

pubs.acs.org/IECR

# Revealing the Structure–Interaction–Dissolubility Relationships through Computational Investigation Coupled with Solubility Measurement: Toward Solvent Design for Organosulfide Capture

Chuanlei Liu, Yuxiang Chen, Hao Jiang, Kongguo Wu, Qilong Peng, Yu Chen, Diyi Fang, Benxian Shen, Di Wu, and Hui Sun\*



structures, weak solute—solvent interactions, and dissolving affinity is fundamentally important to successfully identify potential solvents from a large chemical space for diverse absorption capture and separation. In this study, a series of compounds including alkanolamines, amines with cyclic substituents, etheramines, polyamines, sulfonamides, and several commercial physical absorption solvents were selected and methyl mercaptan (MeSH) was used as a model organosulfide for both the quantum chemistry calculation and solubility measurement. The weak intermolecular interactions within different solvent—solute systems were examined by using reduced density gradient and quantum theory of atoms in molecules analyses. The relationship between the structural characteristics of the solvents and their interactions with MeSH was revealed, and the intermolecular interaction is correlated to the dissolubility of MeSH-in-



solvent. Rules for designing molecules were proposed and used to guide the generation of a potential solvent with enhanced dissolving affinity to MeSH, 1-(2-(diethylamino)ethoxy)butan-2-amine. It is indicated that the designed compound has stronger intermolecular interaction with MeSH as compared to the screened solvent candidate. The present study enables efficient molecular exploration and design of solvent candidates for absorption capture of diverse environmental unfriendly compounds as well as wide separation applications based on selective dissolving.

### 1. INTRODUCTION

Fuel gases such as natural gas, petroleum gases, and oil field gases having high calorific value and low carbon emissions play increasingly important roles in the global fossil energy supply.<sup>1</sup> A variety of sulfides (H<sub>2</sub>S, COS, mercaptans, etc.) contained in fuel gases are toxic and corrosive and cause serious environmental problems.<sup>2</sup> Generally, they can be removed by several industrial processes such as absorption involving solvents,<sup>3</sup> selective adsorption using solid materials,<sup>4</sup> membrane separation,<sup>5</sup> and biological treatment.<sup>6</sup> Physico-chemical dissolution-driven absorption is the most widely applied method for the purification of a wide range of fuel gases in a mature and cost-effective manner.<sup>7</sup>

Chemical absorption commonly employs alkaline organic amine solutions (alkyl amines, alkanolamines, etc.) and alkaline brine solutions (hydroxide bases, ammonia, etc.).<sup>8</sup> Commonly, an alkanolamine-involved absorption process can remove  $H_2S$ to desired levels. However, this process provides limited removal efficiency for organosulfide compounds due to their low reactivity with alkanolamines.<sup>9</sup> As a result, various purified gases still require enhanced removal efficiency to reduce the residual of organosulfides. An example is methyl mercaptan (denoted as MeSH), which can be removed at a restricted efficiency.<sup>10</sup> A number of research studies have been carried out in order to explore physical absorption solvents (including methanol, sulfolane (SUL), *N*-methylpyrrolidone (NMP), propylene carbonate (PC), polyethylene glycol dimethyl ether (PGDE), etc.) as well as formulated solvents by coupling the reactivity of chemical absorption solvents (i.e., primary and secondary alkanolamines) and dissolubility of physical absorption solvents (i.e., sulfolane, methanol, etc.) for achieving promising capture of MeSH.<sup>11</sup> Bedell and Miller<sup>12</sup> reported the solubility of MeSH in several aqueous solutions of alkanolamines including monoethanolamine (MEA), diethanolamine (DEA), and *N*-methyldiethanolamine (MDEA) and discussed the contributions of chemical and physical

Received:January 25, 2022Revised:March 16, 2022Accepted:March 24, 2022Published:April 3, 2022



