



Twin Screw Reactor Design for Biomass Pyrolysis

Debajyoti Bose^{1,a}, Aditya Mekala^{1,b}, Leena Kapoor^{2,c}

¹Department of Electrical, Power & Energy, College of Engineering Studies,
University of Petroleum & Energy Studies, Dehradun, India

²Department of Chemical Engineering, College of Engineering Studies,
University of Petroleum & Energy Studies, Dehradun, India

^{a-c}E-mail address: debajyoti1024@gmail.com , aditya_mekala@yahoo.com ,
lkapoor@ddn.upes.ac.in

ABSTRACT

The process of fast pyrolysis using biomass to produce bio-oil or pyrolysis oil for application as an energy source and a chemical feedstock is of interest in this study. The literature on biomass fast pyrolysis is surveyed here and how parameter such as feed rate, temperature, rate of heating, and residence time affects the process. Investigation for this work includes the pyrolysis of sawdust and bagasse through fast pyrolysis in an auger reactor. Temperatures between 350 °C and 450 °C have been applied to characterize the yields and reactor problem has been identified. This work reports the problems faced with the twin screw reactor, troubleshooting which will result in bio-oil, one of the main products of fast pyrolysis. System produced solid biofuel or bio-char much of which is in the research phase as a climate change mitigation tool. Further use of professional CAD software to model and optimize the system has also been covered. Based on which suitable design changes are also developed to overcome the problems. Analysis of feed material and the solid biofuel is covered in this work as well. Pyrolysis experiments can be done using a wide range of biomass feeds. But not much of it has been studied in twin screw reactors. This scant knowledge over the study of such alternative fuel has been the reason to look into this activity.

Keyword: pyrolysis; screw reactors; bio-oil; bagasse; sawdust

1. INTRODUCTION

The consistent use of renewable energy components is an effective way to reduce the dependence on fossil fuels (crude oil, natural gas and coal) especially in the industrialized nations. The introduction of renewable energy can make a remarkable contribution to reducing CO₂ emissions; which essentially reduces the carbon footprint and thus diminishing the anthropogenic greenhouse effect. Although it makes up only about 5% of global population, statistics reveal that the United States itself was responsible for 22% of world-wide anthropogenic CO₂ emissions caused in 1995 [1].

For example, nearly one-third of the emissions from the United States are attributed to transportation, including aircraft, ships, trains, and motor vehicles [2]. Among all renewables, biomass is the source which is considered carbon neutral hence a suitable alternative to be used in the long run as raw material for production of carbon-containing materials and other energy sources.

The addition of biomass to mobility is however subject to controversy in the public and in professional circles. However, without any doubt, liquid fuels are far more promising as they have high energy densities which will continue to make a significant contribution particularly in the transport sector.

Biomass is a term for all natural material that stems from plants. It has turned into the fourth biggest essential vitality asset on the planet after coal, oil and common gas. In perspective of the lack of fossil fuels and the environment worry about levels of CO₂ in the environment, feasible warmth and force era from biomass are at the focal point of experimental and modern interest. There are numerous change innovations for using biomass, for example, direct ignition process, warm substance process, bio-chemical procedure and agrochemical process.

Pyrolysis is a thermochemical process that can be depicted as the immediate warm deterioration of the biomass without oxygen to acquire strong, fluid and gas items. For building applications, sound comprehension of pyrolysis qualities and energy is a key for planning the suitable reactor. Pyrolysis is the thermal degradation of complex organic molecules in an oxygen-free environment [3].

It is a thermo-chemical process of biomass conversion where the first step is gasification and combustion; compared to other biomass conversion processes it takes place at relatively low temperatures. Pyrolysis gives products in three phases; the char is the solid residue and principally consists of carbon, the liquids in the form of condensable gases in vapor phase, this can be condensed to form bio-oil and the non-condensable gas. The yields distribution among the products depends on the feed composition as well as on the pyrolysis parameters such as temperature, heating rate and the residence time of the vapors.

