

Oil Production from Kraft Lignin via Thermochemical Liquefaction using Ru/Al_y(SiO₄)_x Catalyst

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Abstract

Thermochemical liquefaction of Kraft lignin using Ru/Al_y(SiO₄)_x catalyst produced oil at 300, 350 and 375°C under 40 atm. hydrogen, 40 atm carbon monoxide, inert 40 atm. N₂ atmosphere and under vacuum (20 mmHg). The effect of temperature and atmospheric condition on carbon based yield(%yield), carbon based conversion(%conversion), mass of carbon and hydrogen recovered as oil (%CHR), H/C and O/C atomic ratio of oil parameters were studied. %yield (94.30±0.05), carbon based conversion (75.60±0.01) and %CHR (60.50±0.05) were highest at 375 °C under vacuum. ANOVA showed that all the parameters at different atmospheres and only %yield, %conversion and %CHR at different temperatures varied significantly. Oil of best quality was obtained at 375 °C under vacuum.

Keywords: Kraft lignin, Thermochemical, Liquefaction, Reductants, ANOVA

1. Introduction

With the depletion of fossil fuels and its resultant associated environmental problems, biomass has become an important renewable feedstock for the production of fuels and chemicals. [1]. Biomass such as wood is a renewable and alternative source for the production of fuels and chemicals [2, 3]. Wood comprises cellulose, hemicellulose and lignin portions [4], with proportions of the latter typically one-third by weight. Large amounts of lignin and lignin containing residues are obtained from the pulp and paper industry where lignin-derived compounds can be produced from waste liquor. Lignin is a three-dimensional amorphous cross-linked biopolymer consists of phenyl-propane units, optionally substituted with methoxy and hydroxyl groups [5, 6]. It comprises 15–30% by weight and up to 40% by energy of biomass [7]. In plant cell walls, it is found in the spaces between cellulose and hemicellulose, holding the lignocellulosic matrix together and adding rigidity to plant material [8]. The potential of lignin as useful feedstock for the production of useful chemicals or fuel additives has been reported [9, 10, 11, 12, 13, 14, 15]. Lignin derived from abundant and renewable resources are nontoxic and extremely versatile in performance and qualities that have made them increasingly important in many industrial applications [16]. Utilisation of lignin is significantly growing due to an increasing interest in renewable raw materials. However, only a part of the lignin is used despite its large potential as a petrochemical substitute for fuel, polymers and low molecular weight chemicals. Presently, economic and technological considerations still preclude a large-scale mass production of low molecular weight chemicals from lignin in competition with petrochemicals. Despite the recalcitrant nature of the complex and stable lignin polymer, which makes it difficult to convert it into valuable monomeric chemicals,

lignin has been reported to be broken down to monomeric or low molecular weight compounds by a variety of routes, such as thermochemical liquefaction, alkaline oxidation or hydrolysis, alkali fusion, alkaline demethylation, hydrogenolysis and pyrolysis [17, 18]. High pressures and temperatures in addition to the use of catalyst are required for the optimum conversion of lignin to low molecular weight compounds in good yield [19, 20]. The role of catalysts in the conversion of lignin feedstock to various bulk chemicals or fuel components using various catalysts has been reported. [21, 22]. Biofuel produced by liquefaction of lignocellulosic biomass proves to be a promising potential raw material for liquid energy carriers and in particular liquid transportation fuels [23]. Against this background, this study aims to investigate the effects of temperatures at constant H₂, CO, N₂ pressure and under vacuum as well as that of H₂, CO, N₂ pressure and under vacuum at constant temperature of 300 °C, 350 °C or 375 °C in making oil using Ru/Al_y(SiO₄)_x catalyst. The effects of varying and keeping temperatures constant at different atm condition of 40 atm H₂, CO, N₂ and under vacuum obtained at 20 mmHg as on the quality of oil viz: percentage yield (%y), percentage conversion (%x), percentage C+H recovered as oil (%CHR), H/C and O/C atomic ratios.

2. Experimental

The feed used in the study was a dark brown powdered Kraft lignin processed from straw was obtained from the Department of Biochemistry, University of Manchester, Institute of Science and Technology, Manchester M601QD, UK. The feed was characterized to ascertain its elemental and

