ISSN 2664-4150 (Print) & ISSN 2664-794X (Online)
South Asian Research Journal of Engineering and Technology
Abbreviated Key Title: South Asian Res J Eng Tech

| Volume-6 | Issue-6 | Nov-Dec- 2024 | **DOI: https://doi.org/10.36346/sarjet.2024.v06i06.001**

Review Article

Design of a Bubbling Fluidized Bed Reactor for Bio-oil Production from Sawdust

Utibe Benedict Edem[1*], Onora Okorie[1], Ifreke Okon Akpan[1]

[1]Department of Chemical Engineering, University of Port Harcourt, Choba, Rivers State, Nigeria

***Corresponding Author:** Utibe Benedict Edem
Department of Chemical Engineering, University of Port Harcourt, Choba, Rivers State, Nigeria

Article History
Received: 01.10.2024
Accepted: 07.11.2024
Published: 14.11.2024

Abstract: Due to the ever increase in energy demand, it becomes imperative to design appropriate reactor for the conversion of available raw materials to energy source such as bio oil. A fluidized bed reactor is one the most promising reactor for the conversion of biomass to bio-oil via pyrolysis. This work take into consideration the design of fluidized bed reactor and its subsidiaries (cyclone, filter, condenser and feed hopper) to be used for bio-oil production using sawdust as the feedstock. The operating conditions were temperature between 400-600^{0}C, pressure 9.9atm and flow rate 1.86m/s. From the design calculations, it was found that the volume of the reactor, area, height, diameter and minimum fluidized velocity were 15.0796mm^3, 5026mm^2, 300mm, 80mm and 1.86m/s respectively. The material for construction for the reactor is stainless steel because of its high thermal conductivity and resistance to corrosion.

Keywords: Fluidized Bed, Reactor, Sawdust, Bio-Oil, Condenser, Cyclone, Feed Hopper.

1.0 INTRODUCTION

The exponential increase in world population and the decrease in fossil fuel reserves accompanied with its environmental impact are of global concern. This has put up increasing relevant which call for the search for alternative source of energy to complement the fossil fuel.

In this regard, renewable energy source is one of the most promising energy sources that can replace the fossil energy. Renewable energy is a type of energy generated from biomass. Biomass contribution to global carbon footprint is very low as compared to fossil fuel. It is readily available and does not required complex technology for its processing. According to Li *et al.*, (2004) in Inayat *et al.*, (2022), biomass is becoming the most favourable alternative source for the production of clean and sustainable primarily because of its communal availability, relatively lower price, and zero harmful emissions Biomass, which can be described as a complex mixture of lignin, cellulose, hemicellulose and minor percentage of other organic compounds is a primary source of bio-oil (Kwon *et al.*, 2019).

Before now the production of energy from biomass were done traditionally by burning to generate heat, but with increase in energy demand and advancement in technology, thermochemical method which include pyrolysis and gasification were introduced (Barbuzza *et al.*, 2019). Thermal conversion gives rise to multiple products within short reaction time without the application of inorganic catalyst to improve the quality the products.

The two ways of performing thermal conversion are pyrolysis and gasification. Gasification is the partial oxidation of biomass to produce fuel gas while pyrolysis is thermal treatment of biomass in absence of oxygen to produce liquid as the major product (Stefano *et al.*, 2019). The most used thermal treatment approach is the fast pyrolysis.

Fast pyrolysis is the decomposition of biomass using heat at moderate temperature in the absence of oxygen to convert biomass to bio-oil, charcoal and gas. The method is efficient and gives high yield of oil when fluidize bed reactor

CITATION: Utibe Benedict Edem, Onora Okorie, Ifreke Okon Akpan (2024). Design of a Bubbling Fluidized Bed Reactor for Bio-oil Production from Sawdust. *South Asian Res J Eng Tech*, *6*(6): 162-167.

is used. The high yield recorded by the reactor is due to its flexibility which allowed operating conditions to be controlled easily (Nur *et al.*, 2020).

Bubbling, circulating and dual fluidize bed reactors, are three basic reactors that have been used in literature for the conversion of biomass to bio-oil. Over, the years, various biomass feedstock in the form of rice straw and bamboo sawdust, wood furniture, maize stalk, selected woods types, sawdust, etc. have been used in the production of bio oil by fast pyrolysis ((Nur, *et al*., 2020).

