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CFD Analysis of the Fast Pyrolysis for Empty Fruit Bunches in Fluidized-Bed Reactor

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Abstract: CFD is the essential tool to investigate the complex chemical and physical processes in a fluidized-bed reactor for biomass fast pyrolysis. In this study, has been conducted a CFD simulation of fast pyrolysis process for Empty Fruit Bunches (EFB) in fluidized-bed reactor. EFB particles were injected into the reactor with mass flow rate 500 g h^{-1} at 30°C temperature. The Eularian-Eularian Model was applied for the multiphase model and for the momentum transfer between solid and fluid was used the Syamlal and O'Brien drag model. The mathematical equation which represent the transport phenomena were implemented in CFD software Ansys Fluent 14. This study predicted the yield products (char, bio-oil, non-condensable gas) of fast pyrolysis process for EFB where the prediction of simulation compared with the experimental result and obtained a good agreement.

Key words: CFD, empty fruit bunches, fast pyrolysis, bio-oil, non condensable gas

INTRODUCTION

Potentially of biomass, as renewable energy sources is becoming more important due the decreasing of fossil fuel and its effect on global warming. One of biomass that can be developed as an alternative energy is Empty Fruit Bunches Waste (EFB). EFB is produced in large amounts by the palm oil industry, as in the processing of 1 ton of fresh fruit bunches of palm oil will produce approximately 23% EFB or 230 kg EFB (Umikalsom *et al*., 1997). Therefore, this biomass has great prospects for development as an alternative energy. One of method for processing biomass into renewable energy is pyrolysis process. Pyrolysis is one of thermo chemical conversion process where the solid fuel is being converted into gas and liquid fuel in pyrolysis reactor, such as fluidized-bed reactor. The primary products of biomass particles pyrolysis process are usually referred to as condensable (tars) and non-condensable volatiles and char.

Particularly, the fast pyrolysis process in fluidized-bed reactor has attached many researchers (Boateng *et al*., 2007; Stammbach *et al*., 1989; Bridgwater, 2003), as they offered advantage in heat and mass transfer. The hydrodynamics of fluidized-beds have been studied both experimentally and numerically. Recently most of computational research has been focused on the simulation of the fluidized-bed flow-dynamics, using Eulerian-Eulerian (Pain *et al*., 2002) or the Lagrangian (Kafui *et al*., 2002) formulations of the flow field. Due to the significant increase in computing power in recent years these models have now made computational modelling of multiphase granular flows possible, though it is still very challenging (Boateng and Mtui, 2012).

Computational Fluid Dynamics (CFD) is one of the software for fluid dynamics applications. With the advances in numerical methods and hardware technologies it's possible to use CFD to simulate the fast pyrolysis process in order to obtain the optimize design of reactor for fast pyrolysis process. CFD simulation of fast pyrolysis in fluidized-bed reactor may not give a very accurate prediction of its performance but it can at least provide qualitative guidance on the effect of design and operating or feedstock parameters (Basu, 2010).

This study has been conducted CFD simulation of fast pyrolysis process for Empty Fruit Bunches (EFB) in fluidized-bed reactor. EFB particles were injected into the reactor with mass flow rate 500 g h^{-1} at 30°C temperature. The mathematical equation that represent the transport phenomena are implemented in CFD Software Ansys Fluent 14. This study predicted the yield products (char, bio-oil, non-condensable gas) of fast pyrolysis process for EFB.

MATERIALS AND METHODS

Process description: The 500 g h^{-1} fast pyrolysis lab scale reactor modeled is illustrated in Fig. 1. The reactor design specifications and operating conditions are describes in Table 1. Fluidizing gas is Nitrogen (N_2) that

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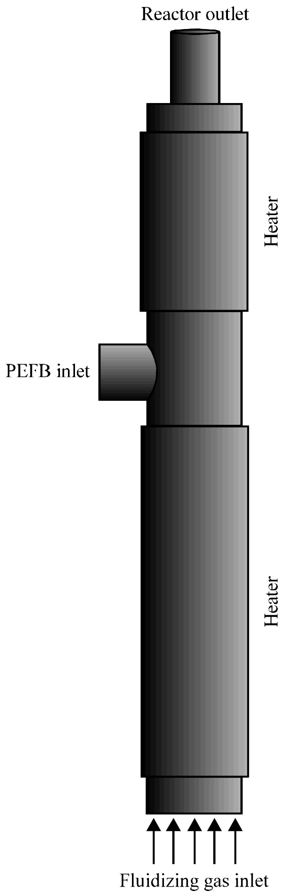

