

Empirical Model of Slow Pyrolysis of Hardwood Chips

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ABSTRACT

The thermal decomposition of mixed hardwood chips was investigated by pyrolyzing 1-kg samples at atmospheric pressure in an electrically-heated batch reactor. The maximum temperature was varied from 464 to 871°C. Yields of charcoal, light oil, heavy oil, water, and gas were determined. The heating value and moisture content were determined for the feed, charcoal, light oil, and heavy oil. Gas chromatography was used to determine the composition of the gas product. Using these data, an empirical model was developed to predict the yields of charcoal, dry light oil, dry heavy oil, water of pyrolysis, C2-C5 hydrocarbons, light organics, and permanent gases—carbon dioxide, carbon monoxide, hydrogen, and methane—in terms of the maximum temperature to which the charcoal was heated.

Index Entries: Slow pyrolysis; batch reactor; hardwood chips; pyrolysis products; empirical model.

INTRODUCTION

This investigation was conducted in support of a feasibility study of the gasification of hardwood chips in a vertical-shaft, updraft, char-recirculation reactor similar to that described by Bowen et al. (1). Here, chips with an appropriate free-moisture content are fed into the reactor and spread over the top of a packed bed. High-temperature gases are formed

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low in the bed and drafted from the top of the bed. They serve as the source of thermal energy to drive the various bed processes. The moist chips are first dried by these gases. Then, as they move deeper into the bed, the chips are heated to their pyrolysis point. These upper bed processes are thermodynamically modeled by simple mass and energy balances.

Continuation of the modeling beyond the pyrolysis point requires knowledge of the products of pyrolysis in terms of the bed temperature. For the present, it has been assumed that this thermal decomposition process may be represented by a slow pyrolysis process. And the pyrolysis products are taken to be those obtained by slow pyrolysis in a batch reactor. Therefore, the objective of this study was to pyrolyze mixed hardwood chips in a batch reactor, determine the products of pyrolysis, and develop empirical relations for the product yields.

METHODS

Experimental System

The experimental system consisted of the pyrolysis reactor shown in Fig. 1 and the off-gas collection unit shown in Fig. 2. The vertical, 10-cm ID, 59-cm high cylindrical reactor vessel was mounted in a 4000 W tube furnace. It was filled with feedstock to within 5 cm of its flange.

In order to minimize condensation on the flanged top of the reactor and on the walls of the 5-cm portion of the reactor that extends beyond the top of the furnace, these areas and the off-gas tubing were wrapped with heat tape, submerged in insulation, and heated to about 120°C prior to starting a pyrolysis run.

The gases and vapors generated in the reactor flowed from it and entered the off-gas collection unit (*see*, Fig. 2). Here, the off-gas stream was sequentially cooled with tap water, -20°C ethylene glycol, and -80°C methanol. The resulting condensates were collected in the 3-neck flasks, the glass-wool traps, and the cold-finger condenser. Residual water vapor was collected with the Drierite trap. The stream exiting the cold-finger condenser flowed through a dry gas meter before being collected in a 100 L Tedlar bag. Two to five bags per run were required.

Experimental Procedures

A sample of equilibrium-moisture mini-chips was prepared by first screening it to remove dust and then preparing subsamples for moisture determinations. About 1.07 kg of the remaining material was accurately weighed and placed in the reactor. The ball valve was closed to prevent loss of moisture prior to starting a run.

The reactor headspace was heated to about 120°C with the off-gas valve closed, and the condensate train coolants were brought on line. At

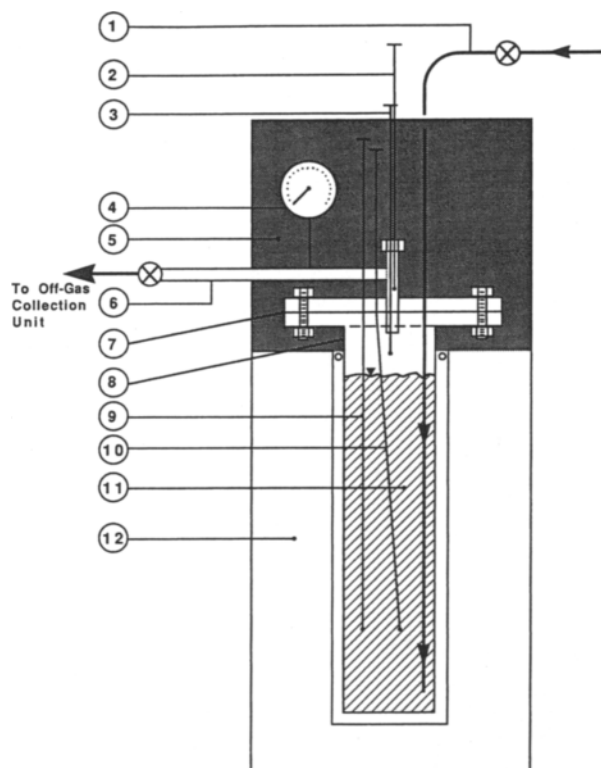


Fig. 1. Pyrolysis reactor.

this point, the ball valve was opened, and 250 L of room temperature nitrogen were injected into the reactor to purge the system of ambient air.