This work focuses a scholarly insight into the design of bubbling fluidized bed reactor for bio-oil production from sawdust via fast pyrolysis. The aim of the research is to provide early scholars in this area of research, with the basic understanding of the process-via the design of a bubbling fluidized bed reactor.

2. METHOD

2.1 Specification Used for the Design

A fluidized bed reactor consists of filter hopper, glass condenser and feed hopper. Their specifications are stated in the subsection of this section. For the initial specification of the bed reactor the following values recorded in Table 1 are used as obtained from literature. This values were used to calculate other important specifications and for scale- up for mass production.

Table 1: Standard Dimensions and Specifications used for the Design

S/N	Description	Specification
1	Type of fluidized bed	bubbling
2	Number required	1
3	Material of construction	Stainless-steel (sus-306)
4	Bed height	300mm
5	Bed diameter	80mm
6	Input feed	sawdust
7	Design temperature	400 – 600^{0}C
8	Design pressure	10 bar (9.9Atm)
9	Particle size	0.7mm
10	Feeding rate	2.5 g/min
11	Flow rate	2.6 m^3/h
12	Fluidizing medium	Inert Nitrogen
13	Output power	5kw
14	Expected products	Bio-oil, Charcoal and gas

A. Volume and Cross Sectional Area of the Reactor

The volume and the cross sectional area of the reactor is very important, because it would determine the quantity of biomass to be charged into the reactor. The most used configuration for fluidized bed reactor is cylindrical configuration, thus:

Volume of the Reactor = Volume of Cylinder (V) = $\pi r^2 h$ 1

Cross- Sectional area (A_C) = $\frac{\pi D^2}{4}$ 2

Where r, h and d are the radius, diameter and height respectively.

B. The Bed Pressure Drop

The pressure drop (ΔP) needed in the fluidized vessel that would be exerted on the particles inside the vessel is given by;

$(\Delta P) = g(\rho_p - \rho_g)(1-\varepsilon)\, h$ 3

Where, g is the gravitational force, ε is the porosity, ρ_p is the density of the sand used, ρ_g is the density of the inert Nitrogen and h is the height.

C. Void Fraction at the Point of the Minimum Fluidization;

The void fraction at the point of minimum fluidization is given by

$$emf = 0.586\,(\Psi)^{-0.072}\left(\frac{\mu^2}{\rho_g\, \eta\, d_p^3}\right)^{0.029}\left(\frac{\rho_g}{\rho_g}\right)^{0.021} \quad 4$$

Where the gravitational term $\eta = g\,(\rho_p - \rho_g)$ 5

μ = is the absolute viscosity of nitrogen gas

Ψ = measure of particles not ideal in both shape and roughness = 0.7

D. Calculating the Reynolds's Number to Determine the Type of Flow;

$$\mathrm{Re} = \frac{124\, d_p\, v_P}{\mu} = \frac{124*0.0007*1.167*10^{-5}}{3*10^{-5}} = 0.03 \qquad 6$$

Since the Re number is less than 10, a laminar flow is expected in the fluidizing vessel

E. Fluidization Velocities

Fluidization velocity is the velocity at a point in which the drag force on the individual particle is about to exceed the gravitational force exerted on it. Above this velocity the sand particles would escape from the bed. The minimum and maximum velocity is given below. The choice of the formula to used is based on Reynolds Number (Nur *et al.*, 2020)

I. Minimum Fluidization Velocity (U_{mf})

$$U_{mf} = \left[\frac{(\varphi d_p)^2}{150N}\right]\left(\frac{emf}{1-emf}\right) \qquad 7$$

Where d_p is diameter of the fluidized bed

Ii. Maximum Fluidization Velocity

Since the Re No: is less than 10, Equation 8.

$$U_t = \frac{\int d_p^2}{18N} \qquad 8$$

F. Calculation of the Bubble Diameter

The bubble diameter is the diameter the bubble form when been fluidized. It is calculated using Equation 9 where d_B is the bubble diameter; d_{Bm} is the maximum bubble diameter, D is the diffusivity constant and z is the height of the bed.

$$d_B = d_{Bm} - (d_{Bm} - d_{Bo}) \exp\frac{-0.3z}{D} \qquad 9$$

But,

$d_{Bo} = 0.376\,(U_o - U_{mf})^2$ and $d_{Bm} = 411.38\,[A_c(U_o - U_{mf})]^{0.4}$

Where,

d_{Bo} is the minimum bubble diameter

U_o is superficial gas velocity, U_{mf} is maximum fluidized velocity and A_c is cross sectional area of the bed.