Fig. 1: Fast pyrolysis lab scale reactors model

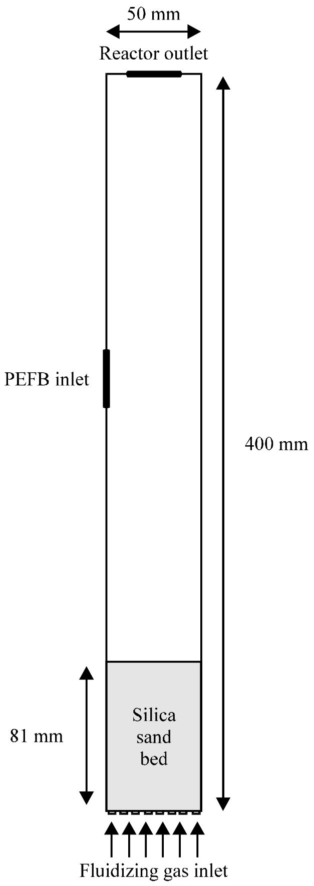

Fig. 2: Computational domain

Table 1: Design criteria of fluidized bed reactor for fast pyrolysis

Objects	Parameters	Units
Reactor	Height (mm)	400
	Diameter (cm)	50
	Wall material thickness (mm)	3
	Wall temperature (°C)	450
	Insulation thickness (mm)	15
Feed geometry	Diameter (mm)	31.75
	Height from top (mm)	150
PEFB	Feed flow rate (kg h^{-1})	0.5
	Feed material density (kg m^{-3})	3140
	Feed particles size (mm)	7e-2
	Feed material temperature (°C)	30
Heater	Numbers of heaters	2
	Heater capacity (Watt)	1500
	Heater wall temperature (°C)	500
Silica sands	Sand density (kg m^{-3})	1258
	Sand particle size (microns)	180
	Static height of sand (mm)	81
	Specific heat (kJ/kg-K)	830
Fluidization	Medium	Nitrogen
	Fluidization velocity (m sec^{-1})	0.21
	Nitrogen temperature (°C)	500

flows through a perforated plate from the bottom of the reactor which is preheated in its flow line by the electric heater. At the same time, the reactor bed was initially filled with silica sand to a depth of 81 mm and expands during fluidization. EFB as solid fuel were injected to the reactor using screw conveyor at 250 mm height from the bottom of reactor.

CFD Model: Figure 2 showed the computational domain used in the present computational study which was initially descritized for iterative solution. Initial conditions determined for the static bed of silica sand, mass fraction of the gas and solid species (EFB) inside the reactor. EFB as feedstock was analyzed by proximate and ultimate to find out the its species where the datas are presented in Table 2 (Lahijani and Zainal, 2011). Inflow boundary for fludizing gas (N_2) is specified by the velocity boundary, however for the EFB inflow boundary is specified by the mass flow rate and the reactor outlet was modeled as pressure outlet boundary. Heat transfer to the wall was set as temperature from heating element to keep the walls at given temperature (Table 2). The Eularian-Eularian Model was applied for the multiphase model and for the momentum transfer between solid and fluid was used the Syamlal and O'Brien drag model (Syamlal and O'Brien, 1988).

Eulerian approach was used in this study for the conservation of mass and momentum of multiphase flow in fluidized-bed. Eulerian multiphase system consist of secondary phase in continuous fluid phase (primary phase) which allows for mixing and separation of phase, as well as heat and mass transfer between the phase. Boateng and Muti (2012) described the equations of Eulerian multiphase conservation laws considers that discrete secondary phase (solid) and continuum primary phase (fluid) are similar and illustrated for the primary phase. This partial differential equations were solved iteratively in time increments set by Ansys Fluent 14. The time step for the computationwas automatically adjusted for numerical stability and convergence.