The objective of this exploration is to add to a structure for a frameworks situated way to deal with the assembling, position, and ideal estimating of a Fast Pyrolysis Units producing base that lessens capital costs, speculation hazard and is more receptive to changes in vitality requests. The proposed approach underpins the advancement of a disseminated bioenergy framework. This work concentrates with respect to the assembling procedure appraisal of biofuel generation units. The exploration yield is fuse into progressing endeavours to further improvement of bioenergy frameworks [4-10].

In this work we have tackled four issues related to this field of work.

1. 1. Complete overhauling of the existing screw reactor

The existing screw reactor suffered from problems of regular choking, such is minimized. System was dismantled carefully assembled, the main components of the system are:

- Biomass feeding assembly
- Heat carrier sub-system
- Auger (Twin Screw) reactor assembly
- Product recovery through condenser and Char tank system

After assembling standard experiments were performed with Bagasse and sawdust as feed, to check the whole assembly, choking problem has significantly minimized but not totally.

Other developments:

- Frog pumps were installed and related piping arrangement connecting the condensers to one another and establishing the water circulation network through the condensers.
- Insulation with glass wool wherever required.
- Nitrogen cylinders connected to the system via rotameter is operated under 2 bar pressure.

1. 2. Developing design changes to achieve improved quality (or better yield) of the biofuel

1. 3. Production of biofuel using twin screw reactor from various biomass sources

1. 4. Optimization and modelling of the screw reactor

The above three mentioned (1.2, 1.3, & 1.4) has been discussed in the results and discussions section. Bio-oil has many environment-based advantages over fossil fuels as it is a clean fuel. Bio-oils are CO₂/GHG neutral. Hence, they will generate carbon dioxide credits. SO_x emissions are relatively less, as plant biomass contains minute percentages amounts of sulfur. Hence, pyrolysis oil will not be subjected to SO_x related taxes. Bio-oil or pyrolysis oil generates 50% lower NO_x emissions compared to diesel oil in a gas turbine. Efforts are underway for developing this fuel from organic wastes and other related wastes as well. Thus bio-fuels are cleaner and cause less pollution [11,12].

2. METHOD

In this we have shown that an extruder could be used as a reactor for liquefying biomass feed through exothermic reactions in an auger reactor. A lot of research has been done worldwide on biomass pyrolysis using various types of reactor but not much work has been done in a screw reactor, this scant knowledge has prompted us to foray in this activity. The process employed is fast pyrolysis, which is a high-temperature process in which biomass is rapidly heated in the absence of oxygen. The main body of the reactor is a horizontal pipe made of AISI 316 steel. Inside the main pipe, assembled two screws goes along all pipe length of the pipe. At both the ends, gear arrangement is done with the screw imposing a

rotation movement on it. The rotation of the screw carries the biomass sample from the biomass inlet towards the heating/reaction. A resistance coiled over main pipe provides heat for the reaction and defines the reaction zone. The temperature is monitored using thermocouples located along the pipe. Nitrogen is used as inert and carrier gas. After reaction, char is quickly collected in an enclosed flask and bio-oil is collected in flasks by rapid condensation of the hot vapors in two condensation stages. The non-condensable gases proceed their way to an exhaust system.

