Interaction of Soot–SO\textsubscript{2}: Experimental and Kinetic Analysis

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ABSTRACT
This study aims to evaluate the capability of SO\textsubscript{2} to interact with soot and to determine the kinetics of this reaction under conditions of interest for combustion. The conditions of the soot reactivity experiments were: 1% SO\textsubscript{2} with nitrogen to balance, around 10 mg of soot, and different reaction temperatures for each run: 1275, 1325, 1375, 1425, and 1475 K. Results demonstrate that SO\textsubscript{2} does interact with soot. The evaluation of the soot reactivity has been based on the calculation of the time for the complete conversion of carbon through the employment of the Shrinking Core Model equations for decreasing size particle with chemical reaction control. The reactivity of soot with SO\textsubscript{2} increased by a factor of about 3 when increasing the reaction temperature of the test from 1275 K to 1475 K. Kinetics in terms of Arrhenius parameters showed that the activation energy of the interaction of soot with SO\textsubscript{2} was around 82 kJ/mol.

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Introduction

Usually, sulfur is present in fossil fuels and even in biofuels and household wastes. The combustion of these sulfur-containing fuels releases the sulfur to the gas-phase, principally as sulfur dioxide (SO\textsubscript{2}) (Cullis and Mulcahy, 1972; Glarborg, 2007; Johnsson and Glarborg, 2000). When the flue gas recirculation (FGR) technique is applied in combustion processes, the SO\textsubscript{2} in the flue gas can be removed before or after the recirculation of the gases, which in the latter case may affect the overall combustion scheme and/or the fate of other pollutants, such as soot. The interactions between sulfur dioxide and soot can be produced through indirect ways, by altering the radical pool (SO\textsubscript{2} has been reported to act as a radical sink, e.g., Alzueta et al., 2001) or through direct reaction of SO\textsubscript{2} with the soot and hydrocarbons involved in the soot formation processes (see, e.g., Abián et al., 2015a; Gülder, 1993; Lawton, 1989).

The interaction of carbon with SO\textsubscript{2} has been studied for different carbon materials. Humeres et al. (2002) studied the kinetics and product distribution under chemically controlled steady-state conditions of the reactivity of SO\textsubscript{2} with various carbon materials with different degrees of crystallinity. The authors found CO\textsubscript{2} and S\textsubscript{2}, in the ratio 2:1, as the main products for all of the carbon materials analyzed. The reaction sequence suggested involved the adsorption of SO\textsubscript{2} on an active site of carbon to consecutively lead to the main products CO\textsubscript{2} and S\textsubscript{2}. Globally, the SO\textsubscript{2} + C → CO\textsubscript{2} + ½ S\textsubscript{2} reaction was
proposed as the path for SO₂ reduction, as it is the only reaction whose stoichiometry corresponds to the ratio CO₂:S₂ equal to 2 (Humeres et al., 2002).

The reactivity of soot towards different oxidants has been studied under a variety of conditions. In the review presented by Stanmore et al. (2001) on the oxidation of soot, the oxidizing compounds considered are oxygen, carbon dioxide, water vapor, and nitrogen dioxide, but no mention is done to sulfur dioxide. To our knowledge, there is a lack of studies on the oxidation of soot with SO₂ under non-catalyzed combustion conditions. In this context, the objective of this work is to study, in terms of kinetic analysis, the reactivity of soot with SO₂ at high temperatures (1275–1475 K). To that end, a series of experiments was performed under chemically controlled conditions to further analyze the kinetics of the soot-SO₂ interaction and determine the activation energy of the reaction. Soot samples obtained in a laboratory facility, from the pyrolysis of ethylene (one of the main soot precursors) in a N₂ atmosphere at high temperature (1375 K) were selected for this study. This soot was characterized and used in a previous study regarding the oxidation of soot with O₂ and CO₂ (Abián et al., 2012).

**Experimental installation and procedure**

The soot samples were prepared in a quartz flow reactor from the pyrolysis of 30,000 ppm of ethylene in a N₂ atmosphere at 1375 K, following the methodology described in Abián et al. (2014). The experimental installation used for the formation of soot has been successfully used thus far in a number of earlier works by our group (e.g., Abián et al., 2015a; Esarte et al., 2009; Ruiz et al., 2007a).

