Thermodynamic and Kinetic Aspects of Sulfur Evaporation from Fe–C Alloy Droplets

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Evaporative loss of sulfur from Fe-C-0.1 mass% S alloys was investigated using electromagnetic levitation. An inert atmosphere was maintained with a constant flow of purified argon. The influence of carbon concentration, up to carbon saturation, on the reaction kinetics was determined at 1873 K. The effect of carbon on the activity coefficient of sulfur in liquid iron was also evaluated. While the value for the first order interaction parameter was found to be in good agreement with data in the literature, the value for the second order parameter was higher than those measured using a conventional crucible approach involving gas dissolution into liquid iron. The results are consistent with the premise that sulfur loss is primarily due to the evolution of monatomic sulfur vapor.

KEY WORDS: electromagnetic levitation; iron-carbon alloys; sulfur evaporation; interaction parameters; reaction kinetics.

1. Introduction

Electromagnetic levitation is a technique well suited to the study of gas-liquid metal reactions. This containerless experimental approach offers many advantages over conventional crucible-furnace arrangements. The absence of crucible contact with the molten specimen effectively rules out contamination from refractory materials. The vigorous inductive stirring ensures melt homogeneity and refreshes the solute-depleted layer close to the liquid metal surface thereby increasing the rate of liquid phase mass transport. Due to rapid kinetics, the time required to reach thermal and chemical equilibrium is particularly short. With levitated droplets, the spherical geometry provides the additional benefits of well-defined and high surface area to volume ratio, which is important in surface controlled processes such as impurity evaporation. Due to the absence of potential heterogeneous nucleation sites, high degrees of undercooling may be achieved with levitated droplets, thus providing the opportunity to evaluate liquid metal properties over an extended temperature range.

In a recent paper by the current authors,1) sulfur loss was observed during the decarburization of Fe–Cr–S–C levitated droplets with CO2–Ar gas mixtures. Similar behaviour has been reported elsewhere. For example, Nagasaka and Fruehan2) found that sulfur loss was 5–12% during decarburization of levitated Fe–C–S droplets when exposed to CO2–Ar, CO2–H2O and CO2–H2O–Ar atmospheres. Sain and Belton3) have also reported sulfur loss, of up to 22%, during decarburization of Fe–C–S melts in alumina crucibles with an impinging jet of CO2–Ar. While it is well known that sulfur removal from steel is most effective under reducing conditions, a number of studies4–6) have shown that steel desulfurization can be achieved by vaporization. More recently, investigations7,8) were carried out to study sulfur removal during ladle vacuum degassing. Fruehan and Turkdogan,4) in their study on the formation of SiS vapor, indicate that rapid desulfurization during vacuum degassing is likely due to the formation of sulfur-bearing volatile species, which significantly improve the sulfur transfer between steel and slag. It is therefore speculated that, in the absence of a slag phase, sulfur volatilization may be responsible for the loss observed from levitated droplets exposed to the CO2–Ar atmosphere.

As noted in the previous work,1) depending on the carbon concentration in the melt, sulfur loss varies between 18 and 64%. The detailed study on the kinetics of sulfur evaporation by Sehgal et al.6) found that sulfur removal rate was increased by 40% when the carbon concentration was increased by approximately 1 mass%. These authors went on to suggest that carbon affects the desulfurization rate only through activity interaction effects within the metal phase. Since carbon substantially increases the activity of sulfur in liquid iron, most desulfurization practices are performed during hot metal pretreatment. The purpose of the present investigation is to examine the thermodynamic and kinetic aspects associated with the effect of carbon on sulfur removal from levitated iron droplets exposed to an inert argon atmosphere.

2. Experimental Aspects

Fe-C-0.1 mass% S alloys with various carbon contents

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were prepared by melting predetermined amounts of electrolytic iron, high purity ferrous sulfide and graphite powders in an alumina crucible. Allowing sufficient time for the melt to reach homogeneity, alloy samples were subsequently taken by suction through a quartz tube, thereby producing rod-shaped specimens with diameter of 4 mm. These rods were then sectioned into equal length pieces where each piece weighs about 0.7 gram.

