normal gas substances formed are Carbon Monoxide (CO), Oxides of Nitrogen (NO_x), and Oxides of Sulfur (SO_x). It is usually operated at sub-stoichiometric air level, enabling first stage temperatures to be maintained at relatively low levels of about 1000°C [2]. The products of incomplete combustion in the primary stage are then channeled into the secondary combustion chamber.

Most combustion processes are completed in secondary stage gas phase reactions. The gases and particulate products of primary combustion enter the secondary chamber and are re-burned. Heat and air are introduced strategically to achieve optimum burnout of the exhaust gases. Therefore, secondary stage combustion is combustion of gases acting to reduce the emission level of the overall combustion process.

1.1.1 Cascading Hearth

The cascading hearth is a modification of the traveling grate concept and also referred to as “stepped hearths”. It is operated with a charging ram mechanism that conveys the solid fuel from a container through the incinerator furnace to the ash residue discharge. The design applies two effective cascading hearths. The discharge from the first hearth is actuated by the ram and tumbles onto a second unit, thereby mixing, breaking and redistributing the fuel bed on the second stage. This redistribution is then repeated, increasing combustion efficiency as a more complete burnout of the solid fuel is achieved. Three charging rams are utilized to convey the fuel to the ash residue discharge.

1.1.2 Secondary Swirl Combustor

Swirl is used extensively in combustion chambers as a means of controlling flame size, shape, stability and combustion intensity [3]. Swirling flows result from the application of a spiraling motion, swirl velocity component (or tangential component) being imparted by direct tangential entry into the chamber. The principle of swirl flow operation in a secondary combustion process is where the mixture of air and combustible gases from primary combustion swirls along the circular walls of the secondary chamber. Intense recirculation patterns occurs in swirling flows, where the burning gases travels back towards the burner

bringing heat energy and reactive species to promote ignition in the entering fuel-mixture.

Swirl burners are applied mainly to combust poor quality fuels efficiently, particularly gaseous fuels with calorific values as low as 1.3-1.4 MJ/m³ [4]. It has the advantage of a longer gas residence time, higher temperatures, and more effective mixing of the hot, partially combusted gases from the primary chamber with the combustion air. In their works, Edelman and Harsha [5] have pointed out that swirl flows in combustors affect the flame length, shape, combustion intensity, and stability for the reacting flows.

1.2 Oil Palm Shells

Malaysia is the largest palm-oil producer in the world. In 1999, the country produced 51% of world palm oil production and 62% of the total world export, with a total production of 10.55 million tones of crude palm oil from a total plantation area of 3.31 million hectares, and a total export revenue of RM19.21 billion [6]. The Department of Statistics of Malaysia [7] has reported an estimated palm oil production of 1.44 million tons annually.

Palm shells are waste products of oil palm processing. They are oval in shape with a maximum dimension that varies between 10-20 mm. It is hard physically, with good resistance to breaking in handling. Proximate and ultimate analysis of palm shells are shown in Table 1.

Table 1 Properties of oil palm shell [8]

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	55.35
H	6.27
O	38.01
N	0.37
Moisture (wt % air dry)	8.4
Gross CV (HHV) (MJ/kg)	20.7
Average bulk density (kg/m ³) <18 mm	440

Palm shells can be incinerated to provide heat energy for plant utilities. The higher heating energy value (HHV) was analyzed at 20.7 MJ/kg, or equals to 4950 kcal/kg. For comparison, the heat produced by burning 1 kg of dry wood is about 12.5 MJ/kg (3007 kcal/kg) [9]. The practice of solid waste combustion on palm shells as boiler fuel for steam raising and electricity generation is estimated

at a usage of 80% from a 1.1 ton per hectare of palm shell production [10]. This application was assumed to have saved the country about 326 million liters of diesel, amounted at about RM212 million [11]. It is also reported in 1992, that the energy generated from the oil palm wastes in processing mills was as high as 650 kW from fibers and palm shells [8].

