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Performance evaluation of pyrolysis reactor for soybean crop residue

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Abstract
Pyrolysis is the one of the best the technique for production of bio-oil from agricultural crop residues. It is one of the alternatives to replace fossil fuels with the help of feed stocks. Bio-oils may be shipped, stored and utilized much like conventional liquid fuels once their specific fuel properties are taken into account. The soybean crop residue was selected for carrying out research work. Biomass particle size plays an important role during the design of bio-oil reactor and recovery of bio-oil. It was suitable for satisfying the condition of fast pyrolysis. The screw conveyor feeding method was used to feed the raw material in reactor chamber. Temperature throughout reactor was not same. It varies according to height and also with the distance from wall of the reactor chamber. In temperature profile of reactor, it was found that temperature at middle region of reactor chamber was higher than that of top and bottom regions of reactor chamber. The performance of pyrolysis reactor was taken at different temperature of 450, 500, 550 and 600 ^{o}C respectively at that time feeding rate of pyrolysis unit was kept constant i.e. 1 kg/h. The maximum recovery of bio-oil from soybean crop residues was found as 11 (wt.) % at temperature of 550 ^{o}C. The highest recovery of bio-char was found 40 (wt.) % at temperature of 450 ^{o}C. The highest yield of NCG + Bio-oil was estimated 28.5 % at temperature of 600 ^{o}C.

Keywords: Bio-fuel, bio-oil, feed stocks, particle size and pyrolysis reactor

Introduction

Fossil fuels are having very few limited resources, expensive and not globally distributed. Moreover, their use is associated with GHG emission such as CO_2, CH_4, SO_2 and NO_2. Now a days more focus has been placed on the developing the technologies for the conversion of biomass into biofuels as alternative liquid transportation fuels to gasoline and diesel oil (Shi *et al*., 2009) [7]. Among the major reasons cited for the development of biofuel technologies are high crude fuel prices, reduction of dependence on fossil fuels, growing concerns about GHG emissions, which contribute to climate change, potential contribution to sustainable development and rural revenue generation (World watch, 2006) [9]. Globally, about 60% of fossil fuels produce disutilized for transportation. Approximately 98% of transportation fuels used is produced from crude oil. However, the availability, economic sustainability and GHG emissions associated with their utilization pose major problems with transportation fuels. Fast pyrolysis is a viable option uses a non-food renewable resource, which is low cost and globally available unlike fossil fuels, which are finite and located in just a few regions in the world. Bio-oil production as replacement or supplement would reduce the dependence on fossil fuels for transportation and consequently contribute to the national economy through foreign earning savings, job creation and rural development. Moreover, the use of bio-oils would result in reduced GHG emissions compared to conventional fossil fuels.

Biomass sources including wood and wood wastes, energy crops, aquatic plants, agricultural crops and their waste by-products, and municipal and animal wastes can be considered as potential sources of fuels and chemical feed stocks (Shuping *et al.* 2010) [8]. Biomass can be treated in numerous ways to produce gases, liquids or solids, but one of the technologies that has the best industrial perspectives is pyrolysis (thermal decomposition in absence of oxygen or with a low concentration of oxygen without affecting the process to a large extent) since the process conditions can be optimized to maximize the yields of bio-oil, char or bio-char or NCG+BV (gases) products (Amutio *et al.* 2012) [2].

Biomass fuels account for approximately 14 % of the worldwide energy consumption (Hall & Scrase, 1998) [4]. Researchers are concentrating on developing alternative and renewable sources of liquid fuels which are “environmentally friendly.”

