

Carbon Disulfide Production via Hydrogen Sulfide Methane Reformation

H. Hosseini, M. Javadi, M. Moghiman, and M. H. Ghodsi Rad

Abstract—Carbon disulfide is widely used for the production of viscose rayon, rubber, and other organic materials and it is a feedstock for the synthesis of sulfuric acid. The objective of this paper is to analyze possibilities for efficient production of CS₂ from sour natural gas reformation (H₂SMR) (2H₂S+CH₄ =CS₂ +4H₂). Also, the effect of H₂S to CH₄ feed ratio and reaction temperature on carbon disulfide production is investigated numerically in a reforming reactor. The chemical reaction model is based on an assumed Probability Density Function (PDF) parameterized by the mean and variance of mixture fraction and β-PDF shape. The results show that the major factors influencing CS₂ production are reactor temperature. The yield of carbon disulfide increases with increasing H₂S to CH₄ feed gas ratio (H₂S/CH₄≤4). Also the yield of C(s) increases with increasing temperature until the temperature reaches to 1000°K, and then due to increase of CS₂ production and consumption of C(s), yield of C(s) drops with further increase in the temperature. The predicted CH₄ and H₂S conversion and yield of carbon disulfide are in good agreement with result of Huang and T-Raissi.

Keywords—Carbon disulfide, sour natural gas, H₂SMR, probability density function.

I. INTRODUCTION

CARBON disulfide is a volatile liquid with a pungent smell and is widely used for the production of viscose rayon, rubber, and other organic materials. It has been known for its toxicity to animals and aqueous organisms. It is one of the sulfur-containing compounds that is produced via hydrogen sulfide methane reformation. Carbon disulfide (CS₂), a valuable product that is more desirable than elemental sulfur as a feedstock for the production of sulfuric acid (H₂SO₄). Furthermore, CS₂ can be hydrogenated to produce gasoline-range hydrocarbon liquid fuels [1]. It also has been useful as substrate probes for enzyme activities [2] and can greatly reduce the lifetime of the ammonia synthesis catalyst [3]. Carbon disulfide is classified as a hazardous pollutant and is emitted by either natural or industrial sources. direct conversion of methane and hydrogen sulfide, which are the main components of sour gas that called sub-quality natural

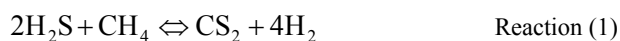
gas (SQNG), has widely been studied in order to obtain more valuable chemical products such as carbon disulfide [4]. At oil flow stations it is common practice to flare or vent sub quality natural gas, which is produced along with crude oil [5]. Gas flaring has also been blamed for environmental and human health problems such as acid rain, asthma, skin and breathing diseases [6]. The removal of H₂S from SQNG is expensive and not commercially viable for large-scale plants. In a reactor, hydrogen sulfide methane reformation produces carbon, sulfur and CS₂ [7]. The purpose of this paper is to assess production of carbon disulfide from sub-quality natural gas (SQNG) using a 3D numerical technique that employs the model of probability density function for modeling of turbulent-chemistry interaction leading to production of carbon disulfide.

II. REFORMING REACTOR GEOMETRY

The reactor used in this investigation is a small-scale axial flow reactor identical by Gruenberger [5]. The basic geometry of the reactor is shown in Fig. 1. In the inlet, the tangentially injected hot gases (without oxidant) enters to reactor through two tangential inlets. Then, the highly swirling hot gases mix with the sub-quality natural gas injected radially into the reactor in the proximity of the mixing zone. vigorous mixing of the SQNG fuel with the hot gases as a result of sudden increase in the tube diameter at the exit of the choke leading to thermal decomposition of CH₄+H₂S and carbon disulfide formation [8].

III. CHEMICAL REACTION MODELING

H₂S can react with methane, according to Reaction (1), producing not only 4 mol of hydrogen, but also 1 mol of carbon disulfide (CS₂) [9].



H₂SMR (Reaction (1)) proceeds via H₂S and methane pyrolysis according to following reactions (2, 3):



Since reaction 2 is highly endothermic, temperatures in excess of 1500°K is required for achieving reasonable rates [7], and, as reaction 3 is mildly endothermic, it requires

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temperatures higher than 850°K to proceed at reasonable rates [10].

IV. TURBULENCE CHEMISTRY INTERACTION

The mixture fraction / PDF method is used to model the turbulent chemical reactions occurring in the diffusion, combustion and thermal decomposition of natural gas in the carbon black furnace. This method, which assumes the chemistry is fast enough for a chemical equilibrium to always exist at molecular level, enables handling of large numbers of reacting species, including intermediate species. Transport equations are solved for the mean mixture fraction \bar{f} , its variance $\overline{f'^2}$ and for enthalpy \bar{h} . Calculations and PDF integrations are performed using a preprocessing code, assuming chemical equilibrium between 30 different species. The results of the chemical equilibrium calculations are stored in look-up tables which relate the mean thermochemical variables (species mass fractions, temperature and density) to the values of \bar{f} , $\overline{f'^2}$ and \bar{h} [11].

