Hydrodesulfurization of Thiophene, Benzo thiophene, Dibenzo thiophene, and Related Compounds Catalyzed by Sulfided CoO-MoO₃/γ-Al₂O₃: Low-Pressure Reactivity Studies


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Hydrodesulfurization experiments were carried out with a sulfided CoO-MoO₃/γ-Al₂O₃ catalyst in a pulse microreactor operated at atmospheric pressure and temperatures of 350 to 450°C. The reactants were hydrogen and pure sulfur-containing compounds (or pairs of compounds), including thiophene, benzo thiophene, dibenzo thiophene, several of their hydrogenated derivatives, and various methyl-substituted benzothiophenes and dibenzothiophenes. The aromatic compounds appeared to react with hydrogen by simple sulfur extrusion; for example, dibenzothiophene gave HS + biphenyl in the absence of side products. The reactivities of thiophene, benzo thiophene, and dibenzo thiophene were roughly the same. Each hydrogenated compound (e.g., tetrahydrothiophene) was more reactive than the corresponding aromatic compound (e.g., thiophene). Methyl substituents on benzo thiophene had almost no effect on reactivity, whereas methyl substituents on dibenzo thiophene located at a distance from the S atom slightly increased the reactivity, and those in the 4-position or in the 4- and 6-positions significantly decreased the reactivity. In contrast to the observation of a near lack of dependence of low-pressure reactivity on the number of rings in the reactant, the literature shows that at high pressures the reactivity decreases with an increased number of rings. The pressure dependence of the structure-reactivity pattern is suggested to be an indication of relatively less surface coverage by the intrinsically more reactive compounds (e.g., thiophene) at low pressures but not at high pressures. The relative reactivities are also suggested to be influenced by differences in the structures of the catalyst at low and high hydrogen partial pressures, which may be related to the concentrations of surface anion vacancies and the nature of the adsorbed intermediates.

INTRODUCTION

Hydrodesulfurization of petroleum distillates has been practiced for many years, but basic questions about the catalyst structure and the reaction mechanism remain unanswered. The current technological emphasis on hydrodesulfurization of petroleum residua and of coal-derived liquids points to the need for understanding the chemistry of hydrodesulfurization of the heterocyclic compounds, which are expected to be among the least reactive compounds in these feedstocks. Thiophene, the simplest compound in this class, has
often been chosen for kinetics studies, and thiophene has often been assumed to be representative of the whole class of sulfur-containing aromatic compounds. Even though thiophene hydrodesulfurization has received much attention, the reaction mechanism remains to be clarified. Owens and Amberg (1) concluded that hydrogenolysis of the C-S bond in thiophene, which leads to the formation of 1,3-butadiene, precedes hydrogenation of the aromatic ring. Kolboe (2) alternatively proposed an intramolecular dehydro sulfuration, whereby the hydrogen in the product $H_2S$ comes from positions $\beta$ to the sulfur of the thiophene; Kolboe’s suggestion is supported by product distributions of the D$_2$-thiophene reaction (3).

The literature of reaction studies of hydrodesulfuration of benzothiophene, dibenzothiophene, and related compounds (4-11) is fragmentary, failing to establish structure-reactivity patterns that might shed light on the reaction mechanisms. The results of this literature were obtained with various catalyst compositions and various reaction temperatures and hydrogen partial pressures, and the lack of a pattern points to the need for systematic experiments with a series of reactants and a single catalyst. The experiments reported here were performed with a variety of reactants and a commercial Co-Mo/γ-Al$_2$O$_3$ catalyst operating at atmospheric pressure.

The objective was to provide qualitative results for a range of important reactant structures at comparable reaction conditions. The pulse microreactor method (12) was chosen since it has the advantage of allowing rapid generation of data from only small amounts of reactants (many of which had to be synthesized for this work) and since it readily allows vapor-phase reactant flow with the relatively non-volatile dibenzothiophene and methyl-substituted dibenzothiophenes.

### EXPERIMENTAL METHODS

#### Reactants

The following compounds were obtained commercially and used without further purification: n-heptane (J. T. Baker, 98%, Baker Grade), n-dodecane (Aldrich, 99%), thiophene (Aldrich, 99+%, Gold Label), tetrahydrothiophene (Eastman), benzo thiophene (Aldrich, 99%), ethylbenzene (Aldrich, 99%), $m$-ethyltoluene (Aldrich, 99%), cumene (Eastman), $n$-propylbenzene (Aldrich, 98%), dibenzothiophene (Aldrich, 95%), biphenyl (Eastman), and cyclohexylben zene (Aldrich, 96%).