Plant/vegetable-derived oil is attracting increased interest in this respect. The pyrolysis process carried out at lower temperature, the bio-oil yield is low due to the less sufficient pyrolysis reaction, which will produce a high content of the char at the same time. Likewise, the excessive temperature will also lead to bio-oil yield decreased resulting from the increase of gas product. In order to achieve high bio-oil yield, the pyrolysis reaction temperature was better to controlled around 500 ºC in the vapor phase for most forms of woody biomass. Vapor residence time was also important to the liquid yield of pyrolysis reaction (Yufu *et al*., 2010) [10].
The main motive of studied here was to investigate effects of temperature on bio-oil, bio-char and gases (bio-oil vapor) yield in the continuous feed reactor in which soybean stalk used as fuel, with the objective of determining the effect of temperatures and biomass particle size on bio-oil yield, important parameter condition and key variable. The project work investigated the impact of reactor temperature on bio-oil yield and other parameter. Study the proximate and ultimate properties of soybean crop residue.

Methodology
Pyrolysis technology is one of the best methods to convert all biomass materials into bio-oil, char and volatiles. Pyrolysis is the process of heating of organic materials in the absence of air or oxygen at high temperature of 500 – 750 ºC. The bio-oil obtained by this process contains 10-20% water. Bio-oil is produced by rapidly and simultaneously depolymerizing and fragmenting the cellulose, hemicelluloses, and lignin components of biomass. In a typical operation, the biomass is subjected to a rapid increase in temperature followed by an immediate quenching to "freeze" the intermediate pyrolytic products. Rapid quenching is important, as it prevents further degradation, cleavage, or reaction with other. Bio-oil is a micro emulsion, in which the continuous phase is an aqueous solution of the products of cellulose and hemicelluloses decomposition, and small molecules from lignin decomposition. The discontinuous phase is largely composed of pyrolytic lignin macromolecules.

Collection of soybean crop residues
The soybean crop residue was collected from Dr. PDKV farm field and store in dry room. Soybean crop residue was chopped and dry in sunlight for a week before being grinded to reduce its particle size as per requirement.

Size reduction of soybean crop residue
Biomass particles have to be very small size to fulfill the requirements of rapid heating and to achieve high bio-oil yields. Biomass feed specifications range less than 2 mm for fluid beds and less than 6 mm for transported or circulating fluid beds. The size reduction of soybean crop residue was done by biomass grinding machine.

Selection of particle size by Sieving
The sieving was done for separating different size of particle from crop residues comes from the hammer mill. The particle retained on sieve and percent weight retained on sieve was determined by following formula.

$$\text{Partical retained on sieve, g} = W_1 - W_2$$

$$\text{Percent weight retained on sieve, \%} = \frac{W_1 - W_2}{W} \times 100$$

Where,
W = Weight of sample taken, g
W1 = Total weight (Sample + Sieve), g
W2 = Sieve weight, g

Moisture content
Electric oven was used to determine the moisture content. Moisture content was determined by heating 1 g of air dried biomass samples to 105 ºC to 110 ºC for 1 h and calculating the loss in weight as percentage.

Volatile matter
Volatile matter was determined by heating 1 g of air dried biomass sample exactly for 7 minutes in translucent silica crucible of specified dimensions at a steady temperature of 925 ºC in a muffle furnace. The loss in weight calculated as percentage minus the percentage moisture gives the percentage volatile matter.

Ash content
Ash content was determined by heating biomass samples at 400 ºC. A known quantity of powdered sample until most of the carbonaceous matter is burnt off and then heating for 1 h at 750 ºC to complete the combustion. The weight of the residue reaming in the crucible corresponds to the ash content of the biomass, which was reported on percentage basis.

Fixed carbon
The sum total of the percentages of moisture, volatile matter and ash was subtracted from 100 to give the percentage of fixed carbon.

Ultimate analysis
The ultimate analysis determines the elements analysis containing carbon, hydrogen, oxygen, nitrogen and sulpher. The elemental analysis of the sample was done by CHNS analyzer. The known quantity of sample was placed in analyzer and data of carbon, hydrogen, oxygen, nitrogen and sulpher was recorded.