2.0 STAGED COMBUSTION SYSTEM

The combustion system consists of six main component systems, i.e. fuel feed mechanism, primary combustion chamber, secondary combustion chamber, combustion air line, pneumatic circuit, and the Programmable Logic Controller (PLC) unit. The combustion system has the capability to handle a maximum of 40 kg/hour of solid fuel feed, and handling bulk solids of different shapes, sizes and characteristics. The fuel is fed in periodic batches, and due to the estimated variations in process sequence, PLC controlled and pneumatically driven conveying system was installed. A cascading hearth system with underfire air feed was applied for higher combustion efficiency in the primary combustion chamber. Secondary combustion process takes place in the swirl combustor. The combustion system is designed to closely comply with BS3813: Part 1 (1964) [12], and following the operating requirements shown in Table 2.

For a swirl combustor assuming uniform exit axial velocity profile, the swirl number can be related to dimensional parameters [13]:

$$N_{sc} = \frac{\pi \cdot D_e \cdot D_o}{4 \cdot A_T} \quad (1)$$

where D_e is the diameter of exit throat, D_o is the diameter of main section, and A_T is the area of the tangential inlet. The flows within a swirl combustion chamber can be seen to be sensitive to the inlet and outlet configuration, relative inlet-outlet, chamber dimensions, and presence of vanes or other flow modifiers on the sidewalls or end plates. The swirl number for the secondary stage swirl combustor design is 1.57.

A gas ignition burner located axially at the ignition chamber supplies heat for secondary combustion. The burner has a diameter of 25 mm and utilizes LPG as its fuel. A separate air port is designed to supply the necessary air for the burner. Two air inlets are positioned tangentially inside the ignition chamber for supplying combustion air to the secondary combustor. The air inlet nozzle is strategically directed towards the mixing chamber for creating a turbulent and swirling airflow inside the firing chamber (55° injection angle with respect to the x-axis). Figure 1 shows the schematic diagram of the swirl combustion chamber.

The charging ram mechanism is powered by a pneumatic cylinder system, with the application of Programmable Logistic Controllers (PLC) as the control system. The conveyor system consists of 7 main components; the charging rams,

ram chambers, gate, cascading hearths, pneumatic actuator circuit, the PLC, and support frame structure. Figure 2 illustrates the schematic feeder system arrangement and Figure 3 shows the overall design of the staged combustion system.

Table 2 Design operating requirements

Estimated Generated Power	= 30 – 50 kW
Capacity of Fuel Feed	= up to 40kg/hour
Operating Temperature, Primary Chamber	= max. 1200°C
Secondary Chamber	= up to 1000°C