moisture composition. The suspension medium, tetralin (3, 4 tetrahydronaphthalene) supplied by Hulls Limited was used as organic solvent. The catalyst, $Ru/Al_y(SiO_4)_x$ was ruthenium supported, greyish black spherical pellets obtained from Johnson Matthey Research centre, UK. The thermochemical liquefaction of Kraft lignin was carried out by charging a previously pressure tested autoclave with the 50 g of feedstock, 400 g of suspension medium and 1 g of catalyst with continual stirring to ensure slurry. The autoclave was sealed off after the charge and clamped in an electric furnace in the reaction cell. The autoclave was evacuated with an in-line cold trap and a vacuum pump at 20 mmHg and pressurised to 40 atm with hydrogen, carbon monoxide, nitrogen as the case may be and thereafter the furnace was switched on and allowed to warm up the autoclave and its contents to attain the specific reaction temperature after which the reaction proceeded further for a further reaction time of two hours at the fixed temperature. The normal air breathing apparatus was used to avoid the risk of inhalation where carbon monoxide was used. Temperature-pressure-time were recorded at a regular interval as a means of monitoring the reaction. The furnace was switched off at the end of two hours reaction time and the autoclave with its contents were allowed to cool gradually overnight with continuous agitation and discharged when it had cooled to room temperature. The reactions were carried out at three different fixed reaction temperatures of 300, 350 and 375 °C. Pressurization at 40 atm effected with H_2 , CO as reductants, N_2 provided an inert atmosphere and some reactions were carried out in vacuum obtained at 20 mmHg. After the reaction, product gas which was a mixture gases and volatile organic compounds generated by the reaction were collected through a gas storage system comprising a vacuum pump, several pre-evacuated glass storage bulbs of known volumes and an in-line nitrogen cold trap for further analysis while the product mixture of solid and liquid products was transferred and were subjected to atmospheric distillation for the separation and collection of aqueous and organic components using a standard laboratory equipment and a heating mantle to avoid the use of naked flame in a fume cupboard until the first sign of the distillate at about 60 °C up to 98 °C when the last drop of distillate appeared. The process took about three hours. The atmospheric residue was subjected to vacuum distillation at 1.5 mmHg principally for the recovery of slurry solvent-tetralin between 30-50 °C using a vacuum pump, vacuum stat and standard laboratory equipment including a heating mantle and an in-line liquid nitrogen cold trap to trap any volatile component which were not completely removed during the initial atmospheric distillation. The process took about three and a half hours. A procedure to reduce the about seven hours for both atmospheric and vacuum distillation processes was later successfully devised by by-passing the atmospheric distillation stage and adapting the vacuum distillation approach at room temperature with constant

stirring and with no heat applied at 1.5 mmHg. Under these set of conditions all the volatile materials were trapped in the cold trap. This procedure took about one hour followed by applying heat to remove the slurry solvent in the 30-50 °C range. The resultant oil fraction was refluxed in acetone, centrifuged at 2000 rpm and filtered under water vacuum using a buchner funnel and Whatman no. 1 filter paper and washed severally until the filtrate became clear to ensure separation of the acetone insoluble char from the acetone soluble oil. The combined char from the bottom of the centrifuge and the filter paper was placed in a watch glass, dried in an oven at 100 °C overnight, cooled in a desiccators and its weight which included the spent or recovered catalyst was determined. The acetone soluble material which is black and viscous, hereafter referred to as the oil was recovered by stripping the acetone on a rotary evaporator under water vacuum. High value of carbon and hydrogen coupled with low value oxygen and ash are particularly desirable for good quality oil.

The elemental analysis provided information on %C, %H, %S and %Ash while %O was estimated by difference.

$$\text{Carbon based yield} = \frac{\text{mass of C in feed} - \text{mass of C in char}}{\text{mass of C in feed}} \dots\dots\dots (1)$$

$$\text{Carbon based conversion} = \frac{\text{mass of C in oil}}{\text{mass of C in feed}} \dots\dots\dots (2)$$

$$\text{CHR} = \frac{\text{mass of C and H in oil}}{\text{mass of feed}} \dots\dots\dots (3)$$

$$\text{HHV} = 0.338C + 1.422 (H - O/8) \dots\dots\dots (4)$$

Where C, H, O are the mass percentages of carbon, hydrogen and oxygen respectively.

$$\text{Energy Yield} = \frac{\text{mass of Carbon and hydrogen in oil product}}{\text{mass of carbon and hydrogen in feed}} \dots\dots\dots (5)$$

Product oil parameters namely, percentage carbon based yield, carbon based conversion, percentage carbon and hydrogen recovered (%CHR), hydrogen carbon (H/C) and oxygen carbon (O/C) atomic ratios were determined from the analysis of the oil obtained. The values of these parameters were subjected to statistical analysis using analysis of variance (ANOVA) at 5% significance level. Post Hoc test using Tukey was used to ascertain the direction of the variance. The schematic diagram [24] of the thermochemical liquefaction of Kraft lignin is shown in Figure 1.