The experiments were conducted using the electromagnetic levitation equipment shown in Fig. 1. The water-cooled levitation coil was wound from copper tubing of 3.2 mm (1/8 inch) in outer diameter. The quartz tube, 15 mm in outer diameter, 13 mm in inner diameter and 304 mm in length, is sealed at the upper end with O-rings and an optical grade quartz window to permit temperature measurement using a Chino twocolour IR pyrometer, which was calibrated against the melting point of copper. An O-ring sealed rotatable platform made from aluminum was used to seal the bottom chamber. This platform is fitted with a copper mold for droplet quenching and an alumina charging rod for loading solid specimens into the electromagnetic field within the levitation coil. The rotating action of the platform allowed either the copper mold or the charging rod to be aligned directly below the levitated droplet.

All of the experiments were carried out at 1 873 K with a precision of ±15 degrees. An inert atmosphere was maintained with a constant argon gas flow rate of 1 L/min. Moisture was removed from high purity argon gas with drierite columns and the dried argon then deoxidized by passing through heated titanium pellets. After exposing the liquid metal samples to the purified argon atmosphere for a predetermined time, power was turned off, allowing the droplet to fall into the copper mold and be quenched. Metal samples were analyzed for carbon and sulfur using a LECO CS-244 analyzer.

3. Results and Discussion

Experimental results presented in Fig. 2 show the decrease in sulfur concentration as a function of time. The carbon concentration remains virtually constant throughout the experiments as shown in Fig. 3. Two noticeable features can be observed from the desulfurization behavior: i) The rate of sulfur removal is consistent with a first-order reaction relative to sulfur concentration in the melt, and ii) The rate increases with increasing carbon content of the melt.

3.1. Kinetics of Sulfur Removal

Sulfur removal from the molten alloy follows first order kinetics, according to the relationship:

\[
\frac{d[S]}{dt} = k_a \frac{A}{V} \text{(mass% S)} \quad \text{(1)}
\]

Upon integration:

\[
\ln \frac{S}{S_0} = k_a \frac{A}{V} \quad \text{(2)}
\]

The apparent rate constants, \(k_a\), can be obtained from the lin-

![Fig. 1](image1)

Fig. 1. Schematic diagram of the electromagnetic levitation equipment.

![Fig. 2](image2)

Fig. 2. Change in sulfur concentration with time.

![Fig. 3](image3)

Fig. 3. Change in carbon concentration with time.
ear slopes of $lnS_/_S_0$ vs $t$ plots, as shown in Fig. 4, where $S_0$ is the initial sulfur concentration of the alloy and $S_t$ is the sulfur concentration at time $t$. The compositions of the alloys and values of $k_a$ are summarized in Table 1.

In the absence of a slag phase, sulfur is expected to leave the droplet in gaseous form.

The kinetics of sulfur removal involves the following steps:

1. Liquid phase transport of sulfur to the metal-gas interface.
2. Surface reaction involving desorption of the sulfur species at the interface.
3. Gaseous diffusion within the gas boundary layer.

Due to the relatively high argon flow, the transport of gaseous product across the boundary layer is not expected to hinder the desulfurization rate. With induction stirring of the melt and constant surface renewal, the rate of sulfur removal should not be impeded by sulfur transport in the liquid phase. Therefore mass transport should not have been rate-limiting under the conditions prevailing in the current work.

This is further substantiated by the fact that carbon concentration in the melt exhibits a beneficial effect on the desulfurization rate whereas, Kawai found that carbon decreases the diffusion coefficient of sulfur in steel. This argument is consistent with observations made by previous investigators, which also suggest that the rate is controlled by a surface reaction.

Based on the investigation by Mukawa et al., at 1873 K, oxygen is approximately three times more surface active than sulfur in liquid steel. However, due to the relatively high carbon contents studied in the present work, the dissolved oxygen concentration is expected to be less than 50 ppmw. In contrast, sulfur concentration (0.1 wt pct) is at least 20 times greater. Thus, formation of COS and surface coverage by oxygen are considered negligible. The volatile sulfur-bearing species relevant to the current work are listed in Table 2. It can be seen from Fig. 5 that the equilibrium vapor pressure for monatomic sulfur above Fe-C-0.1 mass% S alloys is several orders of magnitude higher than other co-existing species. This is in good agreement with the mass spectrometric study by Kato and Fukube, which indicated that monatomic sulfur is the principal sulfur-bearing species leaving the surface of Fe–C–S melts. At 1873 K, evaporation of sulfur in the form of $S_{(g)}$ is more favorable and is therefore taken as the dominant species for subsequent evaluations of kinetics and thermodynamics in the present work.