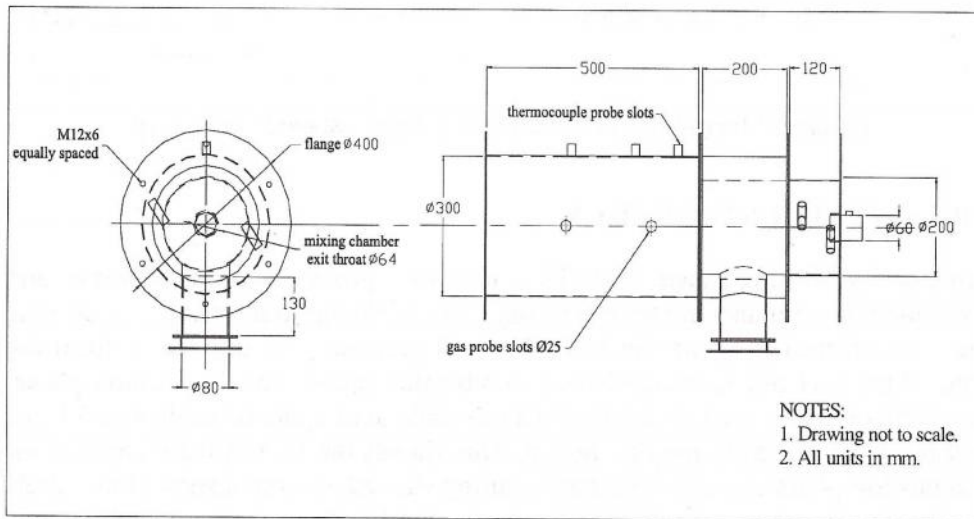


Figure 1 Secondary stage swirl combustion chamber

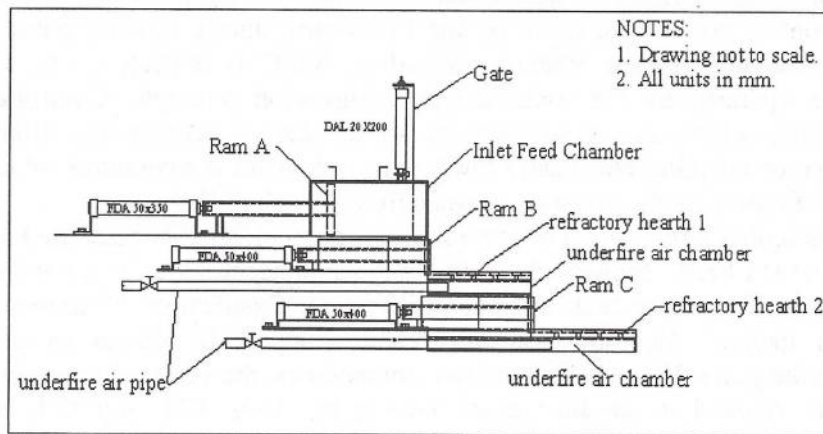


Figure 2 Feeder system arrangement with cascading hearth and charging ram

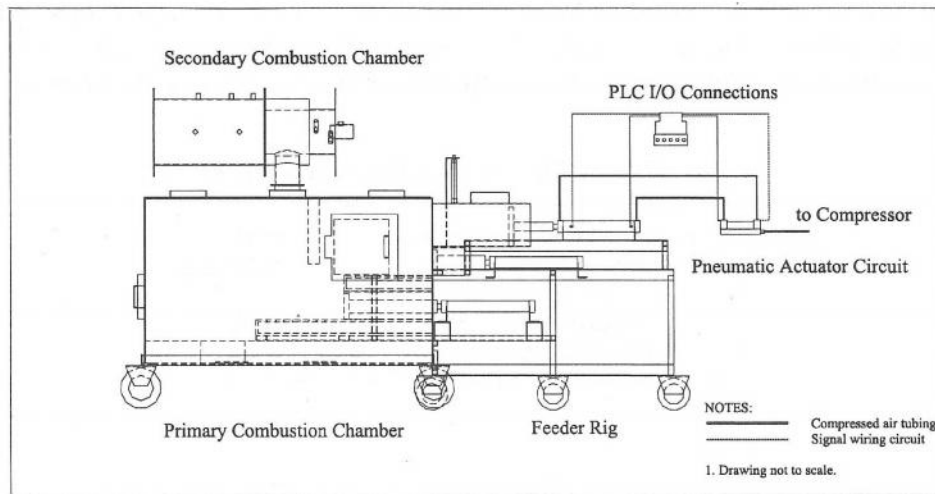


Figure 3 Overall design of cascading hearth staged combustor

3.0 EXPERIMENTAL SET-UP

Primary combustion stage is divided into two phases – ignition phase and controlled air combustion phase. The objective of the ignition phase is to provide the required heat to ignite the fuels that will eventually be utilized to form the core of the fuel bed in controlled air combustion phase. For the ignition phase, raw palm oil shells are fed at 5 minutes intervals, until approximately 4 to 5 kg of fuel has been loaded to the first hearth. This signals the start of the controlled air combustion phase at faster feed rates. During starved air combustion phase, fuels on the first hearth are discharged to the second hearth at approximately 3 to 4 minute intervals.

The first hearth is used to ignite newly fed fuels during ignition phase combustion, and fuel drying during starved air combustion phase. High intensity flame front is expected to occur on the first hearth during ignition phase, with direct flame temperature readings exceeding 700°C is expected. The second hearth is operated by the controlled air combustion principle. Controlled air combustion, where air is supplied at lower than stoichiometry, offers the advantage of attaining reasonably low primary chamber temperatures while still capable of removing the organic materials from the ash [14].