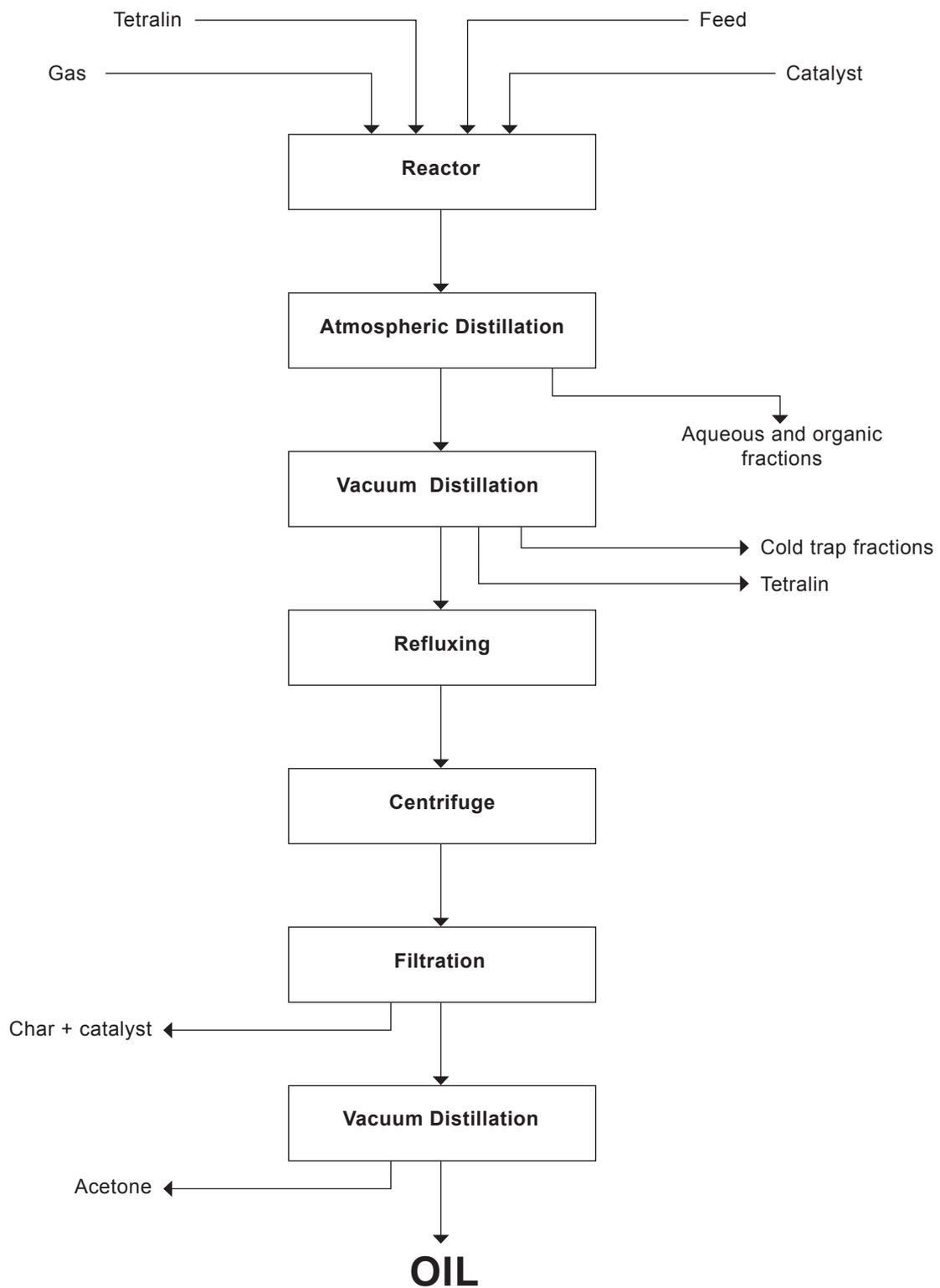


Fig. 1: Schematic diagram of the liquefaction of Kraft-lignin [24]

3. Results and Discussion

3.1. Analysis of feedstock

The results obtained from the chemical analysis of the feedstock are reported in tables 1 and 2

Table 1 : Characterization of the feedstock

Parameters	Moisture [wt%]	C [wt%]	H [wt%]	N [wt%]	O [wt%]	S [wt%]	Ash [wt%]	H/C atomic ratio	O/C atomic ratio
Amount	4.0	58.8	5.7	1.4	28.5	2.4	3.2	1.16	0.36

Table 2 : Trace metal analysis of feedstock

Element	Na	K	Mg	Ca	Fe
Amount [wt%]	1.0	0.1	0.02	0.1	0.1

3.2. Effects of varying atmospheric conditions at fixed temperature and varying temperature at fixed atmospheric conditions:

The effects of varying atmospheric conditions at fixed 300, 350 and 375 °C respectively and varying temperature at fixed hydrogen, carbon monoxide, nitrogen and vacuum atmospheric conditions respectively on the oil produced from the liquefaction of Kraft lignin are presented in figures 1 to 7. Both atmospheric condition and temperature variables were at constant pressure of 40 atm. except the reactions carried out under vacuum condition of 20 mmHg.

Tables 3a and 3b as well as Figure 2 showed the C based yield obtained at fixed temperature of 300 °C under different atmospheres and revealed that reaction condition under 40 atm. of CO produced oil with highest C based yield while 40 atm. of hydrogen produced oil with lowest value (the trend in C based yield is as follows: CO > Nitrogen > Vacuum > H₂). The difference in the C based yield obtained under various atmospheric condition is statistically significant using ANOVA (p<0.05). Follow up test for the ANOVA using Tukey confirmed the trend stated earlier. For the C based yield of oil obtained at 350 °C and 375 °C under different atmospheric condition, reaction under vacuum (20 mmHg) produced oil with highest

Table 3a : Effects of varying atmospheric conditions and temperature on product oil.

	Temperature (300°C)				Temperature (350°C)			
	H ₂ (40 atm)	N ₂ (40 atm)	CO (40 atm)	Vacuum (20 mmHg)	H ₂ (40 atm)	N ₂ (40 atm)	CO (40 atm)	Vacuum (20 mmHg)
C based yield	56.00±0.05	69.60±0.05	76.40±0.05	56.20±0.05	57.30±0.05	71.20±0.05	64.60±0.05	78.90±0.04
C based conversion	51.90±0.05	48.20±0.08	57.70±0.05	58.60±0.05	56.30±0.04	57.00±0.40	57.20±0.01	66.00±0.50
%CHR	36.80±0.01	44.50±0.06	49.00±0.05	36.10±0.03	36.80±0.02	45.50±0.05	41.30±0.05	50.80±0.04
% Energy Yield	56.98±0.02	69.06±0.03	75.88±0.01	55.91±0.03	57.01±0.01	70.89±0.03	64.08±0.02	78.83±0.01
HHV (mJ/Kg)	28.37±0.03	32.48±0.02	31.67±0.01	32.48±0.03	32.95±0.03	33.14±0.02	33.78±0.02	30.69±0.01
H/C atomic ratio	1.40±0.01	1.05±0.05	1.07±0.02	1.08±0.02	1.08±0.02	1.04±0.06	1.06±0.04	1.12±0.03
O/C atomic ratio	0.20±0.01	0.15±0.05	0.16±0.03	0.17±0.02	0.15±0.02	0.13±0.02	0.13±0.01	0.18±0.03