From the transition state theory, where quasi-equilibrium exists between reactants and activated complexes, the reaction involving sulfur vaporization is written as:

$$xS = (Sx)^7$$  \hspace{1cm} (3)$$

The corresponding equilibrium constant is given by:

$$K_s = \frac{a_s}{a_{Sx}}$$  \hspace{1cm} (4)$$

### Table 1. Experimental results.

<table>
<thead>
<tr>
<th>Droplet mass (g)</th>
<th>Initial [C] (mass%)</th>
<th>Initial [S] (mass%)</th>
<th>[S] at $t = 40$ min (mass%)</th>
<th>$k_a$ (cm min$^{-1}$)</th>
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<tr>
<td>0.726</td>
<td>0.063</td>
<td>0.131</td>
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<td>0.683</td>
<td>0.704</td>
<td>0.119</td>
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<tr>
<td>0.750</td>
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<td>0.112</td>
<td>0.0398</td>
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<tr>
<td>0.713</td>
<td>1.96</td>
<td>0.120</td>
<td>0.0283</td>
<td>-0.00429</td>
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<tr>
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<td>0.141</td>
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<td>-0.00665</td>
</tr>
<tr>
<td>0.714</td>
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<td>0.0081</td>
<td>-0.0104</td>
</tr>
<tr>
<td>0.704</td>
<td>5.06</td>
<td>0.104</td>
<td>0.0039</td>
<td>-0.0286</td>
</tr>
</tbody>
</table>

**Fig. 4.** Desulfurization of Fe–C–S alloys at 1873 K.

**Fig. 5.** Equilibrium vapor pressures over Fe-C-0.1 mass% S alloys at 1873 K.

### Table 2. Equilibrium vapor pressures of sulfur-bearing gases over Fe-C-0.1 mass% S alloys at 1873 K.

<table>
<thead>
<tr>
<th>Species</th>
<th>Gibbs Energy Change (J/mol)</th>
<th>Equilibrium vapor pressure at 1873 K (atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S = S_{(g)}$</td>
<td>341 988 -- 79.19T$^1$</td>
<td>4.0 x 10$^{-8} f_c$</td>
</tr>
<tr>
<td>$S = \frac{1}{2} S_{(g)}$</td>
<td>125 100 -- 18.50T$^1$</td>
<td>9.0 x 10$^{-8} f_c^2$</td>
</tr>
<tr>
<td>$C + S = CS_{(g)}$</td>
<td>324 093 -- 68.52T$^1$</td>
<td>3.5 x 10$^{-8} a_c f_c$</td>
</tr>
<tr>
<td>$\frac{3}{2} C + 2S = CS_{2(g)}$</td>
<td>236 948 -- 11.40T$^1$</td>
<td>9.7 x 10$^{-9} a_c f_c^2$</td>
</tr>
<tr>
<td>FeO + $\frac{3}{2} S = FeS_{(g)}$</td>
<td>428 540 -- 111.36T$^1$</td>
<td>7.3 x 10$^{-8} f_c$</td>
</tr>
</tbody>
</table>

$f_c$: Activity coefficient of sulfur.

$a_c$: Activity of carbon.

$^1$NIST-JANAF Thermochemical Tables (Fourth Edition).

$^2$Thermodynamic Data For Steelmaking.
where $a_1$ is the activity of the complex $(S_x)_1$ and $a_S$ is the sulfur activity in the melt.

Following the approach of Fruehan and Turkdogan,\textsuperscript{4)} the rate equation is represented by:

$$\frac{d\text{mass}\%S}{dt} = \frac{-100A kT}{\rho V h} M_S \Gamma_a \theta^3$$ \hspace{1cm} (5)

where $\rho$ is the density of liquid iron, $A$ is the surface area of the droplet, $V$ is the volume of the melt, $k$ is the Boltzmann constant, $T$ is the absolute temperature, $h$ is Planck's constant, $M_S$ is the molecular mass of sulfur, $\Gamma_a$ is the total available sites for chemisorption, and $\theta^3$ is the fractional coverage occupied by the activated complexes. Since sulfur is highly surface active, the effect of fractional surface coverage by sulfur, $\theta^3$, on $\theta^3$ must also be considered when interpreting the rate data. $\theta^3$ can be expressed using the Langmuir adsorption equation:

$$K_S = \frac{\theta_S a_S^{ad}}{(1 - \theta_S a_S)}$$ \hspace{1cm} (6)

where $a_S^{ad}$ is the activity coefficient of sulfur in the adsorbed layer and $a_S$ is the activity of sulfur in the melt. $K_S$ is known as the sulfur adsorption coefficient. For carbon saturated alloys, Sain and Belton\textsuperscript{14)} provided an expression for the effect of temperature on the adsorption coefficient, which was based on measurements taken between 1 553 K and 1 873 K.

