Effect of operating parameters on production of bio-oil from fast pyrolysis of maize stalk in bubbling fluidized bed reactor

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The yield and composition of pyrolysis products depend on the characteristics of feed stock and process operating parameters. Effect of particle size, reaction temperature and carrier gas flow rate on the yield of bio-oil from fast pyrolysis of Pakistani maize stalk was investigated. Pyrolysis experiments were performed at temperature range of 360–540°C, feed particle size of 1–2 mm and carrier gas flow rate of 7.0–13.0 m³/h (0.6–1.1 m/s superficial velocity). Bio-oil yield increased with the increase of temperature followed by a decreasing trend. The maximum yield of bio-oil obtained was 42 wt% at a temperature of 490°C with the particle size of around 1.0 mm and carrier gas flow rate of 11.0 m³/h (0.9 m/s superficial velocity). High temperatures resulted in the higher ratios of char and non-condensable gas.

Keywords: fast pyrolysis, bio-oil, temperature, particle size, carrier gas flow rate, maize stalk.

INTRODUCTION

Pakistan is an agricultural country and produces around 69 million tons of field based crop residues annually, out of which 2.50 million tons is maize stalk. Maize stalk can be used for the production of renewable energy through pyrolysis process. Pyrolysis is a thermochemical conversion process used to convert biomass into liquid fuel^{1, 2}. It is thermal decomposition of biomass by heat in the absence of oxygen to yield liquid, solid and gaseous products^{3, 4}. It is not possible to define pyrolysis specifically because in early times it named as carbonization in which primary product is charcoal. Today the term pyrolysis is understood for the process in which liquid fuel is the key product. In present energy development, pyrolysis process has attained distinct consideration because of biomass conversion into energy rich products. Pyrolysis is thought to be a promising route for conversion of biomass into bio-fuels and chemicals^{5–7}. The basic reaction taking place during pyrolysis process is:

Biomass → Charcoal + Volatiles

The process of pyrolysis may be categorized as fast pyrolysis, conventional pyrolysis and flash pyrolysis^{8, 9}. Conventional pyrolysis may be known as slow pyrolysis or carbonization which takes place at reaction conditions of low temperature, slow heating rate and high vapor residence time. Charcoal is known as the principal product of this pyrolysis process. Fast pyrolysis process is conducted to yield liquid fuel at moderate reaction temperature and short vapor residence time whereas flash pyrolysis follows at high heating rate, very short vapor residence time of few seconds or less and very fine feed particle size (≤ 2 mm)^{10–12}.

The yield and composition of bio-oil depend on the biomass feedstock and the operating conditions^{8, 13–15}. Reaction temperature, biomass feed size, residence time, heat transfer rate, flow rate of carrier gas, mineral matter and reactor types are the major parameters to consider for pyrolysis^{16–18}. In pyrolysis, the biomass goes through primary and secondary reactions. The key components of

biomass (cellulose, hemicellulose and lignin) decompose according to primary reactions resulting into primary- and intermediate products. The intermediate products further go through secondary reactions depending on the operating conditions and nature of the biomass^{19, 20}.

Reactor temperature is very important concerning the yield of pyrolysis products²¹. A temperature range of 450–550°C is reported for different biomasses²². In general the yield of bio-oil first increases reaches a maximum and then declines with increasing reactor temperature. The actual maxima are specific to the biomass, reactor type and design. The secondary vapor cracking reactions strongly affect the bio-oil yield^{23–26}. The bio-char formation takes place at relatively low temperatures due to the lower heating rate and slow pyrolysis. Above 500°C, yield of non-condensable gases increases with subsequent decrease in bio-oil yield^{23, 27}. The char yield decreases with the increase of temperature²⁸. The char produced at higher temperature contains higher carbon content²⁹. Lowering the reaction temperature ($< 400^\circ\text{C}$) leads to formation of lower molecular weight liquids³⁰. Different researchers investigated the effect of temperature on the yield of pyrolysis products for pine wood, miscanthus cassava rhizome (CR), cassava stalk (CS) and mallee bark^{31–34}.

