

Design, Fabrication and Performance Study of a Biomass Solid Waste Pyrolysis System for Alternative Liquid Fuel Production

M. R. Islam, M. N. Islam and M. N. Nabi

Department of Mechanical Engineering

Rajshahi University of Engineering & Technology (RUET)

Rajshahi-6204, Bangladesh

E-mail: mrislam1985@yahoo.com

(Received on 9 Sep 2002, revised on 17 Apr 2004)

Abstract

A laboratory scale fluidized bed pyrolysis system has been designed and fabricated for obtaining liquid fuel from biomass solid wastes. The components of the system are: fluidized bed reactor, gas preheating chamber, reactor feeder, heating system, heater feeder, liquid condenser and liquid collectors. The reactor operating parameters and dimensions have been considered on the basis of cold model study and thermo-gravimetric analysis (TGA) of the feedstock. The major components made of stainless steel. A number of trial runs have been carried out with jute-stick as feedstock. At an optimum pyrolysis condition of fluidized bed temperature of 425°C with 300-600µm feed particle size and 30 l/min fluidizing gas flow rate, the oil product is found to be 50 wt% of dry biomass feed. The oil obtained at this optimum condition is analyzed for their fuel properties-compared with other biomass pyrolysis oils and petroleum product. The fuel properties compared are physical properties, calorific value, elemental (CHNOS) analysis and chemical composition using FTIR spectroscopy.

Nomenclature

TGA	thermo-gravimetric analysis
CHNOS	carbon, hydrogen, nitrogen, oxygen and sulfur analysis
FTIR	Fourier transform infrared
ASTM	American Society for Testing Materials
AISI	American Iron and Steel Institute
IP	Institute of Petroleum
cSt	centistoke
pH	negative logarithm of hydrogen ion concentration
kg/m ³	kilogram per cubic meter
kJ/kg	kilojoule per kilogram
O-H	hydroxyl stretching
C-H	carbon hydrogen stretching and bending
C=O	carbonyl stretching
C=C	carbon carbon double bonding stretching
-NO ₂	nitrogen dioxide stretching
C-O	carbon oxygen stretching
wt%	weight percent
cm ⁻¹	per unit centimeter

Introduction

Biomass has been recognized as a major alternate energy source to supplement declining fossil fuel reserves [1]. Currently biofuel production is becoming much promising [2]. Transformation of energy into useful and sustainable forms that can fulfill and suit the needs and requirements of human being in the best possible way is the common concern of the scientists, engineers and technologists. From the view point of energy transformation, fluidized bed pyrolysis is more attractive among various thermochemical conversion processes because of its higher conversion capability of biomass and its solid wastes into liquid product [3].

Bangladesh, India, Nepal, Pakistan and Bhutan are predominantly agriculture-based countries. The major agricultural by-products of these countries are rice-straw, jute-stick and bagasse. The conventional uses of these biomass solid wastes are as fuel for cooking, cattle feed, raw material for paper and pulp industries. In 1998-99, the production volume of these by-products in Bangladesh was 25876.50, 1218.00 and 1390.20 thousand metric tons respectively [4]. These carbonaceous solid wastes are alternative energy source and therefore, the potential of converting them into useful energy such as liquid fuel should be seriously considered. In this way, the wastes would be more readily usable and environmentally more acceptable.

The proximate analysis, elemental composition and thermalgravimetric analysis (TGA) of the biomass solid wastes show that these wastes may be used for energy recovery as fuel [5]. The TGA at a heating rate of 60°C/min indicate that devolatilization starts at around 250°C and is completed at around 450°C. The maximum rate of devolatilization takes place between the temperature of 300°C and 400°C [5]. From a recent cold model study of the fluidized bed reactor it was found that a fluidizing gas flow rate of $2U_{mf} \leq U_f \leq 3.5U_{mf}$ for an average sand particle size of 181µm with 5cm bed height with a distributor plate of 9 nozzles and feed particle size of 300-600µm a very good fluidization and solid mixing situation was obtained [6]. Thus, the conversion of these biomass solid wastes into liquid product by fluidized bed pyrolysis method may be considered as a promising option. The three common products from the pyrolysis system are oil, char and gas. The pyrolytic oil is of moderate heating value and easily transportable. Also it can be burnt directly in the thermal power plant, possibly injected into the flow of a conventional petroleum refinery, and burnt in a gas turbine or upgraded to obtain light hydrocarbons for transport fuel [7, 8]. The solid char can be used to make activated carbon. Besides the char has its potential to be used as fuel. The gas has high calorific value, sufficient to be used for the total energy requirements of the pyrolysis plant [9].

This paper addresses the design and fabrication of a laboratory scale fluidized bed system for the pyrolysis of jute-stick and analyzed the fuel properties of the oil derived thereof.

Design and Fabrication of the Rig

Due to corrosive nature of pyrolysis liquid, especially derived from biomass, and high operating temperature range of the process (400°C to 600°C), stainless steel of grade ASTM A 240 and AISI 304, were selected as the material for most of the components of the system. Oxy-acetylene gas welding was used for joining the parts of each component using brass as filler metal in the fabrication of the rig. To make a clear idea about the design and fabrication of the fluidized bed pyrolysis system, the important components have been described with their detail drawings.

