Coal liquefaction in lignin-derived liquids under low severity conditions

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It is found that lignin-derived liquids when reacted with coal under mild reaction conditions (375°C and $2.17 \times 10^9 - 3.53 \times 10^{10}$ N m$^{-2}$) enhance the rate of coal depolymerization. Up to 30% enhancement in coal conversion rate is achieved using lignin-derived liquids. The influence of time of reaction and temperature on the degree of reaction was investigated. The lignin liquid-assisted coal depolymerization products (liquids) are observed to contain a significant amount of the desirable pentane-soluble fraction. Influence of the time of storage of lignin-derived liquids on coal conversion was also determined. Also reported are data on elemental analyses of the solid and liquid products. The liquid product analyses using n.m.r. and s.c.c. techniques are also presented. Based on the experimental data collected, it is hypothesized that enhancement in coal depolymerization rate can be explained by a reaction pathway involving intermediates formed from lignin-derived liquids. A mathematical model describing the reaction chemistry has been developed. Computed rate constants are also reported. The analysis indicates that the lignin-derived intermediates are short-lived as compared to the time needed for complete coal depolymerization.

(Keywords: coal; liquefaction; coal depolymerization)

It is anticipated that due to uncertain supplies of crude oil, more markets will develop for low-cost energy substitutes that take advantage of the wide distribution and renewability of lignocellulosics and other biomass resources. It has been shown by Coughlin and Davoudzadeh$^1$ that addition of lignin to coal in the presence of a hydrogen donor solvent and high pressure (13.2 $\times 10^9$ N m$^{-2}$) results in an enhancement in coal liquefaction. It is hypothesized that phenox radicals and other reactive intermediates produced from lignin at relatively low temperatures can attack the coal causing scission of aliphatic C–C bonds in the coal. Atteri and Coughlin$^2$ have characterized the products of coliquefaction of lignin and bituminous coal at 400°C and 13.2 $\times 10^8 - 16.6 \times 10^9$ N m$^{-2}$. The filterable solids from coliquefaction showed enhanced solubility in benzene. In a recent study, Sato et al.$^3$ have reported that the influence of lignin on coal liquefaction yields is temperature dependent. In a recent paper, Lalvani et al.$^4$ have confirmed the synergistic role played by lignin in coal liquefaction albeit under relatively mild reaction conditions ($\sim 4.24 \times 10^9$ N m$^{-2}$ and 375°C).

In the studies cited above, lignin (solid) was used to depolymerize coal. It was assumed that lignin conversion in the presence of coal remains unaltered, but the coal conversion is enhanced by the lignin-derived intermediates. In order to verify this hypothesis, lignin-derived liquids were used to depolymerize coal in this study.

EXPERIMENTAL

The reactor used was a glass-lined 300 ml autoclave, and it was charged with ground (to $\sim 200$ mesh) Illinois coal (Illinois Basin coal sample no. 105 obtained from the Argonne Premium Coal Sample Bank). The caustic lignin used was obtained from steam-exploded aspen. Lignin (12 g) was added to 120 ml tetralin and heated to 200°C in the presence of hydrogen gas (1.07 $\times 10^9$ N m$^{-2}$ initial pressure). The reaction time (t) reported refers to the time after the reactor has attained the desired temperature. A constant temperature was maintained for the duration of the reaction after which the heat supply to the reactor was shut off. The reacted lignin was filtered, dried and weighed. A portion (48 ml) of the filtrate (referred to as lignin-derived liquids) was added to tetralin (72 ml); the resultant solution was used as a solvent for coal liquefaction in the presence of hydrogen gas (1.07 $\times 10^9$ N m$^{-2}$ initial pressure). During the course of the reaction, the gas pressure was observed to increase: Figure 1 is a typical plot of the temperature and pressure of the reactor. For a reaction time of 85 min, it was observed that the maximum pressure in the reactor rose to $\sim 3.07 \times 10^9$ N m$^{-2}$. The reacted coal was filtered, dried and weighed.

