

AN EQUILIBRIUM-THERMODYNAMIC ANALYSIS OF SULFUR RELEASE AND CAPTURE
IN A GASIFICATION/COMBUSTION ENVIRONMENT

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ABSTRACT

Coal and coal-derived liquids and gases constitute an economically attractive alternative energy source to liquid petroleum fuels. Ongoing research programs at DOE-METC are currently examining the potential of inexpensive production of clean liquid and solid fuels from coal by mild gasification, and of gaseous fuels by countercurrent pressurized fixed-bed gasification. The simultaneous release of gaseous sulfur species (H_2S , COS , SO_2 , SO_3) is an inherent environmental limitation to a large-scale practical application of these processes. A computational technique to estimate the release of sulfur from coal and subsequent capture by calcium-based sorbents is presented here, where both processes are assumed to proceed to equilibrium under devolatilization, gasification (reducing), and combustion (oxidizing) conditions. A free-energy minimization computer program (PACKAGE) is used here to simulate local thermochemical equilibria in these reactive atmospheres. Predicted partial pressures of sulfur species are compared with experimental data on sulfur release and sorption, and conclusions are drawn regarding the usefulness and limitations of an equilibrium approach to modeling these processes.

1. INTRODUCTION

Coal use for electric power generation has increased in the past decade, and coal use for propulsion is a distinct possibility in the near future; however, the economic conversion of coal to clean fuels still remains a considerable technological challenge. Coal pyrolysis is perhaps the oldest technique for the derivation of hydrocarbon fuels from coal. In all coal conversion and utilization processes (including gasification, combustion, and liquefaction), some form of coal pyrolysis occurs. Gasification is closely related to pyrolysis in that when coal is gasified by reacting it at high temperature with steam and air, pyrolysis is the first stage of the reaction as the coal is heated to reaction temperature. Similarly, pyrolysis occurs at the first stage of combustion and in liquefaction because of the high temperatures employed when solvents are reacted with the coal.

1.1 Coal Devolatilization: Current Status of Modeling Efforts

The need to understand devolatilization reaction chemistry is obvious from the above discussion. Khan (1) has described the experimental procedure used to generate coal pyrolysis liquids, gases, and solids in the METC Slow Heating Rate Organic Devolatilization Reactor (SHRODR). This unit simulates, to an extent, the heating rates and residence times of the devolatilization zone of a fixed-bed gasifier. In this 500 ml fixed-bed reactor, 100 grams of coal (particle size -8 by +100 mesh) were heated to 500°C in 40 minutes and maintained at that temperature for 1 hour. Two high-volatile coals, Pittsburgh No. 8 (containing 2 weight percent sulfur) and Illinois No. 6, were tested. A sulfur sorbent, CaO, was added to the coals by direct mixing of the components. Product gases were collected and analyzed using gas chromatographs. Results demonstrated that the presence of lime significantly reduced the yield of H_2S . Total gas yield remained almost unchanged, and the yield of (C_1 - C_8) hydrocarbon

gases and hydrogen increased significantly. Greater sulfur capture was seen with smaller CaO particles and at higher pyrolysis temperatures.

Typically, correlation techniques (e.g. [2,3]) are utilized to predict product yield and composition during coal devolatilization. Kinetic schemes proposed to represent the mechanism of coal pyrolysis range from two independent parallel reactions (4) to 42 reactions of 14 different functional groups in coal (5). Scaroni, et al. (6), have presented a compromise based on a hierarchy of bond energies in the coal structure. Serio, et al. (7), have reviewed available models to describe the kinetics of volatile product evolution in coal pyrolysis. All these approaches suffer to varying extents from empiricism. The degree of coal devolatilization depends on several parameters, such as coal type, heating rate, temperature, pressure, residence time at pyrolysis temperature, etc. The extent of sulfur release depends on several additional variables, such as the form of sulfur in the coal (inorganic, organic), sulfur trapped in the pyrolysis liquid, intimacy of contact between CaO and the primary products of devolatilization, etc. Given the uncertainties that unfortunately detract from any effort to describe the kinetics of these individual processes, an alternative systematic yet tractable predictive procedure to assess the products of the basic devolatilization reaction would be of immediate use.