Particle size of feedstock is important for fast pyrolysis process. The larger size of particles has tendency to give more char by controlling the release of primary pyrolysis vapors and increasing secondary char producing reactions³⁵. Thus, for the production of char, large size biomass particles are required whereas in order to get maximum yield of bio-oil, small size particles are preferred. With the increase of particle sizes, bio-oil yield decreases and char yield increases as these particles heat up more slowly³⁶. On the other hand, small particle size increases the gas yield as a result of greater heat transfer coefficient³⁷. So distribution of the products strongly depends on the particle size, demanding a practically uniform temperature distribution inside the reactor. Moreover, biomass particle size is also reliant on the

type of reactor used for fast pyrolysis. In continuous-feed fluidized bed reactors, small biomass particle sizes (≤ 2 mm)^{3, 22} is agreed to achieve high heating rates. A small biomass particle size is required in order to get rapid heating and complete devolatilization in the pyrolysis process^{38, 39}. The effects of biomass particle sizes in fast pyrolysis can be compared only for similar types of biomasses having the same milling methods, shape and physical properties⁴⁰. Many tests have been carried out to investigate the effect of particle size on yields of pyrolysis oil, char and gas for aspen popular wood, jatropa oil cake, eucalyptus wood, Japanese larch and miscanthus^{32, 41–44} in fluidized bed reactor. For these biomasses, with the increase of particle size, the bio-oil and char yield was reduced and gas yields increased. Some researchers studied the effect of particle size on the yield of pyrolysis products in modified forms of fluidized bed reactor^{45, 46}.

The carrier gas removes the pyrolysis products from hot zone to reduce the secondary cracking reactions⁴⁷ for example thermal cracking, polymerization and condensation to maximize bio-oil yield. High flow rates of carrier gas allow short vapor residence time and vice versa. Short vapor residence time is a key factor to get the maximum bio-oil yields^{48–50} and perfect quenching of pyrolysis vapors is required to restrict the secondary reactions⁵¹. Vapor residence time is the available reaction time for secondary tar reactions in biomass pyrolysis which affects the yields of gaseous and liquid products. The recommended value of vapor residence time from the literature³⁸ for fast pyrolysis of biomass at a temperature of 500°C is ≤ 2 seconds to attain the maximum bio-oil yield. Vapor residence time of a few hundred milliseconds is needed for the production of optimum yields of chemicals and food additives⁵². Longer vapor residence times in fast pyrolysis result in significant decrease in the yield of bio-oil due to secondary cracking reactions^{4, 30}. Park et al.⁵³ investigated the influence of the nitrogen flow rate on the pyrolysis products distribution. By the decrease in gas flow rate, the oil yield was decreased, however yields of char and gas increased due to incomplete fluidization and chances of the happening of secondary vapor cracking reactions may be due to the longer vapor residence time. Heo et al.³² explained the effect of carrier gas flow on the yields of biomass pyrolysis products. Piskorz et al.²⁴ described the effect of vapor residence time on pyrolysis of sorghum bagasse feedstock. Scott et al.⁵⁴ investigated the effect of vapor residence time on the product yields of lignocellulosic wastes in a bench scale fluidized bed reactor. Heo et al.⁵⁵ explained the effect of gas flow rate of nitrogen and pyrolysis gas on the product distribution of waste furniture saw dust in fluidized bed reactor. Raja et al.⁵⁶ investigated the flow rate of nitrogen gas from 1.25–2.4 m³/h for pyrolysis of pungam oil cake in electrically

heated fluidized bed reactor. Sulaiman et al.⁵⁷ studied the impact of key parameters to determine the maximum yield and quality of liquid fuel in bench scale fluidized bed reactor. The vapor residence time was set in the range of 0.79–1.32 s by the change of carrier gas flow rate. Mante et al.⁵⁸ investigated the parametric study on fast pyrolysis of manure and wood shavings in fluidized bed reactor. The experiments were conducted at nitrogen flow rates of 0.72–1.44 m³/h. Tsai et al.⁵⁹ discussed the effect of carrier gas flow on fast pyrolysis of rice husk.