The soot produced was collected in a quartz fiber thimble (mesh light lower than 1 μm) placed at the outlet of the reactor. Previously to the reactivity experiments, each soot sample is annealed by heating for 1 h in a nitrogen atmosphere at its formation temperature (1375 K), to remove adsorbed compounds on the surface of the particles. Afterwards, the soot sample is subjected to the reactivity experiments.

The interaction experiments of the soot samples with the reactant SO₂ were carried out in an experimental installation, which has been also used with success in a number of earlier works by our research group, addressing heterogeneous gas-carbon materials reactions (e.g., Arnal et al., 2012a; Guerrero et al., 2005).

In the reactivity experiments, the reaction takes place in a quartz tubular reactor with a 15-mm inside diameter and with a bottle neck in the middle where a quartz wool plug is placed. A mixture of around 10 mg of soot and 350 mg of silica is deposited over the plug resulting in a thin layer. Silica is used to facilitate the introduction of the sample in the reactor and prevent the agglomeration of soot particles. A given SO₂ concentration of 1% has been used for all of the experiments, whereas the influence of different reaction temperatures (specifically 1275, 1325, 1375, 1425, and 1475 K) has been analyzed. Gases are fed into the reaction system through mass flow controllers at a total flow rate of 1000 mL (STP)/min. N₂ has been used to balance. During the heating of the reaction system up to the reaction temperature, an inert flow of N₂ is fed. Once the desired temperature is reached, the reactant gaseous mixture is fed into the reactor.

In each experiment, the reaction products are cooled down at the reactor outlet up to room temperature by means of external air refrigeration and analyzed as a function of the reaction time. To measure the concentration of the product gases, a continuous infrared (IR) CO/CO₂ analyzer and a Fourier transform infrared (FTIR) analyzer calibrated to determine sulfur compounds have been used. The estimated uncertainties of the measurements are ±5% for
the continuous IR analyzer and ±10% for the FTIR, but not less than 10 ppm. The uncertainty in the experimental procedure was analyzed by performing repeatability experiments (an example is included in Figure 1). Considering the different experimental uncertainty sources, a general good response was obtained in the results, with an agreement within 20% in the subsequently determined time for the complete conversion of carbon.

**Results and discussion**

**Interaction soot-SO$_2$: experimental results and product distribution**

In order to analyze the interaction of soot with 1% SO$_2$, several experiments were performed at different reaction temperatures (specifically at 1275, 1325, 1375, 1425, and 1475 K). Previous studies regarding the interaction of carbon materials with SO$_2$ show
that products from the reaction are mainly \( \text{CO}_2 \) and \( \text{S}_2 \), but also CO, COS, and CS\(_2\), depending on the specific operating conditions the carbon sample considered and whether

the reaction was diffusional or chemically controlled (Humeres et al., 2002). As previously

mentioned in the present work, the outlet gas composition was analyzed by means of a

continuous IR CO/CO\(_2\) analyzer and a FTIR. In the present experiments, the formation of

CO, CO\(_2\), and CS\(_2\) was experimentally observed. COS was not detected under any

experimental condition analyzed. SO\(_2\) concentration was quantified and results indicated

that it was kept practically constant at 1% throughout the experiments; therefore, no more

considerations are given in relation to the time evolution of this reactant.

Elemental analysis of the soot samples revealed the following composition: 97.77 wt% C,

1.01 wt% H, and 0 wt% N (Abián et al., 2012). Considering the resultant H/C ratio in

weight (equal to 0.01), the composition of the reacting mixture (1% SO\(_2\) in N\(_2\)), and the

estimated uncertainty of the FTIR measurements, the formation of \( \text{H}_2\text{S} \) and of any other

hydrogen-containing compound was directly disregarded.

Figure 1 shows the concentration results (in ppm) of CO, CO\(_2\), and CS\(_2\) obtained from

the interaction soot-SO\(_2\) at the different reaction temperatures. This figure also shows, as

an example, repeatability experimental results obtained at 1475 K.