1.2 Coal Gasification: Current Status of Modeling Efforts

The attractiveness of such an interim approach is reinforced by the accumulating sulfur-sorption data from the METC fixed-bed gasifier, which still await fundamental analysis. A countercurrent fixed-bed gasifier consists of four overlapping zones ([3]; Figure 1). At the top of the gasifier, the coal is dried and preheated by the exiting hot product gases. In the second zone, the coal is devolatilized and gases and tars are released. In the gasification zone, endothermic reactions occur forming carbon monoxide, carbon dioxide, water, hydrogen, and methane. Combustion of coal and oxygen occurs in the combustion zone, releasing heat to support the gasification reactions. Dry or molten ash will form in this zone depending on the maximum combustion temperature. The effects of pressure, calcium/sulfur ratio, and coal and limestone feedstock on sulfur removal efficiency have been investigated in a series of runs on the METC fixed-bed gasifier. Preliminary results indicate that sulfur capture decreases as pressure increases, and that recycle of regeneration gases to the gasifier may be required to obtain significant sulfur capture at higher pressures.

Several computer models (e.g. [3,8,9,10,11]) have been developed to simulate the chemical and physical processes that occur during steady-state gasification and hot gas cleanup. In these models, typically, carbon outlet flow and outlet gas composition and flow rate are predicted, but sulfur chemistry and the effects of additives are not included in the calculations. In addition, the finite chemical kinetic rate expressions used by these models require a knowledge of the appropriate activation energies and rate constant coefficients for various coal types. To obtain a sufficiently comprehensive reliable data base is thus a Herculean task. This problem can be circumvented to a certain extent by assuming that all chemical reactions proceed to equilibrium, but this would still require that the individual equilibrium rate constants be specified. The free-energy minimization procedure developed by White, et al. (12), is a numerically attractive alternative since it specifies no reaction paths and has been used to perform the equilibrium thermodynamic calculations presented in this report.

1.3 Modeling Sulfur-Lime Reaction Kinetics: Uncertain Effect of Pore Structure

The equilibrium approach is also necessitated by the lack (particularly in a fixed-bed environment) of a systematic procedure for the description of the high-pressure sorptive capacity for SO₂ (or H₂S) removal of a given limestone (or dolomite) starting from basic physical principles and experimental information. The effect of the initial pore structure of the sorbent, structural changes during the calcination

process, accumulation of a surface char layer on the sorbent particles in their transit through the (low-temperature) devolatilization and gasification zones in a gasifier column are among the phenomena that few of the presently available kinetic models incorporate. Ideally, presently available kinetic codes (13,14) should be developed to the point where they can describe these phenomena quantitatively; but in view of the time and effort that would involve, an interim procedure that is insensitive to these microscopic-level details constitutes a feasible alternative.

These considerations have led to the conclusion that a systematic approach to describing sulfur release and sorption processes in coal conversion applications is needed at this stage, even if the approach can only yield (infinite-rate) "limiting" information on sulfur release, sulfur removal, and lime utilization. While the usefulness of the present local thermodynamic equilibrium approach would doubtless be enhanced by interfacing it with the overall material balance for any specific coal conversion application, the advancement of understanding attained with the present preliminary scheme is still considerable. In subsequent sections the fundamentals of the chemical-equilibrium algorithm used here are described, its ability to deal with the complex chemistry of coal conversion product mixtures demonstrated, and its validity evaluated by comparing predicted and measured gas/solid/liquid phase compositions in lime-treated coal process streams.