Fluidized bed reactor

The selection of the size of the fluidized bed reactor depends primarily on the fluidizing gas flow rate. The gas flow rate and the volume of the reactor determine the apparent vapor residence time in the reactor, an important parameter in fast pyrolysis process for maximizing liquid product. For fast pyrolysis the residence time should be in between 1 to 5 sec [3]. For simplicity of the fabrication, a cylindrical reactor was designed that was fabricated using a stainless steel pipe of internal diameter of 7cm. The effective volume of the reactor was 1443 cm³. From the cold model study, it was found that the gas flow rate was

within the range of 22 l/min to 40 l/min for proper fluidization [6]. The calculation for estimation of the reactor size as follows:

Volume of the reactor, $V_r = 1443 \text{ cm}^3$

Gas flow rate for proper fluidization, $U_g = 22 \text{ l/min to } 40 \text{ l/min}$
 $= 366.66 \text{ cm}^3/\text{sec to } 666.66 \text{ cm}^3/\text{sec}$
 $= 1.32 \text{ m}^3/\text{h to } 2.40 \text{ m}^3/\text{h}$

Apparent vapor residence time, $t = V_r/U_g = 3.935 \text{ sec to } 2.164 \text{ sec}$

Internal diameter of the reactor, $d = 7.00 \text{ cm}$; Cross-sectional area, $A = 38.48 \text{ cm}^2$.

Effective length of the reactor, $L = V_r/A = 37.5 \text{ cm}$.

The sectional view of the reactor is presented in Fig. 1.

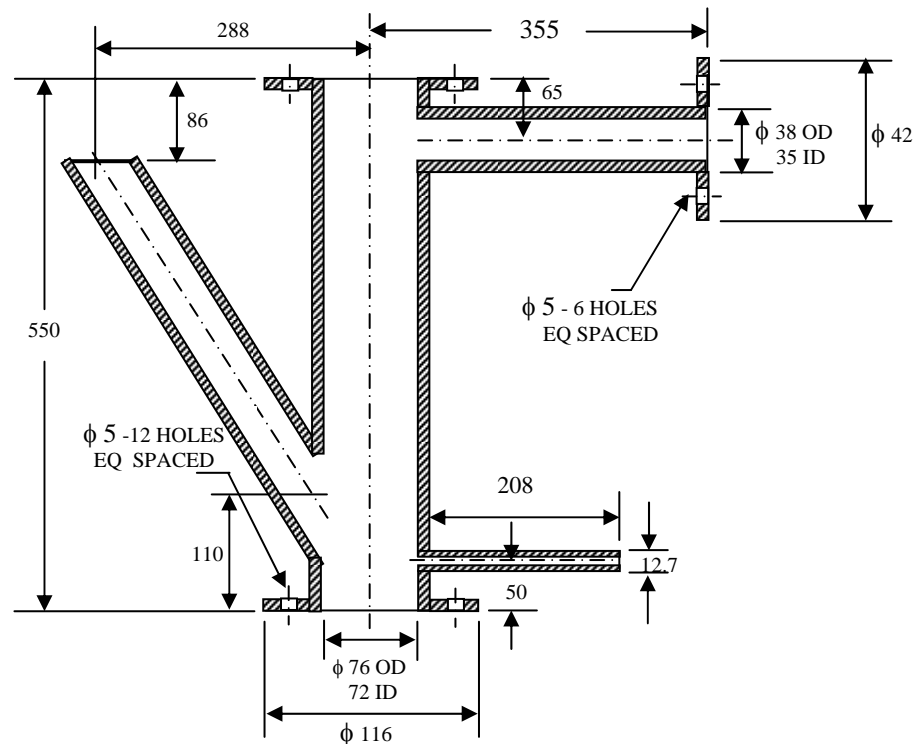


Fig. 1 Sectional view of fluidized bed reactor

Reactor feeder

A gravity feed type reactor feeder was fabricated from 5mm thick acrylic plate. It was designed as tapered shape in longitudinal direction with square cross-section. The volume of the feeder was such that a sufficient amount of feedstock could be contained. A lever operated feedstock control valve system was designed at the bottom of the feeder. A constant feed rate was maintained for a certain valve opening. The feeding of the feedstock from feeder to the reactor was due to gravity force. The sectional view of the feeder is shown in Fig. 2.

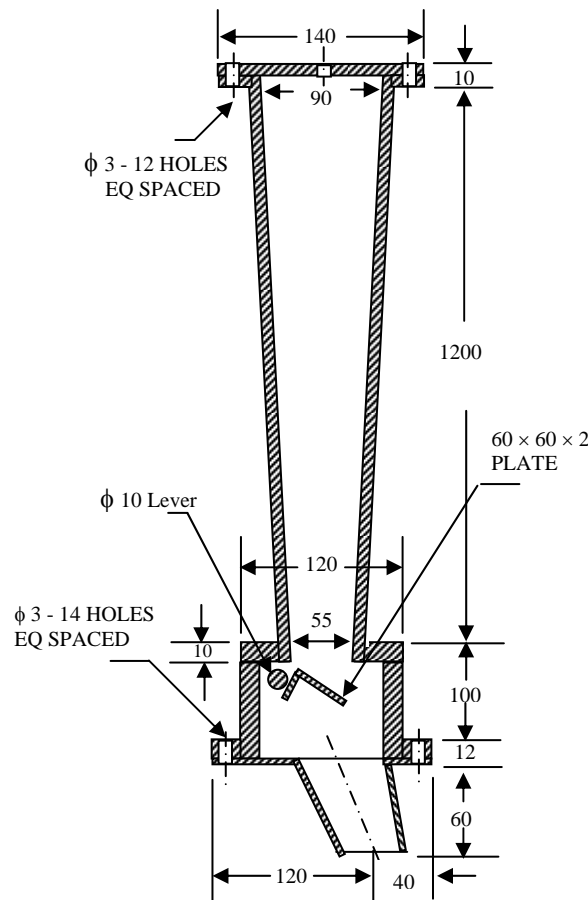


Fig. 2 Sectional view of reactor feeder

Gas distributor

A gas distributor in a gas fluidization system is designed with the following characteristics:

There are a number of gas distributor configurations used in gas fluidization technology, the more common types are the perforated plate and the tuyere-type or stand pipes with nozzles on a plate [10]. For this reactor configuration, a simple nozzle-type tuyere gas distributor was adopted. This design had been proven to work quite well, in promoting particle circulation in the bed and in preventing back flow of particles to the air plenum as found in the cold model study [10]. The details of the gas distributor are shown in Fig. 3. The distributor plate was fabricated from 2 mm thick stainless steel of grade ASTM A 240 and the tuyere nozzles were made from 1/2 inch diameter brass rod.