The stoichiometric air/fuel mixture ratio for palm oil shell is calculated at 5.37 kg air/fuel (as fired). Sub-stoichiometric oxygen concentrations in a combustion process, relative to the fuel, leads to gasification. 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 H₂, CO₂, CO, and CH₄ as the combustible constituents. Gasification process is fundamentally based upon the chemical reactions between carbon and oxygen, steam or carbon dioxide, with the

presence of heat. In a combustion zone, the oxygen is rapidly consumed near the air inlets to form CO₂ and CO (oxidation zone). At positions further from the air inlet, the concentration of CO₂ increase and reach a peak value at a point in the bed just before all the oxygen disappears. Subsequently, the concentration of CO₂ decreases since it is reduced to CO by the excess carbon present (reduction zone). Figure 4 illustrates the various zones and reactions in a gasifier bed.

3.1 Temperature Measurement

Temperature profiles in primary and secondary combustion stages are important indication to combustion performance and behavior. Temperature levels are monitored closely for its relationship with fuel and air feed parameters. The desired conditions are to maintain primary chamber temperature relatively low, between 600°C to 900°C, while still succeeding in achieving 400°C to 800°C in the secondary combustion chamber.

Five pre-calibrated thermocouple probes of type-K, 0.65 mm in diameter, were used to measure bed temperature. The first point (T1) is located 200 mm above the center of the first hearth (H1), for the purpose of measuring flame temperatures. The second point (T2) is located 200 mm above the center of the second hearth (H2), to measure gas/flame temperatures rising from H2 combustion. The third point (T3) is located directly before the exhaust opening of the primary chamber that leads to the swirl chamber. The fourth point (T4) is positioned at the exit throat of the swirl combustion chamber, measuring post-combustion temperatures from secondary stage combustion. The final point (T5) is positioned on the center of the second hearth (H2) surface, to measure the fuel core temperatures.