Table 3b : Effects of varying atmospheric conditions and temperature on product oil

	Temperature (375 °C)			
	H ₂ (40 atm)	N ₂ (40 atm)	CO (40 atm)	Vacuum (20 mmHg)
C based yield	58.20±0.05	94.00±0.50	81.70±0.05	94.30±0.05
C based conversion	61.70±0.02	66.60±0.04	71.30±0.05	75.60±0.01
%CHR	37.70±0.05	59.60±0.02	52.40±0.04	60.50±0.05
% Energy Yield	58.47±0.02	94.17±0.03	81.16±0.04	93.78±0.02
HHV (mJ/Kg)	34.52±0.03	34.43±0.02	34.58±0.01	34.71±0.03
H/C atomic ratio	1.22±0.03	1.18±0.04	1.07±0.04	1.09±0.02
O/C atomic ratio	0.10±0.04	0.11±0.05	0.11±0.01	0.09±0.02

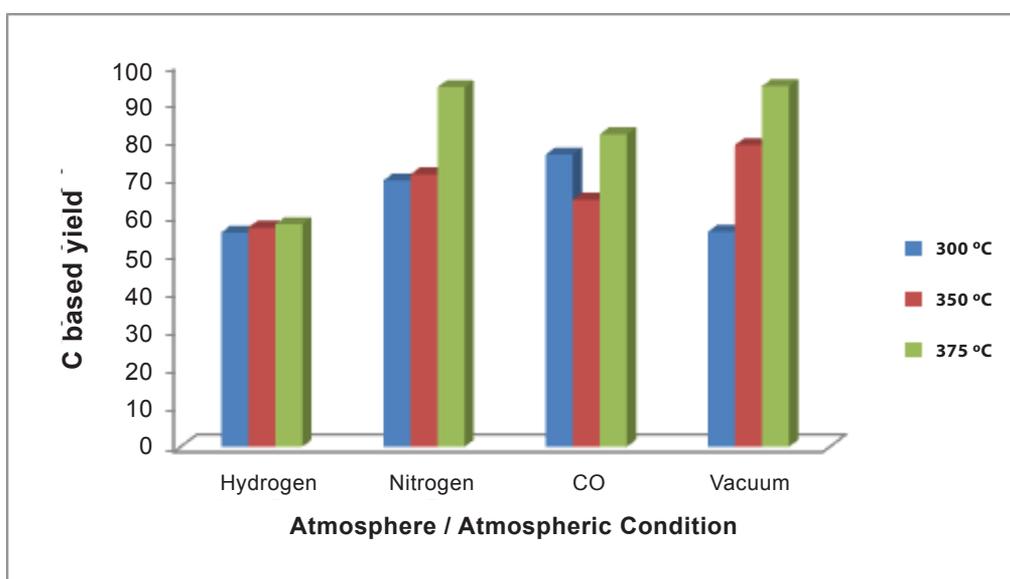


Fig.2 : Effect of temperature and atmospheric condition on C based yield

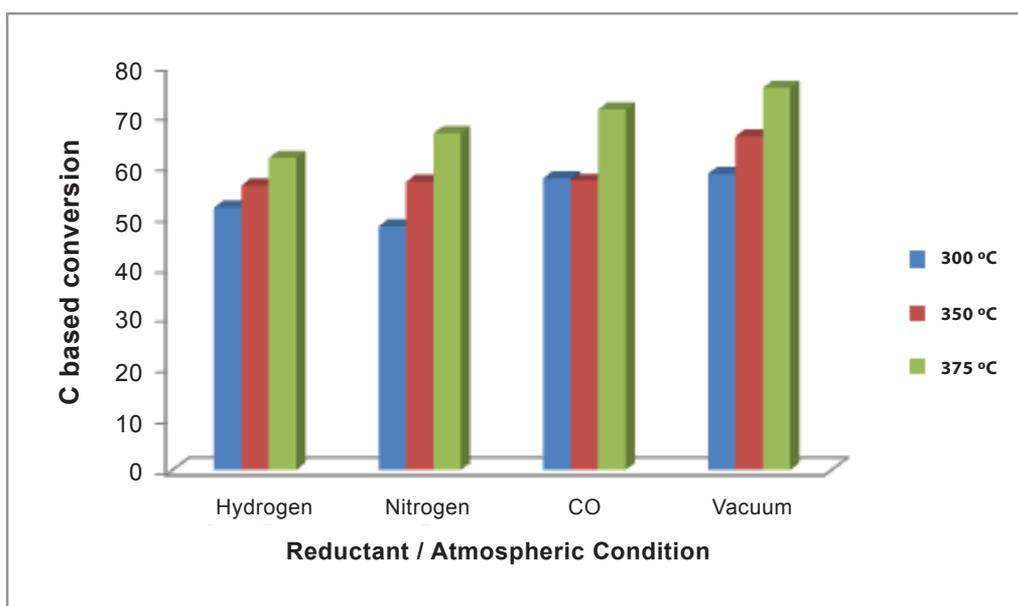


Fig.3 : Effect of temperature and atmospheric conditions on C based conversion

C based yield while 40 atm. Hydrogen produced oil with the lowest value (the trend in C based yield is as follows: Vacuum > Nitrogen > CO > H₂). On the other hand, reactions at fixed constant atmospheric condition with varying temperature gave oil of highest C based yield at 375 °C and oil of lowest value at 300 °C (the trend in C based yield is as follows: %yield at 375 °C > 350 °C > 300 °C) for each of the different atmospheres except under CO atmosphere in which C based yield obtained at 300 °C was greater than that obtained at 350 °C. This implies that both temperature and atmospheric condition in which liquefaction process was carried out significantly affected the C based yield of oil obtained. Similar previous researches support these findings [25, 26, 27].