Presently, there is no comprehensive research about the effect of temperature, feed particle size, carrier gas flow rate on pyrolysis of maize stalk in bubbling fluidized bed reactor. This study is carried out to determine the optimum temperature, feed particle size and carrier gas flow rate to obtain maximum yield of bio-oil and its characterization.

EXPERIMENTAL PROCEDURES

Material and methods

Maize stalk used as feedstock was collected from Pakpattan, District Sahiwal, Pakistan and shredded into coarse particles. The samples were finally ground in the grinding mill to the particle size of 1–2 mm and were air dried to decrease the moisture content. The feedstock was dried in an oven at 105°C for overnight to reduce the moisture less than 10 wt% prior to the pyrolysis experiments.

Ultimate analysis, proximate analysis and higher heating value (HHV) of the maize stalk was determined as per standard procedures using the standard analyzers (Vario Micro CHNS & Leco TGA701 analyzer & Leco AC 500 calorimeter). The chemical composition of feedstock was determined by standard Tappi procedure. The results of ultimate analysis, proximate analysis, HHV and compositional analysis with their standard deviations (SD) are described in Table 1. In which ash was the remains after complete combustion, volatile matter was volatilized fraction from maize stalk when it was heated in the absence of oxygen, fixed carbon was the leftovers after complete volatilization and higher heating value was the thermal energy comprised in the maize stalk.

GC-MS analyser (Shimadzu GC/MS-QP2010) was used to identify the chemical compounds present in the bio-oil. Composition of incondensable gas was obtained by GC analyser (Cp-3800/3300 Netherland). The oven ramp rate, hold up time and injector temperature details can be seen at⁶⁰.

Experimental apparatus

Bubbling fluidized bed fast pyrolysis system (Fig. 1) was used for the investigations under study. The fluidized bed reactor was made of stainless steel (SS 316 L) and had internal diameter of 100 mm with feed capacity of

Table 1. Characteristics of maize stalk

Ultimate Analysis [wt%]			Proximate Analysis [wt%]			Chemical Composition [wt%]		
Carbon	40.72	0.3	Volatile Matter	62.94	0.4	Cellulose	29.7	1.0
Hydrogen	5.68	0.1	Fixed Carbon	30.24	0.2	Hemicelluloses	15.2	0.5
Oxygen	47.51	0.2	Ash	4.20	0.1	Lignin	17.2	0.9
Nitrogen	0.92	0.02	Moisture	1.14	0.2	–	–	–
Sulfur	0.12	0.01	HHV(MJ/kg)	15.87	0.2	–	–	–

2 kg/h. The reactor was heated indirectly with carbide heating rods to maintain the pyrolysis reaction temperature. More details of the experimental setup and its operational procedure can be seen at⁶⁰.

The maize stalk was pyrolysed in the fluidized bed reactor at temperature 360–540°C and yield of bio-oil, charcoal and incondensable gas were determined from condensed liquid collected from water and dry ice condensers, from two cyclones and by difference. These calculations were based on mass balance from the different components of pyrolysis system.

Figure 1. Schematic of experimental apparatus

1. Nitrogen Gas Header; 2. Feed Hopper; 3. Screw Feeder; 4. Fluidized Bed Reactor; 5. Reactor Heater; 6. Cyclone Separators; 7. Char Collectors; 8. Hot Filter; 9. Water Condenser; 10. Dry Ice Condenser; 11. Bio-oil Collectors; 12. Frame; 13. Exhaust Gas

Reaction conditions

The various reaction conditions for fast pyrolysis of maize stalk are shown in Table 2. The temperature from the exit of the reactor to inlet of condenser was maintained at 350–400°C in order to avoid condensation of pyrolysis vapors prior to the bio-oil formation.

