Properties Evaluation and Computational Analysis of Gasifier Chamber Unit Using Agricultural Waste

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ABSTRACT

Malaysia is projected to produce 16.8 billion tonnes of biomass annually, thereby leading to the accumulationof agricultural waste in great abundance Thus, the country is indeed facing a big challenge related to handling and disposing of these wastes. As the world is moving towards a greener earth, the act of dumping the waste in landfills or resorting it to open burning seems irresponsible and looks as if the nation is left with no sustainable choice or option to overcome the problem. Nevertheless, the nation must be proactive and need to respond positively to avoid or minimize the predicament. The process of gasification could help to address the matter, for instance, taking the palm kernel shell as feedstock, turning it into synthesis gas (syngas). This is one of the alternative solutions that could be used as an alternative fuel that will benefit the nation. The objective of this study is to establish the fuel properties of the syngas database using a proximate analysis method and also to determine the fluid flow in a gasifier chamber unit of the gasification system via a computational approach (numerical simulation).Computational fluid dynamic (CFD) simulation was carried out using the ANSYS Fluent software, taking into account different swirler angles(30º, 40º and 50º) to observe the effect of using the swirler in the chamber unit. Five agricultural wastes were utilized as samples, namely, the palm kernel shell (PKS), ground coconut shell (GCS), torrefied rubber seed (TRS), empty fruit bunch (EFB) and wood chips (WC), each of which obtained a specific high heating value (HHV) as a fuel propertyof 18.53, 18.00, 17.94, 18.37 and 17.39 MJ/kg, respectively. From the computational analysis, the CFD simulation is capable to determine the flow characteristics in the gasifier chamber unit. A swirler angle of 40° appearedas ideal to beimplemented inthe gasifier chamber unit sinceit produced better results in terms of the gasification residuals and static temperature distribution.

1.0   INTRODUCTION

Malaysia is blessed with an abundance of natural resources which could produce approximately 16.8 billion tons of biomass annually. As reported by Palm Oil Refiners Association of Malaysia, Malaysia comes second after Indonesia in contributing to palm oil production in Southeast Asia at 36.7% [1].

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However, the profusion of biomass from the forestry and agricultural sector has in turn created a profusion of processing residues or wastes that have no economic value unless they are put to energy generation use. Department of Environment in Malaysia has discouraged the open burning of biomass wastes which consequently leads to a major disposal problem [2].

Nonetheless, biomass can be beneficial with an extra edge of advantage over other resources in the context of renewable energy. This is due to its availability and mass resources with easy storage. A recent paper has shown a significant total deployment status of 17% in comparison to other technologies [3]. This means that studies of renewable energy have been positively increased in addition to a statistic revealing around 100 relevant documents have been published in Malaysia as the largest abstract and citation database of peer-reviewed literature.

Biomass is the plant material derived from the reaction between CO_2 in the air, water and sunlight through photosynthesis, to produce carbohydrates that form the building blocks of biomass. The biomass resource can be considered as an organic matter, in which the energy of sunlight is stored in chemical bonds. Some examples of biomass are energy crops, virgin wood, agricultural residues, food waste and industrial waste. To produce the syngas, the experimental test rig called gasifier unit is deemed necessary. In general, the whole unit is called gasification system.

Specifically, the gasification is a conversion technology that converts any carbon-containing material, coal for example, into synthesis gas[4]. Gasification is a conversion process from a solid/liquid organic compound into a gas or vapour phase and solid phase, also known as the gas phase, syngas[5]. Carbon reacts with water in the form of steam and oxygen at a relatively high pressure greater than 3000kPa and common temperature 1100ºC to produce the raw syngas, a mixture composed mainly of carbon monoxide and hydrogen. There is also a possibility that it might produce the syngas consisting of ash, char and carbon which would undergo the clean-up process to produce syngas capable of generating electricity or steam [4]. Table 1 shows the main chemical reactions in biomass gasification.