Several of the liquefaction products were subjected to detailed spectroscopic, chromatographic and elemental analyses. The samples were first vacuum distilled to remove tetralin. The concentrated products were separated into benzene-soluble and insoluble fractions: benzene-soluble fraction was subsequently extracted with pentane to generate a pentane-soluble fraction$^6$. The benzene-insoluble products are only slightly soluble in common solvents for s.c.c. and n.m.r.; results for the solution without silylation only represent the small soluble fraction. To prepare soluble forms of the benzene-insoluble fractions, these samples were first silylated by refluxing with hexamethyl disilazane and trimethyl chlorosilane, using standard procedures$^6$. 

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N.m.r. spectroscopic data were collected using a 300 MHz instrument. Proton experiments were carried out in the conventional manner. Other experimental details are reported elsewhere.

RESULTS AND DISCUSSION

All the conversions reported are based upon a dry ash free mass of the starting solid material (i.e. conversion = g of solids reacted/g of solid material present initially). Lignin-derived liquids were produced by reacting 12 g of lignin in 120 ml of tetralin at 200°C for 1 h. Lignin conversion was found to be ~35.4%. The significant amount of conversion that occurs at time zero (Table 1) reflects the reactions that occur during the heat-up period to the desired reaction temperature; time (t') is measured once the reaction temperature is attained. Almost no enhancement in coal conversion in lignin-derived liquids was observed at a temperature of 350°C (Table 1). This observation is in agreement with our previous findings where lignin (solid) was reacted with coal in tetralin under similar reaction conditions. However, enhancement in coal conversion was obtained at higher temperatures. In one set of experiments carried out at 375°C, the influence of lignin-derived liquids (48 ml of filtered L + 72 ml of tetralin) on coal conversion was significant. As a comparison, coal conversion in tetralin alone (120 ml) was also determined. As can be seen from the data presented in Table 1, coal conversion in tetralin alone increased slightly with the time of reaction for short reaction times (< 85 min), whereas conversion in lignin-derived liquids increased rapidly during the same time interval. Coal was found to be more reactive in lignin-derived liquids than in tetralin for the reaction time period < 85 min; however, no appreciable difference in the reactivity in the two solvent systems was observed for a reaction time of 120 min. The enhancement of coal conversion in lignin-derived liquids over tetralin was observed to increase with time and reach a maximum value of 30% at 85 min. A similar behaviour of coal conversion versus time was observed when lignin (solid) was added to coal. The following reaction mechanism is proposed to explain the enhancement in coal conversion with time:

Lignin liquids (L) \( \xrightarrow{K_1} \) Intermediates (I) \( \xrightarrow{K_2} \) Products (P)

(1)

Coal (C) \( \xrightarrow{} \) Products (P)

(2)

C + I \( \xrightarrow{K_3} \) Products (P)

(3)

Reactions (1) and (2) are hypothesized to occur when lignin-derived liquids or coal alone are reacted. When lignin-derived liquids are added to coal, the intermediates from reaction (1) further depolymerize coal via reaction (3). The enhancement in coal conversion obtained is due to reaction (3). The concentration of I should be dependent on time; it is zero at the beginning of the experiment and should increase with time as lignin-derived liquids are reacted further. At a certain time, \( t_1 \), I should reach a maximum value after which it would

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**Table 1** The influence of lignin-derived liquids on coal conversion

<table>
<thead>
<tr>
<th>Reaction time (t') min</th>
<th>Coal conversion (%) in tetralin</th>
<th>in lignin-derived liquids</th>
<th>Enhancement in coal conversion</th>
<th>Statistically determined enhancement in coal conversion %</th>
</tr>
</thead>
<tbody>
<tr>
<td>45.0</td>
<td>46.3</td>
<td>2.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0</td>
<td>34.0</td>
<td>29.7</td>
<td>-12.7</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>49.0</td>
<td>51.0</td>
<td>4.1</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>53.1</td>
<td>63.7</td>
<td>20.0</td>
<td>20.0 ± 5.2</td>
</tr>
<tr>
<td>85</td>
<td>53.0</td>
<td>69.1</td>
<td>30.4</td>
<td>30.1 ± 10.8</td>
</tr>
<tr>
<td>120</td>
<td>68.2</td>
<td>66.9</td>
<td>-1.9</td>
<td>-1.9 ± 9.5</td>
</tr>
<tr>
<td>70.7, 63.7, 70.3, 63.5, 68.3, 68.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lignin (12 g) was reacted in 120 ml tetralin at 200°C for 1 h. The sample was filtered (conversion 35.4%). Coal (4 g) was reacted in a mixture of 48 ml of the filtered liquid from the lignin experiments to which 72 ml of tetralin were added.