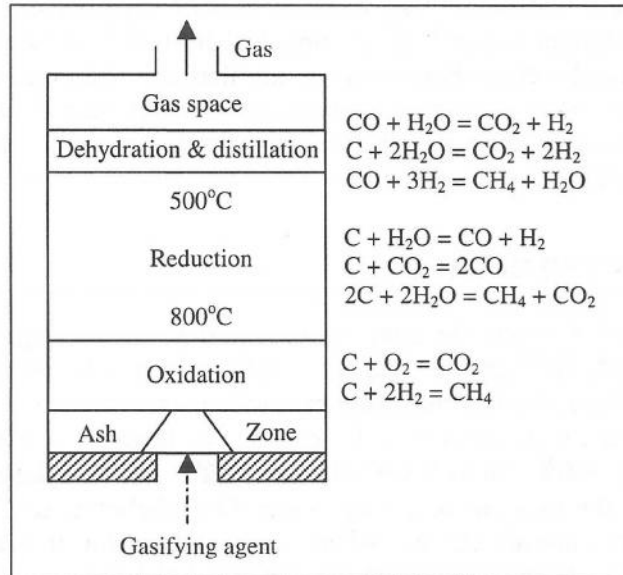


Figure 4 Various zones and reactions in gasifier bed

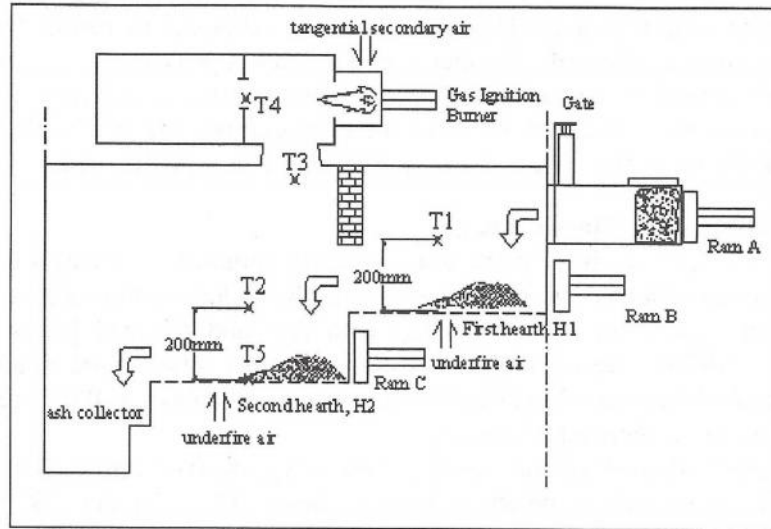


Figure 5 Temperature probe locations and combustor set-up

3.2 Fuel Feed Rate

The feed rate is discretely controlled by the operator by means of the PLC controlled charging ram. To study the effect of varying feed rates to combustion process temperatures, the experiment was carried out at three different feed rates; 0.1 kg/min, 0.15 kg/min, and 0.2 kg/min. For a feed interval of 5 minutes per discharge, this amount is equal to 0.5 kg/fuel feed, 0.75 kg/fuel feed, and 1.0 kg/fuel feed. Phase one of primary stage combustion (ignition), is conducted in approximately 40 minutes (for fuels to burn efficiently) with a constant air supply of 425 liters/min (15 cfm). Phase two (controlled air) is carried out to a final amount of 12 kg, and at a constant air supply of 227 liters/min (8 cfm). Air to the secondary swirl combustor was supplied between 43 liters/min (1.5 cfm) to 57 liters/min (2.0 cfm).

4.0 RESULTS AND DISCUSSION

Figures 6, 7 and 8 show the temperature profiles of the staged combustion experiment at 0.5, 0.75 and 1.0 kg/fuel feeds respectively. Analysis is made according to the location of temperature measurements.

Flame temperature above the first hearth (H1) is shown by T1. The maximum T1 attained was 900°C for 0.5 kg/fuel feed, 862°C for 0.75 kg/fuel feed, and merely 467°C at the feed rate of 1.0 kg. A significant behavior of T1 temperature trend is the rise-and-fall curves, where each subsequent increase to higher temperature peaks is a result of increasing exothermic reactions of a larger available fuel quantity. Higher T1 registered at 0.5 kg/fuel feed is a result of

higher air-fuel ratio of 0.94, compared to only 0.71 and 0.58 respectively for 0.75 and 1.0 kg/fuel feeds. The availability of more combustion air increases the rate of combustion reactions, and promotes high flame temperatures. Fuel feed at larger amounts (1.0 kg/fuel feed) also reduces the rate of flame propagation on H1, resulting in lesser flame intensity, as effects of flame quenching and gasification is more severe due to larger surface area for oxidation to occur than at lesser fuel feed rates (0.5 and 0.75 kg/fuel feeds).

For T2, the measured level at 0.5 kg/fuel feed is in the range of 100°C to 150°C, showing the existence of flame in the fuel bed. At 0.75 and 1.0 kg/fuel feed, the recorded levels are lower than 100°C. Low temperature levels above the hearth during controlled air combustion and gasification were caused by minimal flame propagation, due to low stoichiometric air ratio between 0.3 and 0.5. From Figure 9, increasing the air ratio fraction higher than 0.48 registers T2 readings exceeding 100°C. Flame temperatures as high as 200°C were recorded as the ratio increases to 0.57. This shows that flame propagation is promoted by the availability of more oxygen for fuel oxidation.

T3, which is positioned at the exit of the primary combustion chamber, is not an accurate presentation of the temperature of rising flue gases to the secondary combustion chamber. Existence of flame on both or either hearths significantly increases T3 measurements by convection and radiation of the heat. Flame existence on the second hearth (measured by T2) has a major influence on T3 compared to T1, especially during controlled air combustion phase, due to its positioning directly above the second hearth.

T4 is the probe located downstream of the main combustion region of the swirl combustor. During combustion phase with high flame intensities ($T1 > 200^\circ\text{C}$), the average T4 measurements were lower than 400°C due to lower availability of combustible gases and particulate volatiles for secondary combustion. During controlled air combustion phase, the average T4 for each fuel feed was 400°C, with a gradual increase observed for 1.0 kg/fuel feed experiment, to a maximum of 490°C. This is caused by good gasification conditions at primary stage combustion where a constantly increasing concentration of combustible gases and volatiles were supplied for secondary stage combustion (fuel rich gases).

T5 measures the fuel core bed temperature on the second hearth during controlled air combustion, and it is a rate-governing requirement to increase kinetic reactions. The required level of core temperatures for satisfactory combustion kinetic rates should be in the range of 900°C to 1400°C [15]. Higher fuel feed rates at constant air flow rate of 227 liters/min (8 cfm) lead to higher bed temperatures, where the maximum temperature was 1225°C at 12 kg fuel. Increasing the air flow rate may also increase bed temperatures, but flame propagation will significantly increase due to availability of more oxygen to speed combustion reactions of fuel layers above the core. Fuel distribution is another important factor influencing fuel core temperatures. Cold fuels must be distributed evenly in stacked layers on top of the hot core bed. Adequate exposure to heat is required to increase kinetic reaction rates of the colder fuels,

but closely stacked fuel layers may quench any flame formation of the hotter fuel layers at the core.