2. THE COMPLEX CHEMICAL EQUILIBRIUM APPROACH: METHODOLOGY

Product gas, liquid, and solid phase compositions are estimated here using an equilibrium-thermodynamic computer program on the premise that the species distribution predicted by a free-energy minimization algorithm is the one likely to prevail. Stinnett, et al. (15), have previously applied the principle of thermodynamic free-energy minimization to fossil fuel gasification processes to predict the effect of operating variables on the composition of the product gas (in the absence of a sulfur sorbent). This approach enables the estimation of the partial-pressure distribution of all sulfur-bearing species in the gas, as well as the mole fractions of the sulfur-containing species in the solid and liquid phases; the analysis is thus not limited to a few user-specified reactions and products. The utility of this method is limited only by the available thermodynamic data base and its assumption of ideal solution phases. Due to the demonstrable efficiency of the PACKAGE computer code (16) in modeling complex phase equilibria in coal conversion gas streams and cleanup devices, the PACKAGE program has been used to perform the equilibrium thermodynamic computations presented here. Input to this program consists of elemental compositions of the reactant streams, relative mass flow rates of the reactant streams (e.g., the fuel/air ratio in a combustion case, $[\text{coal}+\text{lime}]/[\text{air}+\text{steam}]$ in a gasification situation), pressures, and temperatures of interest. In the case of coal devolatilization, coal composition, devolatilization temperature, and pressure would constitute the input parameters. Output from the PACKAGE program typically consists of phase fractions and species mole fractions within each phase as a function of temperature. The results of exercising the PACKAGE programs under conditions representative of coal devolatilization, gasification and combustion are presented in the next section.

3. THE COMPLEX CHEMICAL EQUILIBRIUM APPROACH: FEASIBILITY

In order to demonstrate the suitability of an equilibrium approach to characterizing coal conversion product streams, illustrative calculations have been performed over a wide range of operating conditions simulating coal devolatilization, gasification, and combustion environments. The parametric studies presented in this section are meant to constitute the operating "envelope" for these systems. The results presented here are mostly qualitative and are intended only to show the feasibility of the approach without reference to quantitative accuracy; the latter aspect will be taken up in the next section.

3.1 Devolatilization Products Composition Calculations

The atmospheric pressure devolatilization calculations presented here pertain to slow-heating pyrolysis of Pittsburgh No. 8 coal over a temperature range 600-1200 K. In Figures 2 and 3 the effects of temperature on sulfur release and capture during coal devolatilization are examined. Figure 2 corresponds to untreated coal, whereas Figure 3 displays calculations made for the lime-added case. Under these (fuel-rich) conditions, H₂S is the dominant sulfur-containing vapor species, with the COS concentration being at least an order of magnitude smaller. Both figures show increasing sulfur capture with temperature. Calcium and iron originally in the coal can capture sulfur to a limited extent, forming CaS and FeS, respectively. Sulfur sorption by iron oxide is predicted to be possible at lower temperatures than sorption by CaO, due to the fact that the calcination temperature for CaCO₃ is relatively high at atmospheric pressure. Iron and calcium in the coal can recapture close to 30 percent of the released sulfur at temperatures in excess of 900 K. The effect of varying levels of added lime on H₂S mole fraction in the gas phase is shown in Figure 3 on a semi-logarithmic scale. Clearly, under devolatilization conditions, calcium oxide is potentially a very effective sorbent for H₂S; indeed, the present equilibrium approach can, at best, indicate the maximum sorption potential of any additive and enable the evaluation of different sorbents on that basis.