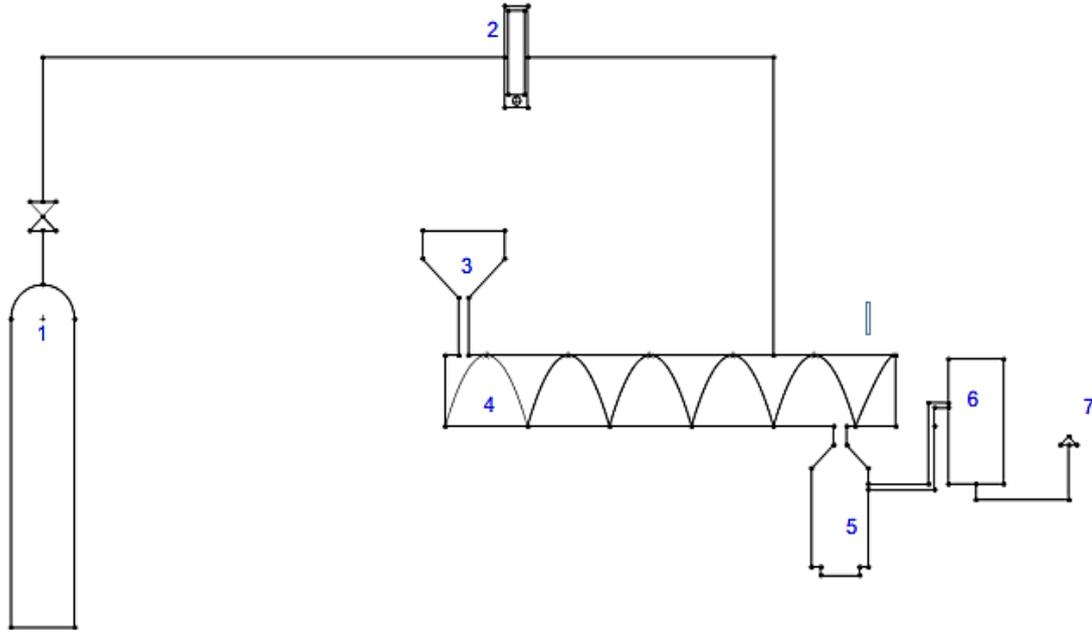


Figure 1. The overall system that was used in this experiment, 1- Nitrogen cylinder, 2- Rota meter, 3-Screw Feeder, 4- Twin screw reactor, 5- Char tank, 6- Condenser assembly, 7- Outlet.

The equipment that was used for this experimental setup was a co-rotating twin-screw extruder with a screw length of 565 mm. Figure 1 (design made in SolidWorks 2014) shows the system assembled that was studied. There were two barrel sections: the first section performed the task of feeding and conveying, and the temperature was monitored using thermocouples through various openings on top of the extruder. The second section was used for heating, mixing; the temperature was 454 °C. Normally, the extruder wall temperature was 25-30 °C lower than the temperature of the coil used to heat it externally. There are 5 orifices on the reactor. The diameter of each orifice was 0.78 mm. Cooling water was added into the condenser using a water pump. The moisture content of sawdust in the extruder was maintained at 5.58%. The sawdust was fed by a screw feeder whose rpm was maintained in the range of 18-30 rpm. The feed rate was highlighted in form of rpm on the control panel. The calibration is shown in Table 2 to convert the feed rate from rpm to kg/h for the biomass feed input. For this work rpm is used instead of kg/h for feed rate in this paper. However suitable ASME graphs can be used to directly obtain relation between these parameters and the volumetric feed rate. For our system, three feed rates 15, 25 and 30 rpm, were used. Another operating variable was screw speed and that was controlled at 45, 55 and 60 rpm.

Table 1. Feed rate calibration adopted from [16].

Screw Feeder (rpm)	Feed rate of Biomass Feed (kg/hr)
10	13.92
15	19.50
20	24.78
25	32.88
30	44.62

3. FEED MATERIAL

Bagasse was brought from Doiwala Sugar Plant in Dehradun, India and it was analyzed, given below are its proximate analysis and GCV.

Table 2. Proximate analysis of Bagasse.

Parameters	Expressed in Percentage
Volatile Matter	76.72
Ash	2.19
Moisture	10.39
Fixed Carbon	10.84
Total	100

Gross Calorific Value for bagasse was determined using Bomb Calorimeter and it was **3965.18 Kcal/Kg**. Sawdust was available at the University campus, here in Dehradun and was subject to similar analysis. Gross Calorific Value was determined using Bomb Calorimeter for sawdust and it was **2069.88 Kcal/Kg**.