G. Bubble Rising Velocity

The bubble rising velocity is the velocity required for the bubble to rise. It is calculated using Equation 10 where U_o is the superficial gas velocity and U_{mf} is maximum fluidized velocity, g is the gravitational drag on the bubble and d_B is the bubble diameter.

$$U_b = U_o - U_{mf} + (g d_B)^{0.5} \qquad 10$$

H. Volume Fraction of Bubble Phase to Overall Bed

This is the volume of the bubble in the bed; it is a fraction of the total volume of the bed and is calculated using the Equation 11

$$\int = \frac{U_o - U_{mf}}{U_b} \qquad 11$$

Table 2: Volumetric Flow rates in the bed

S/N	Volumetric flow rates in bed	Formula
1	Total feed volumetric velocity	$Q_f = U_o A_c$
2	Bubble volumetric flowrate,	$Q_B = (U_o - U_{mf})\,A_c$
3	Dense phase feed volumetric flowrate,	$Q_{Df} = Q_f - Q_B$

I. Overall Heat-Transfer Coefficient (Bubble Phase-Dense Phase)

The overall heat transfer coefficient is the heat transfer across the entire bed. It is calculated based on the volume of the bubble. Equation 12

$$\frac{1}{(H_{bd})_b} = \frac{1}{(H_{bc})_b} + \frac{1}{(H_{cd})_b} \qquad 12$$

Where,

$$(H_{bc})_b = 4.5\left(\frac{U_{mf} S_g C_{pg}}{d_B}\right) + 0.104\left(\frac{U_{mf} S_g C_{pg}}{d_B^{2.5}}\right)^{1/2} \qquad 13$$

$$(H_{cd})_b = 21.44\,(K_g S_g C_{pg})^{1/2}\left(e_{mf} * {}^{U_b}/_{d_B}\right)^{1/2} \qquad 14$$

