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EXPERIMENTAL STUDY ON TEMPERATURE PROFILE OF FIXED-BED GASIFICATION OF OIL-PALM FRONDS

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ABSTRACT
Currently the world's second largest palm oil producer Malaysia produces a large amount of oil palm biomass each year. Although some oil palm parts and derivatives like empty fruit bunch and fibre have been commercialized as fuel, less attention has been given to oil palm fronds (OPF). Initial feasibility and characterization studies of OPF showed that it is highly feasible as fuel for gasification to produce high value gaseous fuel or syngas. This paper discusses the experimental gasification attempt carried out on OPF using a 50 kW lab scale downdraft gasifier and its results. The conducted study focused on the temperature distributions within the reactor and the characteristics of the dynamic temperature profile for each temperature zones during operation. An average pyrolysis zone temperature of 324^{o}C and an average oxidation zone temperature of 796^{o}C were obtained over a total gasification period of 74 minutes. A maximum oxidation zone temperature of 952^{o}C was obtained at 486 lpm inlet air flow rate and 10 kg/hr feedstock consumption rate. Stable bluish flare was produced for more than 70% of the total gasification time. Similar temperature profile was obtained comparing the results from OPF gasification with that of woody biomass. Furthermore, the successful ignition of the syngas produced from OPF gasification ascertained that OPF indeed has a higher potential as gasification feedstock. Hence, more detailed studies need to be done for better understanding in exploiting the biomass as a high prospect alternative energy solution. In addition, a study of the effect of initial moisture content of OPF feedstock on the temperature distribution profile along the gasifier bed showed that initial moisture content of feedstock in the range of 15% gives a satisfactory result, while experiments with feedstock having higher moisture content resulted in lower zone temperature values.

Keywords: Biomass; Gasification ; Oil-palm fronds

1. INTRODUCTION

Currently exploiting the energy potential of renewable fuels is becoming a focus of interest due to increase in the price of fossil fuels and the higher environmental concern caused by their use. One form of renewable energy that is available abundantly is biomass waste. Considering the biomass energy potential of Malaysia, oil-palm waste has the second largest energy potential, next to forest residues, as shown in Table 1 (Jaafar et al., 2003). The main types of biomass wastes obtained from oil palm mills and plantations include Empty Fruit Bunches (EFB), Kernel Shells, Palm Oil Mill Effluent (POME), Trunks and Oil Palm Fronds (OPF). The amount of each type of biomass waste produced annually; from the oil-palm industry as of 2009 in Malaysia is given in Table 2 (Mohammed, et al., 2010).

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A number of studies had been carried out in literature to study the gasification performance of many biomass types. Studies conducted in earlier times are found to mainly focus on gasification of coal and woody biomass (Baker, et al., 1984; Borisov, et al., 1998; Fredriksson, 1999; Guo, et al., 1997; Guoet al., 2008; Li et al., 2001). In recent years more gasification studies were conducted on agricultural residue biomass wastes; such as rice husks (Ani, et al., 2008; Bhat, et al., 2001; Yusof, et al., 2008), hazelnut shells (Dogru, et al., 2002a; Midilli & Dogru, 2001), peanut shells (Hanping, et al., 2008), vine shoots (Ganan, et al., 2006), coconut shells (Bhattacharya & Hla, 2001). More recently, the search for sustainable biomass resources expanded to industrial and household disposals like tires (Mitta, et al., 2006) and municipal solid wastes (Dogru, et al., 2002b; Dong, et al., 2002).

Studies that are previously done on oil palm wastes were limited to bio-diesel extraction (Abdullah & Bridgwater, 2006; Abdullah & Gerhauser, 2008; Amin, et al., 2010; Kalam & Masjuki, 2002; Yang, et al., 2006; Yang, et al., 2004), mostly from EFB biomass. No study had been carried out on gasification of OPF for production of syngas previously. This current study focuses on gasification of OPF as they are easier to prepare as feedstock and regularly available throughout the year, with frequent pruning done in the oil palm plantations. The composition of the produced syngas, its cleanliness and most importantly its calorific value are highly dependent on the temperature profile of each zone of gasification (Bridgwater, 1995; Higman & Van der Burgt, 2008; Reed & Das, 1988). Therefore, in this study a set of gasification runs of OPF biomass with different initial moisture content were carried out to study the temperature profile of each zone of gasification.