Figure 10 shows that fuel core temperatures (T_5) have an affecting correlation with secondary stage combustion temperatures. As T_5 increases to 1225°C , T_4 shows a similar increase from 360°C to 490°C (Figure 10). To obtain maximum usable heat energy from palm shell combustion by controlled air combustion, fuel core temperatures must be at least 1400°C for increased kinetic reaction rates of carbon to carbon monoxide. It is important to note that the low measurements of T_4 (max 490°C) is not the definite presentation of secondary stage combustion temperatures due to the positioning of the thermocouple probe downstream of the main combustion region.

5.0 CONCLUSION

Controlled air combustion conditions in primary stage combustion significantly lowers combustor temperatures below 500°C while still capable of promoting the release of combustible gases and volatiles. Flame temperatures during ignition phase reaches as high as 900°C at lesser fuel feeds (0.1 kg/min) due to higher air ratio fraction supply of 0.94. During controlled air combustion phase, low fuel feeds with supplied air ratio fraction exceeding 0.48 promotes propagation of flame on the fuel bed. Increase in fuel feed with constant air supply and good fuel distribution on the hearth surface are important factors to achieving sufficient fuel core temperatures for faster gasification rates. Increase in fuel core temperatures also shows a significant effect on achievable secondary combustion temperatures. The maximum secondary stage combustion exhaust temperature attained was 490°C at 1.0 kg/ fuel feed , at a secondary air supply of 1.5 cfm and a corresponding fuel core temperature of 1225°C . Analysis of the temperature data obtained from experimental tests, these processes has managed to provide fundamental understanding on the characteristics of palm oil shell combustion in a cascading hearth staged combustor.

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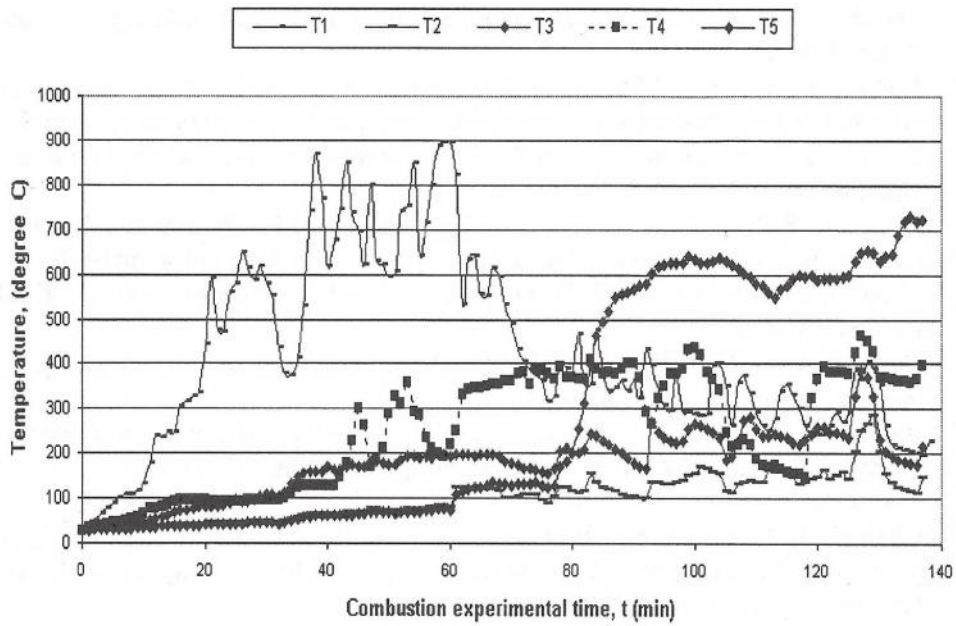