Table 1: Main chemical reactions in biomass gasification [6]

Type of reaction	Reaction number	Equation	ΔH_{298} kJ/mol
Pyrolysis	2.1	Biomass $\rightarrow$ Char (C) + CO + CO_2 + H_2O + H_2 + tar + light hydrocarbons	<0
Gas-solid reactions	2.2	Char (C) + $1/2O_2$ $\leftrightarrow$ CO	-111
	2.3	Char (C) + O_2 $\leftrightarrow$ CO_2	-394
	2.4	Char (C) + CO_2 $\leftrightarrow$ 2CO	+172
	2.5	Char (C) + H_2O $\leftrightarrow$ CO + H_2	+131
	2.6	Char (C) + $2H_2$ $\leftrightarrow$ CH_4	-42
Gas phase reactions	2.7	CO + H_2O $\leftrightarrow$ CO_2 + H_2	-41
	2.8	CO_4 + H_2O $\leftrightarrow$ CO + $3H_2$	+296
Comprehensive formula	2.9	Biomass + O_2 $\rightarrow$ CO + CO_2 + H_2O + H_2 + CH_4 + hydrocarbons + HCN + NH_3 + HCl + H_2S + other sulphur gases + tar + char + soot + ash	>0

The main parts of the gasification system to resolve and produce the syngas based on the fixed-bed reactor are the updraft and downdraft reactors. In the former, the solid moves downwards with the respect to the gasification agent and the syngas produced moves upward in counter-current, while in the latter, both the solid and gas move downward in co-current flow [7]. Consequently, this reactor design is important to be explored and studied.

Therefore, the objective of this study is to establish the data properties of different feedstocks by using proximate analysis. Besides, the application of numerical simulation

in a gasifier chamber unit to observe the flow inside the gasifier chamber unit was also carried-out. Thus, the flow characteristics via simulation in the gasification system can be investigated and analyzed. In this study, the proximate data was analyzed based on five feedstocks samples, namely, the palm kernel shell (PKS), ground coconut shell (GCS), torrefied rubber seed (TRS), empty fruit bunch (EFB) and wood chips (WC). Fixed bed gasifier was used in the simulation study consideringan inlet velocity of 9 m/s. Lastly, the flow was simulated using three different swirler angles of 30°, 40° and 50°. The expected outcomes of this study are to address the fundamental issue of the efficiency and performance through numerical simulation of the biofuel production when combusted in any chamber setup and propose a constructive approach. The biomass characterization through proximate analysis and flow character were examined by observing the residuals, solid particle distribution and static temperature distribution.

2.0   METHODOLOGY

The methodology used in this study involves proximate analysis and computational fluid analysis. To perform the proximate analysis, the experimental setup needs to be appropriately configured for a characterization procedure, the purpose of which is to determine the feedstock properties.

2.1   Experimental Method for Characterization of the Biomass
Three standardized procedures were executed out for the proximate analysis related to moisture content, volatile matter and ash content analyses. Five biomass samples (PKS, GCS, TRS, EFB and WC) were first crushed into smaller bits or fine powders if possible.

Figure 1 shows the standardized procedure to make sure the sample wasadequately refined. Each data was recorded after every heating. Figure 2 shows the test rig setup for the whole unit of gasifier including the chamber unit, nozzle, turbine and compressor.
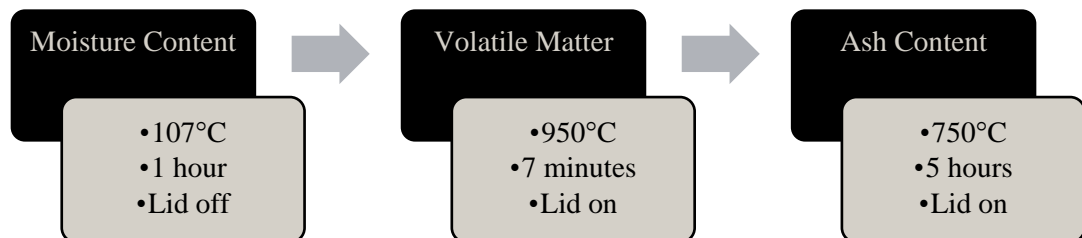
Moisture Content		Volatile Matter		Ash Content
•107°C •1 hour •Lid off	→	•950°C •7 minutes •Lid on	→	•750°C •5 hours •Lid on