V. NUMERICAL SOLUTION PROCEDURE

Fluent CFD software has been used to model the furnace employing solution-adaptive grid refinement technique to solve the 3D problem. The 3D volume grid is represented in Fig. 2. A grid dependence study was conducted to arrive at the appropriate size of the grid for optimal accuracy and efficiency. In the optimal grid, the domain is discretized into a grid of 20493 nodes and 82745 tetrahedral cells. The conservation equations for mass, momentum, energy, Reynold's stresses, dissipation rate, mixture fraction and its variance are solved by finite-volume analysis, using a second-order upwind scheme for discretisation of the convective terms in the transport equations.

The RNG $k - \varepsilon$ model is used for modeling of dissipation rate and turbulence kinetic energy. The conventional wall-function approach is used in the near-wall region. At the inlet boundary, conditions are specified once and did not need updating during the course of the solution procedure. At the outlet boundary, zero gradient conditions are applied. We assumed an adiabatic boundary condition at the wall of the furnace.

VI. RESULT

Numerical calculations were performed on the axial flow gas furnace described by Gruenberger [5] as shown in Fig. 1. The inlet gas flow rate is 0.019 m³/s. Figs. 3 and 4 show the effect of H₂S to CH₄ ratio and temperature on CH₄ and H₂S conversions given by [9]:

$$CH_4 \text{ conversion} = \frac{[CH_4]_0 - [CH_4]}{[CH_4]_0} \times 100,$$

$$H_2S \text{ conversion} = \frac{[H_2S]_0 - [H_2S]}{[H_2S]_0} \times 100$$

where $[CH_4]_0$ and $[H_2S]_0$ denote the initial (input) concentration of CH₄ and H₂S in feed gas, respectively. $[CH_4]$, $[H_2S]$, are equilibrium concentration of CH₄ and H₂S at reactor outlet, respectively. H₂S decomposition is the limiting step in the H₂SMR process as it proceeds by the sequential reaction involving H₂S pyrolysis to form sulfur diatomic gas (S₂) (Reaction (2)), followed by S₂ reaction with CH₄ to produce carbon disulfide (CS₂) and H₂. Figs. 3 and 4 depict that the CH₄ and H₂S conversions drop with decreased H₂S/CH₄ ratio in feed gas; this can be attributed to the endothermic nature of H₂S and CH₄ decomposition reactions. For higher values of temperature CH₄ conversion ($\geq 800^\circ K$) and H₂S conversion ($\geq 1200^\circ K$) sharply increases with increased temperature due to the endothermicity of CH₄ and H₂S thermolysis. Fig. 3 shows that CH₄ conversion reaches 100% at temperatures above 1100° K. This is in accord with the results of Huang and T-Raissi [9].

Figs. 5, 6 depict the yields of sulfur and carbon as a function of H₂S to CH₄ feed ratio and reactor temperature at the outlet of the reactor, that S₂ and C(s) yield is defined as:

$$S_2(\%) = \frac{2[S_2]}{[H_2S]_0} * 100, \quad C(s)(\%) = \frac{[C(s)]}{[CH_4]_0} * 100$$

Where $[X]$ denote the equilibrium molar concentrations of species X [9].

The figure reveals that for high values of H₂S to CH₄ ratio and reactor temperatures, CH₄ and H₂S convert mostly to S₂ and C(s). It can be seen that for higher values of temperature (and high H₂S/CH₄), yield of S₂ and C(s) are quite high. This is due to increased of CH₄ and H₂S conversion. Fig. 5 shows that carbon yield increases with increasing temperature until the yield reaches a maximum value (at 1000°K), and then drops with further increase in the temperature for H₂S to CH₄ ratio ranging from 0.1 to up. In lower temperature than 1000°K, hydrogen and carbon is produced by CH₄ decomposition. As shown in Fig. 7, CS₂ yields depend not only on the temperature, but also on the H₂S/CH₄ feed ratio. In lower temperature than 1000°K, the yield of carbon disulfide (CS₂) approaches zero (Fig. 7). This is in accord with results of Huang and T-Raissi [9].

$$CS_2(\%) = \frac{[CS_2]}{[CH_4]_0} \times 100$$

Where $[CS_2]$ denote the equilibrium molar concentrations of Carbon disulfide.