Table 3. Proximate analysis of Sawdust

Parameters	Expressed in Percentage
Volatile Matter	58.23
Ash	6.98

Moisture	12.95
Fixed Carbon	21.84
Total	100

4. REACTOR AND TWIN SCREWS

The fast pyrolysis system available for this investigation is shown below, following the description of each sub-system that exists with it. The system comprises of the following principal components: screw feeder for biomass, auger reactor assembly with the twin screws, product collection with blast condensers, data acquisition NI Logger and speed control systems.

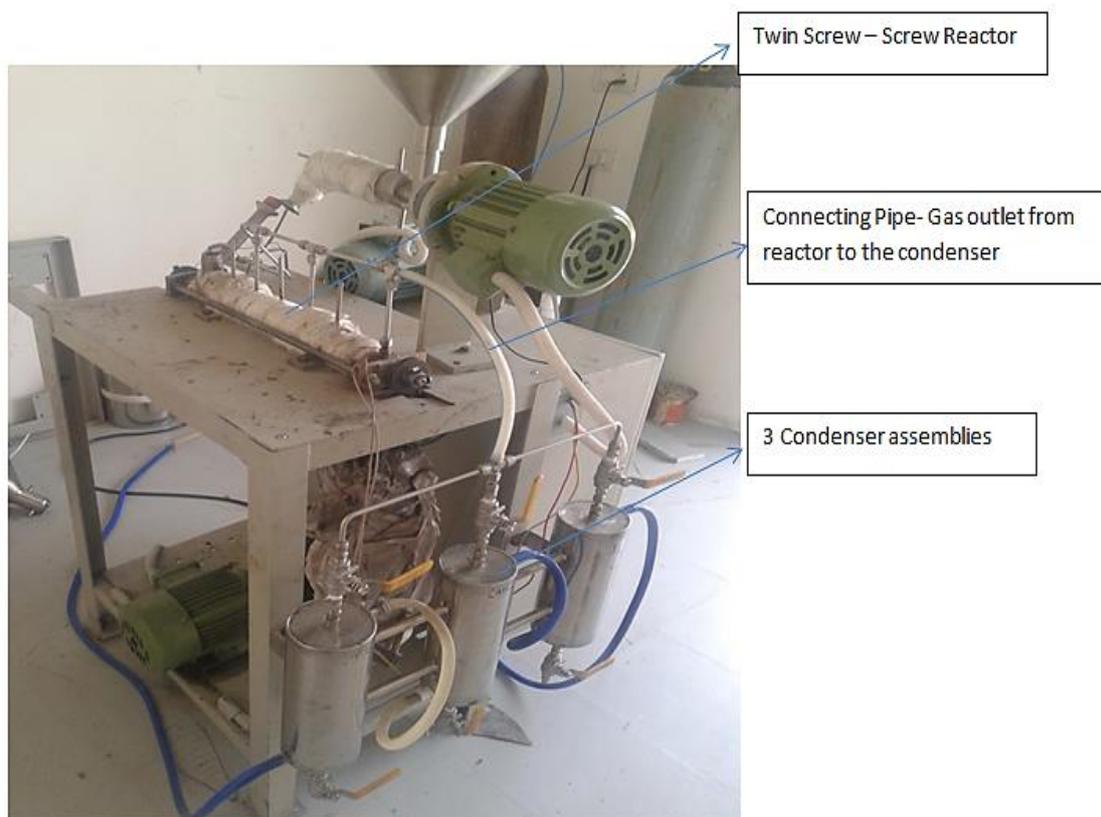


Figure 3. The Pyrolysis System on which experiments were conducted.

For a “lab-scale” biomass fast pyrolysis system, biomass feed rates around 0.5 kg/hr – 2.0 kg/hr are common. Therefore, early in the design phase a nominal biomass feed rate of 1.0 kg/hr was selected and became a fixed parameter. Heat carrier was sand, mixed with biomass (1:1) and charged into the feed hopper. The SolidWorks 2015 Professional software was used extensively during the design phase for liquid bio-fuel.