Table 1 Renewable energy resource potential in Malaysia (Jaafar et al., 2003)

Type of Renewable Energy	Energy Value or Enrgy Price [RM million per annum]
Forest residues	11,984
Oil palm biomass	6,379
Solar thermal	3,023
Mill residues	836
Hydro	506
Solar PV	378
Municipal waste	190
Rise husk	77
Landfill gas	4

Table 2 Amount of oil-palm biomass produced in Malaysia as of 2009 in million ton per year (MnT/year) (Mohammed et al., 2010)

Type oil- palm biomass	Amount produced [MnT/Year]
EFB	17.08
Fibres	9.66
Trunk	8.2
Shells	5.2
OPF	12.9

Qualitative and quantitative studies carried out to determine the potential and feasibility of OPF ascertained that OPF has a higher potential as a gasification feedstock (Atnaw et al., 2011; Mohammed et al., 2010; Sulaiman et al., 2010; Yang et al., 2006; Yang et al., 2004). These studies experimentally determine, the chemical and physical properties of OPF biomass in terms of proximate analysis, ultimate analysis, chemical composition of cellulose, hemicellulose and lignin. The detail study of physical and chemical characteristics, as well as a study of ignitability of OPF feedstock is given in the work of Sulaiman et al. (2010). Comparison of proximate and ultimate analysis of OPF with other biomass types revealed that the physical and chemical composition of OPF is closely similar to other biomass types used for gasification. Table 3 shows the comparison of proximate and ultimate analysis results for OPF, other oil-palm waste biomasses, and commonly used woody biomass types. The proximate analysis results showed that OPF has higher fixed carbon composition compared to other oil-palm waste biomass as well as woody biomass types. As fixed carbon is the solid combustible residue that remains after the volatile matter of biomass is released, OPF will have higher amount of char during gasification.

Table 3 Comparison of proximate and ultimate analysis of OPF with other biomass materials

Waste	Ref.	Proximate Analysis (wt %)				Ultimate Analysis (wt %, dry basis)				
		M_{ad}	V_{ad}	A_d	FC_{ad}	C	H	N	S	O[a]
OPF	(Balamohan, 2008)	-	53	6	41	42.6	5.5	2.2	0.11	45.5
OPF	(Wahid & Weng, 2008)	-	85.1	3.4	11.5	42.4	5.8	3.6	-	48.2
Shell	(Yang et al., 2006)	5.73	73.74	2.21	18.37	53.8	7.20	0.00	0.51	36.30
Fiber	(Yang et al., 2006)	6.56	75.99	5.33	12.39	50.3	7.07	0.42	0.63	36.28
EFB	(Yang et al., 2006)	8.75	79.7	3.02	8.65	48.8	7.33	0.00	0.68	40.18
Eucalyptus	(Gañan et al., 2006)	6.76	73.64	0.53	19.09	46.4	5.73	0.25	0.00	47.25
Pine	(Gañan et al., 2006)	7.99	79.96	0.29	11.79	46.6	6.04	0.07	0.04	46.91
Holm oak	(Gañan et al., 2006)	8.92	78.86	0.94	11.28	44.7	5.9	0.24	0.17	48.51

M: moisture content; *V*: volatile matters; *A*: ash; FC: fixed carbon; ad: on air dried basis; d: on dry basis.
[a]The oxygen (O) content was determined by difference.