$$\log K_S = \frac{3 600}{T} + 0.57$$ \hspace{1cm} (7)

For the composition range studied in the present work, the surface coverage by adsorbed sulfur is within the range $0.95 < \theta_S < 1$. Hence it is reasonable to assume the limiting case of $\theta_S \rightarrow 1$, where $\theta^3$ simplifies\textsuperscript{4)} to:

$$\theta^3 = K_S a_S^{ad} \gamma^3 (1 - \theta_S)$$ \hspace{1cm} (8)

where $\gamma^3$ is the activity coefficient of the complexes. For the limiting case of $\theta_S \rightarrow 1$, $(1 - \theta_S)$ can be represented by $a_S^{ad} / a_S$. Considering the diatomic nature of the activated complexes, which has been expounded by Fruehan and Turkdogan,\textsuperscript{5)} Eq. (8) becomes:

$$\theta^3 = K_S^{ad} a_S$$ \hspace{1cm} (9)

Combining Eqs. (5) and (9) and replacing $a_S$ for dilute solution:

$$\frac{d\text{wt}\%S}{dt} = \frac{-100A kT}{\rho V h} \Gamma_o K_S^{ad} \frac{a_S^{ad}}{\gamma^3} M_S f_S (\text{wt}\%S)$$ \hspace{1cm} (10)

Upon integration, the rate equation can be expressed as:

$$\ln \frac{S_o}{S} = \frac{-100A kT}{\rho V h} \Gamma_o K_S^{ad} \frac{a_S^{ad}}{\gamma^3} M_S f_S t$$ \hspace{1cm} (11)

where $W$ is the weight of the droplet.

Kozakevitch et al.\textsuperscript{19} found that the surface tension of molten Fe–C–S alloys at 1 723 K is solely a function of sulfur concentration, which implies that the activity coefficient of adsorbed sulfur is not a function of carbon concentration. In the present work, the influence of carbon on the desulfurization rate is thus reflected only by virtue of the sulfur activity coefficient, $f_S$. Therefore, the rate data are expected to be represented by a single straight line on a plot of $\ln S_o/S$ vs. $A f_S \cdot t/W$. However, as indicated by Fig. 6, the slopes of the lines were found to vary with different carbon concentrations. This difference may be due to errors in the estimation of carbon’s effect on sulfur behavior. A similar discrepancy was also reported by Belton et al.\textsuperscript{5)} In their analysis they found the experimental desulfurization rate to be consistently higher than the theoretical maximum by approximately 20% for carbon concentrations between 0 and 4.9 mass%. Inaccurate description of solution thermodynamics was postulated to be one of the potential causes for this observed discrepancy.

### 3.2. Thermodynamic Considerations

Studies\textsuperscript{16,17} on the thermodynamic behavior of sulfur in the presence of carbon often utilize the solute dissolution method, where a binary gas mixture such as H$_2$–H$_2$S of known ratio is passed over or bubbled through molten iron–carbon alloys. In the work of Ban-ya et al.,\textsuperscript{17} it was concluded that while this experimental technique is appropriate for studying most other alloying elements, the results for Fe–S–C obtained in this manner are possibly less dependable than measurements made using other techniques. Formation of volatile sulfides during the experiments is thought to have an impact on the reliability of measurements. Also, as pointed out by Sunderland et al.,\textsuperscript{18} when gas mixtures are passed over molten alloys during gas dissolution experiments, the measured steady-state solubilities may differ from the true equilibrium values due to the presence of thermal diffusion effects. By contrast, thermal diffusion may be less relevant in the case of thermodynamic measurements based on sulfur evaporation in vacuum or inert atmosphere with a levitated droplet. Hence this approach could prove useful in determining interaction parameters for solutes in liquid iron alloys.