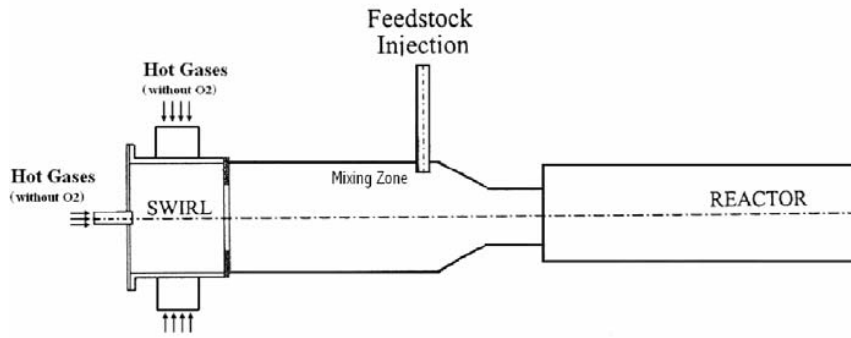


Fig. 1 Reforming reactor

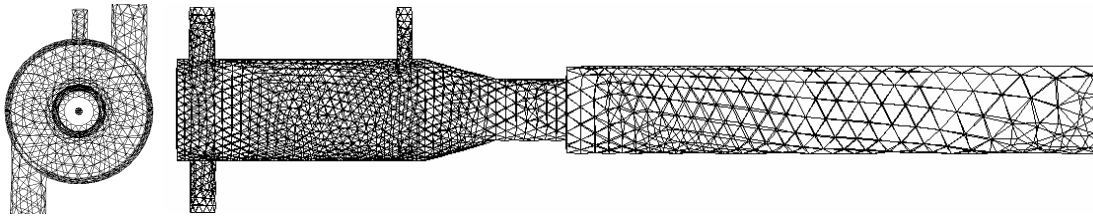


Fig. 2 Three-dimensional tetrahedral grid

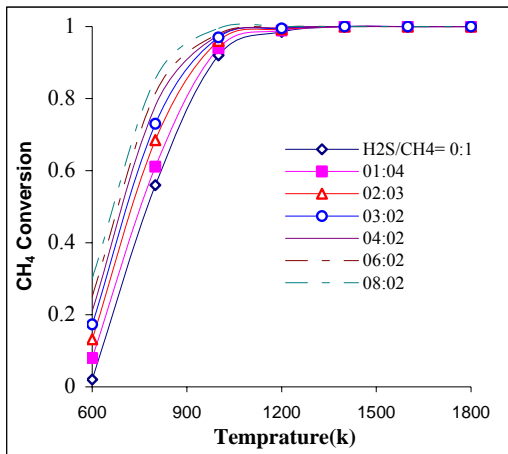


Fig. 3 The effect of temperature and H₂S/CH₄ ratio on CH₄ conversion

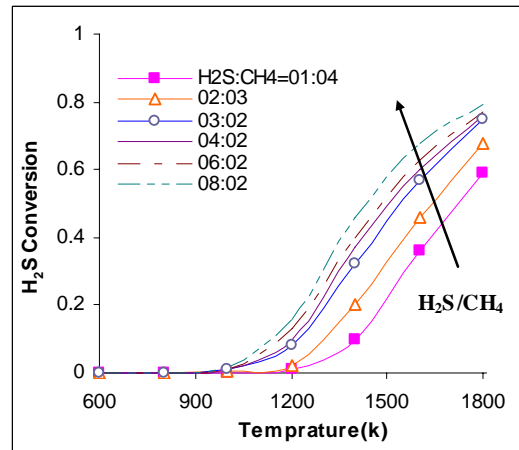


Fig. 4 The effect of temperature and H₂S/CH₄ ratio on H₂S conversion

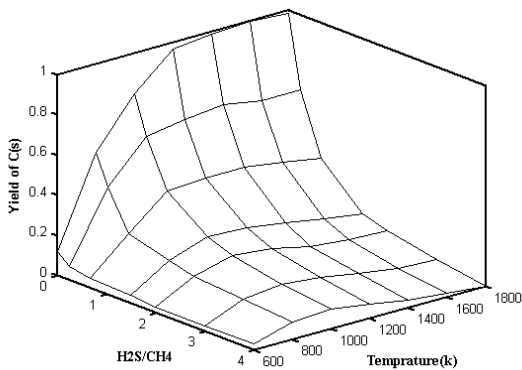


Fig. 5 Yield of C(s) as a function of temperature and H₂S/CH₄ ratio

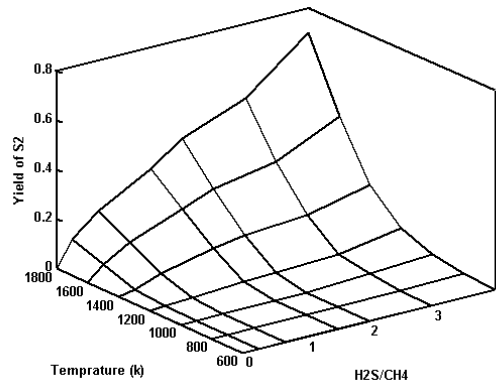


Fig. 6 Yield of S₂ as a function of temperature and H₂S/CH₄ ratio

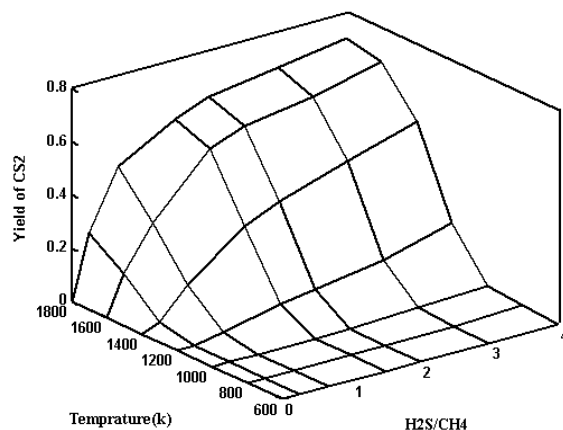


Fig. 7 Yield of CS₂ as a function of temperature and H₂S/CH₄ ratio

VII. CONCLUSION

The production of carbon disulfide from sour natural gas containing methane (CH₄) and hydrogen sulfide (H₂S) has been analyzed. Based on the presented results, the following conclusions may be drawn:

- CS₂ yields depend not only on the temperature, but also on the H₂S/CH₄ feed ratio.
- The carbon disulfide yield increases with increasing H₂S to CH₄ feed gas ratio.
- In lower temperature than 1000°K, the yield of carbon disulfide (CS₂) approaches zero.
- The maximum yield of C(s) is in 1000 °K, then reduces sharply due to increasing of CS₂ production.
- Results show that the yield of S₂ reaches to 0.8 above 1800°K and it has not completed yet.

REFERENCES

- [1] Ereksion, E. J., "Gasoline from natural gas by sulfur processing", Final Technical Report, Institute of Gas Technology, DOE/PC/92114-T12 (1999).
- [2] S-Haritos, V., Dojchinov G., "Carbonic anhydrase metabolism is a key factor in the toxicity of CO₂ and COS but CS₂ toward the flour beetle *Tribolium castaneum*", *J. of Catalysis Today*, 98 (2004) 633–638.