A run was initiated by applying power to the furnace. Full power was maintained until a wall temperature of about 350°C was obtained. At this point, the power was reduced in order to bring the wall temperature to about 450°C at about the same time that the center of the bed reached this temperature. After this initial exothermic pyrolysis process occurred, gas evolution stopped. In order to decompose the material (charcoal) further, the reactor was heated to a higher temperature.

A run was terminated after the target maximum reactor temperature had been reached and held for an hour. Fifty liters of room temperature nitrogen were injected into the reactor to purge it of the residual gas/vapor products of pyrolysis. These were collected as part of the total products. All nitrogen collected was regarded as having been artificially introduced.

At this point, the reactor was cool enough to close the ball valve, thereby isolating the charcoal product in a nitrogen environment. Next,

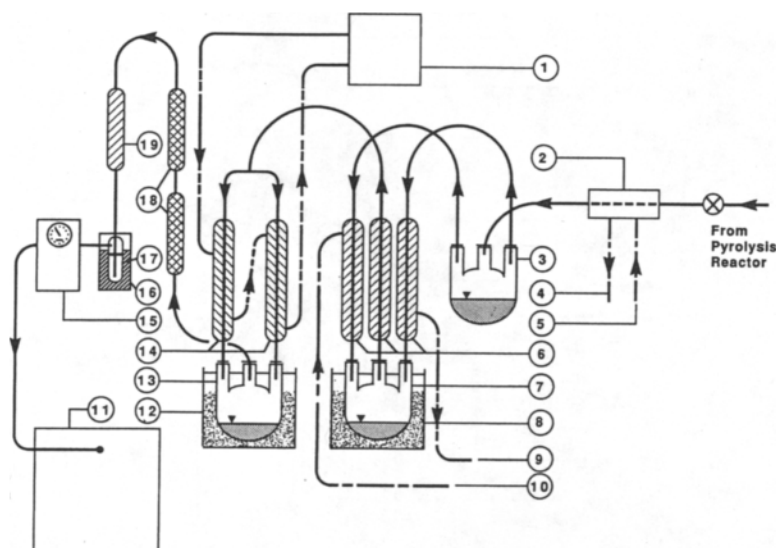


Fig. 2. Off-gas collection unit.

the gas bags were taken to the GC labs for analysis, and the condensation train was disassembled. The condensates were individually weighed and then mixed in a separatory funnel. After overnight storage in a refrigerator, the gravitationally separated oils were decanted into light and heavy oil fractions that were stored in Nalgene bottles. The cold-finger condensate was weighed, transferred to a vial, and stored in a freezer for later analysis. The charcoal was recovered from the reactor the next day. After determining its dry weight, it was stored in zip-lock bags.

Analytical Procedures

Moisture Content

To perform a mass balance, it was necessary to determine the moisture content of the wood chips, charcoal, and two oil fractions. Solid materials were dried at 105°C to constant weight in a ventilated drying oven and then cooled to room temperature in a vacuum desiccator. All weights were determined with an analytical balance.

A K-F automatic titrator with a burette dispenser was used to determine the moisture content of the wood distillate oils. Hydranal Composite/5 was used as the reagent.

Volatile-Matter Content

An ashing furnace was used in the determinations of the volatile-matter, ash, and fixed-carbon contents of the charcoals produced. Since

the model being developed required a determination of the fixed carbon produced by simple thermal decomposition of charcoal, a gas-tight reactor vessel was built to simultaneously process up to eight samples in porcelain crucibles without lids. After placing this vessel in the furnace, it was purged with nitrogen, slowly heated to 950°C, held there for 20 min, and then cooled to room temperature, all under a nitrogen blanket. After removal and storage in the vacuum desiccator for 1 h, each sample was weighed to determine its loss of volatile matter. Standard procedures were then employed to determine the ash content of each sample. The fixed carbon was obtained by difference.

Higher Heating Value

An adiabatic bomb calorimeter, in conjunction with a calorimeter controller, was used to determine the higher heating value for the wood-chip feedstock, the charcoals, and the wood distillate-oil fractions. Since the moisture content of the light-oil fraction was so high (>50%), it was necessary to mix it with a known amount of ground wood in order to burn it in the calorimeter; good results were obtained with this technique.

Gas Composition

An analytical gas chromatograph was dedicated to the determination of the hydrogen content of the collected gases. This unit used a silica gel column with argon as the carrier gas. Isothermal operation at 35°C and thermal conductivity detection for a 1.0 mL sample resulted in an output signal that was analyzed with a signal integrator.