Table 4 Chemical composition of biomass materials

Component	OPF	EFB	Shell	Fiber	Hard Wood
Ref.	(Mohammed et al., 2010)	(Mohammed et al., 2010)	(Mohammed et al., 2010)	(Mohammed et al., 2010)	(Saidur et al., 2011)
Cellulose	49.8	38.3	20.8	34.5	45.8
Hemicellulose	-	35.3	22.7	31.8	31.3
Lignin	20.5	22.1	50.7	25.7	21.7
Ash	2.4	1.6	1.0	3.5	2.7

N.B: OPF, EFB, Shell, Fiber and Trunk are for oil-palm waste biomass

Eventually the solid char which is mainly composed of carbon will be gasified in the reduction zone of the gasifier. The ultimate analysis also revealed that OPF has comparable elemental composition (CHNS), with woody biomasses. Moreover, calorific value of OPF is found to be slightly higher than that of eucalyptus, pine and holm oak (Gañan, et al., 2006). In general cellulose, hemicelluloses, lignin and ash are the major components of biomass materials. Usually biomass material contains 40-60% cellulose, 20-40% hemicelluloses and 10–25% lignin on dry basis (Yang et al., 2006). A summary of chemical composition in weight percent of the different oil-palm biomass types and typical woody biomasses is given in Table 4.

A study carried out on effect of woody biomass components on air- water gasification showed that the conversion in cellulose, hemicellulose and lignin are 97.9%, 92.2%, and 52.8% on carbon basis respectively (Hanaoka, et al., 2005). Furthermore, the product gas composition in cellulose is reported to have higher carbon monoxide composition (35.5 mole %), compared to that of hemicellulose and lignin. Considering the higher carbon conversion efficiency and resulting higher carbon monoxide production in syngas, cellulose is found to be the most favorable chemical component in biomass gasification, while lignin components show inferior quality in terms of thermochemical conversion. Therefore, OPF has higher potential of gasification, as it has the highest cellulose composition of 49.8% compared to other palm-oil wastes as well as woody biomass. In addition lignin and ash composition of OPF, 20.5% and 2.4% respectively, is found to be lower compared to the other biomass types. The high composition in cellulose as well as lower lignin and ash fraction of OPF, is a much desired property for gasification application, as higher composition of cellulose ensures higher carbon conversion efficiency.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1. Experimental Setup

The experimental setup consists of an air blower, batch feed gasifier unit, a cyclone, a condenser unit, an oil bath filter, and a number of flare points as shown in Figure 1. The experiment was conducted using a downdraft gasifier with atmospheric air used as gasification media. The gasifier unit was designed to deliver an estimated thermal power output of 50 kW. The size of the internal cylindrical reactor was 1000 mm in height and 400 mm in diameter. The grate was located at the bottom of the reactor after the necking/constriction in a typical downdraft arrangement. The grate provided support for the fuel bed, while allowing ash to fall down to the ash box through its perforations. The necking of the gasifier had upper and lower diameters of 400 mm and 250 mm, respectively, with 200 mm in height of necking to result in a slope angle of 70o, to avoid interrupted flow due to bridging. The outer wall of the gasifier wall is of rectangular shape of 450 mm by 450 mm. The space between the outer wall and the inner cylinder (effective insulation thickness of 25 mm) was filled with refractory cement for insulation.

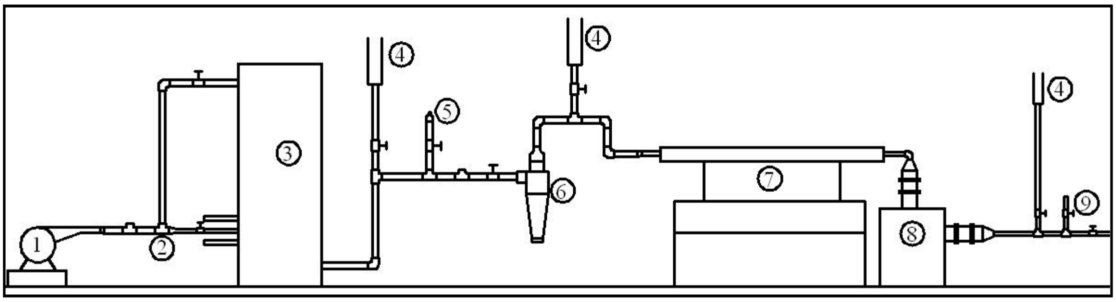

Figure 1 Schematic drawing of experimental setup: (1) air blower, (2) air distribution line, (3) downdraft gasifier, (4) gas flare points, (5) raw gas sampling point, (6) cyclone for gas cleaning, (7) cooling heat exchanger, (8) oil bath filter, (9) clean gas sampling point