Article



dissolubility. It was indicated that the solubility of MeSH in alkanolamine-based solvents can be largely determined by the load of sour gases (typically  $H_2S$  and  $CO_2$ ). Chemical absorption plays a dominant role at a low load of sour gases, while physical absorption dominates the removal efficiency of MeSH at medium to high load of sour species. Charry Prada et al.<sup>13</sup> studied the absorption of MeSH into DEA-methanol aqueous solution under different conditions. The exploration of potential physical solvents with excellent solubility of organosulfide compounds is, therefore, considered to be one of the most promising strategies for deep desulfurization of fuel gases. However, most of the solvents were screened through tremendous absorption experiments as well as performance assessments, which are time-consuming and costly. Computerassisted molecule design based on solubility prediction can largely accelerate solvent identification and, therefore, attract wide research interest from the academic and industrial fields.<sup>14</sup> Consequently, accurate solubility prediction is crucial for the productive finding of solvent candidates. Successful correlation between the molecular structures of solvent compounds and their dissolving affinity to organosulfide species can be expected to guide the screening of promising solvents but is still challenging.

The present investigation is focused on the molecular design of potential solvents for organosulfide removal via unlocking the relationships among molecular structures, weak solutesolvent interactions, and dissolubility.<sup>15</sup> Herein, a series of compounds having distinct molecular structures with different basic functional groups were selected as representatives from the overall chemical space. These compounds were collected considering two aspects. First, a number of solvents with typical structures were identified by referring to a variety of commercial desulfurization solvents, including alkanolamines, sulfones, amides, and esters. Second, amines with cyclic substituents, etheramines, polyamines, and sulfonamides were selected using a custom-developed solvent screening model<sup>16</sup> based on COSMO-RS theory for removing methyl mercaptan. These molecules possessing simple structures and distinct organic functional groups represent a considerable chemical space. In addition, MeSH was used as a model molecule of organosulfide for both the computational and experimental investigations. Using reduced density gradient (RDG)<sup>17</sup> and quantum theory of atoms in molecules (OTAIM) analyses,<sup>18</sup> we examined the weak intermolecular interactions within different solvent-solute systems and discussed the influences of the molecular structure (type and distribution of functional group) of solvent on intermolecular interaction as well as dissolving affinity. Henry constants for MeSH absorption into different solvents were measured to indicate the solubility. A promising compound with enhanced potential for MeSH capture, 1-(2-(diethylamino)ethoxy)butan-2-amine (DEAE-BA), was designed according to the realized relationships. This study enables efficient observation of solvent candidates for capturing environment-unfriendly compounds, including organosulfides, organoiodides, and small molecules such as  $CO_{2}$ ,  $SO_{x}$ , and  $NO_{x}$ , and separation applications based on selective dissolving.

#### 2. METHODS

**2.1. Reagents and Chemicals.** Information for all chemicals used in this study is listed in Table S1. Various properties including melting point, boiling point, toxicity, and price are considered for solvent assessment.

2.2. Static Absorption Equilibrium Measurements. An experimental setup is shown in Figure S1. Considering a suitable gas to liquid volume ratio ranging from 3 to 5, 40 mL of solvent was added to a stainless steel absorption batch.<sup>19</sup> The liquid was heated to 30  $^\circ C$  (having an accuracy of  $\pm 0.1$ °C) under magnetic stirring with valves A, B, C, and D closed. Prior to each measurement, the system was degassed for 0.5 h using an Edwards RV-12 three-phase vacuum pump. Hereafter, a mixed gas of nitrogen with MeSH concentration of around 2700 mg/m<sup>3</sup> (Shanghai Weichuang Standard Gas Analytical Technology Co. Ltd., Shanghai, China) was introduced into the batch and the initial pressure  $P_1$  was recorded. Once the adsorption reached an equilibrium (no pressure change can be detected), the final pressure  $P_2$  was recorded. The equilibrated gas mixture was collected and analyzed using a GC-920 gas chromatograph equipped with a capillary column (ON-PLOT U, 30 m  $\times$  0.53 mm  $\times$  20  $\mu$ m) and a flame photometric detector (FPD). MeSH concentration was determined using an external reference method. Each equilibriated gas mixture was analyzed three times to obtain the average value. The solubility curves can be plotted via changing initial pressure  $P_1$ and repeating the test procedure.