A second analytical gas chromatograph with a helium carrier gas was used to determine the other permanent gases and the C₂–C₅ hydrocarbons. A Molecular Sieve 13X column, operated isothermally at 35°C, was used to determine the oxygen, nitrogen, methane, and carbon monoxide content of the collected gases. And a Chromosorb 102 column, operated isothermally at 35°C, was used to determine the carbon dioxide content of these gases. One milliliter samples and thermal conductivity detection were used in both cases.

A Porapak Q column, operated at 35°C for 4.0 min, then ramped at 10.0°C/min to 180°C, and finally held for 12 min at this temperature, was used to determine the C₁–C₅ hydrocarbons in the collected gases. One milliliter samples and hydrogen flame ionization detection were used. Calibration gases for the permanent gases and the hydrocarbons permitted reliable quantitative analyses for these components.

RESULTS

Feedstock

Since the goal of this research was to experimentally determine the products of pyrolysis of chipped mixed hardwood slabs from sawmills in

the vicinity of the university, the chipped waste stream from a local furniture manufacturer was chosen as the source of feedstock for these studies. This manufacturer makes mini-chips from their dry cuttings. These chips are -4 mesh, as prepared, and they were screened in the laboratory to remove -20 mesh particles. A sample was obtained in January, 1987 for the exploratory studies. This material had a higher heating value of 19,460 kJ/kg dry feed (ovendry feed) and an ash content of 5.9 g/kg dry feed. A second sample was obtained in June, 1988 for the quantitative studies, and corresponding values of 19,600 kJ/kg and 6.2 g/kg were measured for this material.

Exploratory Studies

Following the pattern of Knight's study of pine sawdust (2), exploratory pyrolysis runs were made for maximum reactor temperatures (charcoal temperatures) ranging from 464 to 871°C. The results are given in Table 1 and Fig. 3.

Quantitative Study

Three quantitative pyrolysis runs were made in the 460–640°C temperature range to determine pyrolysis product yields in terms of the maximum charcoal temperature. The results are given in Tables 2 and 3 and Figs. 4 and 5. Using the higher heating value determinations for the feedstock, the charcoal, light oil, and heavy oil, together with computed values for the gas components, the chemical energy contents of these pyrolysis products were computed. The results are given in Tables 3 and 4 and Fig. 5.

DISCUSSION

Exploratory Runs

The results of the exploratory runs, as shown in Fig. 3, clearly indicate that the yields of the products of the slow pyrolysis of mixed hardwood chips are simply a function of the maximum temperature to which the charcoal is heated. Note that the thermal decomposition (devolatilization) of the charcoal in an inert environment ceases at about 650°C.

It was found that chemically-stable charcoal was only produced for maximum reactor temperatures above about 450°C. Therefore, to describe the pyrolytic decomposition of these chips, it is necessary to obtain quantitative data in the 460–640°C temperature range.

Although the condensate data presented in Fig. 3 lack precision, it appears that the condensable organics yield is independent of the maximum charcoal temperature, i.e., these decomposition products are formed during the initial exothermic pyrolysis process. Furthermore, it appears

Table 1
Summary of Product Yield Data
for Exploratory Pyrolysis Runs Using Mixed Hardwood Mini-Chips, Sample 1

Run Number	041487	051287	051987	100987	040888	041588	042988
Maximum temperature, °C	637	781	499	871	649	464	572
Feed							
Moisture content, wt.% ^a	6.09	6.80	7.08	8.70	7.26	6.96	6.13
Total ash, g/kg							
dry feed	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Heating value, ^b kJ/kg							
dry feed ^a	19,460	19,460	19,460	19,460	19,460	19,460	19,460
Amount, g/kg dry feed	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Charcoal							
Dry yield, g/kg							
dry feed	269.8	260.1	304.0	264.7	266.6	317.2	277.8
Total ash, g/kg							
dry feed	5.8	6.0	5.0	6.1	5.5	5.7	5.1
Fixed carbon, g/kg							
dry feed	239.3	237.9	235.8	247.1	241.1	243.0	241.7
Volatiles, g/kg							
dry feed	24.7	16.2	63.2	11.5	20.0	68.5	31.0
Water of pyrolysis							
Yield, g/kg dry feed	235.4	-	-	225.8	230.4	207.3	221.1
Condensable organics							
Dry yield light oil,							
g/kg dry feed	204.0	-	-	173.8	198.0	182.1	193.5
Dry yield heavy oil,							
g/kg dry feed	77.7	-	-	92.4	69.2	87.6	78.8
Dry yield total oil,							
g/kg dry feed	281.7	-	-	266.2	267.2	269.7	272.3
Gas and light organics							
Dry yield (by difference),							
g/kg dry feed	213.1	225.7	195.4	243.3	235.8	205.8	228.8

^aMoisture content on wet basis.

^bHigher heating value.

that most of the water of pyrolysis is formed during the initial decomposition of the wood, but that additional water is formed during the endothermic devolatilization of the charcoal up to about 650°C.