Pyrolysis kinetics: For pyrolysis kinetics model in this study adopted from (Boateng and Muti, 2012) which products were assumed to be three phase, i.e., solid (bio char), liquid (condensable pyrolysis vapors) and Non-Condensable Gas (NCG). The product gases and nitrogen were discharged through reactor outlet located at the top of the reactor. The weight loss can be accounted for by the overall pyrolysis products, i.e.,:

$$\begin{aligned}\text{Biomass} \rightarrow \alpha_1\text{Char}+\alpha_2\text{BioOil}+\alpha_3\text{H}_2\text{O}+\\ \alpha_4\text{H}_2+\alpha_5\text{CO}+\alpha_6\text{CO}_2+\alpha_7\text{CH}_4\end{aligned} \tag{1}$$

The rate of biomass dtying and devolatilization can be described by a first order kinetic equation as:

$$R_m = (1\text{-}\varepsilon)A_m\exp\left(\frac{E}{RT_m}\right) \tag{2}$$

They applied the activation energy, E for drying and devolatilization values, repectively as 8.79E+4 and 131.83E+3 and they modified the values to the experimental data for the biomass. The respective modified pre-exponential constants (Choi *et al*., 2001) were 6.56E-1 and 7.24E-1 established to match experiment data of Boateng *et al.* (2007), Mullen *et al.* (2010) and Boateng *et al.* (2010). The coefficients α_i were solved to predict the local composition and distribution of volatiles in the reactor by solving the transport equations in a fluidized-bed using Ansys Fluent 14. They were calculated coefficients α_1 through α_7 in Eq. 1 for switchgrass were, respectively 0.138, 0.805, 0.150, 0.003, 0.035, 0.018 and 0.008. Similar approach was used to determine the parameters for Empty Fruit Bunches (EFB) which became feedstock in this study.

Table 2: PEFB proximate and ultimate analyses data

Variables	Values
Proximate analysis (weight %)	
Moisture	7.80
Volatiles	79.34
Ash	4.50
Fixed carbon	8.36
HHV, MJ/kg (dry basis)	15.22
Ultimate analysis (weight %)	
Carbon	43.52
Hydrogen	5.72
Nitrogen	1.20
Oxygen (diff.)	48.90
Stoichiometric air/fuel ratio (kg kg^{-1})	4.84

RESULTS AND DISCUSSION

Regularly main reactor of pyrolysis sistem followed by several cyclones used for separating the product char form the pyrolyis vapors and some condensers where pyrolysis vapors were condensed and collected. While the CFD modeling was done for the set of components described, the calculation restricted to the pyrolsis reactor only and this allowed for the simulation of the space-time evolution of pyrolysis products within the boundaries of the reactor (Boateng and Muti, 2012).

Figure 3 is the snapshots of the solid-phase volume fraction during preheating process. It shows the distribution of silica sand inside the reactor from initial fluidization until fully expanded within 25 sec. Meanwhile, the prediction of reactor temperature during preheating process from 0 until 25 sec is described in Fig. 4. Temperature distribution inside the reactor begins uniform when the silica sand is fully fluidized.

The injection of biomass (PEFB) starts after the silica sand is fully fluidized and temperature inside the reactor are uniform which at the time 25 sec. The temperature of EFB while injected through the reactor is 30°C. When EFB entered the reactor then it will decompose to the pyrolysis products. As Fig. 5 shows, bio-oil vapor concentration