**2.3. MeSH Solubility Calculation.** The calibrated volume of the batch is  $V_{\rm m}$ . The volume of solvent introduced into the batch,  $V_0$ , is fixed at 40 mL. In view of the negligible effect of nitrogen absorption into solution at low pressure, the nitrogen partial pressure  $P_{\rm N2}$  is considered to be constant during the measurement process. Using the solvent vapor pressure  $P_{\rm S}$ , the initial pressure  $P_1'$  is corrected using eq 1.

$$P_1' = (P_2 - P_S - P_2 \cdot Y_2) / (1 - Y_1)$$
<sup>(1)</sup>

where  $P_1'$  is the calibrated initial pressure, Pa;  $Y_1$  and  $Y_2$  are the initial and equilibrated concentrations of MeSH, mol/mol.

Solubility of MeSH,  $Q_{MeSH}$  in mg-MeSH/g-solvent, can be calculated using eq 2.

$$Q_{\text{MeSH}} = 48.11 \cdot (P_1' \cdot Y_1 - P_2 \cdot Y_2) \cdot V_q / mZRT$$
<sup>(2)</sup>

where  $V_q$  is the volume of the mixed gas,  $m^3$ ; T is the temperature, K; m is the mass of solvent, g; and R is the molar gas constant, 8.3145 J/(mol·K). Z is the gas compression factor, and it can be easily obtained from the universal compression factor graph.<sup>20</sup>

**2.4. Reduced Density Gradient (RDG) and Quantum Theory of Atoms in Molecules (QTAIM) Analyses.** Intermolecular interactions were evaluated by using a visualized reduced density gradient (RDG) theory proposed by Johnson et al.,<sup>21</sup> which can be expressed as eq 3.

$$s = \frac{1}{2\sqrt[3]{3\pi^2}} \cdot \frac{|\nabla \rho(r)|}{\sqrt[3]{\rho(r)^4}}$$
(3)

where s is the reduced density gradient,  $\rho(r)$  is the electron density distribution in a.u., and  $\nabla^2 \rho$  is the Laplacian value of the electron density value.

Applying the RDG theory, the molecular system is divided into nuclear, chemical bond regions, the weak interaction region, and the molecular edge region. The weak interactions can be judged by using the relative magnitude of the charge density, charge density gradient, and density gradient function in each region. The weak interaction criteria in each region are summarized in Table 1. The RDG method was added to the wave function analysis program Multiwfn developed by Lu and Chen.<sup>22</sup> In combination with Gaussian wave function

Table 1. Parameter Value for Each Region

	near the nucleus	near chemical bond	weak interaction region	molecular edge
$\mid \nabla \rho(\mathbf{r}) \mid$	large	0-less	0-less	wee-little
$\sqrt[3]{ ho(r)^4}$	large	middle	little	0–little
RDG	middle	0-less	0-middle	middle– extreme

calculations, the analyses of weak interactions in molecular systems can be easily implemented. QTAIM quantifies the properties of chemical bonds, molecular structures, and interactions through a topological analysis of an electron density distribution function,  $\rho(r)$ .<sup>23,24</sup> Analysis based on QTAIM provides insight into the location and mechanism of intermolecular interaction. Herein, we focus on critical points (CPs), density functions of CPs ( $\rho(r)$ ), the Laplacian values of electron density  $(\nabla^2 \rho)$ , and energy density (E(r)) to understand the underlying weak interactions determining the MeSH solubility in different solvent compounds. In addition, the electrostatic potential (ESP)<sup>25</sup> for typical solvents was analyzed to explain the solute-solvent interactions in terms of interaction location. Solute-solvent pair models for the 20 selected compounds interacting with MeSH were built using GaussView 5.0 and simulated using a Gaussian 09 package at the m062x/6-311+g(d) theory level. The dispersion correction command em = gd3 was also introduced to calculate the weak intermolecular interactions. The stable configuration for every MeSH-solvent system was confirmed through comparing the energy magnitude of the MeSH-solvent system with different spatial configurations and then used for RDG, QTAIM, and ESP analyses. Additionally, we used the optimized structures to calculate the interaction energy of each solute-solvent system,  $E_{(solu + solv)}$ . The structural optimization and vibration analysis for each solvent were carried out, and the steady-state energies of MeSH and solvent were recorded as  $E_{solu}$  and  $E_{solv}$ , respectively. After considering the effect of the basis set superposition error (BSSE),<sup>26</sup> the energy released from the interaction between the solvent and MeSH can be calculated using eq 4. We verified the accuracy of all theoretical calculations via correlating the calculation results with previously reported experimental findings.