Pyrolysis reactor
Pyrolysis reactor developed and fabricated at Department of Unconventional Energy Sources and Electrical Engineering Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola. Pyrolysis of soybean stalk was performed in a continuous feed pyrolysis reactor. The unit was composed of strip heater, hopper, screw conveyor, cyclone separator, condenser and bio-char and bio-oil collection unit. The reactor was made from a MS pipe 100 mm diameter and 1.5 meter height. The reactor was heated by strip heater by providing electrical supply of 7.5 Kw, 5 Nos. of stripper heater having 1.5 Kw capacity output each are fitted around the outer body of reactor pipe at equal distance. Thermal insulation was accomplished with adiabatic material (glass wool) around the reactor and the immediate vicinity to minimize heat losses. The temperature of the pyrolysis system was adjusted using temperature controllers and was monitored using J-type thermocouples. The pyrolysis vapour produced was cleaned up in cyclone separators and a hot filtration unit prior to condensation. Pyrolysis vapour was condensed into liquid product by a water cool heat exchanger and ice/cold water in condenser unit.

Pyrolysis reactor experiments
We selected 4 levels of the temperature i. e., 450 ºC, 500 ºC,

550 °C and 600 °C and the biomass particle size was 2 mm. The feed rate of each experiment trial was around 1 kg/h. Air strip heater was used for heating purpose and temperature control by automatic temperature controller with the help of J-type thermocouple and temperatures is display on digital temperature indictor. The total time of each test run was approximately 1 hour. To achieve the goal of these variables, a total 3 replication of experimental trial runs were performed for accurate result.

Mass balance calculation

The main products from fast pyrolysis process are bio-oil, bio-char and non-condensable gases bio-oil vapour (NCG+BV). The yields of each product were calculated by weighing the output of bio-oil yield, bio-char yield and NCG+BV. The bio-oil yields were the combined weight of liquid from the product collection unit. The bio-char yields were the combined weight of solid from the reactor at outlet. The gas yields were calculated by addition of this two (bio-oil and bio-char) from total biomass fuel used [100- (bio-oil + bio-char)].

Result and Discussion

Selection of particle size of soybean crop residue for experiment

The sieve analysis was done for particle separation from raw material. Table 1 shows that the per cent weight retains on each sieve. The material retain on sieve No. IS-170, IS-140, IS-70, IS-40, IS-20 were 24, 12, 16, 22, 08 and 18 per cent respectively. The highest material retain on sieve No. IS-170 i.e. 24 per cent. The particle size of crop residue less than 0.2 mm shows lowest falling velocity and it remains for falling 2.29 s in reactor. The particle size less than 0.2 mm was suitable for satisfying the condition of fast pyrolysis i.e. these remains maximum time (1 to 5 s) in reactor chamber during free falling.

Table 1: Sieve analysis of soybean crop residue

Sieve No	Sieve weight (g)	Sieve Wt. + sample Wt. (g)	Sample fraction (g)	Per cent weight retain
IS-170	400	500	120	24
IS-140	400	450	60	12
IS-70	300	400	80	16
IS-40	300	400	110	22
IS-35	350	400	40	08
IS-20	300	400	90	18

Table 2: Free falling velocity of different size particle for soybean crop residue

Sieve No	Particle size (mm)	Velocity (m/s)	Time take to travel 1.5 m distance in reactor, (s)
IS-170	1.70	2.42	0.62
IS-140	1.40	1.40	1.07
IS-70	0.70	1.21	1.23
IS-40	0.40	1.14	1.31
IS-35	0.35	0.94	1.59
IS-20	0.20	0.65	2.29

Table 2 also shows that the time taken by particle to travel 1.5 m (height) in reactor chamber. The particle size 1.70, 1.40, 0.70, 0.40, 0.35 and 0.20 mm shows time taken to travel in 1.5 m reactor chamber were 0.62, 1.07, 1.23, 1.31, 1.59, and 2.29 s, respectively.