3.2 Gasification and Combustion Products Composition Calculations

Figures 4-6 represent equilibrium-thermodynamic calculations performed under gasification conditions. These results simulate the products obtained by reacting together varying amounts of coal and moist air at atmospheric pressure, over a temperature range 500-1500 K. The liquid and solid phase fractions in the reaction product mixture are plotted as a function of temperature and coal/air flow rate ratio in Figures 4 and 5, respectively. Sulfur elemental concentration in the product gases is plotted against these variables in Figure 6; no distinction has been made in this representation of gas-phase sulfur between various sulfur-bearing vapor species (such as H₂S, SO₂, SO₃, etc.). With increasing temperature the liquids and solids fractions show a non-monotonic behavior for all fuel/air ratios, while the trend for sulfur elemental concentration is very sensitive to the fuel/air parameter. The condensed phases comprise principally mineral phases at higher temperatures, and sulfates and sulfides at lower temperatures. The program cannot simulate the formation of (thermodynamically unstable) liquid hydrocarbons ("tars"). In the fuel-rich case, (S) in the gas decreases slightly with temperature, as in the case of devolatilization; in the fuel-lean case, CaSO₄(s) will form at temperatures below 700 K, providing a significant "sink" for gas-phase sulfur.

The ability of the PACKAGE program to compute chemical equilibrium compositions under coal combustion conditions has been demonstrated in previous work. In the analysis of ash deposition on coal-fired gas turbine blades, the prediction of condensed liquid ("glue") phase fraction and composition constitutes the first step (17,18). In Figures 7 and 8, respectively, PACKAGE-predicted effects of added calcium on gaseous SO₂ and SO₃ are presented. For temperatures greater than about 1300 K (depending on the calcium level), added calcium gets bound up in high molecular weight vapor and condensed species (e.g., CaAl₂Si₂O₈[s]), and is thus not free to react with all the sulfur present. Unbound calcium is still sufficient, however, to absorb nearly all of the SO₃.

In this section, it has been shown that the PACKAGE equilibrium-thermodynamic computer program can estimate the product stream composition in a variety of coal conversion applications. It remains to be seen whether any of these equilibrium predictions has a basis in reality or is strictly of academic value. This concern will be addressed in the remainder of this paper.

4. THE COMPLEX CHEMICAL EQUILIBRIUM APPROACH: VALIDITY

4.1 Coal Devolatilization Applications

In order to assess the applicability of an equilibrium-thermodynamic procedure to estimate the coal-devolatilization product gas composition, PACKAGE predictions have been compared against in-house SHRODR measurements. Computed and detected molar concentrations of the major vapor species released during atmospheric-pressure slow-heating pyrolysis of Pittsburgh No. 8 coal are presented in Tables 1 and 2. Predicted and observed effects of CaO addition on the composition of devolatilization products are shown in Table 1. Results demonstrate that the presence of CaO during coal devolatilization significantly reduces the yield of H₂S. For example, for this Pittsburgh seam high-volatile coal, the H₂S yield was observed to be reduced from 3.7 volume percent to 0.05 volume percent when 21 weight percent of CaO (Ca:S = 6:1) was added to the coal. The equilibrium code overestimates sulfur sorption in the no-lime added case, but otherwise predicts the extent of sulfur capture with reasonable accuracy, especially when smaller lime particles are added. This accuracy is, at first, surprising because the PACKAGE program does a relatively poor job of predicting the partial pressures of the major C-H-O species. The code underestimates gas-phase hydrocarbons (CH₄, C₂H₄, C₂H₆, etc.) by a factor of 2-5 and CO by a factor of 2-5 (at 500°C); it overestimates CO₂ by a factor of 1.5-5, H₂ by a factor of about 3, and H₂O by an order of magnitude. The code also, in general, underpredicts COS formation.

These gross errors in vapor-phase representation by the PACKAGE computer program would appear to be consequences of an inadequate thermodynamic data base, as well as an inherent failure of the approach itself to model essentially non-equilibrium processes, such as tar cracking. Cracking of tar liquids (phenolic compounds in particular) to lighter products is a primary cause of increased CH₄ and hydrocarbon gases (C₁-C₈) formation (1). The composition of low-temperature (< 700°C) coal tars is very complex and strongly dependent on the conditions at which pyrolysis occurs. Until a comprehensive library of the thermodynamic properties of complex tar liquid mixtures is developed, and utilized along with the equilibrium code, discrepancies between observed and predicted devolatilization product composition are bound to exist. However, the relatively error-free estimation of H₂S(v) concentration in the presence of added lime suggests that the equilibrium approach can serve as a tractable preliminary scheme for the analysis of sulfur chemistry even in the less reactive atmosphere of low-temperature devolatilization.