2.2. Experimental Procedure

The experimental procedure consists of collecting and recording temperature readings along the gasifier bed using six type-N thermocouples. Two more readings were recorded using Type-K thermocouples at the outlet pipe and after the cooler and filter unit. All these temperature readings were collected using USB based temperature data logger every minute and stored in computer. The accuracy of both the Type-K and Type-N thermocouples used was 1.5^{o}C. In addition the amount of OPF feed in to the gasifier was measured using a weigh scale, while the air inlet flowrate in the reactor is measured using a Static Pitot Tube arrangement. Calibration work carried out for determining the accuracy of the Pitot tube showed the pitot tube slightly underestimate the measured flowrate with an average error margin of 6.82%. In the future an online gas analyzer unit will also be used to analyze the syngas at the outlet pipe and record the composition reading every few minutes working connected to a computer set.

3. RESULTS AND DISCUSSION

A number of gasification run of OPF feedstock of varying moisture content values were carried out. The optimum operation of the gasification process is qualitatively controlled by flaring the syngas at the three flare points provided. Flare is obtained for more than 50 minutes of the total 74 minute operation for measured average inlet air flow rate of 486 liters per minute (lpm). A stable flare of bluish color is observed after the cleaning units (cyclone, and oil bath filter) and cooling unit (heat exchanger).

3.1. Dynamic Temperature Profile

After initial combustion is started and the fuel bed kept burning inside the gasifier, by starting the air supply blower, the oxidation zone temperature is increased from 500^{o}C to above 800^{o}C, in a period of 10 minutes. A total of 74 minutes of operation has been carried out. For the following 30 minutes of operation after startup a stable oxidation zone temperature of average value 879^{o}C was attained. During this time a maximum oxidation zone temperature of 952^{o}C was recorded at the 20th minute of operation. In addition average reduction zone temperature of 617^{o}C was recorded.