Tables 3a, 3b and Figure 3 showed C based conversion obtained at 300 °C, 350 °C and 375 °C under different atmospheric conditions. The result indicated that the reaction condition under vacuum produced oil with highest C based conversion while 40 atm. of nitrogen produced oil with the lowest value (the trend in C based conversion is as follows: Vacuum > CO > Hydrogen > Nitrogen). The difference in the C based conversion obtained under various atmospheric conditions was statistically significant using ANOVA ($p < 0.05$). Follow up test for the ANOVA using Tukey confirmed the trend stated earlier. For the C based conversion of oil obtained at 375 °C under different atmospheric condition, reaction condition under vacuum (20 mmHg) produced oil with highest C based conversion while 40 atm. hydrogen produced oil with the lowest value (the trend in C based conversion is as follows: Vacuum > CO > Nitrogen > Hydrogen). For the reactions carried out by varying temperature at fixed constant atmospheric condition; oil of highest C based conversion was obtained at 375 °C while oil of C based conversion was obtained at 300 °C (the trend in C based conversion is as follows: C based conversion at 375 °C > 350 °C > 300 °C) for each of the different atmospheric condition except under CO atmosphere in which C based conversion obtained at 300 °C was greater than that obtained at 350 °C. This implies that both temperature and atmospheric condition in which liquefaction process was carried out have significant impact on the C based conversion of oil obtained. This implies that both temperature and atmospheric condition in which liquefaction process was carried out significantly affected the C based yield of oil obtained. Previous researches carried out by others supported these findings [24, 25, 26, 27].

Biomass is comprised of cellulose, hemicelluloses and lignin as major components. Though approaches to biomass thermochemical conversion include gasification, pyrolysis and liquefaction, the emphasis in this study is that of the liquefaction of straw based kraft lignin in the presence of tetralin, hydrogen, carbon monoxide, nitrogen, vacuum at temperatures within 300 - 375 °C range using 3%Ru/Al_y(SiO₄)_x catalyst to produce an oil product. Historical reviews related

to biomass liquefaction are available but relatively not much has been reported on direct liquefaction of lignin in processes using hydrogen and carbon monoxide as reductants, 3%Ru/Al_y(SiO₄)_x catalyst, elevated temperature and pressure in an organic solvent medium [28]. Our effort focussed on carbon based yield, conversion, energy yield and quality of the initial oil product.

The initial oil products from the thermochemical conversion processes are different from petroleum crude oil and can be further upgraded through deoxygenation processes such as solvolysis, catalytic hydroliquefaction, catalysed pressurised aqueous pyrolysis into compatible products. Upgrading thermochemical processes in the presence hydrogen donor solvents like tetralin, hydrogen and catalysts such as Fe₂O₃, Na₂CO₃, Cu-Ru/C, Pd/ZrO₂, Pt-Re/C, Ni/Mo, Co/Mo, Ra/Ni and Ni-4301 have been reported [18, 29, 30, 31]. Also, several papers have been published on thermochemical conversion processes with different starting materials and conditions.

We also analysed the energy recovery efficiency of the oil product as a potential energy source by estimating the mass of carbon and hydrogen which was recovered as part of an oil product from a given mass of feed (equation 1). This was also compared with energy yield data obtained by estimating the mass of carbon and hydrogen recovered as part of the oil product from a given mass of carbon and hydrogen in the feed (equation 5) [32] and the higher heating values estimated from carbon and hydrogen content of the oil using Dulong's formula (equation 4) [33, 34, 35].

Tables 3a, 3b and Figure 4, showed the %CHR obtained at 300 °C, 350 °C and 375 °C under different atmospheric condition revealed that reaction condition under vacuum produced oil with the highest %CHR while 40 atm. of hydrogen produced oil with lowest %CHR with the exception of %CHR obtained under vacuum at 300 °C. The trend in %CHR increases with temperature generally as follows within similar atmospheric conditions: Vacuum > Nitrogen > CO > Hydrogen except in the case of CO where there was a drop at 350 °C. The difference in the %CHR obtained under various atmospheric condition is statistically significant using ANOVA ($p < 0.05$). Follow up test for the ANOVA using Tukey confirmed the trend stated earlier. For the reactions at varying temperature and fixed constant atmospheric condition; oil of highest %CHR was obtained at 375 °C while oil of lowest %CHR was obtained at 300 °C (the trend in %CHR is as follows: %CHR at 375 °C > 350 °C > 300 °C) for each of the different atmospheric condition, the exception was only under CO atmosphere in which %CHR obtained at 300 °C was higher than that obtained at 350 °C. This shows that both temperature and atmospheric condition in which liquefaction process was carried out have significant impact on the %CHR of oil obtained. Previous studies reported findings