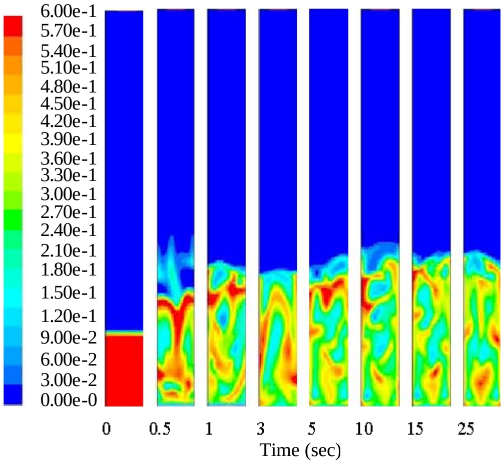

Fig. 3: Contours of solid phase distribution during pre-heating process

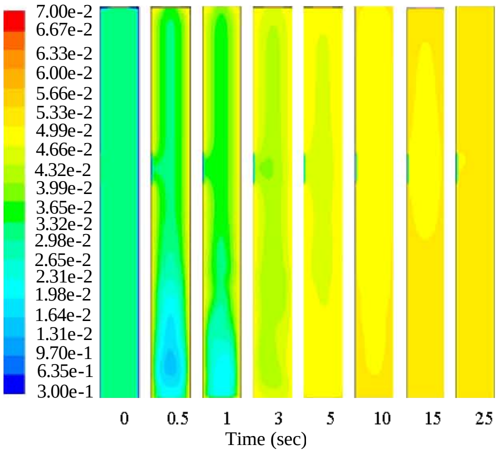

Fig. 4: Contours of reactor temperature during pre-heating process

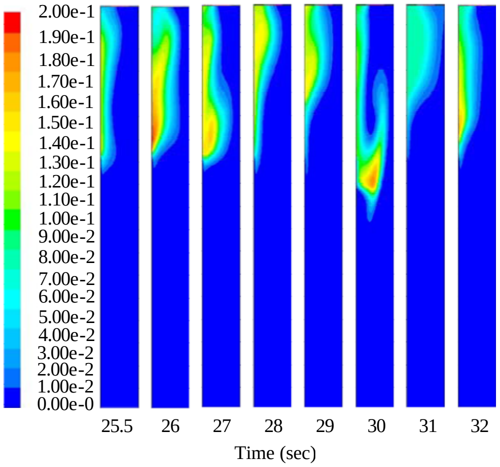

Fig. 5: Contours of bio-oil vapour concentration

appears since the EFB enters the reactor. The yields of char, bio-oil and non condensable gas are obtained from the CFD simulation by integrating across the reactor outlet are presented in Table 3.

To validate the CFD model, the data obtained from simulation was compared with experimental data from Abdullah and Gerhauser (2008). They investigated fast pyrolysis process of Empty Fruit Bunches (EFB) on fluidized-bed bench scale unit with a nominal capacity of 150 and 1000 g h^{-1}. The reactor fills with the inert sand and the fluidising gas is nitrogen with reactor temperature equal to this study at 500°C. They determined the composition and particle size distribution of the washed and unwashed EFB, as well as the effect of ash reduction on yield and the maximum ash level giving a homogenous bio-oil. Their experimental yields compared to the simulation results in this study are shown in Fig. 6.

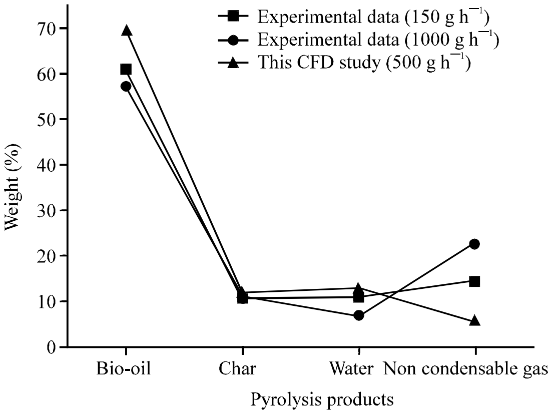

Fig. 6: Yields of EFB fast pyrolysis, experimental compared to the simulation results

Table 3: Fast pyrolysis yields of EFB by CFD study

Pyrolysis yields	Weight (%)
Bio-oil	69.58
Char	11.93
Water	12.96
Non condensable gas	5.53
Non condensable gas composition	
H_2	0.25
CO	3.03
CO_2	1.56
CH_4	0.69

As describes in Fig. 6, the trend between experimental and simulation of fast pyrolysis for EFB obtained a good egreement. The best prediction of simulation refers to the mass fraction of char where the differences with the experimental result is <2%. The differences value of bio-oil mass fraction between experimental and simulation has an over-predict within range of 8-13%. However, simulation predicted less of non condensable mass fraction which has differences of 9-18% with the experimental result.