$$E_{\rm int} = E_{\rm (solu+solv)} - (E_{\rm solu} + E_{\rm solv}) + E_{\rm BSSE}$$
(4)

Furthermore, we performed Pearson correlation analyses on the molecular structure information matrix by using an SPSS Statistics package to figure out the relationship between Henry constant and molecular information. The Pearson correlation coefficient, r, can be calculated using eq 5.

$$= \frac{N\sum x_{i}y_{i} - \sum x_{i}y_{i}}{\sqrt{N\sum x_{i}^{2} - (\sum^{2} x_{i})} \cdot \sqrt{N\sum y_{i}^{2} - (\sum^{2} y_{i})} }$$
(5)

#### 3. RESULTS AND DISCUSSION

**3.1. Intermolecular Interaction Analyses.** The RDG- $\rho$ -(r) diagram is used to examine the weak interaction for each MeSH-solvent system. The RDG- $\rho(r)$  scatter plot for all 20 systems is shown in Figure S2. The position and intensity of the weak interaction are related to the electron density, and the type of interaction can be judged according to the position of the spikes in the RDG- $\rho(r)$  diagram. Specifically, the spikes located at  $\rho(r) < 0.05$  accompanied by the RDG value close to 0 indicate the weak interaction of the non-covalent bond. When the spikes appear at  $\rho(r) > 0.05$ , the covalent bond can be confirmed. To discuss the weak interaction involved in solute-solvent pairs, we mainly focus on the region of  $\rho(r) < 0.05$ . The spike position appearing in the RDG- $\rho(r)$  scatter diagram for all MeSH-solvent systems is shown in Figure 1.

All intermolecular interactions have spikes at  $\rho(r) \approx 0$ , indicating that these bimolecule systems involve non-covalent interactions. In cases of BZA, 4MBA, PPOH, NBEA, DEAPA, and MP, the spikes located at  $\rho(r) = 0.025$  suggest the complex weak interactions within their bimolecule systems. Especially, NMP-, PC-, and SUL-involved systems show the spikes in the region of  $\rho(r)$  ranging from 0.03 to 0.05, indicating that intermolecular interactions have medium strength between the covalent bond and non-covalent bond.

In order to determine the specific type and strength of intermolecular interaction, colorful RDG-sign $(\lambda_2)\rho$  scatter diagrams for all 20 solute-solvent pairs are demonstrated in Figure S3. A color card is also provided to check the type and strength of weak interaction visually. The blue spikes mean strong attraction, which commonly exists along with the hydrogen bond or halogen bond. The red ones indicate a strong repulsion in the system, typically resulting from a steric or cage effect. When the spikes show green, the intermolecular



**Figure 1.** Spike position of the RDG- $\rho(r)$  scatter diagram. The left region presents the RDG- $\rho(r)$  details for an example of compound A from the 20 compounds in the right region.



**Figure 2.** Spike position schematic of the RDG-sign( $\lambda_2$ ) $\rho$  scatter diagram. The left region presents the RDG-sign( $\lambda_2$ ) $\rho$  details for an example of compound A from the 20 compounds in the right region.



Figure 3. RDG equipotential surface diagram of solvent-MeSH systems.



Figure 4. Electron density values at each bond critical point.

interaction is dominated by a van der Waals force. The schematic spike position extracted from the RDG-sign $(\lambda_2)\rho$  scatter diagram of each MeSH-solvent system is plotted as Figure 2. The larger absolute values of the spikes indicate stronger intermolecular interaction.