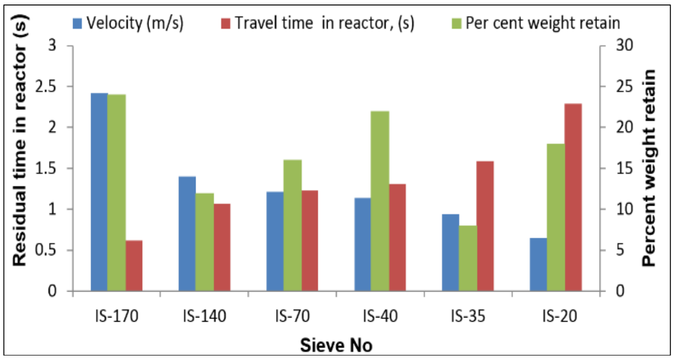

Fig 1: Effect of particle size of soybean crop residue on residual time and velocity

Fig.1 shows that free falling velocity increases with increase in particle size. This is obvious as the higher size particle has higher weight and falls faster than lighter particle, overcoming air resistance in better manner. The particle size less than 0.2 mm shows lowest falling velocity and it remains for falling 2.29 sec in reactor. The particle size less than 0.2 mm was suitable for satisfying the condition of fast pyrolysis i.e. these remains maximum time (1 to 5 s) in reactor chamber during free falling.

Characterization of soybean stalk sample

The proximate and ultimate analysis of soybean stalk are given in Table 3 which shows that the raw materials contains higher per cent of volatile matter 71.13 per cent and less amount of moisture and ash content 6.87 per cent, 5.44 per cent whereas fixed carbon content in sample was found that 16.56 per cent. Volatile matter evolves in the form of gas, hydrocarbon and tars. Higher volatile matter of the biomass makes it more acceptable for bio-oil production. Ash content and moisture content affect the heating value of bio-oil. Ash content depends upon the plant and soil condition in which the plant grows. There characteristics of raw material shows soybean stalk has ability to produces bio-oil. The bulk density of soybean stalk was 128.36 kg/m^3 and calorific value of soybean stalk i.e. HCV and LCV was 16.88 and 15.41 MJ/kg, respectively. High calorific value indicates good characteristics for pyrolysis and gasification, because higher heat generated during combustion leads to high temperature in reaction zone.

Table 3: Proximate and ultimate characterization of soybean stalk sample

Properties	Soybean stalk
Bulk density, (kg/m^3)	128.36
Calorific value, (MJ/kg)	
HCV	16.88
LCV	15.41
Proximate analysis	
Moisture content, (%)	06.87
Volatile matter content, (%)	71.13
Ash content, (%)	5.44
Fixed carbon content, (%)	16.56
Ultimate analysis	
Carbon, (%)	43.63
Hydrogen, (%)	6.67
Oxygen, (%)	1.63
Nitrogen, (%)	0.69
Sulpher, (%)	41.94

Ultimate analysis represents the elemental analysis which belongs to carbon, hydrogen, oxygen, nitrogen and sulpher. Soybean stalk was higher in carbon content and less in hydrogen, oxygen, nitrogen and sulpher content. For thermochemical process, carbon is the most important element in the fuel as it has direct influence on the heating value according to same, higher the carbon content (43.63 %) of soybean stalk represents higher heating value of fuel. Studied the ultimate analysis of palm kernel shell and reported the carbon, hydrogen, oxygen, nitrogen and sulpher content 44.56, 5.6, 49.77, 0.4 and 0.05 %, respectively.

Temperature profile of reactor

The reactor was designed to maintain the desired temperature uniformly throughout the chamber. As the radial heating was used for heating up the system, the uniformity in temperature inside the reactor could not be maintained experimentally. It was due to fact that the existing air in the reactor at initial stage (Under no load condition) under through convective heat transfer. The temperature of middle zone of reactor was found to be higher than the top and bottom region of reactor. Measurement conducted to find out the radial temperature gradient, it was found that center portion of the reactor was high in comparison to the location close to periphery wall of reactor.