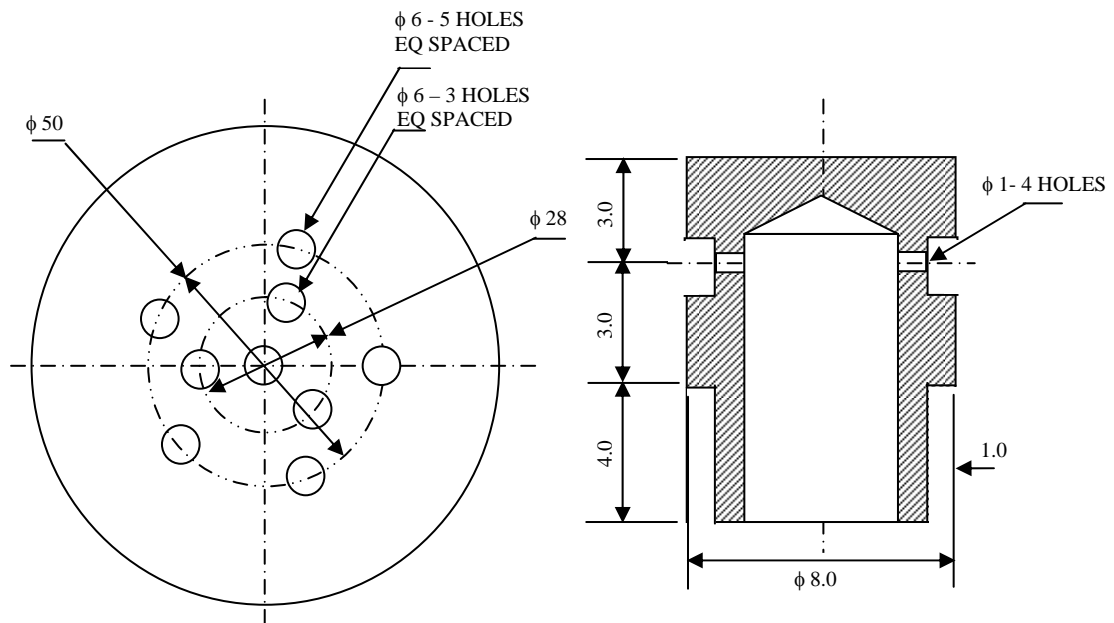


Fig. 3 Distributor plate and tuyere nozzle

Gas pre-heating chamber

Due to high flow rate, the gas entering the reactor should be pre-heated to prevent the cooling effect of the gas. The gas pre-heating would compliment the heating of the bed provided by the reactor heater through the reactor wall. A gas pre-heater system had been designed to heat the fluidizing gas. To extend the residence time of the gas in the pre-heating chamber, the gas was made to flow in a double paths, as shown by the layout in Fig. 4. Three stainless steel pipes of internal diameter 7cm, 4.78cm and 2.24cm were used for the fabrication of the gas pre-heating chamber.

Condenser

A rapid quenching of pyrolysis vapor product promotes high liquid yield. The pyrolysis condensate, especially biomass-derived liquid contains tarry substances which readily forms and deposits in the condenser and pipe lines. To facilitate regular cleaning, a single flow, shell and tube type water condenser was designed. The calculation for determining the condenser dimensions is presented bellow. Due to corrosive nature of the condensate, the condenser was fabricated from two 97.6 mm and 34 mm diameter stainless steel pipes.

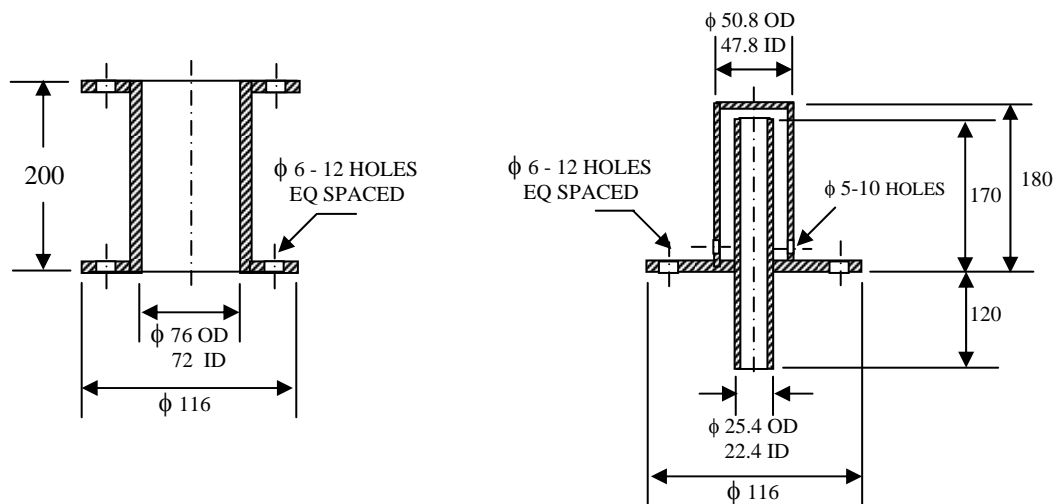


Fig. 4 Layout of gas pre-heating chamber

Condenser dimensions: On the basis of water and heavy hydrocarbon/organic vapor [11].