Figure 4. Char Tank to collect solid biofuel (5.84 liters capacity).

The screw geometry and design holds equal significance. For ensuring proper mixing inside the reactor, a twin screw design which loosely resembles the FZK system was considered. The possibility with a single screw reactor was taken into account but not selected. Literature on mechanical conveying for bulk solids was reviewed to determine proper standards and related parameters. Given is the design of the screw made in SolidWorks 2015.



Figure 5. Made in SolidWorks 2015, one of the twin screws.

There are other auger designs as well those are not considered, owing to the concerns of corrosive, abrasive nature and high temperature inside the reactor. After the above case in (1.50 cm) was selected as a suitable screw diameter, the reactor dimensions were taken into account. And there was some provision maintained for spacing between screws and the reactor. With the twin screw measurements determined, and the base zone and volume prerequisites known, the reactor measurements and geometry were drafted in the PC

supported configuration bundle SolidWorks 2015. To take out any potential "dead space" between twist drill flighting where biomass and warmth bearer are not ready to blend, the reactor cross-area is omega-formed (ω) instead of the rectangular configuration utilized by FZK.

Pinewood, bagasse and Sawdust were pyrolyzed at 450 °C (reactor temperature) with a nitrogen stream rate of 526 mL/min at air weight. Upon these conditions the nitrogen temperature at its channel into the reactor was observed to be 65 ±4 °C. The rotational speed of the screw was held at 55 rpm. The tests were directed with biomass tests of 50 g legitimately arranged as portrayed in segments later. The temperature of the buildup/refrigerant liquid (chilly water) was continued utilizing ice. The test conditions depended on trial concentrates on completed preceding directing the test runs. The trial contemplates brought up the above conditions as the most encouraging states of a fast pyrolysis process with the most elevated yields of bio-oil, without trading off its properties.

Four relevant temperatures are monitored using type-K thermocouples placed along the pipe's outer wall. A developed temperature control system allows the monitoring of such temperatures and the temperature control on the reaction zone. The system consists in a data acquisition board NI-9211 (National Instruments), a Virtual Instrument (VI) interface program for temperatures monitoring and control, and an actuator system based on a multifunction board NI USB-6008 (National Instruments) settled in an auxiliary relay circuit. The system works as a feedback control system, establishing a fixed temperature (reactor temperature) on the reaction zone with the heating resistance. The main pipe is insulated to prevent heat losses.

5. RESULTS AND DISCUSSIONS

The Biomass material used for experiments was locally sourced from inside Dehradun. Bagasse and sawdust came in natural form. Before each test on the pyrolysis reactor, samples of each feedstock were properly prepared. Bagasse was brought from Doiwala Sugar Plant in Dehradun, Uttarakhand whereas simple wooden sawdust and pinewood sawdust were procured from local carpenters at Saharanpur Chowk, Dehradun; Uttarakhand. These raw materials were then screened at approximately 2 mm and then analysed its proximate analysis and GCV are discussed already in the previous section. The utilization of biomass as feedstock from which to create vitality is not a new idea. Be that as it may, innovation exists where these assets are utilized to give vitality and in the meantime the chance to sequester C from the environment. The pyrolysis of biomass serves to give vitality (by means of bio-oil and syngas that are in this way used to run steam turbines) and the intentionally delivered material "biochar."

Table 4. Biochar characteristics of the biomass feeds used in the system.