The curves in Fig. 3 are fits of the charcoal, condensable organics, and water of pyrolysis yield data. A curve for the gas yield was determined by difference, but it was omitted since it is practically coincidental with the water of pyrolysis.

Quantitative Runs

After making three trial runs, three quantitative runs were made for maximum charcoal temperatures of 486, 561, and 638°C. The results of these runs are discussed by pyrolysis product.

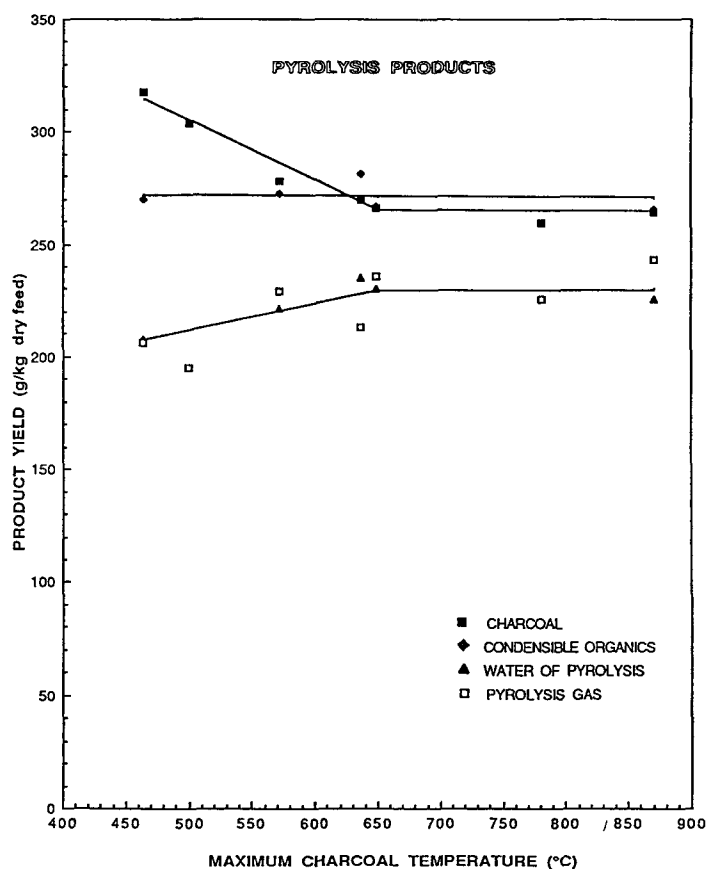


Fig. 3. Product yield vs maximum charcoal temperature for slow pyrolysis of mixed hardwood mini-chips (Sample 1).

Charcoal and its Components

Figure 4a presents the yield of charcoal and its components as a function of the maximum temperature to which the charcoal was heated.

Although it may be difficult to detect an anomaly in such a limited data set, consideration of all of the product data for the 561°C run clearly showed that the data of this run did not fit the trends found in either the exploratory runs or the other two quantitative runs. After a careful review of the product properties, it was concluded that these data are sound. However, review of the run logs revealed that during the warm-up for this run, the headspace heater had failed at a headspace temperature of about 106°C and that this temperature had dropped to a low of 82°C during the actual heat-up. This resulted in both water-vapor and organic-vapor condensation in the top of the reactor, thereby creating reflux loops for these materials. Also, the off-gas temperature did not exceed the steam point until after the centerline temperature had reached the steam point and the wall temperature had reached the wood pyrolysis point.

Table 2
Summary of Product Yield Data
for Quantitative Pyrolysis Runs Using Mixed Hardwood Mini-Chips, Sample 2

Run Number	071988	080288	080988
Maximum temperature, °C	561	486	638
Feed			
Moisture content, wt. % ^a	6.08	6.85	8.21
Total ash, g/kg dry feed	6.2	6.2	6.2
Heating value, kJ/kg dry feed ^b	19,600	19,600	19,600
Amount, g/kg dry feed	1000.0	1000.0	1000.0
Charcoal			
Dry yield, g/kg dry feed	289.4	297.0	272.0
Total ash, g/kg dry feed	5.7	5.5	5.5
Fixed carbon, g/kg dry feed	247.9	237.3	244.6
Volatiles, g/kg dry feed	35.8	54.2	21.9
Water of pyrolysis			
Yield, g/kg dry feed	238.0	221.3	235.1
Condensable organics			
Dry yield light oil, g/kg dry feed	192.5	211.3	200.8
Dry yield heavy oil, g/kg dry feed	69.4	69.8	75.6
Dry yield total oil, g/kg dry feed	261.9	281.1	276.4
Deposits			
g/kg dry feed ^c	1.7	1.2	1.0
Gas and light organics			
Dry yield (by difference), g/kg dry feed	209.0	199.4	215.5

^aMoisture content on wet basis.

^bHigher heating value.

^cCracked organics residue in reactor and tar in condenser.