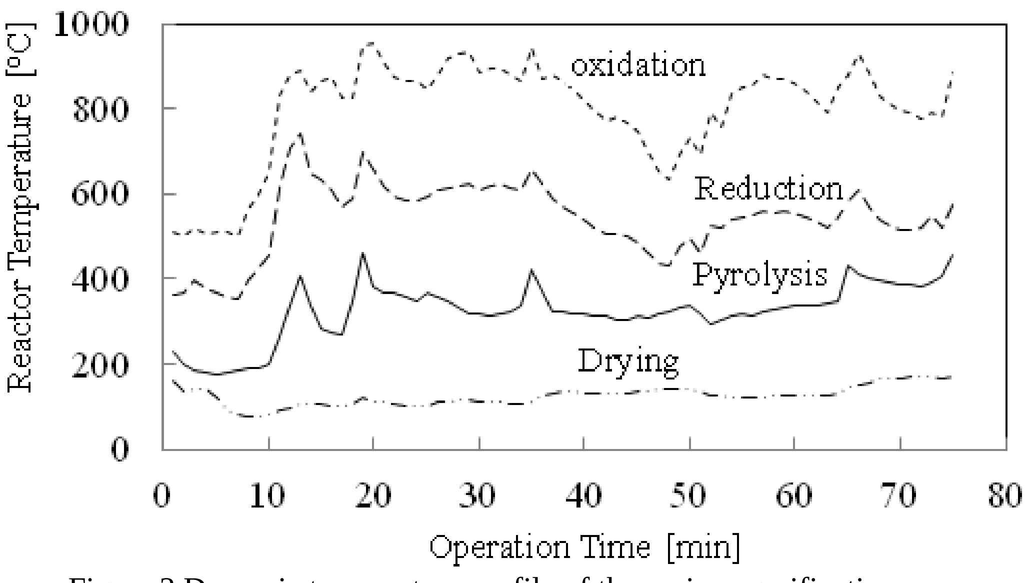

Figure 2 Dynamic temperature profile of the various gasification zones

As shown in Figure 2 the oxidation zone temperature was found to be lower (in the range of 500^{o}C) at start up and it increased to a value above 800^{o}C in about 15 minutes as the combustion process advance. After the first 15 minutes of operation a relatively stable temperature profile is obtained as the reactions advance. In addition it is observed that the oxidation zone temperature keeps on decreasing for about 15 minutes in the middle of the operation. This could be because of the endothermic nature of the overall gasification process. The reduction zone temperature also showed a similar pattern while the pyrolysis and drying zone temperatures remain relatively stable. The average temperature values of the drying, pyrolysis, reduction and oxidation zone recorded over the total operation time were 125°C, 324°C, 543°C, and 796°C respectively, which are found to be in agreement with the range of zone temperature values reported in literature (Borisov et al., 1998; Zainal et al., 2002). The peak temperature values observed in the dynamic temperature profile, could possibly be caused by the sensitivity of the measuring thermocouples, as well as the direct exposure of the thermocouple surface to the glowing char at high temperature, as the fuel goes down to the grate.

The dynamic temperature profile with operating time for the gasification of OPF is found to be in close agreement, with the work of Borisov et al. (1998) shown in Figure 3. In the work of Borisov et al. (1998) the dynamic temperature profile is obtained for downdraft gasification of furniture wood. The results are not directly comparable as the size and dimension of the gasifiers as well as the type of biomass used were different. However, fairly close results are obtained for the range of values of temperatures for each zone of gasification. For both cases the oxidation zone temperature is found to vary between 800°C and 1000°C for most of the run (as shown in Figures 2 and 3), which is favorable for gasification. The pyrolysis zone temperature for gasification of OPF is found to be slightly lower compared to that reported in the literature. Therefore, in future experiments proper regulation of the inlet air flow rate and avoiding the problem of bridging need to be done to obtain improved reactor temperature profile, and to avoid the unsteady variation of the dynamic temperature with operation time. The effect of bridging is also observed to contribute to the decrease of the oxidation zone temperature in the middle of the operation, which is mitigated by shaking the fuel bed during the experiment. In addition, the average oxidation and pyrolysis zone temperature values of 796°C and 324°C respectively are comparable to results reported in literature (Borisov et al., 1998; Zainal et al., 2002).

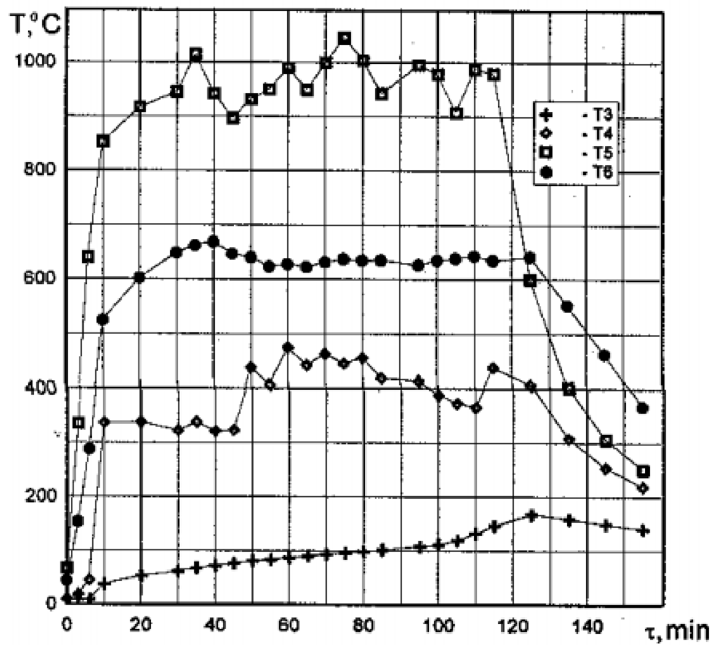

Figure 3 Dynamic temperature profile for downdraft gasification of wood (Borisov et al., 1998): T3 – drying zone, T4 – pyrolysis zone, T5 – Combustion zone, T6 – Reduction zone