The synthesis techniques for the substituted benzothiophenes and dibenzothiophenes are cited in Table 1. The 1,2,3,4,10,11-hexahydrodibenzothiophene was prepared from 1,2,3,4-tetrahydrodibenzothiophene, which was obtained by a procedure similar to that of Campagne et al. (17).

#### Pulse Microreactor Experiments

Hydrodesulfuration experiments were carried out with a pulse microreactor operating at atmospheric pressure and temperatures of 350 to 450°C. Purified

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TABLE 1

<table>
<thead>
<tr>
<th>Compound</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Methylbenzothiophene</td>
<td>13</td>
</tr>
<tr>
<td>3,7-Dimethylbenzothiophene</td>
<td>14</td>
</tr>
<tr>
<td>2-Methylbenzothiophene</td>
<td>15</td>
</tr>
<tr>
<td>7-Methylbenzothiophene</td>
<td>16</td>
</tr>
<tr>
<td>2,3-Dihydrobenzothiophene</td>
<td>5</td>
</tr>
<tr>
<td>4-Methyldibenzothiophene</td>
<td>17</td>
</tr>
<tr>
<td>2,8-Dimethyldibenzothiophene</td>
<td>18</td>
</tr>
<tr>
<td>4,6-Dimethyldibenzothiophene</td>
<td>18</td>
</tr>
</tbody>
</table>

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5 A complementary set of experiments at pressures of the order of 100 atm is to be reported elsewhere (11).
TABLE 2
Catalyst Properties

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>CoO content (wt%)</th>
<th>MoO₃ content (wt%)</th>
<th>Pore volume (cm³/g)</th>
<th>Surface area (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Cyanamid (HDS-16A)</td>
<td>5.6</td>
<td>11.2</td>
<td>0.50</td>
<td>176</td>
</tr>
<tr>
<td>Ketjen (124-1.5E HD)</td>
<td>4.0</td>
<td>11.8</td>
<td>0.53</td>
<td>256</td>
</tr>
</tbody>
</table>

* Properties of the original oxidic catalysts as specified by the manufacturers.

Hydrogen served both as the reactant and carrier gas.

The microreactor was a 0.085-in.-i.d. stainless-steel tube. It was heated externally with Briskheat flexible heating tape, and it was surrounded by Cerafelt insulation. The reactor temperature was measured with a sheathed XACTPAK chromel-alumel thermocouple positioned at the external tube wall.

The reactor was packed with 2% to 4% mesh CoO-MoO₃/γ-Al₂O₃ catalyst particles (American Cyanamid AERO HDS-16A, MTG-S-0731), received as 1/8-in.-diameter extrudates. In some preliminary experiments, the catalyst was a similar Ketjen product (type 124-1.5E HD, test number 18043). The catalyst properties are summarized in Table 2.

Reactant solutions were prepared with a 50 wt% n-heptane in n-dodecane solvent and a single sulfur-containing compound (or occasionally a pair of them) added to give a solution containing 0.3 wt% sulfur. The maximum standard sulfur concentration was limited by the solubilities of dibenzothiophenes in the paraffinic solvent; aromatic solvents were avoided since aromatic compounds are reaction inhibitors. Liquid samples (0.5 μl) were injected by syringe into the hydrogen stream, which flowed at 40 cm³ (STP)/min. Alternatively, in some experiments the pure sulfur-containing compound was injected as a pulse in the absence of solvent. This method was applicable only to the more volatile reactants, including thiophene, benzothio-

HDS OF POLYCYCLIC AROMATICS

A standard series of hydrodesulfurization experiments with a given reactant solution was carried out with a catalyst charge of 5 mg in the microreactor. Immediately after charging the catalyst to the reactor, it was heated from ambient temperature to 400°C with hydrogen flow and then presulfided by contacting with 10 mol% H₂S in H₂ at 400°C flowing at a rate of 40 cm³ (STP)/min for 2 hr. In each standard experiment, the following procedure was followed: First, two or three injections of reactant (e.g., benzothiophene) were made through the bypass loop to obtain a g.c. analysis of the unreacted sample; next, hydrogen was allowed to pass through the reactant feed line for a few minutes at the desired reaction temperature, and the catalyst was conditioned by injection of five sequential 1.0-μl pulses of pure CS₂ into the hydrogen stream. Four to ten 0.5-μl pulses of the reactant solution were then injected in sequence at 35-min intervals (or 1-hr intervals in the case of two-component reactant mixtures) until a repeatable conversion was observed. Finally, two or three pulses were injected through the bypass loop to confirm that there was no change in the detector response for the unconverted reactant. This procedure was found by
trial and error to be the one best suited to
determination of repeatable data.