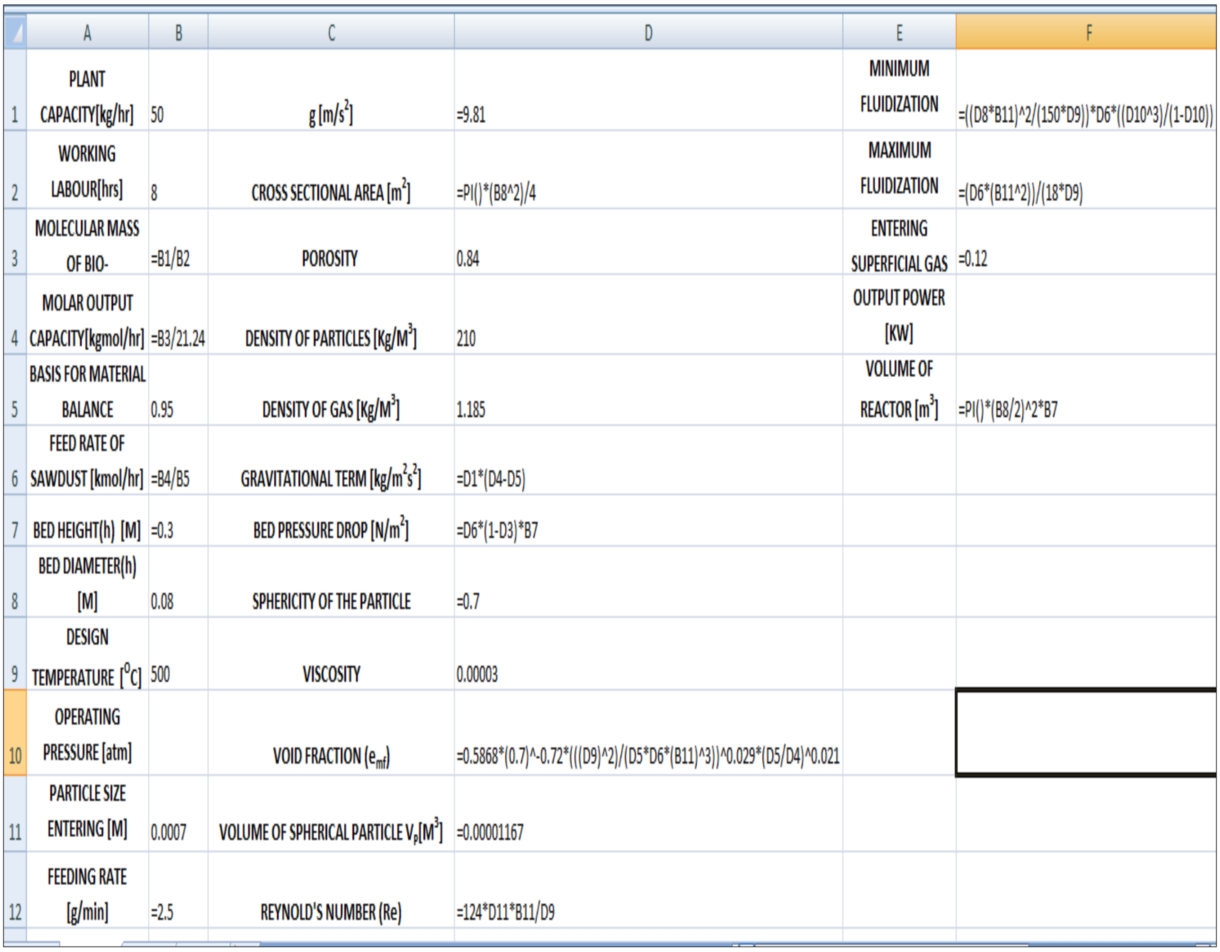
$C_{pg} = Cp_g$ is the heat capacity of the bed materials =1050JKg^{-1}K^{-1}; $K_g = 0.15W_m^{-1}K^{-1}$

Table 3: Summary of Calculated Specification of the fluidized bed

S/N	Description	Value
1	Volume of the reactor	15.08mm^3
2	Cross sectional area of the reactor	5026mm^2
3	Pressure drop in the bed	93.3N/m^2
4	Void fraction at point minimum fluidization	0.44
5	Regnold Number	0.03
6	Minimum fluidization velocity	1.86m/s
7	Bubble diameter	6.24m
8	Bubble rising velocity	7.93m/s
9	Over all heat transfer coefficient	14.29Jm^{-2}K^{-1}
10	Total feed volumetric flowrate	0.000603m^3/s
11	Bubble volumetric flowrate	0.000518m^3/s
12	Dense phase feed volumetric flowrate	0.000086m^3/s