*The reaction time (t') is measured after the reactor has reached the desired reaction temperature.

*Calculated by the formula \( \frac{B - A}{A} \times 100 \)

*Using a Z test with a 90% confidence level.
decline as it is consumed in reactions (1) and (3). Thus, the enhancement in coal conversion should also increase with an increase in I₁ and hence with the time of reaction. Evidence for the hypothetical reaction (1) is obtained by analysing the products obtained from experiments that involved processing of lignin-derived liquids in tetralin (in the absence of coal); the data are provided below.

According to Pelipets², the solubility of coal in benzene is a measure of the extent of coal hydrogenation, while solubility in a benzene/pentane mixture is a measure of the "oil" formed during coal processing. The pentane-insoluble but benzene-soluble fraction is called the asphaltene fraction. Asphaltene is a high molecular weight intermediate product in coal liquefaction. The presence of asphaltene in coal-derived liquids has also been discussed by Weller and Pelipetz². The viscosity of the coal-derived liquids is affected by the amount and the molecular weight of the asphaltene.¹⁰

The results of fractionation of the liquid products from lignin in tetralin at 200 °C (L); lignin-derived liquids from L processed at 375 °C (LLT) in tetralin; coal in tetralin at 375 °C (CT); and coal reacted in a mixture of L and tetralin at 375 °C (CLLT), in terms of pentane solubles, asphaltene and benzene insolubles are shown in Table 2. As compared to CT and L, the liquid sample obtained from CLLT contains a significantly greater amount (up to 60–83% higher) of the more desirable pentane-soluble fraction. The data indicate that the lignin-derived liquid addition to coal is synergistic in that the distribution of the various fractions in CLLT is not an arithmetic summation of the corresponding fractions observed in L and CT. If the lignin-derived liquids (L) are processed in tetralin at 375 °C, the liquid (LLT) obtained contain a high pentane-soluble fraction (66%). The benzene-insoluble fraction content also increases to ~2% upon the processing of lignin-derived liquids. Thus, one may conclude that at higher temperatures (>350 °C), the lignin-derived liquids react via two parallel pathways, one involves the decomposition to lower molecular weight pentane-soluble fractions while the other one is a retrogressive reaction that results in the formation of benzene-insoluble molecules. It is, therefore, possible that the high pentane solubility observed in CLLT liquids could in part be attributed to the processing of L.

¹H n.m.r. spectra were obtained for all the fractions (Table 3). To more generally evaluate the n.m.r. data, the spectra were also classified in terms of aliphatic and aromatic hydrogen (i.e., corrected for phenolic hydrogen, Table 3). All of the fractions from the coal and coal-
lignin experiments exhibited aliphatic/aromatic hydrogen ratios which were lower than those for lignin-derived liquids. Also, the aliphatic/aromatic hydrogen ratios of the benzene-soluble fractions for the coal liquids are lower than the corresponding ratios for the coal/lignin liquids.

Data from s.e.c. of the various fractions were also obtained. The number average molecular weights (Mₙ)
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and the weight average molecular weights \( (M_w) \) are shown in Table 4. The dispersivity \( (D) \) is defined as \( M_w/M_n \). This is an index for the homogeneity of the sample. If \( D = 1.0 \), then all the molecules in the sample have the same size. A notable observation is that the relatively low molecular weights of the CLLT in various fractions, as compared with the molecular weights of the corresponding fraction for L, processed LLT and CT. Another interesting feature is that \( D \) of the coal–lignin liquids is very close to 1.0 in comparison to \( D \) values of all the other liquids produced at the same temperature (i.e. 375°C) in this study. Thus, it is concluded that coal liquefaction in lignin-derived liquids results in lower molecular weight products which have molecules of comparable size.