Analysis	Sawdust	Bagasse
Ash (%. Wt.)	11	36
Moisture (%Wt.)	3.2	1.3

C (%Wt.)	75	60
H (%Wt.)	3.5	2.9
N (%Wt.)	<0.5	2.2
S (%Wt.)	<2	<2
O (%Wt.)	19	32.9
O/C	0.25	0.55
H/C	0.09	0.05
Higher Heating Value, MJ/Kg	26.3	21.6
Low Heating Value, MJ/Kg	24.9	22.9

Biochar is a carbon rich material from the pyrolysis of biomass. The use of biochar to soil is a noteworthy long haul sink of barometrical carbon dioxide in physical biological systems. The part of biochar in carbon sequestration in decreasing the emanation of nursery gasses, and enhancing soil ripeness prompted the suggestion of biochar as an alteration of soils. Also, biochar offers a basic, manageable device for turning so as to oversee rural and urban squanders it into significant items. Consolidation of biochar in soil can apply both short and long haul impact on its wellbeing. Transient advantages incorporate a liming impact for soils with low pH and long haul impacts incorporate expanded supplements and water maintenance limit of soil that can influence the harvest efficiency.

The reason for applying biochar to soil mostly falls into four general classes:

- Agricultural gainfulness;
- Management of contamination and eutrophication danger to nature;
- Degraded Land Restoration and
- Sequestration of C from the air

Agricultural Gainfulness

Eutrophication is worldwide natural debasement. Leachable supplements and pesticides from soil to decrease eutrophication and contamination dangers in nearby water bodies, and also to diminish the requirement for compost application that would be required to make up for such supplement misfortunes. Biochar adsorbs supplements phosphate and ammonium that cause eutrophication, and by adsorbing pesticides before they enter neighbourhood water sources.

Degraded Land Restoration

Re-vegetation endeavours for disrupted terrains, by biochar, goes about as a transporter for advantageous soil microorganisms, for enhanced CEC, soil accumulation, and water-holding limit. Biochar application rate relies on soil sorts and yields. Biochar application on product yields with rates of 5-50 tons of biochar per hectare, with suitable supplement administration. Biochar hard-headedness to disintegration in soil, single utilizations of biochar gives advantageous impacts more than a few developing seasons in the field.

The objective application rate differs with the accessibility of the biochar supply, and the dirt administration framework, corrections can be connected in increases.

Sequestration of C from the air

Most carbon in the dirt is lost as nursery gas (carbon dioxide, CO₂) into the air if characteristic environments are changed over to rural area. Soils contain 3.3 times more carbon than the air and 4.5 times more than plants and creatures on earth. This makes soils an imperative wellspring of nursery gasses additionally a potential sink if right administration is connected. The utilization of yield build ups for bio-vitality generation diminishes the carbon stocks in cropland. Further the devotion of cropland to bio-fuel creation builds the range of developed area and subsequently carbon misfortune from soils and vegetation.

Pyrolysis of waste biomass can produce fills and biochar headstrong against decay. In the event that biochar is come back to agrarian area it can build the dirt's carbon content for all time and would set up a carbon sink for climatic CO₂. For this situation the utilization of product deposits as a potential vitality source might enhance soil quality and lessen nursery gas discharges in a reciprocal not contending way. Biochar is proposed as a dirt correction in situations with low carbon sequestration limit and already drained soils (particularly in the Tropics). From past studies it is realized that dirt biochar changes increment and keep up soil ripeness and the human-made Terra Preta soils in the Amazon demonstrate that barren soils can be changed into fruitful soils and long haul carbon advancement is possible even in situations with low carbon sequestration limit.

The theoretical establishments of biochar as an air CO₂ evacuation component lie in the photosynthetic procedures that create the biomass to be utilized for biochar generation. As biomass develops it uproots air CO₂. The creation of biochar changes over relatively labile C present in the biomass into stubborn C intensifies that oppose mineralization. Thusly the rate of return of C to the climate is extraordinarily restrained. It is the contrast between the (moderately quick) rate of air CO₂ sequestration into biomass contrasted with the ensuing (generally moderate) rate at which biochar C is mineralized that offers ascend to net stockpiling of C; and by this token the chance to create warmth and force by C-negative means.