Figure 1: Standardized procedure for the proximate analysis procedure

Figure 2: Fixed bed gasifier

2.2   Computational Modeling of the Gasifier Chamber

To determine the flow inside the gasifier chamber unit,a computational fluid analysis was carried out. Starting with the CAD modeling for the gasifier chamber unit, the mesh generation was doneonce the modeling was completed. The computational modeling of the chamber was executed according to the real model in the Combustion Laboratory as shown in Figure 3.
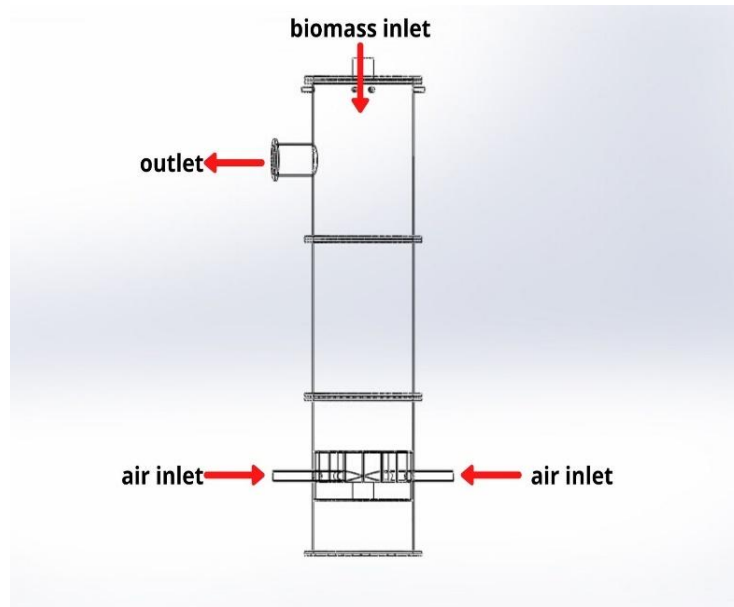

Figure 3: Cross-section of the chamber unit reactor

In addition, the dimensional drawing related to the assembled parts, plan view and front view of the reactor is shown in Figure 4. In this study, the effect of varying the swirler angles to the flow inside the gasifier chamber unit was studied. The angles of the swirler in the reactor were set to 30º, 40º and 50º as shown in Figure 5.
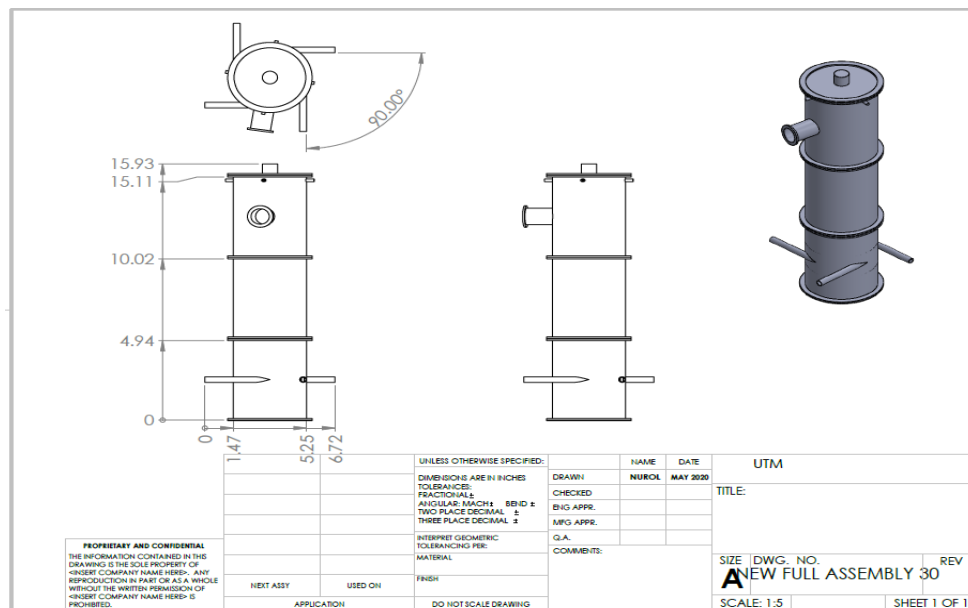