This tentative conclusion is strengthened by additional comparisons between predicted and observed effects of variations in coal and lime particle size, the devolatilization temperature, and the sulfur sorbent employed. Data obtained with smaller coal particles and smaller CaO particles (< 10 micrometers) reveal improved agreement between predicted and measured sulfur capture (Table 1). This suggests that a better mixture of coal and CaO components (and, hence, greater contact between CaO and devolatilized sulfur products) is possible when the smaller size fraction is utilized. This increased intimacy of contact also implies closer approach to equilibrium; indeed, near-equilibrium sulfur capture may be obtained when hydrated lime is introduced as a "mist" spray. To investigate the influence of pyrolysis temperature on product yield and composition, experiments and computations have been performed at 649°C with and without the presence of calcium compounds. The predicted and observed percentage of sulfur content (H₂S and COS) in the product gases is slightly reduced at 649°C compared to that at 500°C (Table 1). The increased levels of CO and H₂ and the reduction in CO at higher temperature are also simulated by the equilibrium code. At both temperatures the influence of CaO addition on sulfur products is seen to be qualitatively similar, as predicted.

The equilibrium model cannot simulate differences in the performance of the same sorbent (e.g., CaO) prepared from different sources (e.g., CaCO₃, Ca(OH)₂, dolomite,

calcined dolomite, hydrated calcined dolomite), since these differences are caused largely by the varying pore structures of the sorbent. Differentiation of additives generated from various parent compounds and at different treatment conditions necessarily involves kinetic modeling; however, the present equilibrium-rate chemistry model can still be used to compare the maximum reactivity of the CaO additive with that of other low-cost inorganics (e.g., CaCO_3 , Fe_2O_3 , MgO , SiO_2). These observed and predicted effects on the SHRODR products are listed in Table 2. Adding 35 weight percent CaCO_3 (Ca/S of about 6) to the Pittsburgh coal at 500°C is observed to reduce H_2S from 3.7 volume percent to only about 2.3 volume percent, whereas the PACKAGE code predicted a greater reduction. This is perhaps a consequence of previously reported (19) kinetic limitations to the calcination process below 600°C. A 21 weight percent Fe_2O_3 significantly reduces the yield of H_2S and COS; this reduction is accompanied by the formation of FeS (troilite, identified by X-ray diffraction). These observed effects of Fe_2O_3 addition are also predicted theoretically. SHRODR experiments and simulations were also performed with MgO and SiO_2 additives. However, the presence of these inorganics has very little influence on devolatilized product yield and composition, as predicted by the PACKAGE computer program.

4.2 Coal Gasification Applications

In view of the long residence times (2-3 hours) associated with fixed-bed gasifiers, the use of an equilibrium approach is well-suited to this environment. Comparisons between PACKAGE predictions and experimental gas-phase sulfur data obtained under gasification conditions in the presence of sorbents are presented in Table 3. The H_2S concentrations reported here were obtained by on-line laboratory analyses of gases generated during a series of METC fixed-bed gasifier runs. Since water was removed from all samples subjected to on-line analyses, results are reported on a dry gas basis; computer predictions are reproduced in Tables 3 and 4 on the same dry basis. The single-temperature, single gas/solid ratio analysis presented here is based upon the hypothesis that sulfur sorption in the gasifier column is controlled by fast chemical reactions that occur in a narrow section of the column, just above the combustion zone (see Figure 1). Further up in the column, calcination of the limestone additive is not thermodynamically feasible, implying severely reduced sulfur uptake by limestone; whereas, below this critical section, the lime is either saturated (due to absorption of recycle sulfur dioxide) or bound up in the form of silicates, aluminosilicates, etc., resulting from ash interactions under oxidizing conditions.