The feed hopper had equal proportions of sand and biomass mixed as it was charged inside the reactor, using the sand as a heat carrier, in principle using a heat carrier like sand should not be a problem, but problems related to trouble with wear has been reported. For the setup that has been demonstrated here we found that the passage of nitrogen was often obstructed, and the gas formed after heating of the biomass found it very difficult to travel to the condenser and got accumulated mostly inside the char tank, although it has to be mentioned that some leaks were detected in the system that contributed to the condensable and uncondensed gases escaping from the system. Based on the aforementioned observations the design improvements are considered.

Char is formed successfully in the present system within the residence time of 8 seconds. Based on the above the following design is suggested. It is reported that the formation of the pyrolysis oil or bio-oil is a tricky process, and this proposed design is presently being worked upon, given below are the dimensions in inches for the system that is being designed presently.

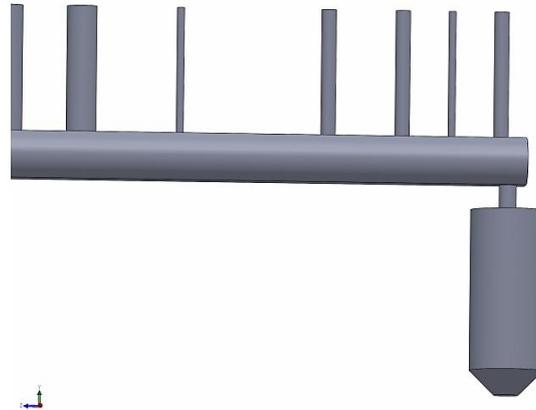


Figure 6. Proposed design with separate feeders for sand & biomass.

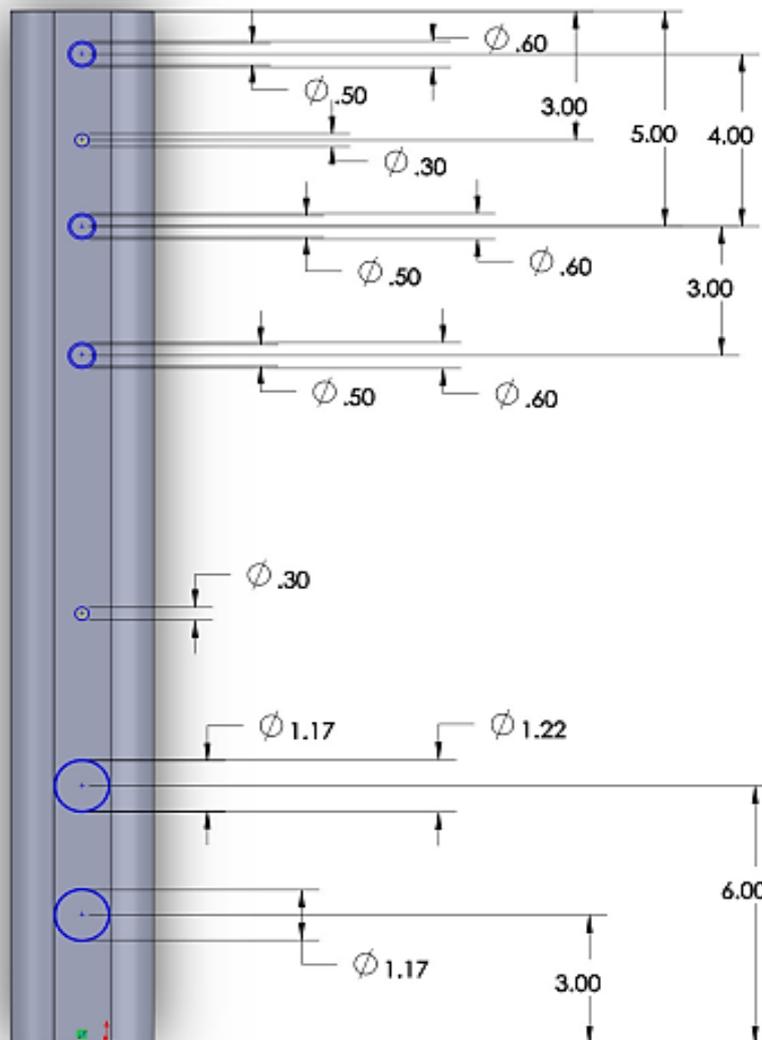


Figure 7. All dimensions are in inches; dimensions for Figure 4.