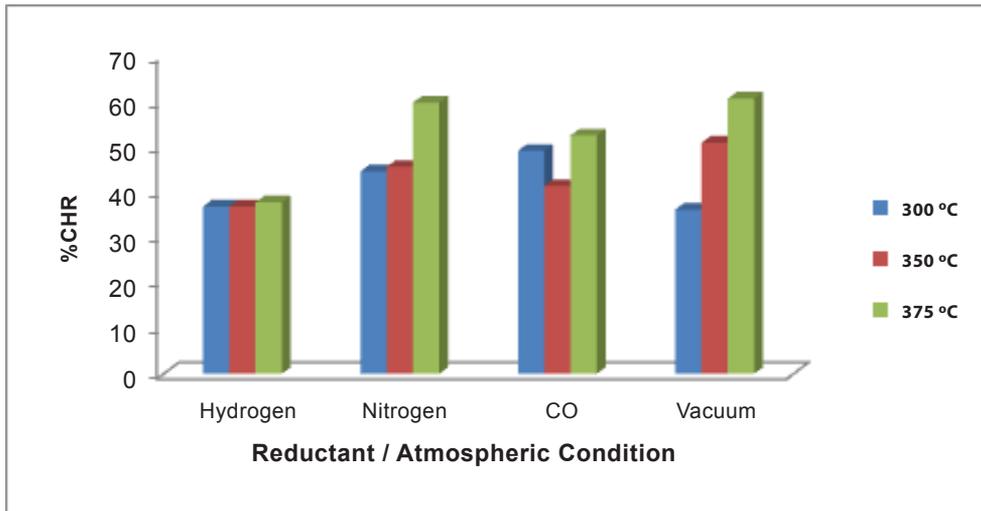


Fig.4 : Effects of temperature and atmospheric conditions on %CHR

in line with the result obtained [25, 26, 27].

Figures 5 and 6 showed that a similar trend observed with the energy yield and higher heating values respectively with the exception of the drop in higher heating value at 350 °C under vacuum and the drop in energy yield value at 350 °C under CO. The range of values for CHR, energy yield and higher heating values are 36.8 – 60.5 %, 56 – 94 % and 28.3 – 34.7 MJ/Kg respectively. Despite the varying oil yields, the elemental analysis in an estimated higher heating value in the range 28.3

– 34.7 MJ/Kg against a wider range of 25 – 39 MJ/Kg reported previously for other feedstock types [H]. Petroleum crude in contrast range from 41 - 48 MJ/Kg [36]. The lower higher heating values of the oil could be as a result of the higher nitrogen content 1.02% and higher oxygen content in the range 11- 22% of the product oil in comparison with petroleum crudes which typically have less than 2%. Energy values are generally influenced by the amount of oxygen in the oil. The higher the oxygen the lower the energy value.