Without the headspace heater, the primary means of heating the head of the reactor is by convection/condensation from the "off-gas" stream. Thus, one would expect a significant water reflux loop up to and during the early stages of the primary pyrolysis process. Also, a condensable organic reflux loop was likely during the pyrolysis processes. The 561°C data are included in the tables and figures to show the magnitude of the effect of water and condensable organics reflux on product yields.

Two-point "fits" of the charcoal yield and the volatile matter yield are shown in Fig. 4a, and the corresponding equations are given in Table 5 as a function of the dimensionless temperature, \bar{T}_{\max} .

The ash content of the charcoals was about 5.5 g/kg dry feed, nearly the same as obtained for the feed. Using the expressions for the charcoal and the volatile matter yields, and this value for the ash, an expression for the fixed-carbon yield was determined by difference; it is shown in

Table 3
Summary of Gas and Light Organics Data
for Quantitative Pyrolysis Runs Using Mixed Hardwood Mini-Chips, Sample 2

Run Number		071988	080288	080988
Maximum temperature, °C		561	486	638
Component yield				
Hydrogen	g/kg dry feed	0.54	0.22	1.14
	kJ/kg dry feed	77	31	162
Methane	g/kg dry feed	13.98	10.35	18.73
	kJ/kg dry feed	776	574	1039
Carbon monoxide	g/kg dry feed	54.75	50.82	57.74
	kJ/kg dry feed	553	513	583
Carbon dioxide	g/kg dry feed	107.12	103.19	107.64
	kJ/kg dry feed	0	0	0
C2-C5 Hydrocarbons				
C2s	g/kg dry feed	3.57	3.40	3.33
	kJ/kg dry feed	184	175	171
C3s	g/kg dry feed	1.86	1.88	1.53
	kJ/kg dry feed	92	93	76
C4s	g/kg dry feed	0.92	0.94	0.75
	kJ/kg dry feed	45	46	37
C5s	g/kg dry feed	1.72	0.99	0.77
	kJ/kg dry feed	83	48	37
Total C2-C5s	g/kg dry feed	8.07	7.21	6.38
	kJ/kg dry feed	404	362	321
Light organics (by difference)	g/kg dry feed	24.45	27.65	24.07
	kJ/kg dry feed ^a	818	925	806
Total	g/kg dry feed	208.91	199.44	215.50
	kJ/kg dry feed	2,628	2,405	2,911

^aHigher heating value taken to be 33,470 kJ/kg light organics.

Fig. 4a and given in Table 5. (Note that the fixed carbon increases with increasing temperature, a trend that has been found in all studies to date.)

Condensible Organics

The condensible organics yields are shown in Fig. 4b. Knowing the oil moisture contents, the amounts of dry light oil and dry heavy oil were computed. Their sum is reported as the total dry organics. Two-point fits of these data are shown in Fig. 4b and the corresponding equations are given in Table 5.

From the exploratory studies, it was expected that the organics yields would be independent of the maximum charcoal temperature since it was surmised that the condensible organics were produced during the primary pyrolysis process. The fact that the yields of total organics and light oil decrease with increasing temperature supports this proposition. These decreased yields are apparently owing to secondary reactions in the resi-

dual organic vapors in the reactor during the secondary pyrolysis/devolatilization process.

Water of Pyrolysis

From the Karl-Fischer moisture determinations for the light and heavy oils, the sum of the resulting moisture components of these oils and the moisture collected in the Drierite trap was taken to be the water of pyrolysis plus the free moisture of the feedstock. Knowing the initial mass of the feed and its moisture content, the water of pyrolysis was obtained by difference. The results are shown in Fig. 4c. A two-point fit of the data is shown in this figure and given in equation form in Table 5.

Pyrolysis Gas and Light Organics

Knowing the yields of the charcoal, the total condensibles, except those of the cold finger, and the system residues, the pyrolysis gas and light organics yield was determined by difference. These data are also shown in Fig. 4c, together with a curve that was determined by difference. This difference equation is given in Table 5.

In addition to this gross determination of the yield of pyrolysis gas and light organics (components that are not condensed and collected in the primary condensation train, but including those that were condensed in the cold finger), gas component determinations of the permanent gases and the C₂-C₅ hydrocarbons were made using gas chromatography. The permanent gas results are illustrated in Fig. 5a, together with their two-point fits; the corresponding equations are given in Table 5.