The Figure 7 shows the top view of the reactor. Starting from the bottom of the figure the first opening is for the Sand feed with a motor is given. Then the second opening is given for the Biomass feed. Then the small slots which are given and are of dia 0.3 inch are given for thermocouples for measuring temperatures. The remaining three slots are given for the Gas outlets. The gas is collected from the three slots and further combined as 1 slot and then it is condensed through a condenser and is converted into oil. This oil is the final product of the project.

Present work ends here with the possibility of bio-oil production from this new improved design, this work has demonstrated the system is feasible for producing biofuel, and hence it can be speculated to have this design take a future leap from R &D to commercialization, with help of platforms such as the National Biofuel Policy pyrolysis units can cater to the needs of alternative fuel [13-16].

6. CONCLUSIONS

It is believed that the fast pyrolysis for biomass can cater the world's need for liquid fuels and, ultimately, simultaneously it is effective for producing chemicals. However, the complex feeding parameters coupled with other variables makes it difficult to come up with a definitive standard process. In this investigation, the available Twin screw pyrolysis reactor has been demonstrated as a research tool to study the pyrolysis process and speculate the possibility of making it commercially viable. The pyrolysis experiments were carried out using Sawdust & Bagasse mostly, as reference feedstock. The investigated parameters were the reactor temperature of 350-450 °C, the initial flow rate and the residence time of the solids of 1.5 kg/h and 8-10 seconds, to emphasize on the effect of the heating rate on such processes, and we found that in this setup solid bio-char is formed successfully but the liquid product requires further system integration, suitable changes has been proposed and developed to continue this study further which would lead to the speculation of producing liquid biofuel or bio-oil from this system.

The feeding system has shown some limitations namely dealing with the low "fluidity" of biomass in the feeding column, which led to blockage of biomass in many cases and the sabotage of the test. Furthermore, bigger amounts of biomass sample to pyrolyze led to bigger cases of blockage. A new configuration for the feeding system (e.g. hopper and screw feeder) should be useful to pyrolyze bigger quantities of biomass and to permit a continuously operation for the reactor that simplifies the experiments in many aspects. A preliminary project of the screw, attending fast pyrolysis features, would be an extra aspect to optimize results. The material and geometry of the new screw would have to permit a consistent transport of the particles, an efficient and rapid heating rate with a good escape of the hot vapors. A more rapid heating rate would be achievable if the screw was heated internally through an incorporated resistance. This would be an interesting point to keep in mind for a new design.

The pre-heating of nitrogen to considerable temperatures was an experimental fact shown in other works and has been pointed out as a possible reason to decrease the performance of the reactor, as far as it may increase thermal losses. So, it would be interesting to pre-heat nitrogen to higher temperatures and analyse its effect on the results. A new design of the main pipe with a more efficient separation of products at its end would also be an

improvement to achieve better results. The char must be removed as soon as possible from the reaction to avoid secondary reactions. This would be achievable through a possible cyclone connected directly to the main pipe that would separate the solid phase from the gas/vapour phase. A thermal blanket at 400 °C applied around the cyclone till the condensation stage would avoid the pre-condensation of vapors.

In regard to the condensation, it would be interesting to analyze the influence of other type of condensers on the results since condensation is crucial in any pyrolysis process. As said before, the condensers used in the present work showed a compromising behaviour since the trial tests and may have induced bigger water content, in relative terms, in the bio-oil sample.

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