T_1 = water inlet temperature, t_{w1} – vapor outlet temperature, $t_{v2} = 28 - 25 = 3^\circ\text{C}$;

T_2 = vapor inlet temperature, t_{v1} – water outlet temperature, $t_{w2} = 600 - t_{w2}$

Water flow rate = 5 l/min = 0.083 kg/sec; Specific heat of water, $C_w = 4.2 \text{ kJ/kg-K}$

Vapor flow rate = 50 l/min = 0.002 kg/s ; Specific heat of vapor, $C_v = 2.0 \text{ kJ/kg-K}$

$Q = 0.002 \times 2 \times (600 - 28) = 0.083 \times 4.2 \times (t_{w2} - 25)$

$Q = 2.288 \text{ kW}$;

$$\therefore t_{w2} = 31.56^\circ\text{C} \quad (1)$$

The overall heat transfer between water and vapor,

$$Q = U_o A \Delta T_m \quad (2)$$

Where, U_o = Overall heat transfer co-efficient $\cong 350 \text{ W/m}^2\text{-K}$

A = Minimum area of condenser tube

ΔT_m = Minimum log mean temperature difference = $(T_1 - T_2)/[\ln(T_1/T_2)]$
 $= 107.82^\circ\text{C}$

From equation (1) & (2)

$$2288 = 350 \times 107.82 \times A ; \therefore A = 0.06063 = \pi d_c L_c$$

If diameter of the condenser tube, $d_c = 34 \text{ mm}$;

Then condenser tube length, $L_c = 567.62 \text{ mm}$ (minimum).

Liquid collectors

Two liquid collectors, arranged in series were fabricated to collect the condensate. During the experimental run, they were put into a ice-cooled water bath. The volume and design of the collectors were such that the condensable vapour get sufficient time for maximum condensation. Due to corrosive nature of the biomass derived oil, the liquid collectors were also fabricated from two 97.6 mm and 34 mm diameter stainless steel pipes.

Heating system

A biomass source cylindrical heater was designed to supply heat to the fluidized bed reactor and to the gas pre-heating chamber. The heater was made of $\frac{1}{2}$ mm thick stainless steel sheet of grade AISI 304. The height and diameter of the drum were 78 cm and 46 cm respectively. Rice-husk was compacted in the heater drum in annular form of 15 cm inside diameter, 45 cm outside diameter and 37 cm height. Air required for combustion of rice-husk, was supplied by a hand blower at the base of the heater through an annular space. The variation of the amount of air supply that was related to the blower operating speed controlled the temperature of the heater. Burning characteristics and the temperature of the heater depended on moisture content and compactness of rice-husk in the heater drum. In this study air-dry rice-husk collected from local rice mill was used. The ash was disposed by gravity action from the heater through an ash disposal system at the bottom of the heater. A 5cm thick glass-wool pad was used as insulation to reduce heat loss from the heater drum. A gravity feed type heater feeder was designed at the top of the heater for continuous feeding of the heater. The performance curve and sectional view of the heater are shown in Fig. 5 and Fig. 6 respectively. It is mentioned that the temperature in the bed falls for a few minutes when nitrogen gas for fluidization was flown into the reactor. After reaching the desired temperature of the reactor bed the blower speed should be reduced by about 20% to maintain the constant value of temperature.

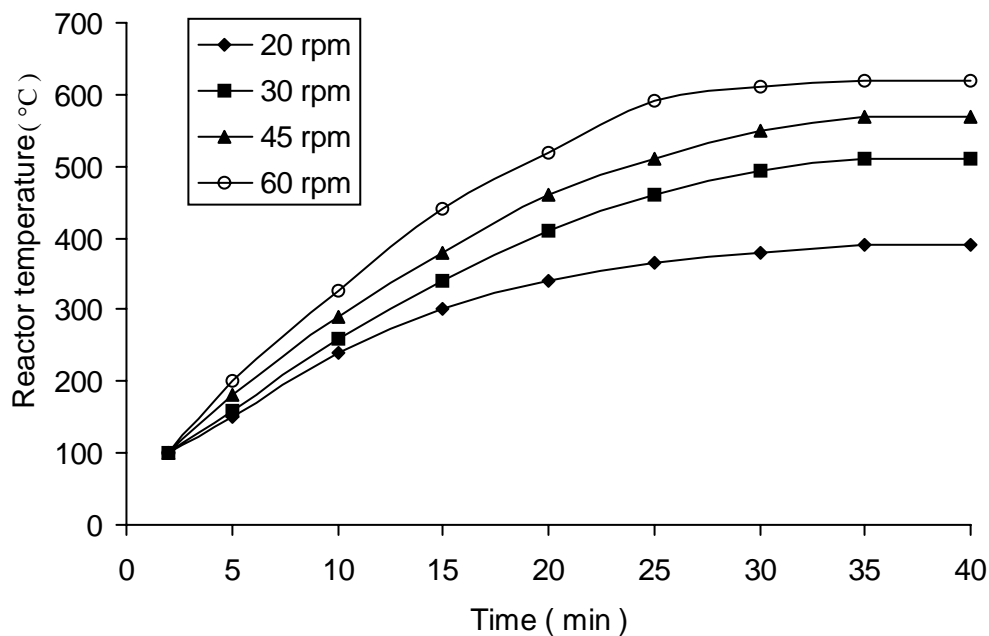


Fig. 5 Performance curve of the heating system

Gravity feed type heater feeder

It was made of $\frac{1}{2}$ mm thick stainless steel sheet of grade AISI 304 of pyramid shape. It was filled with rice-husk before running the system. There was a hand operated door mechanism at the bottom of the feeder in which four holes were designed to feed the reactor heater. When the door was opened, the feed materials fell into the heater drum due to gravity action through these four bottom holes. Feed material from the heater feeder was used after the compacted feed being burnt in the heater drum.