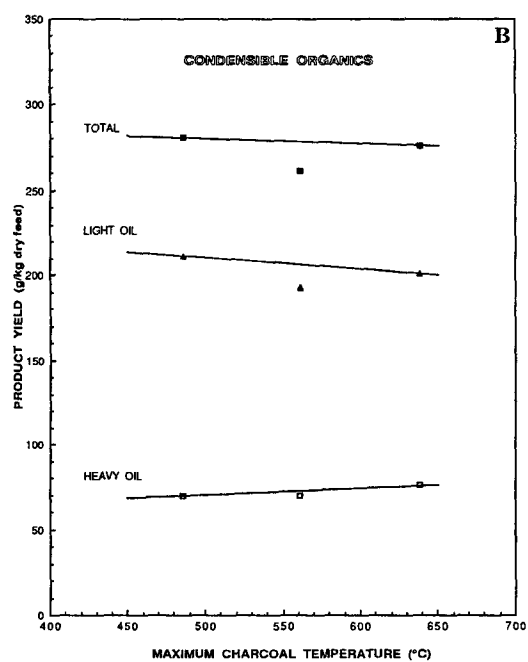
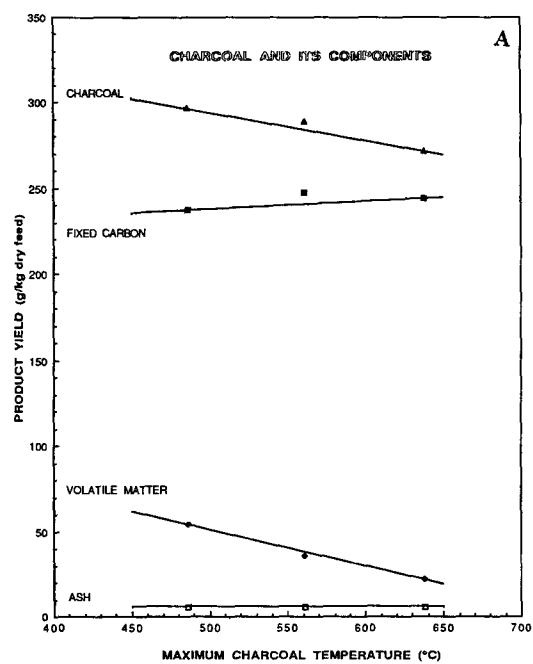
The hydrocarbon data are presented in Fig. 5b. An empirical equation for the hydrocarbon yield was obtained by a two-point fit; this equation is also given in Table 5.

Note that there is a slight decrease in the hydrocarbon yield with increasing temperature. As in the case of the condensible organics, it appears that the hydrocarbons are produced during the primary pyrolysis process and that their residuals also undergo secondary chemical reactions in the reactor during the secondary pyrolysis process.

Having these gas component yield data for each run, their total was subtracted from the total gas and light organics yield, thereby giving mass closure. The resulting yield was taken to be light organics. These data are also presented in Fig. 5b. The curve shown was obtained by adding the equations for the fits for each of the gas components and subtracting this equation from that obtained earlier for the total gas and light organics yield. The resulting equation is given in Table 5.

Note that the decrease in the light organics yield with increasing temperature supports the premise that the organics are produced during the primary pyrolysis process and are partially lost owing to secondary reactions in the reactor.

One might question taking all of the unidentified mass to be light organics. The FID chromatograms clearly showed significant amounts of



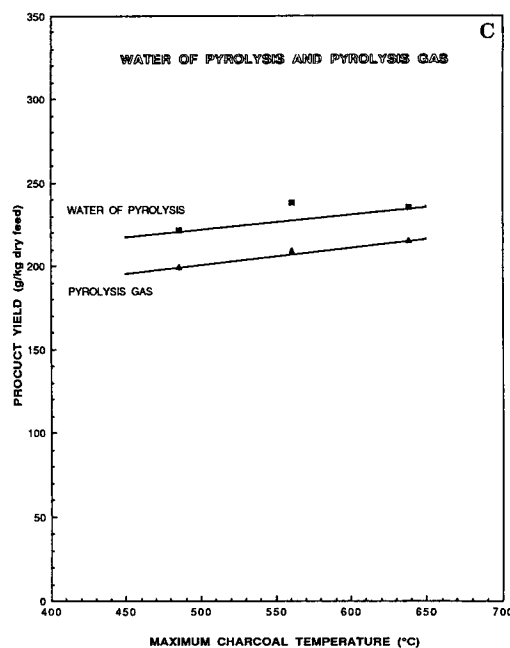


Fig. 4. Yields of charcoal and its components (A), condensible organics (B), and water of pyrolysis and pyrolysis gas (C) vs maximum charcoal temperature for slow pyrolysis of mixed hardwood mini-chips (Sample 2).