3.2. Temperature profile along gasifier bed

Shown in Figure 4 is a typical average temperature profile along the gasifier bed for a selected period of 10 minutes of operation. In this figure, the peak temperature value at bed height of 300 mm from the bottom is the oxidation zone temperature and the reduction; pyrolysis and drying zone temperature are measured at 200 mm, 500 mm and 800 mm height above the grate respectively. The top part of the gasifier bed above bed height of 600 mm from the grate showed temperature values lower than 300°C, indicating that the feedstock in this region is undergoing drying. The fuel near bed height of 500 mm began to thermally decompose and pyrolyzed as the temperature rises to 400°C. The temperature profile of the gasification process showed satisfactory results compared to literature (Borisov et al., 1998; Dogru et al., 2002a; Hanping et al., 2008; Zainal et al., 2002). In addition Figure 5 shows the variation of the temperature profile along the gasifier bed at different operation time. The variation of the temperature profile at different operation times is suggested to be partly created by the endothermicity of the gasification reaction and partly due to occurrence of bridging.

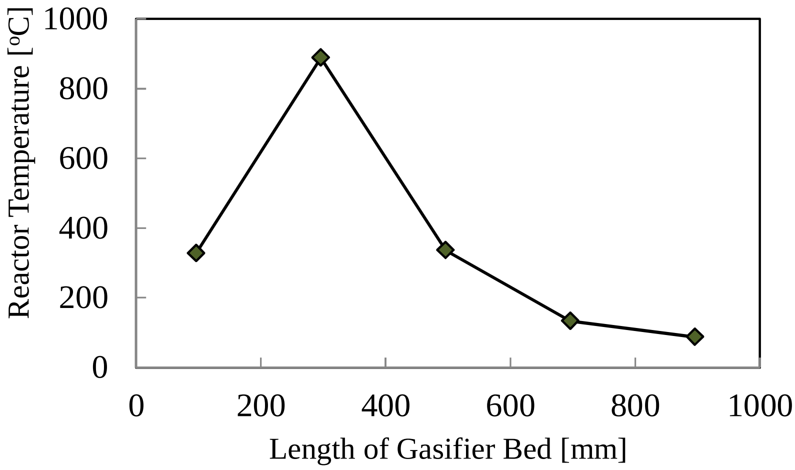

Figure 4 Typical temperature profile along gasifier bed

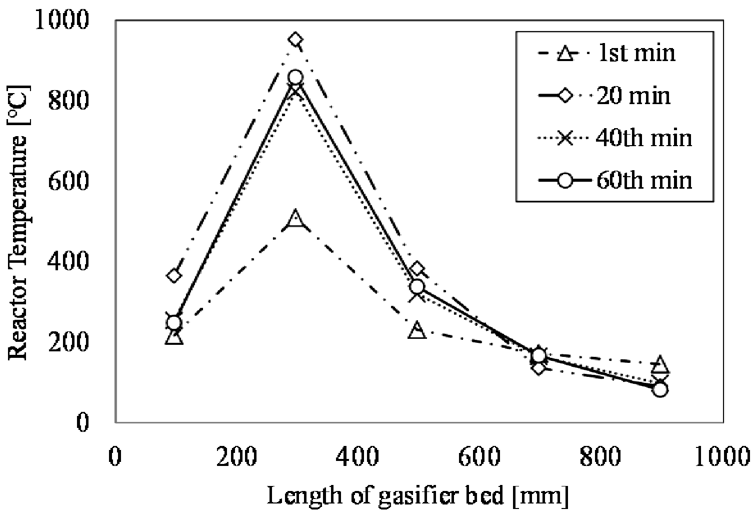

Figure 5 Variation of temperature profile along gasifier bed, at different operation time