Figure 6 Temperature profile of combustion process at 0.5 kg/fuel feed

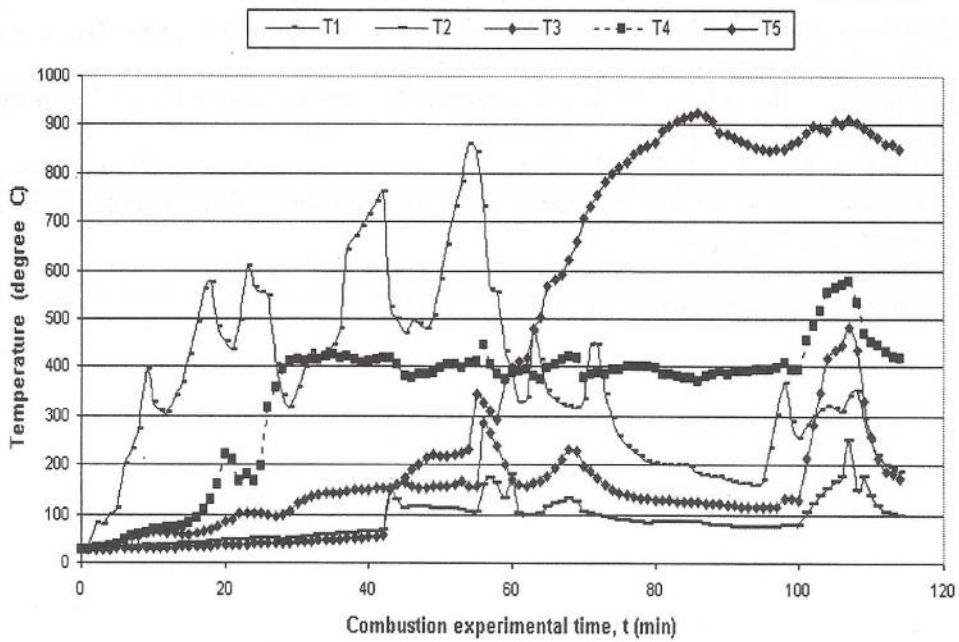


Figure 7 Temperature profile of combustion process at 0.75 kg/fuel feed

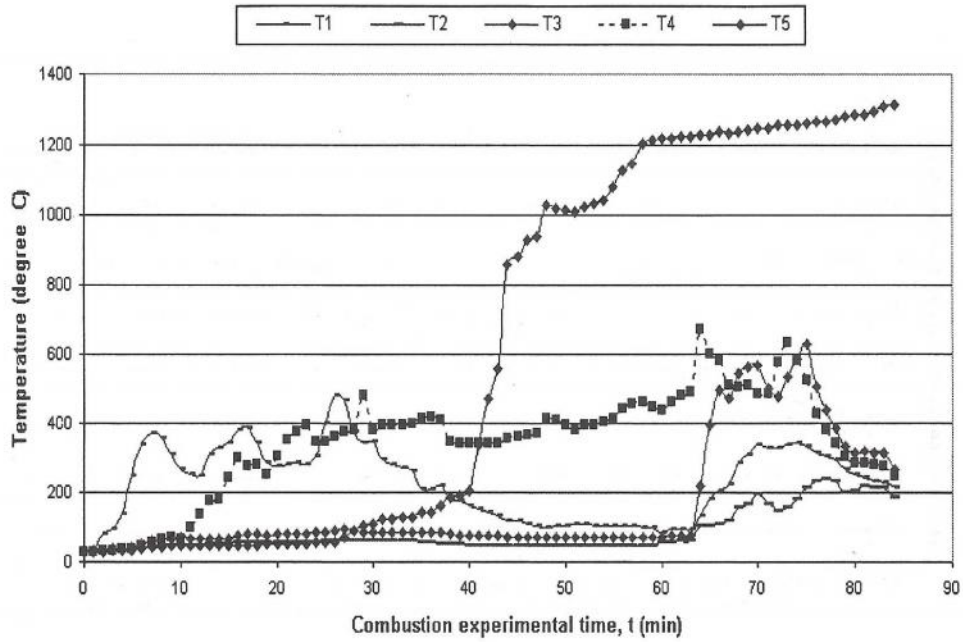


Figure 8 Temperature profile of combustion process at 1.0 kg/fuel feed