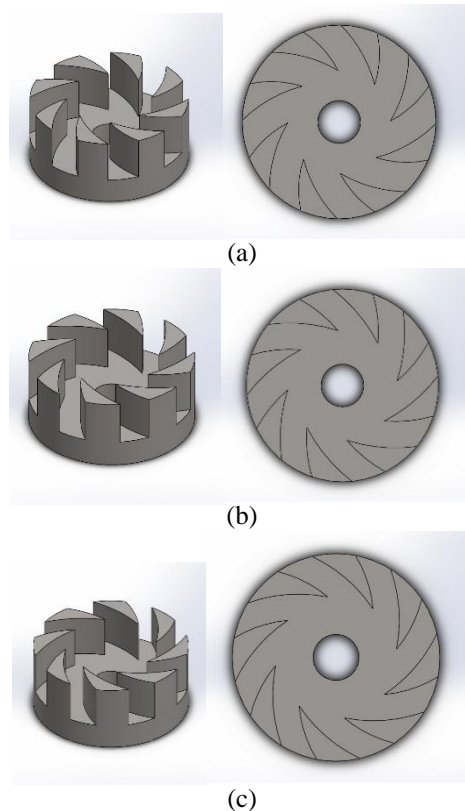**Figure 4**: Assembly drawing for the reactor

(a)

(b)

(c)
Figure 5: Swirler plate with angles (a) 30º (b) 40º (c) 50º

Table 2 shows the swirlersareconfigured differentlyfor the width(*h*) with the outer and inner diameters(*D* and *d*, respectively) of the swirler and blade depth (*L*) are kept the same. This swirler was assembled into a full chassis in the gasifier reactor for the simulation used. The working principle of the gasification unit is such that the air goes from bottom area to the combustion area from its 90º inlet section and up to the outlet, thereafter producing a 'cyclone' effect. Biomass was filled through the inlet section, letting it to sit above the grater during combustion as shown in Figure 3. The swirler plate angle was purposely designed to reduce the temperature consistently.

Table 2: Swirler information

Parameter	Swirler angle (º)		
	30	40	50
Wide *h*, (mm)	13.6	12.3	11.2
Outer diameter *D*, (mm)		98	
Inner diameter *d*, (mm)		50	
Blade depth *L*, (mm)		25	

The solid geometry was imported into *AnsysFluent* to generate the meshing. The quality of the meshing depends on the type, size, location and density of the grid. Table 3 shows the mesh value used in this study to perform the convergence status for the meshing process. The elements are obtained as 309506. The simulation was performed under the assumptions and boundary conditions as shown in Table 4. In this study, it is essential to key in the temperature parameter at different zones with its own specific temperature. The air flows in at high temperature of 1473 K and later cooled down to an approximate temperature of 573 K moving to the outlet. The air velocity in this study was set at 9 m/s. Table 5 shows the input parameters for the simulation related to the model setting, boundary condition and solvers setting. For the models setting, the *k*-epsilon for

turbulence model with intensity of10% was used. For boundary conditions, seven boundaries were considered while for solvers among the five variable conditions, only pressure was assigned as the simple scheme while other variables were regarded as a second order upwind.