RESULTS AND DISCUSSION

Effect of temperature on products yield

The effect of temperature on pyrolysis product distribution of maize stalk in the fluidized bed fast pyrolysis system is described in Figure 2. The rise of temperature from 360 to 540°C, yield of char decreased while yield of gas increased. By the increase in the reaction temperature from 360 to 490°C, the yield of bio-oil increased, even though at the considerable greater temperature of 540°C, there was a drop in the yield of bio-oil. The value of bio-oil obtained was maximum (42 wt%) at a pyrolysis temperature of 490°C. These results lead that bio-oil and char decreased whereas gas increased with the increase of reaction temperature. The results were due to secondary cracking reactions by the conversion of pyrolysis vapors and char into gas at elevated temperatures. These trends of pyrolysis liquid, char and non-condensable gas yields

with temperature were in agreement to the results in the literature^{61–65}. The yields obtained by Park et al.⁵³ & Asadullah et al.⁶⁶ were 50, 66% for fast pyrolysis of radiata pine sawdust and jute stick in fluidized bed reactor at 450°C and 500°C respectively. The difference in yields and composition of pyrolysis products identified was described due to the type of feedstock, reaction conditions, size of reactor and experimental errors. In large reactors, a significant fraction of tar was trapped in the pipes and lines of the fast pyrolysis reactor which reduced the yield of liquid product. This proportion of the product was very difficult to collect physically from the system.

Figure 2. Effect of temperature on the yield of bio-oil, char and gas

Effect of particle size on products yield

Biomass particle size was found to influence the yield of pyrolysis products. With the increase of particle size, bio-oil yield decreased and char yield increased as these particles heat up more slowly³⁶. On the other hand, small particle size increased the gas yield as a result of greater heat transfer coefficient³⁷. So distribution of the products yields strongly depend on the particle size, demanding a practically uniform temperature distribution inside the reactor. Moreover, particle size of biomass was especially reliant on the type of reactor used for fast pyrolysis. In continuous-feed fluidized bed reactors, small biomass particle sizes (≤ 2 mm)^{3, 22} was agreed to achieve high heating rates. The small biomass particle size was required in order to get rapid heating and complete devolatilization in the pyrolysis process^{38, 39}.

Pyrolysis of maize stalk for feed sizes of 1.0, 1.5 and 2.0 mm is depicted in Figure 3 for pyrolysis products distribution. It was evident that yield of bio-oil was decreased with the rise of feed particle size and also visible that effect was linear over the selected range of particle sizes. It was shown from the graphs that the bio-oil yield was decreased by increasing the feed size of maize stalk whereas char and gas yields were increased. For maize stalk, the bio-oil yield decreased from 42 to 35 wt%, char yield from 22 to 25 wt% increased and gas yield was increased from 36 to 40 wt% by the

Table 2. Reaction conditions[illegible]

increase of particle size of feedstock. This effect of particle size of biomass during pyrolysis was conceived due to the heating rate. Heat transfer in the pyrolysis was related with the particle size of feed, greater the particle size, lower would be heat transfer and vice versa. The greater heat transfer in case of fine particles produced more volatiles which condensed consequently resulting in higher bio-oil yield. The trends in literature^{44, 63, 67} regarding the effect of feed particle size in pyrolysis favored these results.

Figure 3. Effect of feed particle size on the yield of bio-oil, char and gas

Effect of carrier gas flow rate on products yield

The effect of carrier gas flow rate on pyrolysis product distribution of maize stalk is shown in Figure 4. It was found that with the increase of gas flow rate, bio-oil yield was first increased and then decreased. The maximum amount of bio-oil obtained for maize stalk was 42 wt% at the carrier gas flow rate of 11.0 m³/h (0.9 m/s superficial velocity). The increase in carrier gas/ N_2 gas flow rate decreased the yield of bio-char while the yield of gas was decreased first and then increased. This was for the reason that at low flow rate of carrier gas, fluidization was not completely attained and hence, fast pyrolysis could not occur fully⁶⁸ and secondly, due to long vapor residence time, secondary reactions such as cracking and re-polymerization might take place. Conversely, the high flow rate of carrier gas decreased the bio-oil yield due to the reason that volatiles left the pyrolysis system without effective condensation and results in gas formation.