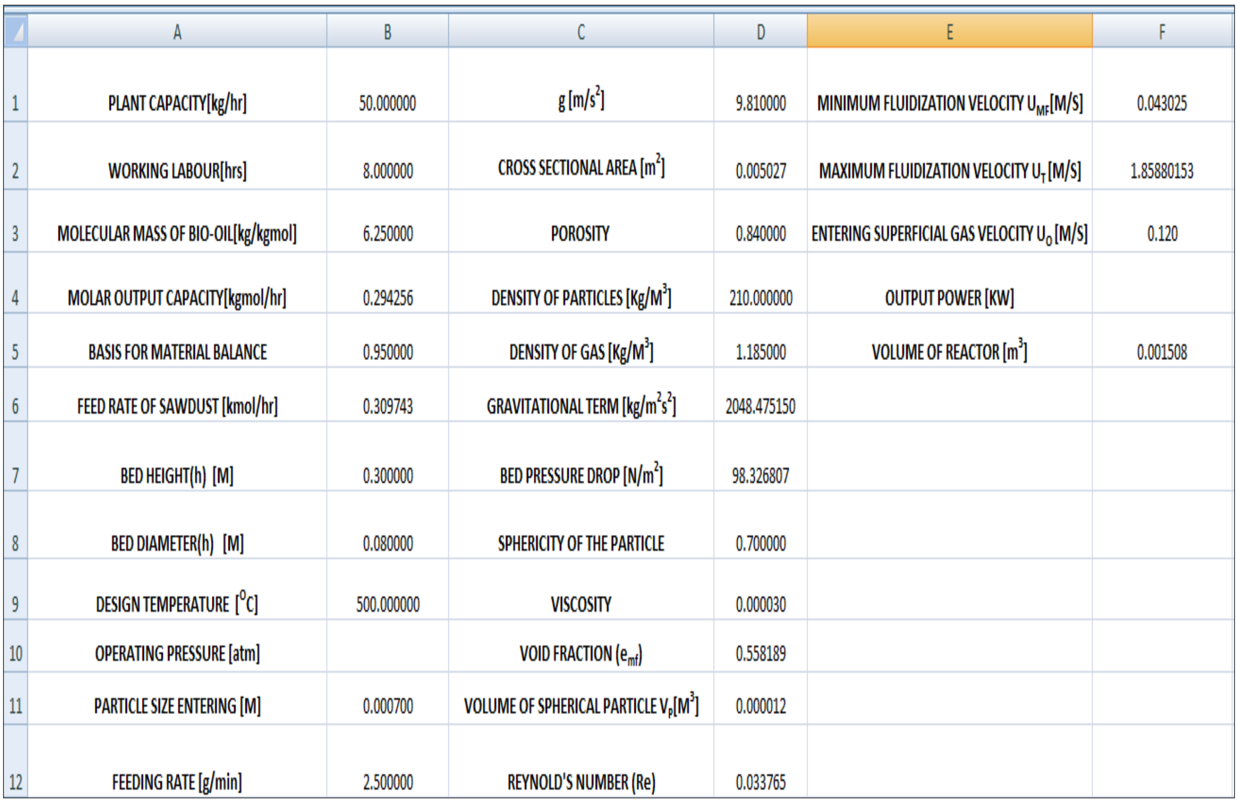
2 Excel Implementation of the Design of the Bubbling Fluidized Bed Reactor

Figure 1 below shows the design implementation using Microsoft Excel while Figure 3.2 gives the results obtained.



	A	B	C	D	E	F
1	PLANT CAPACITY[kg/hr]	50	g [m/s^2]	=9.81	MINIMUM FLUIDIZATION	=((D8*B11)^2/(150*D9))*D6*((D10^3)/(1-D10))
2	WORKING LABOUR[hrs]	8	CROSS SECTIONAL AREA [m^2]	=PI()*(B8^2)/4	MAXIMUM FLUIDIZATION	=(D6*(B11^2))/(18*D9)
3	MOLECULAR MASS OF BIO-	=B1/B2	POROSITY	0.84	ENTERING SUPERFICIAL GAS	=0.12
4	MOLAR OUTPUT CAPACITY[kgmol/hr]	=B3/21.24	DENSITY OF PARTICLES [Kg/M^3]	210	OUTPUT POWER [KW]	
5	BASIS FOR MATERIAL BALANCE	0.95	DENSITY OF GAS [Kg/M^3]	1.185	VOLUME OF REACTOR [m^3]	=PI()*(B8/2)^2*B7
6	FEED RATE OF SAWDUST [kmol/hr]	=B4/B5	GRAVITATIONAL TERM [kg/m^{2}s^2]	=D1*(D4-D5)		
7	BED HEIGHT(h) [M]	=0.3	BED PRESSURE DROP [N/m^2]	=D6*(1-D3)*B7		
8	BED DIAMETER(h) [M]	0.08	SPHERICITY OF THE PARTICLE	=0.7		
9	DESIGN TEMPERATURE [^{0}C]	500	VISCOSITY	0.00003		
10	OPERATING PRESSURE [atm]		VOID FRACTION (e_{mf})	=0.5868*(0.7)^-0.72*(((D9)^2)/(D5*D6*(B11)^3))^0.029*(D5/D4)^0.021		
11	PARTICLE SIZE ENTERING [M]	0.0007	VOLUME OF SPHERICAL PARTICLE V_p[M^3]	=0.00001167		
12	FEEDING RATE [g/min]	=2.5	REYNOLD'S NUMBER (Re)	=124*D11*B11/D9		