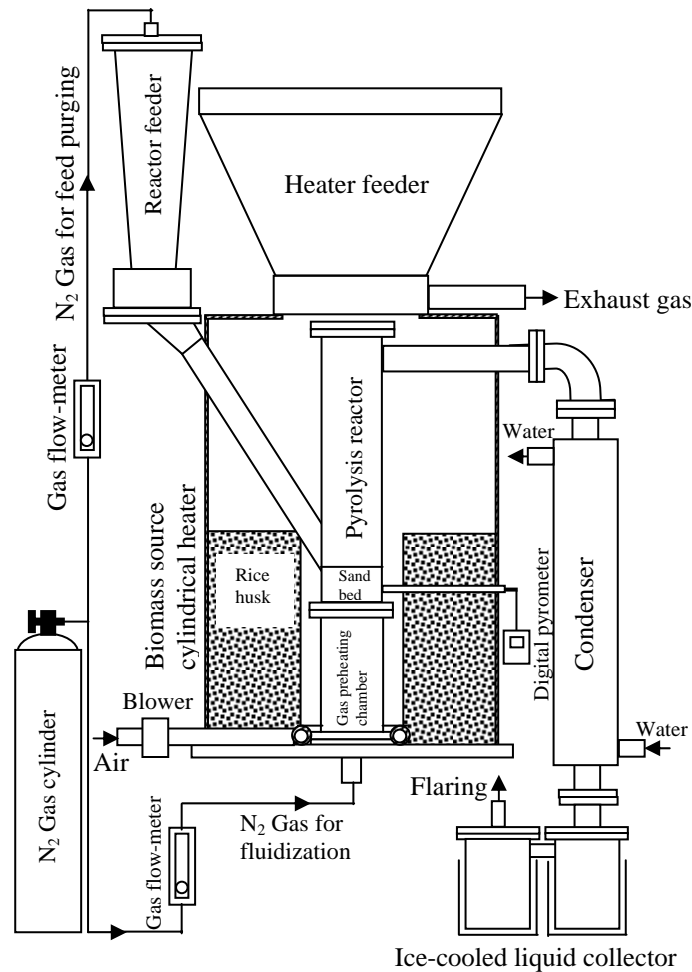


Fig. 6 Schematic diagram of fluidized bed pyrolysis system

Ash disposal and air supply system

There was an ash disposal system and an air supply system at the bottom of the heater. The ash disposal system was fabricated from 5mm thick mild steel sheet. It supported the biomass material and ash. The ash was disposed when required, through a hand operated door mechanism designed in the system. When the door was opened, the ash disposed due to gravity force. The air supply system consisted of a hand driven blower and a 25.4 mm diameter stainless steel pipe. The air from blower came into the heater drum through the steel pipe. Variation of the speed of the blower for regulating the heater temperature controlled the amount of air supply. The blower was driven with care such that the fluctuation of temperature in the reactor was within the range of $+5^{\circ}\text{C}$ and -5°C . Fig. 7 shows the sectional view of the system. The specification of the blower is given below:

Casing inside diameter of the blower	: 20cm
Blade type	: radial
Number of blades	: 4
Blade dimensions	: 8.5cm \times 4.5cm \times 0.5cm
Power transmission mechanism	: worm and gear type
Speed ratio of the worm gear	: $N_g/N_w = 56/7 = 8$
Length of gear driving handle	: 15cm

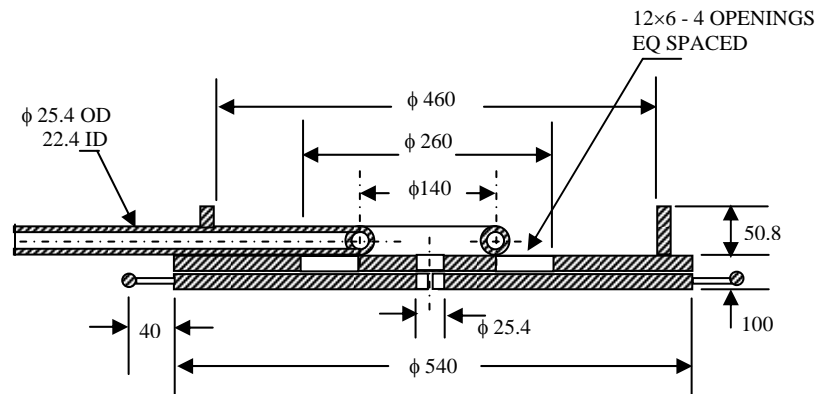


Fig. 7 Air supply and ash disposal system

Fluidizing gas and gas flow rate

Nitrogen gas was metered from gas cylinder, in two streams, one as the fluidizing gas to the reactor and other to the reactor feeder to purge the trapped air. A multi-stage nitrogen gas pressure regulator of model MUREX N-10 was used to regulate pressure of the gas from the cylinder. During the experimental run, the outlet gage reading was set at 1 bar. The fluidizing gas entered at the bottom of the reactor through the gas distributor plate situated at the top of the gas pre-heating chamber.

A nitrogen gas flow-meter of model MUREX 0011 with a variable control valve of capacity 0-40 l/min was used to control and measure the fluidizing gas flow rate. The purging gas flow rate was metered by a similar type of flow-meter.

Temperature measurement

The reactor temperature was measured by a digital pyrometer of model Lutron TM914C and its operating range was from -40°C to 1200°C . The pyrometer probe was inserted into the reactor at 5cm above the distributor plate where the pyrolysis conversion took place.

Assembly of the rig

The rig was assembled on a frame structure, made of mild steel angle bar of dimensions $56\text{cm} \times 56\text{cm} \times 195\text{cm}$. The rig was mounted using nuts and bolts. The components subjected to high temperature such as reactor, gas distributor and gas pre-heating chamber as well as pipe joints and fittings were sealed using asbestos sheet and high temperature liquid gasket. The other components were sealed using soft rubber and low temperature liquid sealants to ensure the system completely leak-proof from air. The connecting pipe joining the reactor and the liquid condenser was wrapped with asbestos rope to maintain high temperature by reducing heat loss and hence to prevent condensation of pyrolysis vapor in this earlier part. The polymer hosepipes were used for the gas and water supply lines. Fig. 6 shows the schematic diagram of the fluidized bed pyrolysis system.