The carrier gas flow affects the residence time of the vapors produced by pyrolysis reactions which removes the pyrolysis products from the reactor hot zone immediately and minimizes the secondary cracking vapor reactions⁶⁹. It is known that pyrolysis process conversion is increased in minor amounts and influence on yield of char with increasing the flow rate of nitrogen/carrier gas is insignificant. By increasing the carrier gas flow rate, there is an increase in the bubbling motion which enhances the mixing between bed material and biomass. Ultimately, vapor residence time is decreased lowering the secondary reactions. But at higher carrier gas flow rate, bubbling of the sand bed starts vigorously which reduces the solid mixing and gives low heat transfer decreasing the pyrolysis oil yield.

Figure 4. Effect of carrier gas flow rate on the yield of bio-oil, char and gas

Characterization of Bio-Oil

The bio-oil consists of water and organic compounds which were condensed and collected after pyrolysis experiments. The liquid oil was characterized by measuring the density, viscosity, water content, acid number and calorific value. The amount of water in the bio-oil was determined by Karl Fischer titrator which was based on the theory of Karl Fischer titration. The chemical composition of bio-oil was analysed with gas chromatography-mass spectroscopy (GC-MS). The properties and chemical composition of bio-oil is elaborated in Tables 3 and 4 respectively.

Table 3. Properties of bio-oil

Properties	Value
H ₂ O [wt%]	32.4
TAN [mg of KOH/g]	74
Density [g/m ³]	1150
Viscosity [cP @ 20°C]	104
HHV [MJ/kg]	17.8
C [wt%]	48.6
H [wt%]	6.4
O [wt%]	43.9
N [wt%]	0.9
S [wt%]	0.2

Table 3 shows that energy density of bio-oil was much higher than the feedstock which made it convenient for transportation and utilization. Also liquid product contained small fractions of nitrogen and sulfur which were pollutants. The results of elemental analysis indicated that carbon and hydrogen content was increased as compared with the feedstock and like this oxygen decreased. Due to increase in carbon content and drop in oxygen content, the calorific value was also increased. The similar results were observed by Putun et al.⁷⁰ for pyrolysis of pistachio shell in fluidized bed reactor.

GC-MS analysis was applied to separate and identify the chemical compounds in bio-oil. The chemical compounds were identified from the GC-MS peaks of chromatogram (Fig. 5) by comparison with the spectra of spectrum library. The compounds identified in liquid product from maize stalk pyrolysis in fluidized bed reactor were large in numbers having major and minor concentrations in area percentage but only compounds with major fractions are mentioned in the Table 4. The compounds were acetic acid, aldehydes, ketones, phenols and anhydrosugars. The concentration of acetic acid was

higher than phenols, furfural, furanone and levoglucosan. The results of GC-MS having chemical composition of liquid oil were in agreement with the results by Zheng⁷¹ for rice husk feedstock in fluidized bed reactor.

It could be observed from the qualitative results that acidic acid is the major acidic components of bio-oil, furfural is the furans product and 1-hydroxy-2-propanone, cyclopentanones and cyclopentadiones are the ketones. Levoglucosan is obtained from cellulose pyrolysis and indicates the partial cracking of carbohydrates. The compounds such as 2-methoxy-phenol, 2-methoxy-4-methyl-phenol are methylated or methoxylated phenolic compounds derived from lignin pyrolysis. The compounds in bio-oil were acids, ketones, phenols, furans followed by anhydrosugars, whereas alcohols, aldehydes and esters were present in small fractions. The major organic acid was acetic acid holding the highest part. Bio-oil had the highest acetic acid content of 27 area %. It has been known that acetic acid was produced mainly due to the breakage and removal of acetyl groups linked to the xylose unit on C-2 position and second attributed to the ring-scission of uronic acid residues from elimination of groups such as carbonyl and O-methyl⁷². The amount of acetic acid content of bio-oil would vary due to different chemical structure and content.