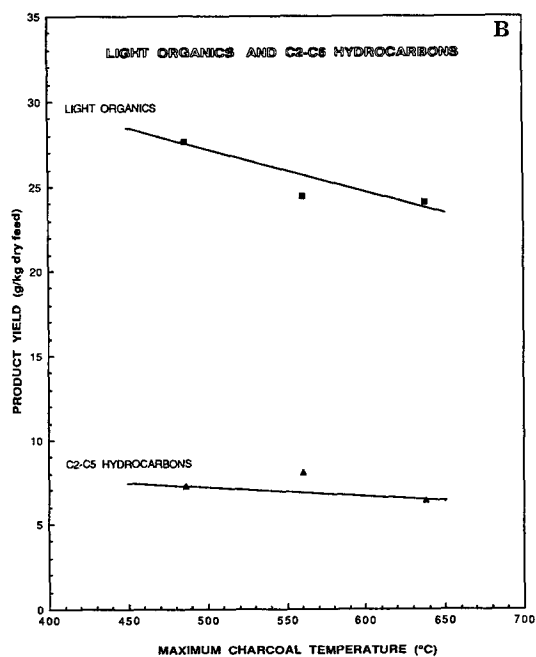
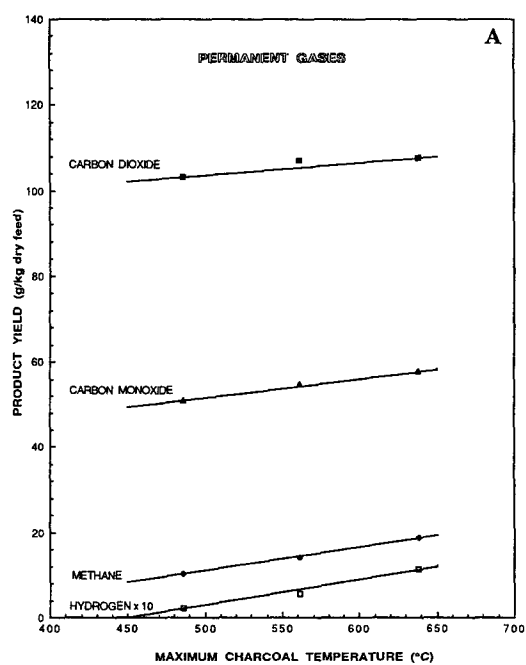
unknown components. Exploratory mass spectrometry studies identified the major components of the cold-finger condensate to be 2-propanone, methyl acetate, 2-butanone, 2-methyl furan, 2-ethyl furan, 2,5-dimethyl furan, ethanone, and methyl benzene. These same components appear to be present in the collected gases.

Since the mass of the dry feedstock and its associated free moisture and the yields of charcoal, condensibles, and gases could be measured with good precision, tagging all of the unidentified mass as light organics was judged to be reasonable.

Chemical Energy

The chemical energy content of the pyrolysis gas and light organic product is given in Table 3, and the specific higher heating value of each major product is given in Table 4. The data of Table 4 are shown graphically in Fig. 5c.

In order to estimate the energy associated with the light organics, the higher heating value of the light organics was taken to be that of the dominant component of the cold finger condensate, i.e., that of 2-methyl furan—33,470 kJ/kg. At only 2.4% of the mass of the total products, the light organics accounted for 865 kJ/kg dry feed, or 4.7% of the chemical energy of the total products, or from 28 to 38% of that of the "gas" product (pyrolysis gas and light organics).



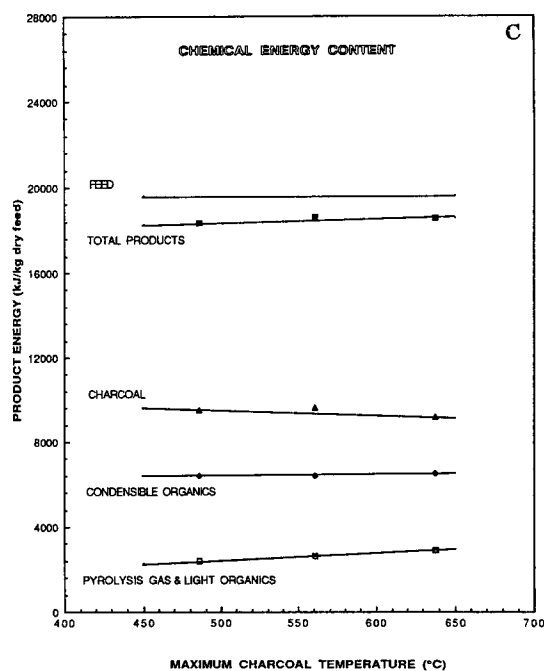


Fig. 5. Yields of permanent gases (A), light organics and C2–C5 hydrocarbons (B), and chemical energy (C) vs maximum charcoal temperature for slow pyrolysis of mixed hardwood mini-chips (Sample 2).

Comparing the total chemical energy of the products with that of the dry feedstock, it is seen that a chemical energy conversion efficiency of about 94% was achieved.

Empirical Model

The primary objective of this study was to develop an empirical model of the thermal decomposition of mixed hardwood chips. Specifically, the yield of each of the pyrolysis products was to be predicted in terms of the temperature to which the solids had been slowly heated.