The calculations shown in Table 3 have been performed at a temperature of about 1000 K, and the gas/solids flow rate ratio (approximately 5) consistent with that temperature in the gasifier. The gas/solids ratio represents the distribution of the components of the reactive mixture in the two phases, and the temperature has been chosen on the basis of maximum availability of calcium to react; any temperature in the "temperature window" of 900-1100 K would have served equally well. These attempts to predict the observed sulfur capture by means of a simple equilibrium thermodynamic approach are no more than a prelude to the combined dynamic-thermodynamic-kinetic analysis planned for the future; yet even these preliminary equilibrium calculations show good agreement with experimental measurements for all gas species concentrations, including the hydrocarbons, CO_2 , CO , H_2 (Table 4), as well as H_2S (Table 3). In the case of the C-H-O species, the higher temperatures involved, the relative insignificance of tar-char chemistry, and the close approach to equilibrium of the water-gas shift reaction, apparently bring about a better match between theory and practice.

The PACKAGE code is equally effective in simulating the effect of changes in operating variables on sulfur uptake. At higher pressures (200 psig), calcination is delayed to higher temperatures, occurring further down in the gasifier column. In the absence of excess (recycled) sulfur, lime, once it forms, immediately reacts with the ash mineral constituents and is thus not available to react with the sulfur.

When sulfur is added in the form of a recycle SO_2 stream, equilibrium favors the formation of CaS and CaSO_4 over calcium silicates and aluminosilicates; this results in increased sulfur capture efficiency and increased sorbent utilization. Thus, in high-pressure runs with no SO_2 recycle, H_2S volume percent in the gas is high and insensitive to Ca/S ratio (calculated with respect to the coal), but low and very responsive to the same parameter when some sulfur is fed back in. These predicted trends are consistent with observed gasifier performance. Some observations, such as the difference in effectiveness of the Germany Valley and Lowellville limestones, are beyond the capability of this approach to rationalize, but the present methodology is still of value in evaluating the limits of performance of gasifiers and sorbents.

4.3 Coal Combustion Applications

The equilibrium-thermodynamic approach has also been used to analyze the effect on combustion gas-phase sulfur concentration of adding calcium to a coal-water fuel. Conditions used in the calculations simulated those occurring in a recent GE LM500 Turbine Simulator run which indicated high sulfur capture (at the cost of increased deposition). In this experimental study, calcium hydroxide was integrated into coal-water mixtures and injected in a combustion system which simulates the thermodynamic and aerodynamic environment of a gas turbine. Sulfur capture was determined by analysis of extracted gas and solid samples. The PACKAGE computer program predicts 80 percent sulfur capture for calcium-to-sulfur (Ca/S) atomic ratio of 1.5, fuel-to-air ratio of 0.07, 1100°C , and 10 atmospheres. This compares well with the reported GE data of 60-70 percent capture (20) for hydrated sorbents. It is intriguing that even short residence time conditions such as these do not necessarily invalidate equilibrium modeling. Even though sorbent utilization is certainly lime-dependent, the assumption of instantaneous reaction is probably not farfetched in the highly reactive, high-temperature combustion environment.

5. CONCLUSIONS AND RECOMMENDATIONS

An attempt has been made in this paper to illustrate and justify the use of an equilibrium-thermodynamic approach to modeling the distribution of sulfur species in the product streams of coal conversion processes. It has been demonstrated that equilibrium calculations simulate the qualitative effects of various sulfur sorbents and gas cleanup conditions (temperature, pressure, sorbent-to-sulfur ratio) with good accuracy, especially in reactor configurations that ensure close mixing of the components. The extent to which equilibrium estimates of sulfur capture and sorbent utilization are quantitatively realistic has been evaluated on the basis of comparisons with data obtained under coal devolatilization (in the METC SHRODR), gasification (in the METC fixed-bed gasifier), and combustion (in the GE turbine simulator) conditions. Preliminary indications are that equilibrium composition predictions are in surprisingly good quantitative agreement with measured data for all species included in the extensive thermodynamic data base employed. This tentative conclusion will be verified by repeated comparisons of model predictions with other sulfur-removal data as it becomes available. The unexpected success of the present preliminary computational model for sulfur sorption bodes well for the more comprehensive theoretical analyses planned for the future. The anticipated failure of this simple algorithm to simulate transport and kinetic limitations to the sulfur-lime reaction notwithstanding, the most attractive features of the equilibrium approach remain the elimination of the uncertainties surrounding more detailed gas/solid interfacial kinetic models, and the relative ease and convenience of its application.