For the region of sign( $\lambda_2$ ) $\rho$  ranging from -0.01 to 0.01, only the van der Waals force should be considered. Specifically, the spikes in the region of sign $(\lambda_2)\rho < 0$  indicate the attractive interaction between solvent and MeSH. MDEA, BZA, 4MBA, DEAPA, and NovM all have dense spikes in this region, illustrating the complex van der Waals force resulting from the branched structures (MDEA, DEAPA, and NovM) or the benzene rings (BZA and 4MBA). In the region of sign $(\lambda_2)\rho$ ranging from -0.01 to -0.02, a system tends to form a weak hydrogen bond, which is of stronger attraction as compared to the aforementioned van der Waals force. All 20 solute-solvent systems except MeSH-PC find their spikes in this region. In particular, the systems concerning IPOPA, NovM, NMP, and DLM have more dense points than others, suggesting that these four molecules have more hydrogen bond acceptors to interact with MeSH via a hydrogen bond. As for the region of  $sign(\lambda_2)\rho < -0.02$ , these systems concerning PPOH, NBEA, DEAPA, and MP have spikes, indicating the strong attractive interactions, probably resulting from strong hydrogen bonds. Several solute-solvent systems with regard to BZA, 4MBA, PPOH, NBEA, NovM, NMP, and DLM exhibit extensive spikes in this region of sign $(\lambda_2)\rho$  ranging from 0.01 to 0.02, representing that not only remarkably repulsive intermolecular interactions but also the intramolecular repulsions are involved in these MeSH-solvent systems. These solvent molecules containing larger cyclic substituents or more alkyl substituents exhibit complex repulsion toward MeSH. Moreover, BZA, 4MBA, PPOH, NBEA, NMP, and SUL show spikes in the region of sign $(\lambda_2)\rho > 0.02$ , suggesting stronger intramolecular repulsion at the center of the ring structure of the molecule. However, this kind of intramolecular repulsion exerts a negligible effect on MeSH-solvent interactions.

Additionally, we present an RDG equipotential surface diagram to visually locate diverse weak interactions within solute-solvent systems (Figure 3). The arrows showing different colors in the RDG equipotential surface diagram indicate the location details of intermolecular interactions. The RDG diagrams illustrate that the weak interactions between solvent and MeSH molecules are dominated by the van der Waals force represented by a large surface area in green and orange colors. The red spindle-shaped equipotential surface in the center of the ring structure suggests a strong intramolecular steric hindrance. The green-to-blue pie-shaped equipotential

surface clearly indicates the location of the hydrogen bond interactions. Alkanolamine compounds interact with MeSH mainly through the intermolecular attraction resulting from hydroxyl or amino groups. The situation for amine with a cyclic substituent is more complex. BZA attracts MeSH through the amino group, while 4MBA exerts attraction interaction through the benzene ring. Both PPOH and NBEA with a secondary or tertiary amino group exhibit strong affinity to MeSH. Moreover, etheramines contribute attractive interaction with MeSH through oxygen atoms of alkoxyl groups. In addition, polyamine compounds can interact with MeSH through a variety of amino groups. In comparison, the tertiary amino in DEAPA has stronger affinity to MeSH due to its shorter substituents and lower steric hindrance. Moreover, polar solvents including sulfone or ester compounds typically demonstrate attractive interactions with the solute of MeSH through an oxygen or sulfur atom. In summary, molecules having cyclic groups (i.e., BZA and PPOH) and molecules with more branched chains (i.e., DEAPA and NovM) are more prone to form large van der Waals areas with MeSH. MeSHsolvent interactions generally occur in the vicinity of polar groups, with secondary and tertiary amines having a stronger attraction to MeSH.

3.2. QTAIM Analyses. Furthermore, OTAIM analyses were performed to quantitatively describe the strength of these interactions within different MeSH-solvent systems. These analyses were focused on the electron state parameters including  $\rho(r)$ ,  $\nabla^2 \rho$ , and E(r) of the critical point (CP). All CPs are classified into four categories: the (3, -3) CPs are nuclear critical points, the (3, -1) CPs are chemical bond critical points, the (3, +1) CPs are ring critical points, and the (3, +3) CPs denote cage critical points. Here, the weak intermolecular interaction analyses are, therefore, focused on (3, -1) CPs. The visualized QTAIM results were obtained through finding CPs as well as topological paths (Figure S4). The orange ball and line illustrate the (3, -1) CPs and topological paths, which connect the atoms having weak interaction. In addition, the serial numbers of bond critical points indicating the weak interaction are also represented in the figure. First, we focus on hydrogen bonds within different binary molecule systems. Therefore, the bond critical points and topological paths relating to dispersion forces or resistance effects (like  $S-C--O-C_2$  and  $C-S--N-C_3$ ) are excluded from the illustration in Figure S4. The bond critical point and topological path information with regard to hydrogen bonds are summarized in Table S2. According to the method proposed by Overgaard and Iversen<sup>27</sup> and Rozas et al.<sup>28</sup> for determining hydrogen bonds using QTAIM analysis,