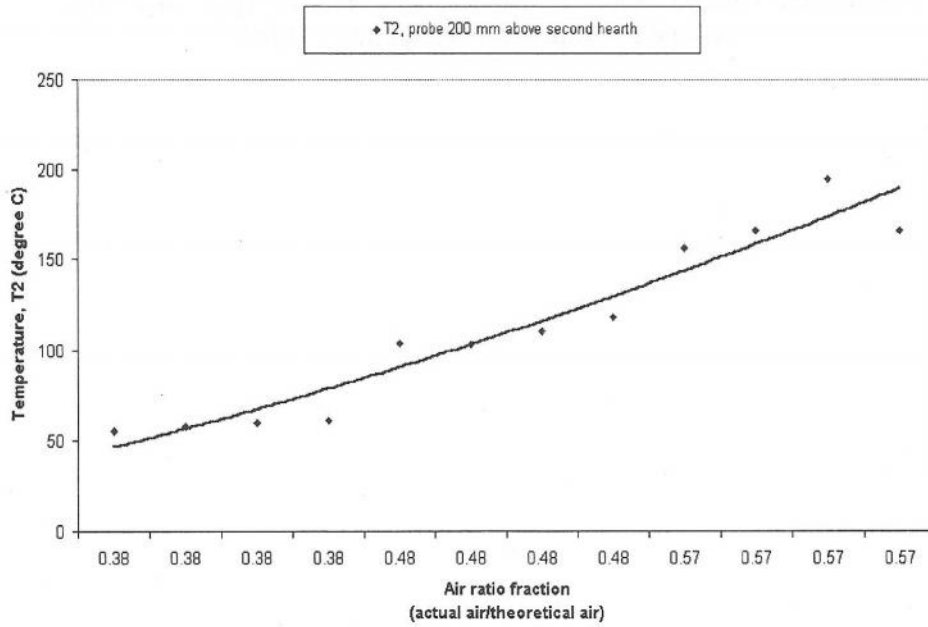


Figure 9 Influence of stoichiometric air ratio to flame propagation on second hearth at 0.5 kg/fuel feed rate (total fuel amount 12 kg)

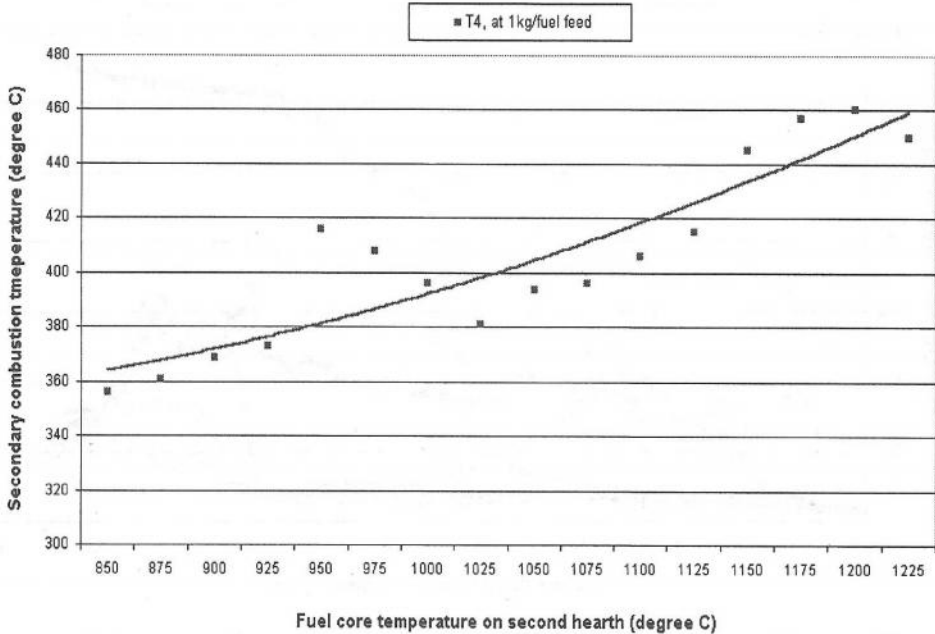


Figure 10 Influence of fuel core temperatures (T5) during gasification to secondary combustion temperatures (T4)