The elemental analyses of solid and liquid samples are presented in Table 5. An interesting feature of the data is that while the sulphur content of coal decreases upon reaction, it increases significantly for lignin. The sulphur in lignin is organically bound in a manner which is fairly unreactive in comparison to its carbon; thus upon liquefaction, the solid residue is observed to contain higher sulphur content (percentage basis). Both CT and CLLT have comparable oxygen and hydrogen contents (wt% basis). The atomic C/H and O/H ratios of solid and liquid products are also shown in Table 5. The CLLT is observed to have the highest C/H ratio of the liquids examined in this study while its O/H ratio is very low and close to that for CT.

The mass measurements for a number of experiments are reported in Table 6. The liquid product yields were calculated by subtracting the mass of solid residue and the gases produced from the initial solid mass and lignin-derived liquid charged to the reactor. The main gases produced were \( \text{CH}_4 \), \( \text{CO}_2 \) and \( \text{CO} \). The enhancement in liquid products obtained due to the lignin-derived liquid addition is found to be 21.3%, which compares favourably with the corresponding enhancement of 20.0% calculated on the solid mass basis (Table 1). Thus, the data show that, due to lignin addition, the increase in liquid products obtained is significant. The data on hydrogen gas uptake defined as the amount of hydrogen consumed per unit mass of solid and liquid charged to the reactor, during the course of the reaction, is also provided in Table 6. A relatively small amount (0.83%) of hydrogen gas is needed to produce the lignin-derived liquids; however, further processing of the liquids requires 7.25% hydrogen gas uptake (LLT). The amount of hydrogen gas uptake for CT and CLLT experiments are modest; 1.6 and 1.8%, respectively. The data suggest that the reaction chemistry is complex and some internal hydrogen rearrangement between the lignin-derived liquid and coal liquids is possible.

The stability of lignin-derived liquids was examined in

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Elemental analyses and atomic C/H and O/H ratios of solid and liquid samples (dry basis only)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solids</td>
</tr>
<tr>
<td></td>
<td>Coal*</td>
</tr>
<tr>
<td>C</td>
<td>62.28</td>
</tr>
<tr>
<td>H</td>
<td>4.38</td>
</tr>
<tr>
<td>N</td>
<td>1.28</td>
</tr>
<tr>
<td>S</td>
<td>4.40</td>
</tr>
<tr>
<td>O*</td>
<td>27.66</td>
</tr>
<tr>
<td>C/H</td>
<td>0.19</td>
</tr>
<tr>
<td>O/H</td>
<td>0.40</td>
</tr>
</tbody>
</table>

* Experimental conditions as in Table 2
* Raw coal and lignin samples

<table>
<thead>
<tr>
<th>Table 6</th>
<th>Mass measurements for liquefaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A initial mass charged (g)</td>
</tr>
<tr>
<td>Sample</td>
<td>Coal</td>
</tr>
<tr>
<td>L</td>
<td>0</td>
</tr>
<tr>
<td>LLT</td>
<td>0</td>
</tr>
<tr>
<td>CT</td>
<td>4.0</td>
</tr>
<tr>
<td>CLLT</td>
<td>4.0</td>
</tr>
</tbody>
</table>

* \( A = (B - C) \)
† \( D = 100 \times \frac{(C - G - E - F)}{100 \times F} \)

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Table 7 Influence of the time of storage of lignin-derived liquids on coal conversion

<table>
<thead>
<tr>
<th>Duration of storage (days)</th>
<th>Coal conversion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68.9</td>
</tr>
<tr>
<td>3</td>
<td>68.3</td>
</tr>
<tr>
<td>5</td>
<td>63.3</td>
</tr>
<tr>
<td>10</td>
<td>61.9</td>
</tr>
</tbody>
</table>

The lignin-derived liquids (L) obtained by the method described in Table 1 were stored at room temperature. Coal (4 g) was reacted in a mixture of L and tetralin at 375°C for 2 h.

the following way. The influence of the time of storage at room temperature of lignin-derived liquids under ambient conditions on coal conversion was determined (Table 7). The extent of coal conversion in lignin-derived liquids is found to decrease with the time of storage. When the lignin-derived liquids were stored for 19 days, the extent of coal conversion declined by 16% over the corresponding conversion observed for reaction of coal in 1-day-old lignin-derived liquid. However, it appears from the experimental data that the lignin-derived liquids retain their reactivity for 3 days as far as coal liquefaction is concerned.