RESULTS

Preliminary Experiments

A series of preliminary experiments was
performed to provide qualitative confirma-
tion of a variety of results expected from
the literature (20, 21). When the reactor
was packed with 5 mg of particles of
\( \gamma \)-Al\(_2\)O\(_3\) (crushed from Harshaw pellets—
AL-0104T \( \frac{1}{2}\)-in.; lot 30; surface area, 140
m\(^2\)/g), neither dibenzothiophene nor bi-
phenyl pulses in hydrogen underwent
detectable conversion at 450°C (confirming
the lack of catalytic activity of the support),
and neither of these compounds experienced
a detectable holdup in the packed bed
(confirming the lack of significant adsorp-
tion on the support). Under comparable
conditions with 5 mg of hydrodesulfuriza-
tion catalyst, thiophene, benzothiophene,
and dibenzothiophene each experienced
measurable conversions into H\(_2\)S and
hydrocarbon products. When 525 ppm of
H\(_2\)S were included in the hydrogen stream,
the conversion of dibenzothiophene de-
creased considerably (confirming that H\(_2\)S
is a reaction inhibitor), and when CS\(_2\) was
included in the dibenzothiophene pulses,
the conversion similarly decreased (again
confirming the inhibition by H\(_2\)S, which
formed rapidly from CS\(_2\) under these
conditions). When benzene was added to
pulses containing benzothiophene, the con-
version was also reduced (confirming that
benzene is a reaction inhibitor).

A series of experiments was performed
with a range of pulse volumes using pure
compounds in the absence of solvent. The
representative results shown in Fig. 1
demonstrate that the conversion decreased
markedly with increasing pulse size,\(^6\) and
the ratio of conversions was approximately
independent of pulse size. These results
confirm that the pulse method gives a
self-consistent set of reactivity data.

Thiophene conversion experiments with
the Ketjen catalyst showed the lack of
intraparticle mass transfer effects, since
conversions with 28- to 48-mesh particles
were the same as those with 270- to 400-
mesh particles at 375 and 400°C. Similarly,
there was no diffusion influence observed
for conversion of dibenzothiophene at
450°C; the performance of 100- to 140-mesh
particles of the American Cyanamid cata-
lyst was indistinguishable from that of
28- to 48-mesh particles.

Most experiments were performed with
reactant pulses including paraffinic sol-
vents. Results of a series of experiments
are summarized in Table 3. The con-
version of dibenzothiophene decreased as
temperature was increased from 350 to
400°C. A somewhat smaller conversion was
observed for dibenzothiophene than for
the substituted compound having methyl
groups in the 2- and 8-positions. The

\(^6\) The decrease in conversion with increasing pulse size is consistent with the increasing depletion of hydrogen in the catalyst bed as the carrier stream was displaced by larger and larger pulses of reactant.
TABLE 3

Hydrodesulfurization of Reactant Pulses in the Presence of 5 mg of Sulfided American Cyanamid HDS-16A (CoO-MoO3/γ-Al2O3): Comparison of Fresh and Broken-in Catalysts. Conditions—Pressure, 1 atm; H2 Flow Rate, 40 cm3 (STP)/min; Pulse Size, 0.5 μl

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Reaction temperature (°C)</th>
<th>Fractional conversion with fresh catalyst</th>
<th>Fractional conversion with broken-in catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dibenzothiophene</td>
<td>350</td>
<td>0.31</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.23</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>0.25</td>
<td>0.12</td>
</tr>
<tr>
<td>2,8-Dimethyldibenzothiophene</td>
<td>450</td>
<td>0.70</td>
<td>0.24</td>
</tr>
<tr>
<td>4-Methyldibenzothiophene</td>
<td>450</td>
<td>0.13</td>
<td>0.047</td>
</tr>
<tr>
<td>4,6-Dimethyldibenzothiophene</td>
<td>450</td>
<td>0.09</td>
<td>0.023</td>
</tr>
</tbody>
</table>

compound with methyl groups in the 4- and 6-positions gave the lowest conversion.