- [3] Yang, J., Juan, P., Shen, Z., Guo, R., Jia, J., Fang, H., Wang Y., "Removal of carbon disulfide (CS₂) from water via adsorption on active carbon fiber (ACF)", *J. of Carbon* 44 (2006) 1367–1375.
- [4] Huang, C., T-Raissi A., "Analyses of one-step liquid hydrogen production from methane and landfill gas", *J. of Power Sources*, 163 (2007) 645–652.
- [5] Gruenberger, T. M., Moghiman, M., Bowen, P. J., Syred, N., "Dynamic of soot formation by turbulent combustion and thermal decomposition of natural gas", *J. Combust. Sci. and Tech.*, 174 (2002) 67-86.
- [6] Lambert, W., Goodwin, M., Stefani, D., Strosher, L., "Hydrogen sulfide (H₂S) and sour gas effects on the eye: A historical perspective", *Int. J. Science of the Total Environment*, 367 (2006) 1–22.
- [7] Huang, C., T-Raissi, A., "Thermodynamic analyses of hydrogen production from sub-quality natural gas", Part II: Steam reforming and autothermal steam reforming, *J. of Power Sources*, 163 (2007) 637–644.
- [8] Lockwood, F. C., Niekerk, J. E., Van, J. E., "Parametric study of a carbon black oil furnace", *J. of Combustion and Flame*, 103 (1995) 76-90.
- [9] Huang, C., T-Raissi, A., "Liquid hydrogen production via hydrogen sulfide methane reformation", *J. of Power Sources*, 175 (2008) 464–472.
- [10] Sakanishi, K., Wu, Z., Matsumura, A., Saito, I. J., "Simultaneous removal of H₂S and COS using activated carbons and their supported catalysts", *Catalysis Today*, 104 (2005) 94–100.
- [11] Saario, A., Rebola, A., "Heavy fuel oil combustion in a cylindrical laboratory furnace: measurements and modeling", *J. Fuel*, 84 (2005) 359–369.