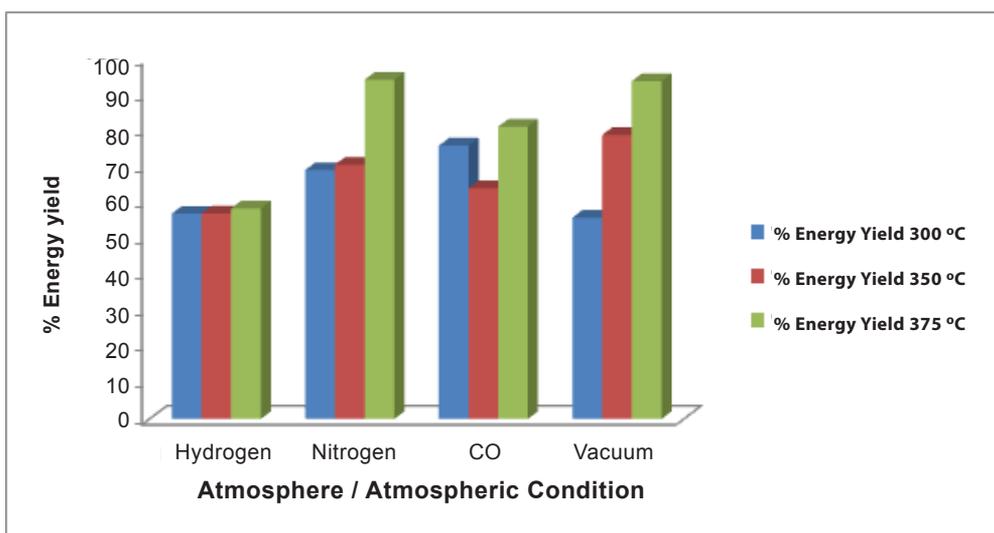


Fig.5 : Effect of temperature and atmospheric condition on % Energy Yield

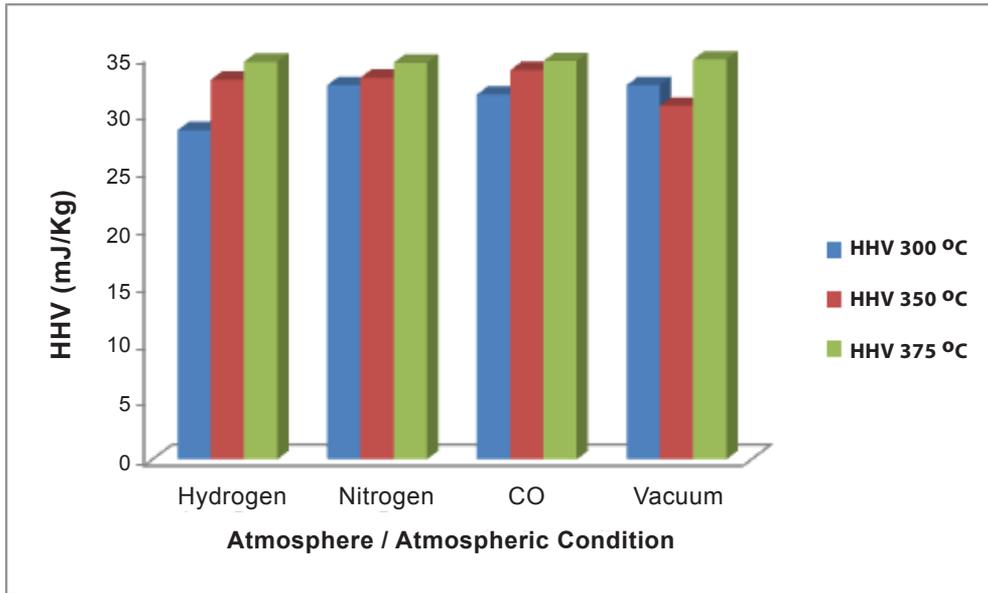


Fig.6 : Effect of temperature and atmospheric condition on HHV

Table 3a, 3b and Figure 7, shows the H/C atomic ratios obtained at fixed temperature of at 300 °C, 350 °C and 375 °C under different atmospheric conditions and the result indicates that the reaction condition under hydrogen produced oil with highest H/C atomic ratio while this ratio obtained under the rest of the atmospheric condition is more or less the

same (the trend in H/C atomic ratio is as follows: Hydrogen > Vacuum ≈ Nitrogen ≈ CO). The difference in the H/C atomic ratio obtained under various atmospheric condition is not statistically significant using ANOVA ($p > 0.05$). Follow up test for the ANOVA using Tukey confirmed the trend stated earlier. At 350 °C, this ratio obtained under the rest of the atmospheric

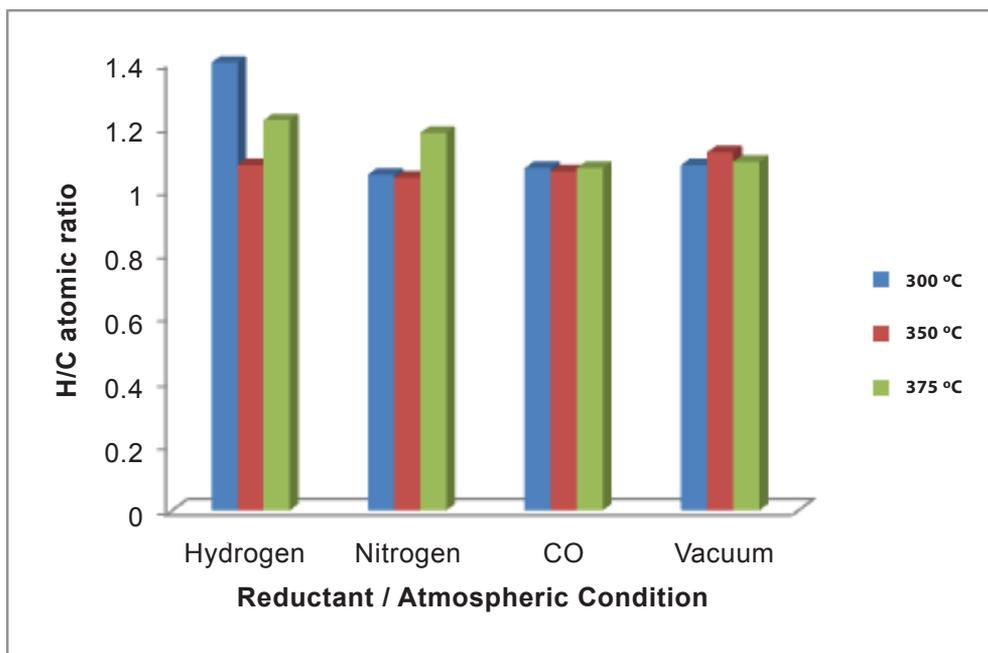


Fig.7 : Effect of temperature and atmospheric conditions on H/C atomic ratio

condition is more or less the same while at 375 °C, the trend of this ratio is as follow: Hydrogen > Nitrogen > Vacuum \approx CO. For the reactions carried out by varying temperature at fixed constant atmospheric condition, H/C atomic ratio were found to be generally below that of the feedstock. The difference in the values of this ratio obtained at different temperature was not statistically significant ($p > 0.05$). This shows that both temperature and atmospheric condition in which liquefaction process was carried out did not significantly affect the H/C atomic ratio of the oil obtained.

Tables 3a, 3b and Figure 8, consider O/C atomic ratio obtained under all the different atmospheric conditions except under vacuum; it was revealed that this ratio was highest at 300 °C and lowest at 375 °C (the trend in O/C atomic ratio is as follows: O/C atomic ratio at 375 °C < 350 °C < 300 °C). Under vacuum, O/C atomic ratio was highest at 350 °C and lowest at 375 °C (the trend in O/C atomic ratio is as follows: O/C atomic ratio at 350 °C > 300 °C > 375 °C). At 300 °C, O/C atomic ratio was

highest under hydrogen and lowest under nitrogen (the trend in ratio is follows: Hydrogen > Vacuum > CO > Nitrogen). At 350 °C, O/C atomic ratio was highest under vacuum and lowest under CO (the trend in ratio is follows: Vacuum > Hydrogen > Nitrogen > CO) while at 375 °C, O/C atomic ratio was highest under nitrogen and CO and lowest under vacuum (the trend in ratio is follows: Nitrogen > CO > Hydrogen > Vacuum).