Table 3: Mesh statistics

Domain	Number of nodes	Number of elements
Reactor	101333	309506

Table 4: Boundary conditions set-up

Inlet-air temperature	1473 K
Outlet temperature	573 K
Magnitude of velocity	9 m/s

Table 5: Parameter inputs for the simulation

	Model	Settings	Information
Model settings	Space	3D	-
	Time	Steady	-
	Viscous	Standard *k*-epsilon turbulence model	Turbulence intensity is 10%
	Wall treatment	Standard wall functions	-
	Heat transfer	Enabled	-
	Species transport	Reacting	Wood-vol-air
	Discrete phase	Surface injection	Inlet-biomass
	Name	**Type**	**Information**
Boundary conditions	Fluid	Fluid	Air
	Inlet-air	Inlet-velocity	9 m/s
	Inlet-biomass	Inlet-velocity	9 m/s
	Drying	Wall (mixed)	Convection and radiation
	Pyrolysis	Wall (mixed)	Convection and radiation
	Oxidation	Wall (mixed)	Convection and radiation
	Reduction	Wall (mixed)	Convection and radiation
	Variable	**Discretisation scheme**	**Information**
Solvers	Pressure	Simple	-
	Momentum	Second order upwind	-
	Turbulent kinetic energy	Second order upwind	-
	Turbulent dissipation rate	Second order upwind	-
	Energy	Second order upwind	-

Figure 6 shows the meshing of the chamber unit in which the combination of the mesh type has been used for the chamber unit modeling. Hexahedral meshing was used in the middle part of the reactor as it was deemed economical for the system. On the top and bottom parts of the reactor, the tetrahedral meshing was used to increase the meshing quality of the valve attachment.
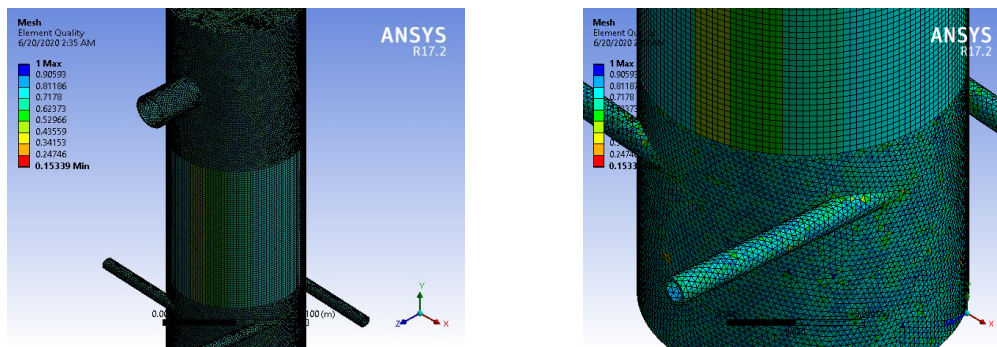
Figure 6: Meshing of the chamber unit

3.0   RESULTS AND DISCUSSION

3.1   Proximate Analysis

The experimental data of proximate analysis is tabulated and presented in Table 6. The ash content for TRS is shown to be significantly different (way off) from the other samples. This might be due to 'mishandling'of the sample duringthe experimental testing. Nevertheless, for the simulation study, the relevant results from previous studies can be used for the simulation [8-9]. Typically, the ash content would end up at less than 10% of the mass fraction.

Table 6: Results of the proximate analysis

Proximate analysis (wt%)	PKS	GCS	TRS	EFB	WC
Moisture content	10.97	10.51	6.60	8.16	9.69
Volatile matter	58.39	68.28	52.65	64.39	68.23
Ash content	8.12	1.39	21.25	5.77	2.85
Fixed carbon	22.52	19.82	19.51	21.69	19.23
HHV,MJ/kg (dry basis)	18.5329	18.0037	17.943	18.3702	17.8881

3.2   CFD Analysis

Observation made on the particle path lines enables the visualization of the trajectories tracked by the individual fluid particles. The path lines also act as a 'recorder' for the fluid element path in the flow over a certain period of time. At any time, the direction of eachtakenpath will be determined by the fluid streamlines. Figure 7 shows the different swirler angles that cause the particle distributions to differ from one another. These results can be related to the Discrete Phase Models (DPM) in *Ansys Fluent*. This phase determines how the particles are being transported from the inlet to the outlet valves. Better particles distributions will in turn ensure better combustion to take place. The biomass feedstock wasset to have a 'reflect' boundary condition type. According to Sukumaran (2015), the particle bounces the boundary off in lieu of a shift in momentum, as defined by the restitution coefficient [11]. Moreover, through proper utilization of the DPM simulation of the particles combustion, we are able to know the volatile development and char combustion to simulate the combustion of coal.