As it can be observed in Figure 1, for all of the temperatures studied, CO is the main

product of the reaction. CO\(_2\) concentrations are always around 25–30 ppm at the first

stages of the reaction to further decrease to concentrations lower than 10–15 ppm, which

can be considered as negligible. CS\(_2\) was only detected at the very first stages of the

reaction, and for temperatures higher than 1275 K. It is important to mention that the

remaining carbon weight decreases as the reaction advances and, thus, for a given

experiment the total amount of the different products is also expected to decrease with
time up to insignificant concentrations when soot is fully consumed.

Considering the product distribution of the present experiments, the possible reaction

paths of the reaction of soot with SO\(_2\) are discussed as follows.

Humeres et al. (2002) proposed that the interaction of different carbon materials with

SO\(_2\) occurs through the adsorption of SO\(_2\) on active sites leading to the formation of CO\(_2\)

and \( \text{S}_2 \) (r.1). Consecutively, insignificant amounts of CO are slowly formed by the

Boudouard reaction (r.2). Once CO is formed, it reacts with sulfur complexed on active

sites to form COS, and possibly CS\(_2\) is produced from the same site active.

\[
\text{SO}_2 + \text{C} \rightarrow \text{CO}_2 + \frac{1}{2}\text{S}_2 \quad \text{(r.1)}
\]

\[
\text{CO}_2 + \text{C} \leftrightarrow 2\text{CO} \quad \text{(r.2)}
\]

Another path for CO formation could be the direct reaction of SO\(_2\) with the carbonaceous

compound to produce CO and COS (r.3):

\[
\text{SO}_2 + 2\text{C} \rightarrow \text{CO} + \text{COS} \quad \text{(r.3)}
\]

As previously mentioned, in our work CO is the main product detected under all

conditions analyzed and CO\(_2\) concentrations can be considered negligible (Figure 1). This

fact indicates that in the case of reaction (r.1) as the main path, the CO\(_2\) formed should

quickly react through (r.2) to form CO. The Boudouard reaction (r.2) for CO formation is

an endothermic reaction and it would be both thermodynamic and kinetically favored by

temperature.
Taking into account these considerations, under the conditions of the present work, the interaction of soot with SO$_2$ could be initiated in a parallel process leading to CO formation through both the reaction sequence (r.1) and (r.2), and the direct CO formation (r.3).

Stoichiometry in reaction (r.3) shows a ratio CO:COS equal to 1. However, COS was not experimentally detected at any of the conditions studied. Therefore, COS must be regarded as an intermediate under the studied conditions. On the basis of the previous carbon-SO$_2$ interaction study (Humeres et al., 2002), the COS consumption could be described according to the global reactions (r.4) and/or (r.5); although, the main elemental reaction pathways involved in the decomposition of CO can be found in Abián et al. (2015b):

$$\text{2COS} \rightarrow \text{2CO} + \text{S}_2 \quad \text{(r.4)}$$

$$\text{2COS} \rightarrow \text{CO}_2 + \text{CS}_2 \quad \text{(r.5)}$$

Reaction (r.5) produces CO$_2$ and CS$_2$ in the same proportion. However, as it can be observed in Figure 1, the amount of CO$_2$ and CS$_2$ are not the same for a given temperature and neither in the time. CS$_2$ is only present as a final product at the very first stages of the reaction and for specific temperatures (1325 K and above), whereas CO$_2$ always appears as a final product. Besides, when present, CS$_2$ concentrations are generally higher than the CO$_2$ ones. Therefore, if reaction (r.5) would occur, most of the CO$_2$ formed should be converted, for example, through reaction (r.2). On the basis of this discussion, both COS consumption paths [(r.4) and (r.5)] may happen.

Regarding the source of the little amount of CO$_2$ quantified, besides the SO$_2$ + C reaction (r.1) and the conversion of COS (r.5), the gas-phase reaction of CO with SO$_2$ can also produce CO$_2$ (r.6) (Alzueta et al., 2001; Giménez-López et al., 2011):

$$\text{CO} + \text{SO}_2 \leftrightarrow \text{CO}_2 + \text{SO} \quad \text{(r.6)}$$

In the case of CS$_2$ formation, besides reaction (r.5), two other possible reaction paths are proposed (Humeres et al., 2002):

$$\text{C} + \text{S}_2 \rightarrow \text{CS}_2 \quad \text{(r.7)}$$

$$\text{C} + 2\text{COS} \rightarrow \text{CS}_2 + 2\text{CO} \quad \text{(r.8)}$$

Taking into account the product distribution of the present work, the formation of CS$_2$ could be produced through any of these reactions [(r.5), (r.7), and (r.8)].