Trial and Experimental Run of The Fluidized Bed Pyrolysis System

Trail run

Several trial-runs were given to enable a smooth and steady attainment of the desired operational parameters of the pyrolysis system. Afterwards the experimental run was conducted using jute-stick as the feedstock. The higher heating value, proximate and ultimate analysis of solid jute-stick are presented in Table 1.

Table 1 Higher heating value, proximate and ultimate analysis of solid jute-stick

Higher heating value	Proximate analysis		Ultimate analysis	
17.321 MJ/kg	Contents	wt%	Elements	wt%
	Volatile	78.40	C	44.94
	Fixed carbon	11.80	H	4.38
	Moisture	9.02	N	-
	Ash	0.78	O	49.90
			S	-

Experimental run

In the experiment nitrogen gas was used as fluidizing gas to make the system inert and dry silica sand as bed material. The sand in the fluidized bed was of mean size 181 μ m diameter with static bed height of 5cm. Fig. 7 shows the schematic diagram of the fluidized bed pyrolysis system. The reactor was 7cm diameter \times 37.5cm high, constructed of stainless steel with full gas flow and temperature control. The reactor was heated externally. The incoming fluidizing nitrogen gas was pre-heated before entering the reactor in a pre-heating chamber. The fluidizing gas flow rate was measured and controlled by nitrogen gas flow-meter. Gas flow rate was maintained with care otherwise fluidization was disturbed or some of the char particles reached the liquid collector with higher gas flow rate. The reactor bed and gas pre-heating chamber were heated by means of renewable energy biomass source cylindrical heater. A blower supplied air required for burning biomass in the heater. By varying the air supply that was directly related to the blower speed controlled the temperature of the reactor. The temperature in the fluidized bed reactor was measured by a digital pyrometer. The gravity feed type heater feeder supplied the heater biomass required for continuous heating of the reactor. The ash of burned biomass in the heater was disposed through the ash disposal system at the bottom of the heater by gravity force. The exhaust gases due to burning of heater biomass were exhausted in the atmosphere through a pipeline at the top of the heater. The biomass solid waste particles were fed into the reactor by a gravity feed type reactor feeder. The feed rate was maintained near about constant by a feed control valve at the bottom of the reactor feeder. Higher feed rate also disturbed the fluidization in the reactor. The gravity force was the main agent for feeding the reactor. The system was maintained at a pressure slightly above atmosphere by a nitrogen gas pressure regulator. The char was collected from the reactor after completing a run. The vapors and gases were passed through a water-cooled condenser to a series of two ice-cooled collectors to trap the derived liquid product. The fluidizing gas and non-condensable vapor were flared to atmosphere.

Generic reaction pathway

Various kinetics modeling studies on pyrolysis of organic materials appearing in the literature present different versions of pyrolysis reaction pathways. However, the most recent and accepted theory is that, when organic matter is heated, the primary vapors are first produced, the characteristics of which are most

influenced by heating rate. These primary vapors then further degrade to secondary tars and gases if held at high temperature for long enough time for secondary reaction to occur. The proportions and characteristics of the secondary material are a function of temperature and time. Rapid quenching causes the liquid intermediate products of pyrolysis to condense, before further reaction breaks down the higher molecular weight species into gaseous products. A possible reaction pathway of biomass solid waste pyrolysis process is shown in Fig.8.

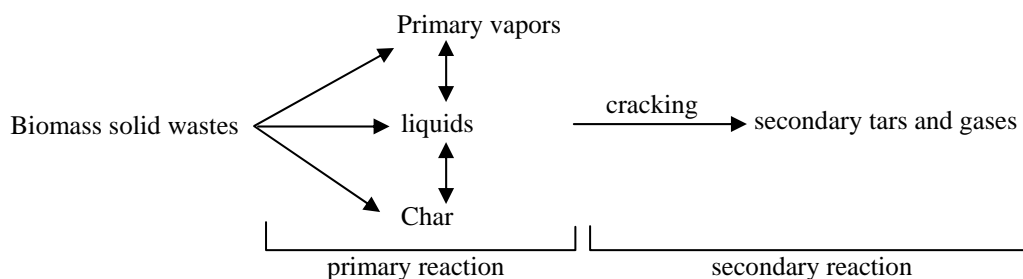


Fig.8 Reaction pathway for pyrolysis process

Results and Discussions

Product yields

In general, three products were recovered after each run. Table 2 shows the product yields obtained due to variation of the reaction conditions. From the two liquid collectors, a fairly fluid, oily organic liquid was obtained. The liquid yield was high showing the potential of recovering of liquid hydrocarbon from the fast pyrolysis of jute-stick. The liquid appeared brownish dark with a strong acrid smell. Careful handling of the liquid was required since the liquid reacted easily with human skins, leaving permanent yellowish brown marks and an acrid smell for a few days, which cannot be removed by bleach or detergent. No phase separation was found to take place. Heavy condensate or tar was also formed and adhered to the inner wall of condenser, liquid collectors and connecting pipes. The tar, which was very viscous at room temperature, could be easily removed from the steel surfaces by detergent and hot water. The char was collected from the reactor. This char was expected to be very reactive, and precautions were required to ensure that it would not be exposed to air when still hot. The gas was diluted by the large flow rate of nitrogen inert gas and flared into atmosphere. During the runs the feed rate was near about constant. A slight variation in its value was due to feed control valve. This variation did not affect significantly on the product yields.