Figures 7(a) and (c) present the particle path lines for the reactor with swirlers 30° and 50°, respectively show a rather similar path line pattern. However, swirler 50° has a circular motion of particles and the movement of the solid particles during combustion is dragged upward with the air flow because it has more slope than at the other swirler angles [10]. However, the reactor with swirler 40° as presented in Figure 7(b) shows a

relatively similartrending with the simulation result by demonstrating an immediate temperature drop once it gets to the grate condition as similarly observed in [11].
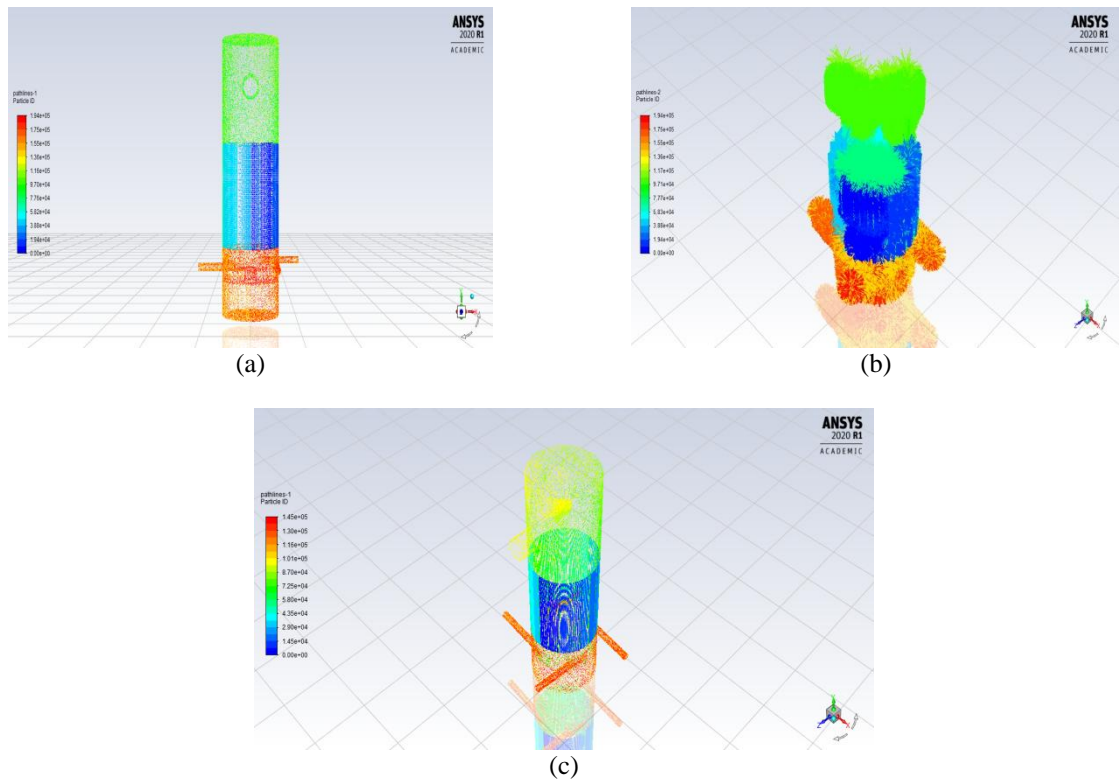

(a)

(b)

(c)

Figure 7: Solid particle path lines at specific swirler angles: (a) 30° (b) 40° (c) 50°