MATHEMATICAL MODEL DEVELOPMENT

During the reactor heat-up period prior to achieving the desired reaction temperature, the chemical reactions (Equations 1)−(3)) take place. In the analysis presented here, t refers to the time since the beginning of chemical reactions, whereas τ refers to the time measured after the reactor achieved the desired reaction temperature (the data reported in Table 1 are for time τ).

Coal depolymerization in tetralin

Coal conversion chemistry, as shown in Equation (2), can be modelled by the following first-order rate expression:

\[
\frac{dc}{dt} = -K_1[C-(1-A)C_0] \tag{4}
\]

In the above formulation, \(C\) is the coal concentration, \([C-(1-A)C_0]\) represents the number density of the reactive sites available for reaction at any time \(t\), \(C_0\) represents the initial coal concentration, \(A\) is an adjustable parameter, which may be viewed as the fractional number of the total reactive sites present in the coal matrix \([C_0-C_{\text{react}}]/C_0\), and \(K_1\) is a rate constant. Both \(A\) and \(K_1\) are expected to be dependent on temperature. The fractional conversion, \(X_{Ct}\), is given by integration of Equation (4):

\[
X_{Ct} = \frac{C_0 - C}{C_0} = A[1 - e^{-K_1\tau}] \tag{5}
\]

Coal depolymerization in lignin-derived liquids

The rate expressions for the three reactions (Equations 1)−(3)) involving the concentrations of the lignin-derived liquids (L), lignin-derived intermediates (I), and coal (C) depolymerization are given below:

\[
\frac{dL}{dt} = -K_1L \tag{6}
\]

\[
\frac{dI_1}{dt} = K_1L - K_2A[I_1 - K_4[C-(1-A)C_0]I_1] \tag{7}
\]

\[
\frac{dC}{dt} = -K_1[C-(1-A)C_0] - K_2[A[C-(1-A)C_0]I_1] \tag{8}
\]

Although an analytical solution for \(I_1\) and hence for \(C\) is not possible, an acceptable approximate solution is deduced. In the absence of reaction (3), \(I_1\) is given by:

\[
I_1 = x_0 e^{-K_1\tau} \tag{9a}
\]

for the initial condition \(t=0, I_1=0\) and \(L=L_0\). The coefficient \(x_0\) is given by:

\[
x = K_1L_0/(K_2 - K_1) \tag{9b}
\]

Thus, it seems reasonable that when coal is also present, there must be even a greater decrease in \(I_1\) (according to Equation (3)) which is assumed to vary exponentially with time. The following expression for \(I_1\) is postulated:

\[
I_1 = x_0 e^{-b t} - d e^{-f t} - g e^{-h t} \tag{9}
\]

where the various constants (a, b, d, f, g and h) remain to be determined.

The first term on the right-hand side of Equation (9) corresponds to the generation of \(I_1\), while the second and third terms correspond to the disappearance due to the formation of products \(P_1\) (Equation (1)) and \(P_2\) (Equation (3)). Implicit in this analysis is the assumption that the rate of \(I_1\) disappearance according to Equation (3) can be modelled by a pseudo first-order reaction. A comparison of Equations (9a) and (9) reveals that the rate constant \(K_1\) must be equal to \(b\), and the rate constants \(K_2\) and \(K_4\) must correspond to \(f\) and \(h\). Whether \(K_2\) corresponds to \(f\) or \(h\) will be determined later.

A relationship between the various constants is obtained by employing the requisite initial condition for \(I_1\) (\(t=0, I_1=0\)):

\[
a = d + g \tag{10a}
\]

Substituting Equation (9) into Equation (8) and using the appropriate initial conditions \(t=0, C=C_0\), yields the following expression for the fractional conversion, \(X_{Ct}\):

\[
X_{Ct} = \frac{C_0 - C}{C_0} = A[1 - \exp[-K_2\tau + \frac{d + g}{K_4}\exp(-e^{-K_1\tau}-1)] - \frac{d}{h}\exp[-K_4(\exp(-e^{-K_1\tau}-1))]] \tag{10}
\]

Experimental data for coal conversion are shown in Figure 2. Plots of Equations (5) and (10) permit the computation of various rate constants. The data were processed using commercially available software.