Maize stalk pyrolysis produced a large amount of ketones of which total amount was around 18–20 area % with 1-hydroxy-2-propanone highest yield up to 16.38 area %. The large molecular weight ketones such as cyclopentanones and cyclopentenones were produced from the degradation of sugar units. The ketones were produced from the pyrolysis of cellulose or hemicellulose of biomass. Furans in the bio-oil can be yielded from the decomposition of hollocellulose, even though both cellulose and hemicellulose can produce furans, however studies has revealed that hemicellulose contributes to the formation of furfural and cellulose to hydroxymethyl furfural and 2-furylmethanol^{73, 74}. Bio-oil from maize stalk pyrolysis has furfural content about 2.31 area % due to hemicellulose content lower than cellulose and lignin in the feedstock. The anhydrosugar compounds were levoglucosan and its dehydration or isomeric forms and produced from degradation of cellulose. The yield of levoglucosan in the bio-oil was 2.36 area % depending upon the amount of cellulose in the feedstock. The quantitative chemical characterization of bio-oil is valuable in order to design the pyrolysis reaction and estimation of economic significance of practical applications like fuels and chemicals. The bio-oil is composed of mainly, water, acetic acid (27 area %), 1-hydroxy-2-propanone (16 area %) and small fraction of other compounds (< 4 area %) such as phenols, aldehydes and levoglucosan.

Bio-oil contains about 32 wt% of water which generally originates from initial moisture in the biomass and dehydration reactions taking place during pyrolysis process. Water content may be different due to nature of feedstock and process conditions. Water at high concentration (15–30%) is miscible with the oligomeric components derived from lignin due to solubilizing effect of low-molecular-weight acids, alcohols, hydroxyaldehydes, and ketones resulting from the decomposition of carbohydrates. Water in the bio-oil has both negative as

well as positive effects on the oil properties. It decreases the heating value and flame temperature and increases the delay in ignition. In contrast, it reduces the viscosity of bio-oil resulting in increase of flow characteristics which has advantage for pumping and atomization in combustion.

In the past, pyrolysis liquids from wood were used to produce chemicals like methanol, acetic acid, turpentine and tars etc. but presently these chemicals are formed from other feed stocks derived from natural gas, crude oil and coal at cheaper cost. The bio-oils have been comprised of more than 200 chemical compounds present in small parts and separation of individual compounds is often practical as well as economic due to complex separation techniques. Thus, producing valuable chemicals from the whole bio-oil or easily separable major fraction is viable and economical. The suitable chemicals can be produced from the whole bio-oil by reacting most abundant functional groups as carbonyl, carboxyl and phenolic in such a way that non reacting part of bio-oil would not be separated from the product. Bio-oil containing acetic acid and phenols has carboxyl and phenolic groups which can easily react with lime to yield calcium salts and phenates. The product obtained is termed as BioLime which can be used to capture SO_x emissions from coal combustors in the industry. BioLime contains about 50% water and 7–14% organic calcium which is four times more efficient for capturing acid gas. The second advantage of BioLime is its oxidation of organic bio-oil derived part resulting in additional energy in the combustor. Based on this principal Dynamotive Corporation⁷⁵ has developed the same product which ascertained effective.

Bio-oil exploits another potential application due to high amount of carbonyl groups such as 1-hydroxy 2-propanone, acetic acids and aldehydes. Various imide and amide bonds are produced between carbonyl carbon and nitrogen from reaction of bio-oil with ammonia, urea and –NH₂ containing materials. In this method, biodegradable slow releasing fertilizer with 10% nitrogen is produced which has lower leachability in comparison to mineral fertilizers producing less pollution to ground water. Moreover, it is good soil conditioning material having humic material (lignin) and use of such type of fertilizer returns carbon to soil and revealed as a method of carbon sequestration. Bio-oil based fertilizers⁷⁶ may be cost competitive in the market.