After the experiments summarized in Table 3 were performed (during a period of 2 weeks), a decrease in catalytic activity was observed. Reduction of the catalyst in hydrogen at 350 to 450°C for 1 to 12 hr failed to restore the catalyst to its initial state. The results indicated, however, that the catalyst had assumed a stable "broken-in" condition, for which reproducibility of ±2% was observed for dibenzothiophene conversion at 450°C. In experiments with all the reactants that followed with this catalyst charge, periodic checks confirmed the stability of the broken-in catalyst. The following results, therefore, provide the desired self-consistent and repeatable data for hydrodesulfurization in the presence of a sulfided catalyst and a basis for comparing reactivities of the various compounds.

Reaction Networks and Relative Reactivities

Single-reactant pulses. The full series of available sulfur-containing compounds was studied with the broken-in catalyst. The group of substituted benzothiophenes is listed in Table 4 with the hydrocarbon products of the reaction of each. The results are consistent with the suggestion that direct sulfur extrusion was the primary reaction for these compounds, although trace amounts of unidentified products were occasionally observed, and the reaction networks are still not fully characterized. One compound in this class, benzothiophene itself, was exceptional, giving not one, but two major hydrocarbon products, ethylbenzene and styrene.

The product analyses showed that dibenzothiophene and related compounds, like the benzothiophenes, can be considered to react by simple sulfur extrusion, since biphenyl and the corresponding methyl-substituted biphenyls were the major hydrocarbon products.

A summary of conversion data is given in Table 5; all the experiments were carried out with the broken-in catalyst at 450°C. Benzothiophene and dibenzothiophene had nearly the same reactivity, which was greater than that of thiophene. Hydrodesulfurization conversion was found to be almost identical for all the methylbenzothiophenes. When a second methyl group was added, the reactivity was reduced.

The result for 2,8-dimethyldibenzothiophene shows that methyl groups situated at a distance from the sulfur atom in the three-ring compound increase the reactivity. Methyl substituents in the β-position, however, reduce the reactivity, as shown by the results for 4-methyldibenzothiophene. The results for 4,6-dimethyl-
dibenzothiophene indicate that incorporation of the second methyl group in the β position reduces the reactivity only little.

The data of Table 5 show a rough parallel between the reactivity and the strength of adsorption of compounds in the dibenzothiophene family (determined from the holdup on the catalyst as calculated from mass balances). The amount held up on the catalyst decreased with incorporation of methyl groups in the 4-position or in the 4- and 6-positions (and the reactivity correspondingly decreased), and the amount held up increased with incorporation of methyl groups in the 2- and 8-positions (and the reactivity correspondingly increased).

Data for hydrogenated sulfur-containing compounds are collected in Table 6. These were found to be significantly more reactive than the corresponding aromatic compounds. Specifically, conversion of tetrahydrothiophene was 96%, and that of thiophene was 7%; conversion of 2,3-dihydrobenzothiophene was 71%, and that of benzo thiophene was 14%; conversion of 1,2,3,4,10,11-hexahydrodibenzothiophene was 19%, and that of dibenzothiophene was 12%. These data show that the effect of prehydrogenation in increasing the reactivity decreases with an increase in the number of rings.

Besides hydrodesulfurization, dehydrogenation was also observed for both dihydrobenzothiophene and hexahydrodibenzothiophene. (Dehydrogenation products were not observed for tetrahydrothiophene.) Reaction of 2,3-dihydrobenzothiophene in hydrogen gave a substantial amount of benzothiophene in addition to ethylbenzene and styrene; the total conversion was about 97% compared with the hydrodesulfurization conversion of 71% reported in Table 6. For 1,2,3,4,10,11-hexahydrodibenzothiophene, the products included

TABLE 4
Structures of Benzothiophene and Related Reactants and Their Hydrodesulfurization Products