Considering all of the above, the overall reaction scheme of possible paths involving the interaction of soot with SO$_2$ (shown in Figure 2) seems to be more complicated than the mechanism for the interaction of carbon with SO$_2$ proposed by Humeres et al. (2002).

**Kinetic study**

The kinetics of the reactivity of soot towards SO$_2$ was obtained from the values of the remaining carbon weight ($W_C$) for different reaction times. The Shrinking Core Model for decreasing size particle with chemical reaction control (Levenspiel, 1999) was used. The
equations of the model have been applied successfully in similar previous studies (e.g., Arnal et al., 2012b; Ruiz et al., 2007b). The remaining carbon weight in the reactor at any time ($W_C$) is calculated from the time variation concentrations of CO, CO$_2$, and CS$_2$ (as main reaction products) in the outlet gas. In this way, $W_C$ can be calculated as:

$$W_C = W_C^0 - M_C \cdot F_T \cdot 10^{-3} \int_0^t (C_{CO} + C_{CO_2} + C_{CS_2}) \, dt$$

(1)

where $W_C^0$ is the initial amount of carbon (in mg) in the reactor [Eq. (2)]; $M_C$ is the atomic weight of carbon; $F_T$ is the exit flow in moles of total gas per second [Eq. (3)]; $C_{CO}$, $C_{CO_2}$, and $C_{CS_2}$ are the concentrations in ppm of CO, CO$_2$, and CS$_2$, respectively, at time $t$.

$$W_C^0 = M_C \cdot F_T \cdot 10^{-3} \int_0^\infty (C_{CO} + C_{CO_2} + C_{CS_2}) \, dt$$

(2)

$$F_T = \frac{Q \cdot P}{R \cdot T}$$

(3)

In Eq. (3), $Q$ is the total flow rate fed to the reactor (m$^3$/s); $P$ is the reactor pressure (Pa); $R$ is the universal gas constant (Pa m$^3$/mol K); and $T$ is the reactor temperature (K).

According to the Shrinking Core Model, the reaction rate can be referred to the external surface of the particle, and may be also described as a function of the remaining carbon weight during the reaction, $W_C$. The expressions for decreasing size particle with chemical reaction control are presented in Eqs. (4) and (5):

$$-\frac{1}{S_{ext}} \cdot \frac{dN_C}{dt} = b k_s C_{reactantgas}^n$$

(4)
In these equations, \( N_C \) are the moles of carbon; \( b \) is the carbon stoichiometric coefficient according to the global reaction with the reactant gas, in this case \( \text{SO}_2 \); \( k_S \) is the rate constant; \( C_{\text{reactant gas}} \) is the inlet gas reactant concentration (\( \text{SO}_2 \)); \( n \) is the reaction order with respect to the gas reactant; \( C \) is a constant equal to \( (4\pi M_C)^{1/2} \cdot (3/\rho_C)^{2/3} \), considering spherical particles; and \( \rho_C \) is the molar density of the particles (moles of carbon/m\(^3\)).

The Shrinking Core Model equations with chemical reaction control must be applied in the carbon weight interval where \(- \frac{1}{W_{C}^{2/3}} \frac{dW_C}{dt} = C b k_S C_{\text{reactant gas}} \) is considered as constant. Figure 3 shows the results obtained at the different reaction temperatures when determining the carbon weight interval where the equations of the model can be applied to analyze the reactivity of soot with \( \text{SO}_2 \).

It can be inferred from the results presented in Figure 3 that the equations of the Shrinking Core Model with chemical reaction control can be applied in the carbon weight interval covering the 20–90% of the soot conversion at any of the temperatures analyzed.