From the tables and figures above, the highest and lowest values of the desirable parameters in terms of C-based yield, C-based conversion, and %CHR were obtained at 375 °C and 300 °C respectively while the least desirable parameter O/C atomic ratio was lowest and highest at 375 °C and 300 °C respectively. This implied that of the highest quality and quantity in this study was obtained at the highest operating temperature of 375 °C. At this temperature, the best atmospheric condition that brought about the oil of best quality and quantity is the vacuum.

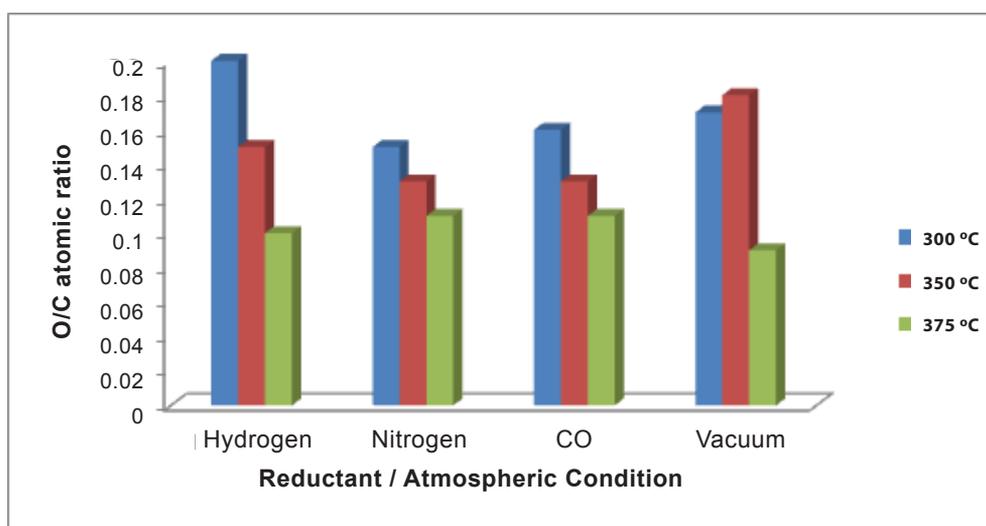


Fig. 8 : Effect of temperature and atmospheric conditions on O/C atomic ratio

3.3. Other important Observations in the Results:

Comparing the H/C and O/C atomic ratios obtained in the feedstock and the product oil; the decrease in the O/C atomic ratio relative to that of the feedstock at 300 °C, 350 °C and 375 °C for all reactions carried out in CO and in vacuum. Increase in H/C atomic ratio occurred in hydrogen and nitrogen at 300 °C and 375 °C respectively relative to the feedstock could be attributed to the increased formation of CO and CO₂ in the reactions. The amount of aqueous fractions formed is higher than those of the gases and excessive formation of water will

decrease O/C atomic ratio to the detriment of H/C atomic ratio [24]. Removal of water in this study has not been an efficient way of reducing oxygen content. Probably the most important overall reaction in converting the lignin material to oil is the splitting out of oxygen to form molecules with higher H/C and lower O/C atomic ratios. Lignin loses water and carbon dioxide on being heated. Oxygen can also be lost by reaction with the added carbon monoxide to form carbon dioxide by hydrogenation, disproportionation or by a combination of these reactions which would result in an oil made up of a complex mixture of different compounds. Replacing carbon

monoxide with hydrogen did not have any appreciable effect on conversion and other quality parameters and therefore it may be more economical to use synthesis gas instead of pure carbon monoxide or hydrogen in the initial charge to the autoclave. Though the objective of low O/C atomic ratio has been attained but increasing the H/C atomic ratio relative to the starting material did not materialise fully.

The high oxygen content of the product oil will be a major challenge in its use in transportation and any upgrading process to lower the oxygen content will be a welcome development to the biofuel industry. Also, sulphur and nitrogen must be removed from the oils to obtain fuels that will burn cleanly. The average process recovery in this study was 96%. The oil contained 1.02% nitrogen and 0.53% sulphur on the average in comparison to the 1.4% nitrogen and 2.4% sulphur found in the feedstock. It is highly probable that some of the nitrogen and sulphur present in the feedstock have been reduced to ammonia and hydrogen sulphide respectively. Possible catalytic contribution of trace metals in the feed could also result in increased conversion and at the same time these inorganic elements can mask the effects of other important factors such as catalyst poisoning thus making interpretation and correlation of data difficult.

4. Conclusion

Thermochemical liquefaction of Kraft lignin using $\text{Ru}/\text{Al}_y(\text{SiO}_4)_x$ catalyst at 300 °C, 350 °C and 375 °C and varying atmospheric conditions of 40 atm. H_2 , CO , N_2 and under 20mmHg vacuum produced oil of varying quality and quantity. The study concluded that oil of best quality and highest yield was obtained from thermochemical liquefaction of Kraft lignin using $\text{Ru}/\text{Al}_y(\text{SiO}_4)_x$ catalyst at the temperature of 375 °C under vacuum.

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