Figure 8 shows the temperature distribution across the chamber unit reactor. Feeds were introduced from the top and air inlet went through from the bottom and passed through the grate. The lowest portion of the reactor is basically the combustion zone where devolatilisation of the biomass was combusted [11]. This activity helps the heating process by increasing the temperature from 800°C to 1200°C (1473 K in *Ansys Fluent*). The upper part of the gasifier is where the hot gas pyrolysis the biomass eventually drying it. The hot gases flowing through the bed was immediately cooled down above the combustion zone. The temperature of cooled gas was typically increasedfrom 200°C to 300°C (573 K in *Ansys Fluent*). As shown in Figure 8(a) using swirlers 30° and 40°, the bottom area of the chamber has a static temperature of around 573 K but when using swirler 50°, the bottom area of the chamber has lower temperature. Thus, in this case, it shows that the swirler angle gives significant effect in reducing the static temperature during combustion. This condition is however, not good for the combustion process. From this study, the ideal swirler to be used is the one with 40° angle because it speedily reduces the hot static temperature at the bottom area (outlet) of the chamber unit.
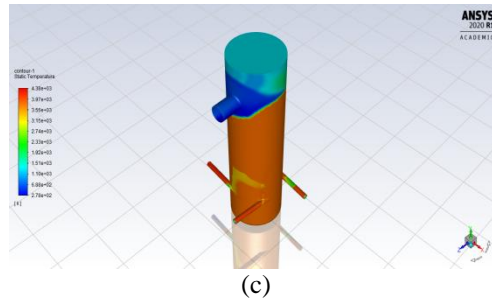

(a)

(b)

(c)
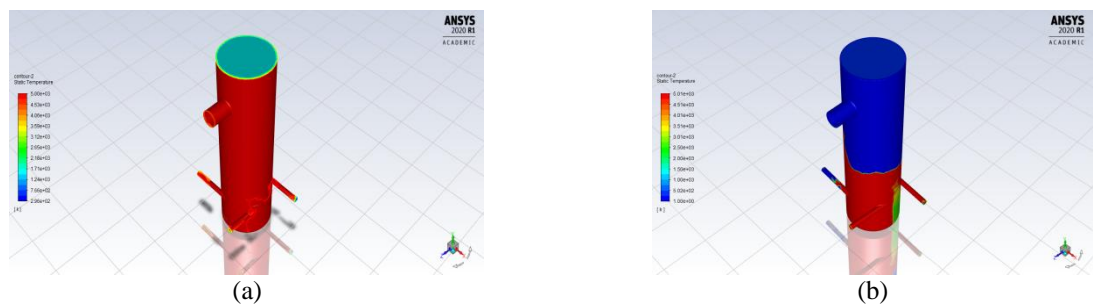
Figure 8: Static temperature distribution at specific swirler angles: (a) 30° (b) 40° (c) 50°

4.0 CONCLUSION

The experimental tests performed in this study enabledthe proximate analysis to be carried out. All the five biomass samples, namely, thePKS, GCS, TRS, EFB and WC, eachgained an acceptable high heating value (HHV) results at 18.53, 18.00, 17.94, 18.37 and 17.39 MJ/kg, respectively. Nevertheless, the data for the TRS showed the 21.25% ash contentwas slightly way off compared to the rest; typically, it should be less than 10%. The proximate analysis has successfully established the feedstock fuel propertyrelated to the HHV that is deemed important to determine the capability of the feedstock to be used in the gasifier system.A fundamental analysis via CFD on three different swirler angles of 30°,40° and 50° has been done to observe the fluid flow inside the gasifier chamber unit. The simulation results for different swirler angles have helped to understand the flow effect in the gasifier chamber unit. This can be seen through the results obtained for the solid particles path lines and the static temperature distribution across the chamber unit. The particle path line seemed to be producing the correct motion using swirler 50°. Lastly, the chamber unit with swirler 40° has the most accurate static temperature distribution where the air is found to be immediately cooled to 573K after the combustion zone. In conclusion, the reactor with swirler 40° emerged as the ideal swirler for gasification as it adequately satisfies the particle path line flow and static temperature distribution.

ACKNOWLEDGMENTS

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