6. REFERENCES

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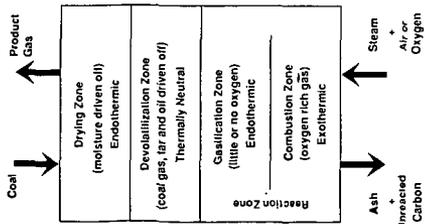


Figure 1. Schematic of Fixed-Bed Gasifier (3)

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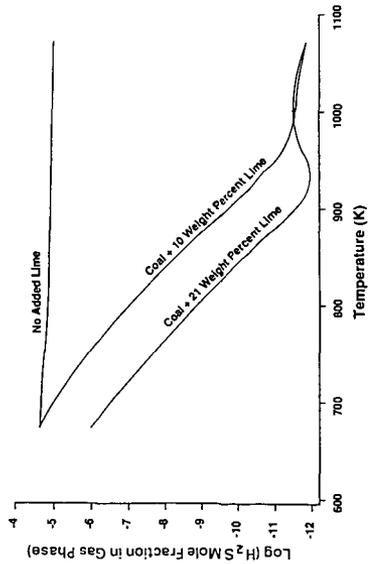


Figure 3. Effect of Added Lime on Gas-Phase Sulfur in Atmospheric-Pressure Devolatilization of Pittsburgh No. 8 Coal

BB-862-B BP4

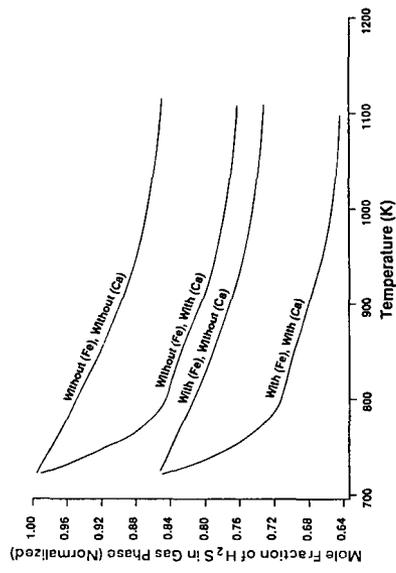


Figure 2. Effect of Iron and Calcium in Pittsburgh No. 8 Coal on Sulfur in the Atmospheric-Pressure Devolatilization Product Gases

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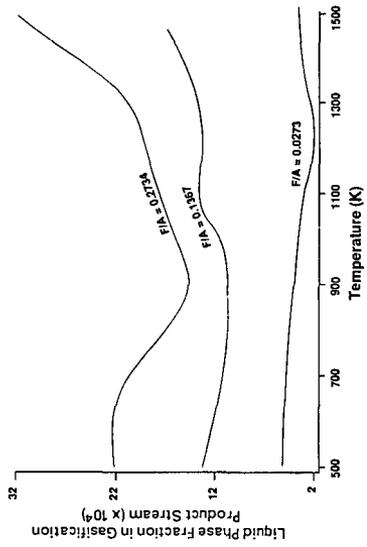


Figure 4. Temperature- and Fuel-to-Air Mass Flow Rate Ratio (F/A) Dependence of Liquids Fraction in the Product Mixture of Atmospheric-Pressure Gasification of Pittsburgh No. 8 Coal