Figure 1: Formula implementation of the design of the Bubbling Fluidized Bed Reactor



	A	B	C	D	E	F
1	PLANT CAPACITY[kg/hr]	50.000000	g [m/s^2]	9.810000	MINIMUM FLUIDIZATION VELOCITY U_{MF}[M/S]	0.043025
2	WORKING LABOUR[hrs]	8.000000	CROSS SECTIONAL AREA [m^2]	0.005027	MAXIMUM FLUIDIZATION VELOCITY U_T[M/S]	1.85880153
3	MOLECULAR MASS OF BIO-OIL[kg/kgmol]	6.250000	POROSITY	0.840000	ENTERING SUPERFICIAL GAS VELOCITY U_0 [M/S]	0.120
4	MOLAR OUTPUT CAPACITY[kgmol/hr]	0.294256	DENSITY OF PARTICLES [Kg/M^3]	210.000000	OUTPUT POWER [KW]	
5	BASIS FOR MATERIAL BALANCE	0.950000	DENSITY OF GAS [Kg/M^3]	1.185000	VOLUME OF REACTOR [m^3]	0.001508
6	FEED RATE OF SAWDUST [kmol/hr]	0.309743	GRAVITATIONAL TERM [kg/m^{2}s^2]	2048.475150		
7	BED HEIGHT(h) [M]	0.300000	BED PRESSURE DROP [N/m^2]	98.326807		
8	BED DIAMETER(h) [M]	0.080000	SPHERICITY OF THE PARTICLE	0.700000		
9	DESIGN TEMPERATURE [^{0}C]	500.000000	VISCOSITY	0.000030		
10	OPERATING PRESSURE [atm]		VOID FRACTION (e_{mf})	0.558189		
11	PARTICLE SIZE ENTERING [M]	0.000700	VOLUME OF SPHERICAL PARTICLE V_p[M^3]	0.000012		
12	FEEDING RATE [g/min]	2.500000	REYNOLD'S NUMBER (Re)	0.033765		

Figure 2: Design results of the design of the bubbling fluidized bed reactor using Excel

A conceptual fluidized bed fast pyrolysis system is shown in Figure 1 indicating the main components which include cyclone, cooling section, feed preparation section and the reactor. All these components are connected such that the process proceeds in sequence.

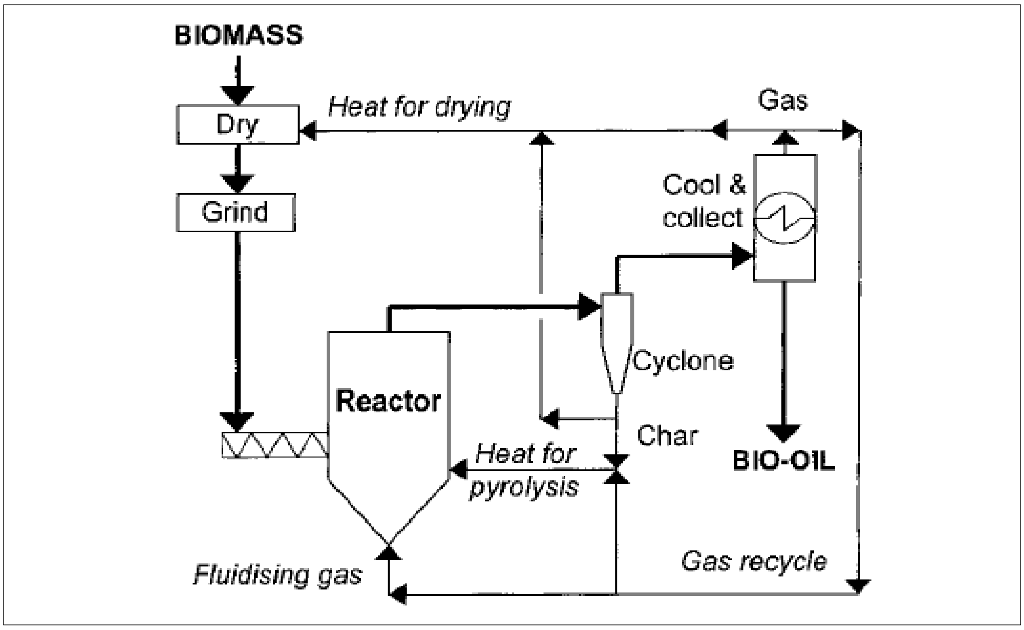


Figure 3: Fast Pyrolysis Principle Bridgwater and Peacocke (2000)