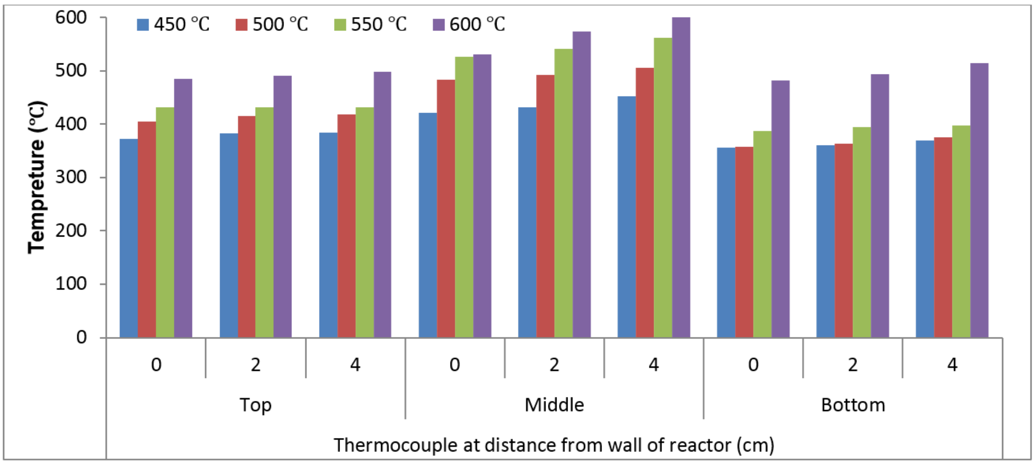

Fig 2: Time required for preheating of bio-oil reactor for different temperature

Recovery of bio-oil and bio-char

Recovery of bio-oil and bio-oil and bio-char was studied and explained in table 4. During the study the feeding rate kept constant i.e. 1 kg/h. Table 3 shows the recovery of bio-oil and bio-char. The recovery of bio-oil at temperature of 450, 500, 550 and 600 ºC were found to be 11.6, 13.8, 12.2, and 10.9 (wt.) per cent, respectively. It showed that highest recovery of bio-oil was obtained at temperature 500 ºC.

Table 4: Recovery of bio-oil at different condition

Sr. No.	Temperature (ºC)	Bio-oil (g/h)	Bio-Char (g/h)	NCG + BV (g/h)
1	450	116	546	338
2	500	138	532	330
3	550	122	498	380
4	600	109	426	465

The recovery of bio-char at temperature 450, 500, 550 and 600 ºC found to be 54.6, 53.2, 49.8 and 42.6 (wt.) per cent respectively. These higher values of char production may be due to presences of some un-charred raw material in experiment conducted due to lower temperature regime inside the reactor. The yield of Non-condensable gases + bio-oil vapour at temperature of 450, 500, 550 and 600 ^{0}C found that 33.8, 33.0, 38.0 and 46.5 (wt.) per cent respectively at feeding rate 1 kg/h. it showed that highest yield of Non-condensable gasses + bio-oil vapor was obtained at temperature 600 ^{0}C. It also showed that yield of Non-condensable gases + bio-oil vapor was high at higher temperature.

Conclusion

The soybean crop residue contains higher per cent of volatile matter 66.66 per cent and less amount ash content 13.33 per cent**.** Whereas fixed carbon content in sample was found to be 10.00 per cent. Temperature in the system set were 450, 500, 550 and 600 ^{0}C then maximum temperature gradient seen at bottom of reactor chamber were 98, 140, 175 and 117 ºC respectively and maximum temperature gradient seen at top region of reactor were 63, 85, 116 and 100 ^{0}C respectively. The feeding rate of system kept constant during recovery of bio-oil and bio-char at both condition. The recovery of bio-oil with different temperature of 450, 500, 550 and 600 ^{0}C were found to be 90, 105, 110 and 95. (wt.) per cent, respectively. The recovery of bio-char different temperature of 450, 500, 550 and 600 ºC were found to be 540, 510, 595 and 360 (wt.) per cent respectively. The yield of Non condensable gases + bio-oil vapour at different temperature of 450, 500, 550 and 600 ºC were found to be 370, 385, 295 and 545 (wt.) per cent respectively.

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