Table 2 Product yields (wt% of solid jute-stick feed) due to variation of reaction conditions

Feed rate (kg/h)	Reaction conditions	Products yields (At fluidizing N ₂ gas flow rate of 30 l/min and feed particle size of 300-600µm)			Feed rate (kg/h)	Reaction conditions	Products yields (At reactor bed temperature of 425°C and feed particle size of 300-600µm)		
	Temperature (°C)	Liquid wt%	Gas wt%	Char wt%		N ₂ gas flow rate (l/min)	Liquid wt%	Gas wt%	Char wt%
0.31	500	36	33	31	0.32	22	36	39	25
0.32	475	40	35	25	0.32	26	42	38	20
0.30	450	45	37	18	0.30	30	50	37	13
0.31	425	50	38	12	0.30	34	48	40	12
0.32	400	44	45	11	0.31	38	46	43	11
0.30	375	38	51	11	-	-	-	-	-

Characterization of pyrolytic oil

Physical and chemical characteristics: Table 3 shows the characteristics of the jute-stick derived oil obtained at the operating fluidised bed temperature of 425°C. The gross calorific value of the oil was 21.091 MJ/kg. It was found to be significantly higher than the energy content of raw jute-stick. The liquid was easily pourable at room temperature of 30°C with low pour point of less than -14°C. The high flash point of greater than 70°C suggests that the liquid can be safely stored and handled at room temperature. The oil was found to be moderate in viscosity. The liquid was acidic with a pH value of 2.92 that indicates its corrosive nature.

The elemental analysis of the oil is an important criterion for the design of a combustion plant utilising the oil. With the help of the elemental analysis, the combustion calculation can be carried out from which the quantities of combustion air and flue gas and the composition of the flue gas can be determined. Bio-crude oils have some properties that are quite different from those of petroleum-driven oils. Biocrude oils contains a large amount of oxygen. The oxygen content of bio-oils (excluding water) is a function of the oxygenated feedstock from which they are made, as well as the residence time and temperature of the pyrolysis step [13]. The oxygen content in the liquid was 44.13%, calculated by difference, was close to that of feedstock composition. The sulfur content of oil is naturally negligible, due to the negligible sulfur content of biomass.

Table 3 The elemental composition and physical characteristics of biomass pyrolysis oil and its comparison

Analysis	Standard	Jute-stick*	Wood [12]	waste* [12]	Diesel [12]
Elemental (wt%)					
C	ASTM D3176-84	47.18	46.24		86.58
H	ASTM D3176-84	8.36	7.55		13.29
N	ASTM D3176-84	Not detectable	0.141		65ppm
S	ASTM D3176-84	Not detectable	0.03		0.11
Ash	ASTM D482-IP 4	0.33	0.04		0.00
O	By difference	44.13	46.00		0.01
Kinematic viscosity @ 30°C (cSt)	ASTM D445-IP 71	12.08	20.99 [#]		2.61 [§]
Density (kg/m ³)	-	1224.7	1199 [§]		827.1
pH value	Digital pH meter	2.92	2.8		-
Flash point (°C)	ASTM D92-IP 36	>70	59		53
Pour point (°C)	ASTM D97-IP 15	-14	-		-
HHV (MJ/kg)	DIN 51900	21.091	19.800		45.180

@ 60°C; § @ 20°C; * wet oil basis

This negligible sulfur content is one of the positive aspects of pyrolytic oil [13]. The amount of sulfur in the biomass derived oils indicates the quantity of the hazardous SO₂ emission in combustion processes. No sulfur was found and the ash content was found to be low as 0.33% of the oil weight. One of the parameter of pyrolytic oil is the nitrogen content of the oil, which reflects the variable protein content possible with biomass. Biomass which has a significant content of green, living plant cells (e.g. green grasses) may have a higher nitrogen content than biomass having a large content of dead plant cells (e.g. straw and wood) [13]. The nitrogen content in the pyrolytic oil contributes to NO_x emissions and it was not detectable in the jute-stick pyrolytic product.

Compositional analysis: From the Fourier transform infra-red spectroscopy of the derived pyrolytic oil, the FTIR functional groups and the indicated compositions of the liquid product were presented in Table 4. The presence of water impurities and other polymeric O-H in the oil were indicated by the broad absorbance

peak of O-H stretching vibration between 3600 and 3200 cm^{-1} . The presence of alkanes were indicated by the strong absorbance peak of C-H vibrations between 3050 and 2800 cm^{-1} and the C-H of deformation vibrations between 1490 and 1325 cm^{-1} . The absorbance peaks between 1775 and 1650 cm^{-1} represented the C=O stretching vibration, indicating the presence of ketones, aldehydes and carboxylic acids. The possible presence of alkenes were indicated by the absorbance peaks between 1680 and 1575 cm^{-1} representing C=C stretching vibrations. The sharp but less prominent absorbance peaks between 1550 and 1475 cm^{-1} represented -NO₂ stretching vibration indicated the presence trace of nitrogenous compounds. The overlapping peaks between 1300 and 950 cm^{-1} were suggested due to the presence of primary, secondary and tertiary alcohols, ethers and esters due to the C-O stretching and O-H deformation vibration of these functional groups. The absorbance peaks between 900 and 650 cm^{-1} indicated the possible presence of single, polycyclic and substituted aromatics groups. These similar functional groups and the indicated composition have been identified in the pyrolytic oils derived from palm shell and rice-husk from fluidized bed reactor by Ani and Zailani [14] and Islam et al [15] respectively.

Table 4 FTIR functional groups and the indicated compounds of biomass pyrolysis oil

Frequency range (cm^{-1})	Groups	Class of compounds
3600-3200	O-H stretching	Polymeric O-H, water impurities
3050-2800	C-H stretching	Alkenes
1775-1650	C=O stretching	Ketones, Aldehydes, Carboxylic acids
1680-1575	C=C stretching	Alkenes
1550-1475	-NO ₂ stretching	Nitrogenous compounds
1490-1325	C-H bending	Alkanes
1300-950	C-O stretching, O-H bending	Primary, secondary & tertiary alcohols, phenol, esters, ethers.
900-650		Aromatic compounds

The pronounced oxygenated functional groups of O-H; C=O; C-O and aromatic compounds showed that the oil was highly oxygenated and therefore, acidic, as have also been indicated by the elemental composition and the pH value. The high fraction of oxygenated compounds reduce the calorific value of the oil since C=O bonds do not release energy during combustion. The presence of hydrocarbon groups C-H; C=C; and alcohols indicate that the liquid has a potential to be used as fuel.