The effect of carbon on the activity coefficient of sulfur in liquid iron is given by:

$$f_S = e_c^S (\text{mass}\%\ C) + r_c^S (\text{mass}\%\ C)^2 + e_S^S (\text{mass}\%\ S)$$ \hspace{1cm} (12)

where $e_c^S$ and $r_c^S$ are respectively the first-order and second-order terms in the activity coefficient of sulfur in liquid iron.
order interaction parameters for the effect of carbon on the activity coefficient of sulfur. The self-interaction parameter for sulfur \(e_s^s\) is given\(^{13}\) as:

\[
e_s^s = \frac{-120}{T} + 0.018
\]

(13)

At 1873 K, the commonly quoted values for \(e_s^c\) and \(r_s^c\) are 0.11\(^{13,18}\) and 0.0058\(^{19}\), respectively; both of which were derived from experimental data\(^{16,17}\). Due to the relatively high carbon and low sulfur concentrations studied in the present work, the contribution from the self-interaction parameter to the sulfur activity coefficient is negligible. Equation (12) is therefore reduced to:

\[
\log f_s = e_s^c (\text{mass}\% \ C) + r_s^c (\text{mass}\% \ C)^2
\]

(14)

In order to confirm the validity of the kinetics analysis discussed in the present work, it is essential to verify the values used for the interaction parameters and hence the sulfur activity coefficients. Values for \(e_s^c\) and \(r_s^c\) can be obtained by examining the extent of desulfurization as a function of melt carbon concentration. As shown in Fig. 2, due to the rapid kinetics associated with the levitation technique, sulfur concentrations in the high-carbon samples approached steady-state after about 30 minutes of exposure to the argon gas flow. Desulfurization behavior of the low-carbon samples suggest that steady-state is not far beyond the 40-minute mark. Thus, droplets at 40 minutes are considered to be in a near-equilibrium state. The overall reaction for sulfur vaporization from liquid iron alloys can be represented by the following:

\[
S = S_{eq}
\]

(15)

for which the equilibrium constant is:

\[
K = \frac{P_S}{(\text{mass}\% S)f_s}
\]

(16)

where \(P_S\) is the equilibrium partial pressure of monatomic sulfur. Combining Eqs. (14) and (16) and rearranging the terms:

\[
\log P_s - \log K - \log(\text{mass}\% S) = r_s^c (\text{mass}\% \ C) + e_s^c
\]

(17)

From Eq. (17), the common practice for determining values for \(e_s^c\) and \(r_s^c\) is by plotting the left hand side of Eq. (17) against carbon concentration in the melt. This approach requires \(K\) and \(P_S\) to be known. Since the present experiments were conducted at a fixed temperature of 1873 K, the value of \(K\) is a constant for all conditions. In the case of measurements made in an inert atmosphere or vacuum, an accurate value for the effective \(P_S\) is not available. However, the atmospheric conditions imposed on the droplets by constant argon flow are identical among the various trials. Therefore, the applied \(P_S\) is not a variable in this investigation. Rearranging Eqs. (17), (18) is obtained:

\[
-\log(\text{mass}\% S) = r_s^c (\text{mass}\% \ C)^2 + e_s^c (\text{mass}\% \ C) + \log K - \log P_s
\]

(18)

A plot of the present results expressed in terms of Eq. (18) is shown in Fig. 7. The y-intercept corresponds to the combination of \(\log K\) and \(\log P_S\). By calculating the value of \(K\) at 1873 K using the free energy expression shown in Table 2, together with the intercept value from Fig. 7, the value of \(P_S\) can be deduced. For the current experimental conditions, the effective partial pressure of monatomic sulfur experienced by the metal droplets is \(2.6 \times 10^{-4} \text{ atm}\), which is in accord with the thermodynamic prediction listed in Table 2.

For comparison purposes, a predicted equilibrium line based on the previously reported interaction parameter values is included in Fig. 7. It can be seen that, at carbon concentrations less than approximately 2 mass%, the present experimental data are in good agreement with the predicted equilibrium line. However as carbon concentration increases beyond 2 mass%, the measured values begin to deviate from the prediction; suggesting a substantial contribution from the second-order term may be important.