3.3. Effect of moisture content of OPF on temperature profile

The effect of initial moisture content of feedstock on the temperature profile has been studied by using OPF feedstock with initial moisture content of 15%, 20% and 30% in the experiment. Shown in Figure 6 is the variation of temperature profile along the gasifier bed for the different initial moisture content values of feedstock. The results showed that the temperature profile for moisture content of feedstock of 20% and 30% is lower than the acceptable range for gasification operation as the peak oxidation zone temperature was found to be below 700^{o}C. Also the reduction, pyrolysis and drying zone temperatures were found to be much lower compared to that of 15% MC, as shown in Figure 6. Moreover, no flare was obtained during the gasification of 30% and 20% initial moisture content feed at the flaring points of syngas outlet pipe. The gasification of 15% MC of OPF however produced a stable flare for more than 50 minutes out of 74 minutes total operation time. This shows that the MC of the feed need to be kept in the range of 15% (or below) for better gasifier operation.

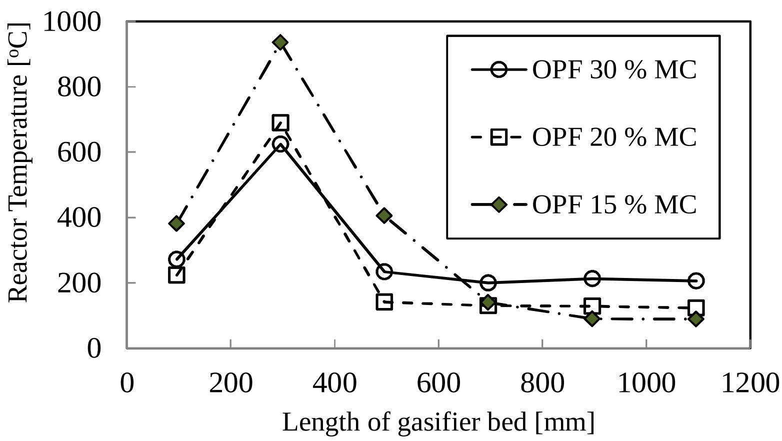

Figure 6 Variation of reactor temperature along the gasifier bed for different initial moisture content of OPF

4. OPERATION PROBLEMS

The primary operational problem encountered in previous gasification experiments was bridging. In the current experiment the size of the feed is reduced to average size of 1” (25 mm) to reduce the occurrence of bridging, yet some bridging was rarely observed. The bridging is typically caused by the non-uniform flow of the fuel bed down towards the gasifier bed. Shaking of the fuel bed is carried out whenever such bridging is observed by opening the top cover of the gasifier. Sometimes decreasing the inlet air flow rate is required to avoid fire hazard while opening the gasifier top cover, which affected the temperature profile for the few minutes of operation when shaking of the grate is done. In future designs it is recommended to incorporate a shakeable grate to easily facilitate the smooth and uniform flow of the fuel bed. The incorporation of a shakeable grate also helps in easing the flow of ash to the ash box at the bottom.

5. CONCLUSION

Initial physical and chemical property test and study of chemical composition of OPF feedstock in terms of cellulose, hemicelluloses, and lignin showed that OPF has a high potential as a gasification energy resource. From the experimental investigation of temperature profile of downdraft gasification of OPF, it is shown that temperature profile was in close agreement with the ones recorded in the literature. A stable flare of blue colour has been obtained for more than 60% of the total operation time. The presence of a blue flare indicated that a high quality syngas containing hydrogen and methane composition was produced from the gasification process. In addition a study of the effect of initial moisture content of OPF feedstock on the temperature distribution profile along the gasifier bed showed that initial moisture content of feedstock higher than 15% resulted in a much lower temperature profile than the acceptable level.

Moreover, the fact that there was no flare obtained during the gasification of 20% and 30% moisture content OPF demonstrated that the MC of the feed needs to be kept below or in the range of 15%. In the future, detailed experimental investigation of downdraft gasification of OPF need to be carried out to study the effects of various operating conditions: AFR, moisture content, oxidation and reduction zone temperature and feedstock particle size on the composition, cleanliness and calorific value of syngas produced.

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