The employment of the equations of this model allows to calculate the time needed for the complete conversion of carbon, \( \tau \), by relating the reaction time, \( t \), and the carbon conversion, \( X_C \), all along the experiment through the use of Eq. (6). The \( \tau \) value is considered as indicative of the carbon reactivity.

\[
\frac{t}{\tau} = 1 - (1 - X_C)^{1/3}
\]

(6)

The conversion of carbon, \( X_C \), at any time, \( t \), is determined as the weight of carbon reacted in the experiment related to the initial weight of carbon:

\[
X_C = \frac{W_{C_0} - W_t}{W_{C_0}}
\]

(7)

From the values of \( 1 - (1 - X_C)^{1/3} \) versus time \( (t) \), the time for the complete conversion of carbon \( (\tau) \) for the different operating conditions can be obtained. The experimental

![Figure 3. Carbon consumption rate expressed as a function of the remaining carbon weight, \( W_C \), in the reaction of soot with 1% \( \text{SO}_2 \) at different temperatures (1275–1475 K).](image-url)
carbon conversion data used in Eq. (6) to determine the \( \tau \) values are the ones corresponding to the carbon weight interval considered as constant in the analysis of results shown in Figure 3.

Table 1 summarizes the values of the time for complete conversion of carbon obtained in the soot-SO\(_2\) reactivity experiments at different temperatures, along with the linear regression coefficient results for each condition.

As it can be observed in Table 1, the complete carbon conversion time, \( \tau \), decreases as the reaction temperature is increased, indicating the higher reactivity of soot towards SO\(_2\) with temperature. In this way, the complete carbon conversion time is in general decreased by a factor of about 3 when increasing the reaction temperature 200 K (from 1275 K to 1475 K).

The results from the interaction soot-SO\(_2\) obtained at different temperatures (1275–1475 K) allowed the calculation of the activation energy (\( E_a \)) value of the process. Considering that \( \tau \) can be expressed through Eq. (8) (Levenspiel, 1999), and displaying the reaction rate as a function of the Arrhenius equation, the activation energy can be derived from the linearization of the Arrhenius equation rewritten as a function of \( \tau \) (9):

\[
\tau = \frac{\rho_C R_0}{bk_0 C_n^{reactant\ gas}}
\]

\[
\ln \frac{1}{\tau} = \ln \left( \frac{bk_0 C_n^{reactant\ gas}}{\rho_C R_0} \right) - \frac{E_a}{R} \frac{1000}{T}
\]

In Eqs. (8) and (9), \( R_0 \) is the initial radius of the soot particle; \( k_0 \) is the pre-exponential factor; \( R \) is the gas constant (J/mol K); and \( T \) is the operating temperature (K).

Figure 4 shows the Arrhenius plot for the soot interaction with 1% SO\(_2\) at the different temperatures analyzed, along with the linear regression coefficient value obtained. From this fitting, an activation energy of about 82 kJ/mol was obtained.

Comparing the reactivity of soot towards SO\(_2\) and O\(_2\) (as the main oxidant in combustion), it is worth noting that the activation energy of the soot-SO\(_2\) interaction (about 82 kJ/mol, present work) is much lower than the activation energy of the soot oxidation process, which was about 152 kJ/mol for the same soot sample (Abián et al., 2012).

**Conclusions**

An experimental and kinetic analysis of the interaction of soot with SO\(_2\) at different reaction temperatures was carried out. The soot samples used in this study were
generated under well-controlled lab-scale conditions from the pyrolysis of ethylene in a N₂ atmosphere at 1375 K. The reactivity experiments involved the interaction of soot with 1% SO₂ at 1275, 1325, 1375, 1425, and 1475 K.

Experimental results showed that CO is the main product obtained from the soot-SO₂ interaction under all of the operating conditions analyzed. CO₂ was also detected but in almost negligible amounts. The formation of CS₂ was detected under specific operating conditions (i.e., temperatures higher than 1275 K and at the very first stages of the reaction). The analyses of the product distribution indicate that the possible mechanism for the reactivity of soot with SO₂ is complex, involving a number of reaction paths that can occur in parallel, but all of them deriving in the final formation of CO, CO₂, and CS₂.

The Shrinking Core Model equations with decreasing size particle and chemical reaction control were used, first to determine the time for the complete consumption of carbon, τ, and further to calculate the activation energy, Eₐ, of the process. The τ values indicated that the soot reactivity is increased by a factor of about 3 when increasing the reaction temperature from 1275 K to 1475 K. In this way, results show that the higher the temperature, the higher the carbon conversion. An activation energy of about 82 kJ/mol was obtained for the interaction of soot with SO₂, which is lower (by about half) than the one corresponding to the oxidation of soot with O₂.

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