3. CONCLUSION

The design specification for the fluidized bed reactor and its subsidiaries components (cyclone, hot filter, condenser and feed hopper) are as stated in the tables above. The bed height, diameter and feed flow rate are 300mm 80mm and 2.6m^3/h respectively. The material for construction is stainless steel. This is considered because of its high resistance to corrosion and good thermal conductivity. The reactor temperature and pressure are 400-600^{0}C and 9.9atm respectively.

Volume of the reactor, cross sectional area and minimum fluidization velocity are 15.08mm^3, 5026mm^2 and 1.86m/s respectively. Some theoretical dimensions were also used to simplify the design calculations. The design specifications and operating conditions were found to be in consonant with contemporary fluidized bed reactor.

REFERENCES

- Adegoke, I. A., & James, R. O. (2020). Preparation and Characterisation of Bio-Oil Produced from Sawdust of Selected Wood Species. *American Journal of Modern Energy*, *6*(1), 16-25.
- Ali, N., Saleem, M., Shahzad, K., Hussain, S., & Chughtai, A. (2016). Effect of operating parameters on production of bio-oil from fast pyrolysis of maize stalk in bubbling fluidized bed reactor. *Polish Journal of Chemical Technology*, *18*(3), 88-96.
- Barbuzza, E., Buceti, G., Pozio, A., Santarelli, M., & Tosti, S. (2019). Gasification of wood biomass with renewable hydrogen for the production of synthetic natural gas. *Fuel*, *242*, 520-531.
- Bridgwater, A. V., & Peacocke, G. V. C. (2000). Fast pyrolysis processes for biomass. *Renewable and sustainable energy reviews*, *4*(1), 1-73.
- Heo, H. S., Park, H. J., Park, Y. K., Ryu, C., Suh, D. J., Suh, Y. W., ... & Kim, S. S. (2010). Bio-oil production from fast pyrolysis of waste furniture sawdust in a fluidized bed. *Bioresource technology*, *101*(1), S91-S96.
- Inayat, A., Ahmed, A., Tariq, R., Waris, A., Jamil, F., Ahmed, S. F., Ghenai, C., & Park, Y. K. (2022). Techno-Economical Evaluation of Bio-Oil Production via Biomass Fast Pyrolysis Process: A Review. *Front. Energy Res*, *9*, 770355.
- Jeon, H., Park, J. Y., Lee, J. W., Oh, C. H., Kim, J. K., Yoon, J. (2022). Fractional Composition Analysis for Upgrading of Fast Pyrolysis Bio-Oil Produced from Sawdust. *Energies, 15*, 2054. https://doi.org/10.3390/en15062054
- Khole, P. R., & Shukla, S. (2018). Bio-oil production through biomass pyrolysis and upgrading research. *Internat. J. Agric. Engg, 11*(1), 257-263, DOI: 10.15740/HAS/IJAE/11.1/257-263.
- Kwon, E. E., Kim, S., & Lee, J. (2019). Pyrolysis of waste feedstocks in CO_2 for effective energy recovery and waste treatment, *Journal of CO_2 Utilization*, *31*, 173–180.
- Nur A, F., Muhammad N. I., & Roslynna, R. (2020). Design and Fabrication of Fluidized Bed Pyrolysis System.
- Stefano, I., Shane, M., & Massimiliano, M. (2020)**.** Fluidised Bed Reactors for the Thermochemical Conversion of Biomass and Waste. *Power and Particle Journal*, *37*, 114 -131.
- Su-Hwa, J., Bo-Sung, K., & Joo.Sik, K. (2008). “Production of bio oil from rice straw and bamboo sawdust under various reaction conditions in a fast pyrolysis plant equipped with a fluidized bed and a char separation system”, *Elsevier J. Anal. Appl. Pyrolysis*, 240-247.