In the absence of cooling during the primary exothermic decomposition process, it was found that pyrolysis products at about 450°C are produced from dry wood at about 230°C. Also, simple thermal decomposition of charcoal apparently stops from about 650°C up to at least 850°C. Therefore, the empirical model is restricted to a solids temperature in the range of 450 to 650°C. The predictive equations are given in Table 5 in terms of a dimensionless temperature, \bar{T}_{\max} , defined as

$$\bar{T}_{\max} = [\bar{T}_{\max}(\text{°C}) - 450]/200$$

where \bar{T}_{\max} is the maximum temperature to which the charcoal has been heated. \bar{T}_{\max} ranges from zero to one.

Table 4
Summary of Higher Heating Value Data
for Quantitative Pyrolysis Runs Using Mixed Hardwood Mini-Chips, Sample 2

Run Number	071988	080288	080988
Maximum temperature, °C	561	486	638
Feed			
HHV, kJ/kg dry feed	19,600	19,600	19,600
Charcoal			
HHV, kJ/kg dry charcoal	33,130	32,000	33,590
HHV, kJ/kg dry feed	9590	9510	9140
Condensable organics			
Light oil			
HHV, kJ/kg dry light oil	22,450	21,180	22,100
HHV, kJ/kg dry feed	4570	4470	4440
Heavy oil			
HHV, kJ/kg dry heavy oil	25,920	27,830	27,340
HHV, kJ/kg dry feed	1800	1940	2070
Total			
HHV, kJ/kg dry feed	6370	6410	6510
Gas			
HHV, kJ/kg dry gas	9810	8620	11000
HHV, kJ/kg dry feed	1810	1480	2105
Light organics			
HHV, kJ/kg dry light organics ^a	33,470	33,470	33,470
HHV, kJ/kg dry feed	820	925	805
Product total			
HHV, kJ/kg dry feed	18,590	18,325	18,560
Chemical-energy conversion efficiency, %	94.8	93.5	94.7

^aHHV taken to be 33,470 kJ/kg light organics.

For design purposes, the energy bridge between dry wood at 230°C and the primary pyrolysis products at 450°C is formed by taking this decomposition process to be one that occurs adiabatically at constant pressure.

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Table 5
Empirical Model of Product Yields
for Pyrolysis of Mixed Hardwood Mini-Chips, Sample 2

Dimensionless temperature

$$\bar{T}_{\max} = [T_{\max}(\text{°C}) - 450]/200$$

Charcoal

$$\hat{m}_{\text{char}} = 302.9 - 32.9 \bar{T}_{\max} \text{ (g charcoal/kg dry feed)}$$

$$\hat{m}_{\text{fc}} = 235.6 + 9.6 \bar{T}_{\max} \text{ (g fixed carbon/kg dry feed)}$$

$$\hat{m}_{\text{ash}} = 5.5 \text{ (g ash/kg dry feed)}$$

$$\hat{m}_{\text{vm}} = 61.8 - 42.5 \bar{T}_{\max} \text{ (g volatile matter/kg dry feed)}$$

Condensible organics

$$\hat{m}_{\text{toil}} = 282.2 - 6.2 \bar{T}_{\max} \text{ (g total dry oil/kg dry feed)}$$

$$\hat{m}_{\text{loil}} = 213.8 - 13.8 \bar{T}_{\max} \text{ (g dry light oil/kg dry feed)}$$

$$\hat{m}_{\text{hoil}} = 68.4 + 7.6 \bar{T}_{\max} \text{ (g dry heavy oil/kg dry feed)}$$

Water of pyrolysis

$$\hat{m}_{\text{wp}} = 218.0 + 18.2 \bar{T}_{\max} \text{ (g water/kg dry feed)}$$

Deposits

$$\hat{m}_{\text{rs}} = 0.8 \text{ (g reactor solids/kg dry feed)}$$

$$\hat{m}_{\text{tar}} = 0.5 \text{ (g tar/kg dry feed)}$$

Pyrolysis gas and light organics (by difference)

$$\hat{m}_{\text{pg+lo}} = 195.6 + 20.9 \bar{T}_{\max} \text{ (g gas and light organics/kg dry feed)}$$

Pyrolysis gas components

$$\hat{m}_{\text{H}_2} = 0.00 + 1.21 \bar{T}_{\max} \text{ (g hydrogen/kg dry feed)}$$

$$\hat{m}_{\text{CH}_4} = 8.37 + 11.03 \bar{T}_{\max} \text{ (g methane/kg dry feed)}$$

$$\hat{m}_{\text{CO}} = 49.18 + 9.11 \bar{T}_{\max} \text{ (g carbon monoxide/kg dry feed)}$$

$$\hat{m}_{\text{CO}_2} = 102.14 + 5.86 \bar{T}_{\max} \text{ (g carbon dioxide/kg dry feed)}$$

$$\hat{m}_{\text{C}_2\text{-C}_5} = 7.41 - 1.09 \bar{T}_{\max} \text{ (g C}_2\text{-C}_5\text{ hydrocarbons/kg dry feed)}$$

$$\hat{m}_{\text{lo}} = 28.50 - 5.22 \bar{T}_{\max} \text{ (g light organics/kg dry feed)}$$

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