Upon evaluation by polynomial regression, it is found that \(e_s^c = 0.113\) and \(r_s^c = 0.028\). The value obtained for \(e_s^c\) is in accord with those reported in the literature: 0.108\(^{17}\), 0.11\(^{13,19}\), 0.12\(^{12,21}\). However, for the second-order interaction coefficient \(r_s^c\), the value determined in the present work is appreciably higher than those found in previous studies that utilized the solute dissolution approach. It should be noted that there are large discrepancies among the reported values: 0.0058\(^{19}\), 0.0091\(^{17}\), 0.013\(^{22}\). This relatively wide range of values seems to indicate that, for experiments conducted in a H\(_2\)-H\(_2\)S atmosphere, the measurements are more susceptible to errors that may arise from the effects of thermal diffusion\(^{19}\).

### 3.3. Integrated Rate Analysis

The parameters determined from the equilibrium study permit reevaluation of the sulfur activity coefficients from the kinetic analysis. On a plot of \(\ln S_t/S_0\) vs. \(A \cdot f_S t/W\), as shown in Fig. 8, the desulfurization data are well-described by a single straight line. The gradient of the line, based on Eq. (19), can be used to compute the desulfurization rate constant, \(k_{s'}\).

\[
-\ln \frac{S_t}{S_0} = k_{s'} \frac{100A}{W} f_S t
\]

(19)

For the experimental conditions prevailing in the present work, specifically \(T = 1873\ \text{K}\) and \(\theta_S > 0.95\), the desulfurization rate constant is found to be \(1.33 \times 10^{-4} \text{ g cm}^{-2} \text{ min}^{-1}\).
To put this value in perspective, experimental data for free evaporation of sulfur from Fe–C–S melts at 1873 K and 1.333 Pa pressure reveals \( k_a' = 2.07 \times 10^{-3} \text{ g cm}^{-2} \text{ min}^{-1} \). Thus it would appear that the rate of evaporative loss of sulfur from Fe–C–S melts at atmospheric pressure is approximately one order of magnitude less than that in vacuum.

In view of the fact that the thermodynamic analysis described in the previous section was based on measurements pertaining to equilibrium conditions and was uninfluenced by reaction kinetics, the validity of the values for the interaction parameters derived in the present work is further supported by their ability to provide an excellent description of the desulfurization rates.

4. Summary and Conclusions

Sulfur loss from levitated Fe–C–S alloys exposed to an inert atmosphere at 1873 K is attributed to the formation of monatomic sulfur vapor. Within the composition range studied, the rate of sulfur removal was found to be in accord with a first-order type reaction with respect to sulfur concentration in the melt. Carbon exerted a positive effect on the rate, by increasing the activity of sulfur. It was found that the values reported in the literature for the second order interaction parameter \( k^c_i \) consistently underestimated the influence of carbon on the sulfur activity coefficient. This led to erroneous assessment of the rate data. Based on a thermodynamic evaluation of the results from the present work, values were determined for the first and second order parameters \( e^c_i \) and \( e^c_i \). While the value obtained for \( e^c_i \) of 0.113 is in excellent agreement with literature data, the value for \( e^c_i \) of 0.028 is significantly higher. Using the proposed new values for the parameters, the desulfurization behavior is well represented by a rate equation describing interfacial reaction as the rate-determining step.

Acknowledgements

Appreciation is expressed to the Natural Sciences and Engineering Research Council of Canada who provided funding in support of this project.

Table of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>Area of droplet (cm²)</td>
</tr>
<tr>
<td>( a_c )</td>
<td>Henrian activity of carbon based on the hypothetical 1 mass% standard state</td>
</tr>
<tr>
<td>( a_s )</td>
<td>Henrian activity of sulfur based on the hypothetical 1 mass% standard state</td>
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<tr>
<td>( a_i )</td>
<td>Activity of activated complex</td>
</tr>
<tr>
<td>( c_i )</td>
<td>First order interaction parameter for effect of carbon on sulfur</td>
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<td>( r^s_i )</td>
<td>Self-interaction parameter for sulfur</td>
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<td>Activity coefficient of sulfur (mass% S⁻¹)</td>
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<td>Planck constant (3.97564 × 10⁻³⁰ m² kg min⁻¹)</td>
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<td>( K )</td>
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<td>Sulfur adsorption coefficient</td>
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<td>Apparent rate constant (cm⁻¹ min⁻¹)</td>
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<td>( \theta^1_f )</td>
<td>Fractional surface coverage by activated complexes</td>
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<td>( \rho )</td>
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REFERENCES