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Benzothiophene" /></td>
<td><img src="image" alt="Ethylbenzene" /> <img src="image" alt="Styrene" /></td>
</tr>
<tr>
<td><img src="image" alt="2-Methylbenzothiophene" /></td>
<td><img src="image" alt="n-Propylbenzene" /></td>
</tr>
<tr>
<td><img src="image" alt="3-Methylbenzothiophene" /></td>
<td><img src="image" alt="Isopropylbenzene" /></td>
</tr>
<tr>
<td><img src="image" alt="7-Methylbenzothiophene" /></td>
<td><img src="image" alt="m-Ethyltoluene" /></td>
</tr>
<tr>
<td><img src="image" alt="3,7-Dimethylbenzothiophene" /></td>
<td><img src="image" alt="3-Isopropyltoluene" /></td>
</tr>
</tbody>
</table>
Hydrodesulfurization of Reactant Pulses in the Presence of Broken-in Catalyst: Conditions—
Catalyst, 5 mg of Sulfided American Cyanamid HDS-16A (CoO-MoO₃/γ-Al₂O₃); Temperature, 450°C; Pressure, 1 atm; H₂ Flow Rate, 40 cm³ (STP)/min; Pulse Size, 0.5 µl

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Fractional Holdupa conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,3,4,10,11-Hexahydrodibenzothiophene</td>
<td>0.12 340</td>
</tr>
<tr>
<td>2,3-Dihydrobenzothiophene</td>
<td>0.24 690</td>
</tr>
<tr>
<td>4-Methylidibenzothiophene</td>
<td>0.047 70</td>
</tr>
<tr>
<td>4,6-Dimethylidibenzothiophene</td>
<td>0.023 0</td>
</tr>
<tr>
<td>Benzothiophene</td>
<td>0.11</td>
</tr>
<tr>
<td>2-Methylbenzothiophene</td>
<td>0.10</td>
</tr>
<tr>
<td>3-Methylbenzothiophene</td>
<td>0.093</td>
</tr>
<tr>
<td>7-Methylbenzothiophene</td>
<td>0.10</td>
</tr>
<tr>
<td>3,7-Dimethylbenzothiophene</td>
<td>0.033</td>
</tr>
<tr>
<td>Thiophene</td>
<td>0.070</td>
</tr>
</tbody>
</table>

a Holdup is defined as the average of the g.l.c. peak areas of the sulfur-containing reactant obtained for a series of bypass injections less the sum of the desulfurized product and remaining reactant areas, averaged over a set of reactor injections.

The results demonstrate that the reaction networks in hydrodesulfurization of benzo-thiophenes and of dibenzothiophenes at low pressure can be approximated as simple sulfur extrusions. The product distribution data are in agreement with those of other authors who performed experiments at atmospheric pressure (6, 23) and the apparent discrepancy between the present results and those of Givens and Venuto (5), who observed dealkylation and alkyl shift reactions, is suggested to be an indication of differences in reaction temperature and/or differences in structure between sulfided and unsulfided catalysts; the CoO-MoO₃/γ-Al₂O₃ catalyst used by Givens and Venuto was reduced in hydrogen but not sulfided before use.

The lack of observed aromatic ring saturation is in accord with the suggestion that ring hydrogenation is not a prerequisite to C-S bond scission and sulfur removal from benzo-thiophenes and dibenzothiophenes (6, 24). The presence of styrene in the product spectrum of benzo-

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Fractional conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,3,4,10,11-Hexahydrodibenzothiophene</td>
<td>0.19</td>
</tr>
<tr>
<td>2,3-Dihydrobenzothiophene</td>
<td>0.71</td>
</tr>
<tr>
<td>Tetrahydrothiophene</td>
<td>0.96</td>
</tr>
</tbody>
</table>

7 Cyclohexylbenzene has previously been reported as a product of dibenzothiophene hydrodesulfuration in batch reactor experiments with MoS₂ (10, 22) and in flow reactor experiments with CoO-MoO₃/γ-Al₂O₃ (9).
thiophene and of dihydrobenzothiophene is consistent with this suggestion (23), and the absence of sulfides and mercaptans in the products is in accord with the identification of the initial C-S bond breaking as a slow reaction step (9).