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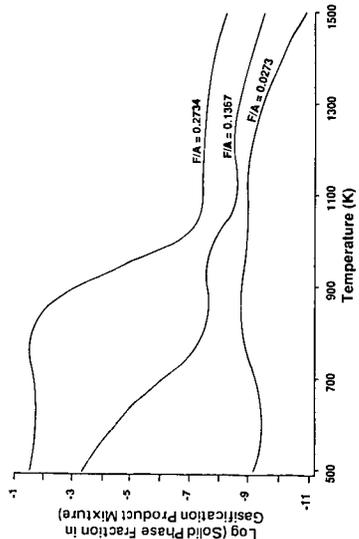


Figure 5. Temperature- and Fuel-to-Air Mass Flow Rate Ratio (F/A) Dependence of Solids Fraction in the Product Mixture of Atmospheric-Pressure Gasification of Pittsburgh No. 8 Coal

MS-555-C BP4

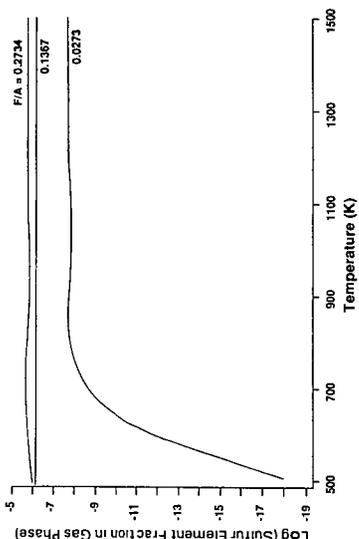


Figure 6. Temperature- and Fuel-to-Air Mass Flow Rate Ratio (F/A) Dependence of Total Sulfur Concentration in the Product Gases of Atmospheric-Pressure Gasification of Pittsburgh No. 8 Coal

MS-555-E BP4

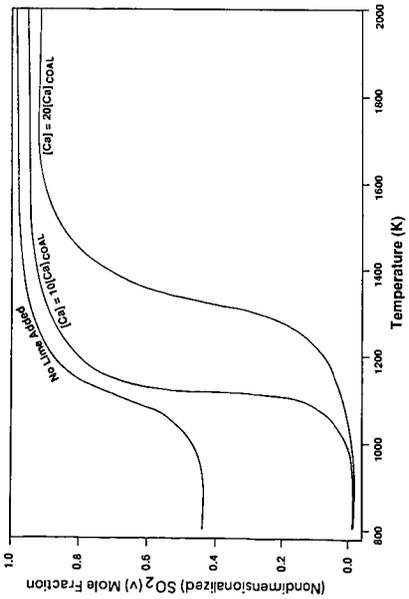


Figure 7. Effect of Temperature and Added Lime on Sulfur Dioxide Concentration in the Product Gases of Atmospheric-Pressure Combustion of Pittsburgh No. 8 Coal

MS-555-C BP3

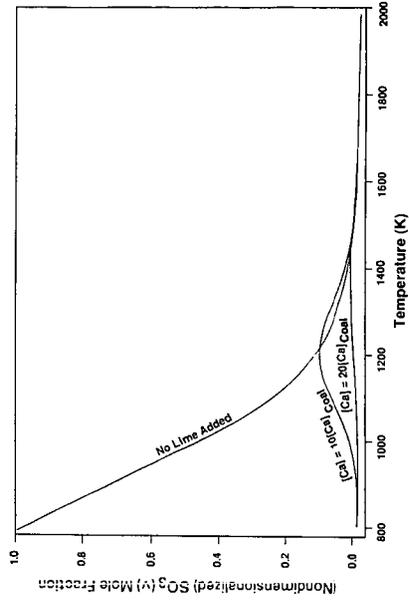


Figure 8. Effect of Temperature and Added Lime on Sulfur Trioxide Concentration in the Product Gases of Atmospheric-Pressure Combustion of Pittsburgh No. 8 Coal

MS-555-B BP3