In addition, various chemicals can be produced from fractionation of bio-oil. Bio-oil can be easily fractionated into two parts on basis of water solubility, an oligomeric lignin derived fraction settles down whereas water soluble fraction containing carbohydrate derived compounds arises as top layer. Solvent fractionation methods other than water have also been developed, however water addition method is most economical option⁷⁷. Water soluble fraction of bio-oil comprising organic acids (acetic acids, formic acids & propionic acids) has a prospective application of production of calcium salts of carboxylic acids. The calcium salts of carboxylic acids can be used as environment friendly road de-icers. The aqueous extract of bio-oil rich in organic acids can be distilled off as sub fraction. This fraction consisting of other volatile compounds such as

aldehydes and esters can react with lime or evaporated in the recovery of calcium salts. The production of biomass derived de-icers is viable. The water insoluble fraction of bio-oil composed of oligomeric fragments is known as pyrolytic lignin can be used as phenol substitute in phenol-formaldehyde resins. Those resins presenting high mechanical strength are effectively used as adhesives in plywood and particle board industry. In comparison to phenol, pyrolytic lignin is an attractive component of adhesives due to low toxicity and cost. NREL⁷⁸ and Biocarbons⁷⁹ in USA has leading contributions in the pyrolytic lignin based resin formulation.

Furthermore to above applications of bio-oil, terpenoid and phenolic compounds present in the bio-oil were identified as insecticides and fungicides which proposed it to be used as wood preservative. Impregnating with bio-oil shields the wood from fungi, conversely efficiency of bio-oil was not found long lasting. After the improve-

ment of retention of bio-oil in the wood, it can be used as environment friendly wood preservative.

Figure 6 represents the feedstock (maize stalk) and pyrolysis products (bio-oil, char) respectively.

CONCLUSIONS

Fast pyrolysis of maize stalk was investigated in locally designed and fabricated fluidized bed reactor. The effect of operating parameters such as pyrolysis temperature, feed particle size and carrier gas flow rate was studied. It was observed from the experiments that reaction temperature had significant influence on the distribution of pyrolysis products. The yield of bio-oil was increased with the temperature to maximum upto a certain temperature and then decreased by the increase of temperature while yield of char decreased and gas increased. In addition to pyrolysis temperature, feed particle size also affects the yields of fast pyrolysis process. The bio-oil yield was decreased by the increase of particle size and yields of bio-char & gas increased. The maximum yield of bio-oil obtained was 42 wt% at the optimum pyrolysis temperature of 490°C, feed size of 1.0 mm and carrier gas flow rate of 11 m³/h. The major compounds found in the bio-oil obtained from the pyrolysis of maize stalk were acetic acid, 1-hydroxy-2-propanone, 2,3-dihydro-benzofuran, phenols, 3-methyl-1,2-cyclopentanedione, 1-(acetyloxy)-2-propanone, 2,3-dimethyl-cyclopenten-1-one, furfural, 2(5H)-furanone and levoglucosan.

ACKNOWLEDGEMENT

Financial support of the Higher Education Commission (Project # 20-1701/R & D/09/2946) and University of the Punjab, Pakistan for this research work is highly acknowledged.

Figure 5. GC-MS Chromatogram of bio-oil

(a)

(b)

(c)

Figure 6. (a) Maize stalk, (b) Bio-oil, (c) Char

Table 4. GC-MS analysis of bio-oil

Peak #	RT [min]	Compound	Area [%]
1	8.15	2-amino-1,3-propanediol	1.47
2	9.39	acetic acid	27.35
3	10.97	1-hydroxy-2-propanone	16.38
4	15.61	1-hydroxy-2-butanone	1.84
5	15.85	acetic acid, methyl ester	3.67
6	18.06	butanedial	2.52
7	18.75	2-cyclopenten-1-one	1.69
8	18.85	furfural	2.31
9	20.85	2,2,4-trimethyl-1,3-dioxolane	1.54
10	21.67	1-(acetyloxy)-2-propanone	2.67
11	22.03	2-butanone	1.18
12	26.93	2,3-dimethyl-cyclopenten-1-one	1.24
13	27.77	2(5H)-furanone	1.13
14	29.76	3-methyl-1,2-cyclopentanedione	3.04
15	31.55	phenol	3.09
16	35.70	4-methyl-phenol	1.27
17	39.69	4-ethyl-phenol	2.15
18	43.62	2,3-dihydro-benzofuran	3.66
19	58.97	levoglucosan	2.36

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