The near lack of dependence of reactivity on the number of rings in the reactant compound is supported by results of several authors, but it appears to contradict the results of some others (19). Bartsch and Tanielian (6) found that at 375°C and 1 atm, dibenzothiophene required about three times as much catalyst as benzothiophene for equal degrees of hydrodesulfurization, but their results were obscured by the influence of pore diffusion, which could account for the discrepancy. Obolentsev and Mashkina (8) reported that in high-pressure experiments, the ratio of rate constants for benzothiophene relative to dibenzothiophene was 2.8, and Frye and Mosby (7) and Nag et al. (11) found that in compounds of this group the reactivity at high pressure decreased even more significantly with an increased number of rings in the reactant. We suggest that the structure-reactivity patterns in hydrodesulfurization are different at low and high pressures, in part because surface coverages may be different, with the intrinsically more reactive compounds (such as thiophene) present in lower surface concentrations than compounds like dibenzothiophene at low pressures, but possibly present in similar surface concentrations at high pressures. Further, the surface structure of a hydrodesulfurization catalyst [the sulfided form may be promoted MoS2 on an alumina support (25)] may depend strongly on the hydrogen partial pressure, which, for example, may determine the number of surface anion vacancies by a reaction such as

\[
\begin{align*}
\text{H}_2 + \text{SSSS} & \rightarrow \text{H}_2\text{S} + \text{SSS} \\
\text{H}_2\text{S} & + \text{S} \rightarrow \text{H}_2
\end{align*}
\]

This suggestion is speculative and in need of critical evaluation, but it provides a basis for interpretation of structure-reactivity data, and it is consistent with the suggestion of a number of authors of the existence of more than one kind of surface site (21, 25, 26). Perhaps one kind of site (such as an adjacent pair of anion vacancies) might allow one kind of adsorption (such as a flat adsorption involving the \( \pi \) electrons of the aromatic system and perhaps also the sulfur atom), consistent with the observed inhibition by benzene; another kind of site (such as a single anion vacancy) might allow another kind of adsorption (such as an end-on adsorption with the sulfur atom at the anion vacancy), which might explain the high reactivities observed for the hydrogenated compounds which lack \( \pi \) electrons required for the flat adsorption.

The small enhancement in dibenzothiophene reactivity upon incorporation of methyl groups in the 2- and 8-positions may be explained by electronic effects, i.e., a combination of induction and hyperconjugation of the methyl groups at positions \textit{para} to the two \( \alpha \)-carbon atoms of the reactant could enrich their respective electron densities and increase the

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Relative reactivity</th>
<th>Relative reactivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dibenzothiophene</td>
<td>0.84</td>
<td>0.50</td>
</tr>
<tr>
<td>2,8-Dimethyl dibenzothiophene</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>4-Methyl dibenzothiophene</td>
<td>0.84</td>
<td>0.10</td>
</tr>
<tr>
<td>4,6-Dimethyl dibenzothiophene</td>
<td>0.17</td>
<td>0.06</td>
</tr>
<tr>
<td>1,2,3,4,10,11-Hexahydridibenzo</td>
<td>1.3</td>
<td>0.54</td>
</tr>
<tr>
<td>7-Methyl dibenzothiophene</td>
<td>0.70</td>
<td>0.55</td>
</tr>
<tr>
<td>Thiophene</td>
<td>0.51</td>
<td>0.62</td>
</tr>
<tr>
<td>Tetrahydrothiophene</td>
<td>0.7</td>
<td>3.3</td>
</tr>
</tbody>
</table>

* Note: Relative reactivity is defined as fractional conversion of the reactant/fractional conversion of benzothiophene.

* Relative reactivity for one-reactant pulses.

* Relative reactivity for two-reactant pulses.
reactivity with an acidic catalytic surface site. The decrease in conversion caused by methyl substituents in the \( \beta \)-position can be explained by a small steric hindrance, i.e., a shielding of the lone pair electrons on sulfur by the hydrogens of either of the two methyl groups, which would reduce the bonding of the sulfur atom at a surface catalytic site.

Little literature is available for comparison with the results of Table 6 for the hydrogenated compounds. Desikan and Amberg (28) and Kolboe (2) compared the reactivities of thiophene and tetrahydrothiophene. The former authors showed tetrahydrothiophene to be more reactive than thiophene over the range 270 to 372°C. Kolboe found, however, that a 288°C, thiophene and tetrahydrothiophene were desulfurized at almost equal rates. Givens and Venuto (5) reported a rapid equilibrium between benzothiophene and 2,3-dihydrobenzothiophene, and Furimsky and Amberg (23) reported dihydrobenzothiophene; benzothiophene conversion ratios of 3 to 7, depending on catalyst loading and temperature; the latter result is consistent with results of this work. Again, we suggest that the apparent inconsistencies may be explained by differences in catalyst structure influenced by the nature of sulfiding, and perhaps the hydrogen partial pressure may be important in determining reactivity patterns.

ACKNOWLEDGMENTS

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