The various rate constants are reported in Table 8. Lignin is known to be very reactive, and it is expected that the rate of lignin-derived intermediates that react via Equation (1) to produce \(P_1\) is much greater than the corresponding rate by which they produce \(P_2\) (Equation (3)). Therefore, \(f\), the computed rate constant, must be equal to \(K_2\) (since \(f > h\)). A comparison of Equation (9) with Equation (9a) indicates that \(a = x\); \(x\) can be computed from Equation (9b) since \(L_0\) can be estimated readily from the data on lignin conversion in tetralin at 200°C. \(K_4(d + g)\) is known to be equal to \(K_2a\) (i.e., \(K_2x\)), according to Equation (10a). This procedure allowed \(K_4\ 
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Figure 2 Coal conversion versus time. Experiments were conducted at 375°C, with other data as in Table 1. ▲, coal liquefaction in tetralin; □, coal liquefaction in lignin-derived liquids.

Figure 3 Computed value of dimensionless $I_1$ versus time.

Table 8 Estimation of various rate constants

<table>
<thead>
<tr>
<th>Computed</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$ 68.6</td>
<td>-</td>
</tr>
<tr>
<td>$f$ (min$^{-1}$)</td>
<td>0.9873</td>
</tr>
<tr>
<td>$h$ (min$^{-1}$)</td>
<td>0.00347</td>
</tr>
<tr>
<td>$K_0$ (min$^{-1}$)</td>
<td>0.00419</td>
</tr>
<tr>
<td>$K_1$ (min$^{-1}$)</td>
<td>0.021</td>
</tr>
<tr>
<td>$K_2$ (g$^{-1}$ min$^{-1}$)</td>
<td>3.02</td>
</tr>
<tr>
<td>$K_3$ (min$^{-1}$)</td>
<td>0.154</td>
</tr>
</tbody>
</table>

$^a$Values obtained using Equations (5) and (10).

The rate of coal conversion can be estimated; it was found to be 3.02 g$^{-1}$ min$^{-1}$. The estimated rate constants are presented in Table 8. Expression for coal conversion are presented below:

1. Coal depolymerization in tetralin

   $X = 68.6\left[1 - \exp\left[-0.021(t-58)\right]\right]$

2. Coal depolymerization in lignin-derived liquids

   $X = 68.6\left[1 - \exp\left[2.52 - 0.021(t-58)\right]
   - 0.22\exp\left[-0.987(t-58)\right]
   - 0.4444\exp\left[-0.0035(t-58)\right]
   + 0.0042(t-58)\right]\$

where $t$ refers to the time since the beginning of the reactor heat up.

A plot of the dimensionless concentration of the intermediates produced from lignin versus time is shown in Figure 3. It is seen that the intermediate concentration rises very rapidly and reaches a maximum at 62 min, and with further increases in the reaction time, it declines rapidly. This evaluation suggests that the intermediates are short-lived, and that from a processing point of view, the lignin-derived liquids should be added to the reactor just after the coal has achieved the desired reaction temperature (or gone into the plastic stage) so as to maximize the enhancement in coal conversion.

The lignin-derived material in the solvent for the coal experiments is small, ~3 wt%. However, it appears to be very effective in enhancing coal conversion yields. A maximum value for $I_1$ was found to be equal to 0.007 g$^{-1}$ by the mathematical analysis presented.

CONCLUSIONS

1. Lignin-derived liquids are effective in increasing the reaction rate of coal depolymerization, under the conditions investigated.

2. The data suggest a reaction pathway involving degradation of coal and lignin-derived liquids, each by series reactions, and a parallel coal depolymerization reaction involving reactive intermediates formed from the lignin-derived liquids.

3. Liquid product quality, as measured by molecular weight and aliphatic/aromatic hydrogen ratios determined by n.m.r. is improved by reaction of coal with lignin-derived liquids, compared to liquids produced from coal alone under similar reaction conditions.

Useful information can be gleaned from the mathematical analysis presented. For example, since the intermediates produced from the lignin-derived liquids are estimated to be short-lived, these liquids should be contacted with coal when it has either reached the desired reaction temperature or gone into a plastic stage so as to maximize the rate of coal conversion. In order to verify this analysis, we will conduct further experiments. The results will be subsequently published.

ACKNOWLEDGEMENTS

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