Conclusions

A fluidized bed pyrolysis system has been completely designed, fabricated and installed for the thermochemical conversion of biomass solid wastes. Jute-stick was successfully pyrolyzed into liquid oil by the system. The maximum liquid yield was found to be 50 wt% of biomass feed at a reactor bed temperature of 425°C and at a gas flow rate of 30 l/min. The liquid product yield was found to be increasing with pyrolysis reactor bed temperature up to 425°C after which it was decreasing with temperature. The char yield was found to be decreasing with the rise of pyrolysis reactor bed temperature for a certain fluidization gas flow rate. Other salient observations are as follows.

- i) The pyrolytic oil was a single-phase liquid product of brownish dark color with acrid smell.
- ii) The elemental composition of the oil was found to better than that of solid biomass. No sulfur and nitrogen was detected in the oil.
- iii) FTIR analysis showed that the liquid was dominant with oxygenated species. Hence, it is important to deoxygenate the liquid.
- iv) The physical properties analysis showed that the oil was heavy and acidic in nature with moderate viscosity. The oil possessed favorable pour and flash points.

- v) The heating value of the oil was low. However, the value was similar to that of other biomass derived pyrolytic oils. This value was significantly higher than that of solid jute-stick. A Plain Oxygen Bomb Calorimeter of model PARR 1341 was used to determine the heating value.
- vi) The jute-stick derived pyrolysis oil can be used as alternative fuel in the thermal power plants, burnt in gas turbines and the upgraded oil may be used as transport fuel.

Acknowledgements

The authors wish to thank the Ministry of Science and Technology of Government of Peoples Republic of Bangladesh and Bangladesh Institute of Technology (BIT), Rajshahi for providing the financial support and necessary facilities for the research study. Thanks are due to the Institute of Fuel Research and Development, and the Analytical Research Division of Bangladesh Council of Science and Industrial Research (BCSIR), Dhaka and the Department of Chemistry of Rajshahi University, Bangladesh for providing necessary facilities for proximate, TGA, CHNOS, FTIR and other analysis.

References

- [1] P. T. Williams, S. Halim, D. T. Taylor, "Pyrolysis of oil palm solid waste," in Biomass for Energy Industry and Environment, edited by G. Grassi, A. Collina and H. Zibetta, Elsevier Applied Science, London, 1992, pp. 757-761.
- [2] M. N. Islam and F. N. Ani, "Characterization of bio-oil from palm shell pyrolysis with catalytic upgrading," in World renewable energy congress, Elsevier Science, 1998, pp 1977-1990.
- [3] A. V. Bridgwater and S. A. Bridge, "A review of biomass pyrolysis and pyrolysis technologies. in Biomass Pyrolysis Liquids Upgrading and Utilization, edited by A. V. Bridgwater and G. Grassi, Elsevier Applied Science, London, 1991, pp 11-92.
- [4] GOB, "1999 Statistical Yearbook of Bangladesh," Bangladesh Bureau of Statistics, Statistical Division of Ministry of Planning, Dhaka, 2001.
- [5] M. R. Islam, M. N. Nabi and Islam MN, "Characterization of biomass solid wastes for liquid fuel production," in Proc., 4th International conference on mechanical engineering, BUET, Dhaka, Bangladesh, vol. 2, 2001, pp 77-82.
- [6] M. R. Islam, R. Ahmed, S. M. S. Ahsan and M. N. Islam, "Hydrodynamic study of fluidized bed cold model reactor for thermal conversion of biomass solid wastes," in Proc., BSME-ASME International conference on thermal engineering, Dhaka, Bangladesh, 2001-2002, pp. 592-598.
- [7] E. Hogan, "Bioenergy development program-thermochemical conversion," in Bio-oil Production & Upgrading, Berkshire, CPL Press, United Kingdom, 1996, pp 1-4.
- [8] P. A. Horne and P. T. Williams, "Petroleum quality fuels and chemicals from the fluidized bed pyrolysis of biomass with zeolite catalyst upgrading," Renewable energy, 5(2), 1999, pp 810-812.
- [9] M. N. Islam, R. Zailani and F. N. Ani, "Pyrolytic oil from fluidized bed pyrolysis of oil palm shell and its characterization," Renewable energy 17, 1999, pp 73-84.
- [10] D. Kunni and O. Levenspiel, "Fluidization engineering," 2nd ed., Stoneham MA, Butterworth-Heinemann, USA, 1991.
- [11] J. P. Halman, "Heat transfer," 7th ed., McGraw-Hill Book Company, London, 1992.
- [12] R. G. Andrews, S. Zukowski and P. C. Patnaik, "Feasibility of firing an industrial gas turbine using bio-mass driven fuel," in Developments in Thermochemical Biomass Conversion, edited by A. V. Bridgwater and D. G. B. Boocock, Blackie Academic & Professional, London, 1997, pp 495-506.
- [13] J. P. Diebold, T. A. Milne and S. Czernik, "Proposed specifications for various grades of pyrolysis oils," in Developments in Thermochemical Biomass Conversion, edited by A. V. Bridgwater and D. G. B. Boocock, Blackie Academic & Professional, London, 1997, pp. 433-447.

- [14] F. N. Ani and R. Zailani, "Characteristics of pyrolysis oil and char from oil palm shells," in *Developments in Thermochemical Biomass Conversion*, edited by A. V. Bridgwater and D. G. B. Boocock, Blackie Academic & Professional, London, 1997, pp 425-432.
- [15] M. N. Islam, F. N. Ani, T. Masuda and K. Hashimoto, "A comparative study on the pyrolytic conversion of rice husk and oil palm shell solid wastes," *Journal of Energy & Environment*, vol. 1, 1999, pp 9-16.