CONCLUSION

A comprehensive CFD model has been conducted for modeling fast pyrolysis process of Empty Fruit Bunches (EFB) in fluidized-bed reactor with nominal capacity 500 g h^{-1}. Complex fast pyrolysis reactions was investigated by applying the single-step chemical kinetics to the pyrolysis of biomass. The fast pyrolysis process was operated at atmospheric pressure and the reactor temperature was at 500°C. The prediction of simulation compared with experimental results and obtained a good agreement. CFD technique could be applied to optimize the pyrolysis reactor design for determining the important conditions, as well as study the impact of key variables which are required to maximise the pyrolysis product.

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NOMENCLATURE

A_m = Pre-exponential constant for drying
E = Activation energy (J)
R = Universal gas constant (J/mol-K)
R_m = Moisture evaporation rate (kg/m^3/sec)
T_m = Length of test model (m)
α_i = Coefficient in Eq. 1
ε = Porosity

REFERENCES

Abdullah, N. and H. Gerhauser, 2008. Bio-oil derived from empty fruit bunches. Fuel, 87: 2606-2613.

Basu, P., 2010. Biomass Gasification and Pyrolysis: Practical Design and Theory. Academic Press, USA, ISBN: 9780080961620 Pages: 376.

Boateng, A.A., D.E. Daugaard, N.M. Goldberg and K.B. Hicks, 2007. Bench-scale Fluidized-bed pyrolysis of switchgrass for Bio-oil production. Ind. Eng. Chem. Res., 46: 1891-1897.

Boateng, A.A., C.A. Mullen, N.M. Goldberg, K.B. Hicks, T.E. Devine and I.M. Lima, 2010. Sustainable production of bioenergy and biochar from the straw of high-biomass soybean lines via fast pyrolysis. Environ. Prog. Sustainable Energy, 29: 175-183.

Boateng, A.A. and P.L. Mtui, 2012. CFD modeling of space-time evolution of fast pyrolysis products in a bench-scale fluidized-bed reactor. Applied Thermal Eng., 33-34: 1903-198.

Bridgwater, A.V., 2003. Renewable fuels and chemicals by thermal processing of biomass. Chem. Eng. J., 91: 87-102.

Choi, Y.C., X.Y. Li, T.J. Park, J.H. Kim and J.G. Lee, 2001. Numerical study on the coal gasification characteristics in an entrained flow coal gasifier. Fuel, 80: 2193-2201.

Kafui, K.D., C. Thornton and M.J. Adams, 2002. Discrete particle-continuum fluid modelling of gasesolid fluidised beds. Chem. Eng. Sci., 57: 2395-2410.

Lahijani, P. and Z.A. Zainal, 2011. Gasification of palm empty fruit bunch in a bubbling fluidized bed: A performance and agglomeration study. Bioresour. Technol., 102: 2068-2076.

Mullen, C.A., A.A. Boateng, N.M. Goldberg, I.M. Lima, D.A. Laird and K.B. Hicks, 2010. Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. Biomass Bioenergy, 34: 67-74.

Pain, C.C., S. Mansoorzadeh, J.L.M. Gomes and C.R.E. de Oliveira, 2002. A numerical investigation of bubbling gas-solid fluidized bed dynamics in2-D geometries in 2-D geometries, Powder Technol., 128: 56-77.

Stammbach, M.R., B. Kraaz, R. Hagenbucher and W. Richarz, 1989. Pyrolysis of sewage sludge in a fluidized bed. Energy Fuels, 3: 255-259.

Syamlal, M. and T.J. O'Brien, 1988. Simulation of granular layer inversion in liquid fluidized beds. Int. J. Multiphase Flow, 14: 473-481.

Umikalsom, M.S., A.B. Ariff, H.S. Zulkifli, C.C. Tong, M.A. Hassan and M.I.A. Karim, 1997. The treatment of oil palm empty fruit bunch fibre for subsequent use as substrate for cellulase production by *Chaetomium globosum* Kunze. Bioresour. Technol., 62: 1-9.