Figure 6. Scanning diagram of the surface electrostatic potential of the C-S structure.





these atoms connecting to hydrogen atoms through topological paths can be considered as hydrogen bond receptors. It can be supported by the found topological path details (Table S2) except for a few special ones with typical hydrogen bond receptors including H———H and H———C. Applying the judgment standards of the hydrogen bond, the  $\rho(r)$  of (3, -1) CPs has at least a one order of magnitude lower CP value (typically in the range of 0.002 to 0.035 a.u.) than that of the covalent bond CP. The  $\rho(r)$  at each bond critical point is

shown in Figure 4. According to the calculation results based on QTAIM analysis, the  $\rho(r)$  of the C–H covalent bond is 0.273 a.u. It can be seen that the  $\rho(r)$  of the CPs coincides the range of the hydrogen bond and is one order of magnitude less than that of the C–H covalent bond.

According to the criterion proposed by Babapulle et al.,<sup>29</sup> the hydrogen bond can be identified if  $\nabla^2 \rho$  at the bond critical point is in the range from 0.024 to 0.139. The  $\nabla^2 \rho$  at all bond critical points are demonstrated in Figure 5. The bond critical

pubs.acs.org/IECR



Figure 8. Hydrogen bond energy at each bond critical point.

points with  $\nabla^2 \rho < 0.024$  are related to two kinds of topological connecting paths, C(S)-H---H-C(S) and C(S)-H----C-S(N), where H----H is the dihydrogen bond topological path. As for C(S)-H---C-S(N), in order to confirm the role of the C atom playing as a hydrogen bond receptor, we used Multiwfn to scan the surface electrostatic potential of the C-S structure in a molecule. The electrostatic potential diagram and electrostatic potential isoline diagram of the C-S structure are shown in Figure 6. It shows that the strongly electron-withdrawing atoms such as S and N cause an extreme point with negative electrostatic potential at the outward end of the C atom along with lone pair electrons. The existence of lone pair electrons makes the C atom become a hydrogen bond acceptor.

As the ratio of the absolute value of the potential energy density to the Lagrangian kinetic energy (|V|/G) at the bond critical point falls in the range of 0 to 1, the bond critical point can be considered as the closed shell interaction.<sup>20</sup> It can be used as a supplementary criterion to judge a hydrogen bond. Figure 7 shows the |V|/G values of all bond critical points, indicating that all bond critical points meet this criteria.

In conclusion, the bond critical points except dihydrogen bonds are ascribed to hydrogen bonds in all systems. To quantify the energy of the hydrogen bond, a correlation expression proposed by Lu et al.<sup>30</sup> is written as:  $\Delta E \approx -223.08$  $\times \rho(r)$  + 0.7423, where  $\Delta E$  is the energy of the hydrogen bond in kcal/mol.  $\Delta E$  at all bond critical points between two atoms are shown in Figure 8. It is evident that etheramines (3EOPA, IPOPA, 3BOPA) and polyamines (DEAPA and NovM) have more (3, -1) CPs and topological pathways interacting with MeSH as compared to other compounds. To understand the underlying mechanism, the molecular surface electrostatic potentials were analyzed on DEA, MDEA, DEAPA, 3BOPA, and PPOH with typical structures (see Figure S5). The light blue points represent the minimum of negative electrostatic potential on the molecular surface. As compared with the secondary amine of DEA, there are more minimum points of negative electrostatic potential near the tertiary amine groups of MDEA, DEAPA, and PPOH, or the alkoxyl group of 3BOPA. As for the bond critical points, all solute-solvent systems except for 4MBA and PC show the weak-to-middle hydrogen bonds with exothermic energy below 2 kcal/mol.<sup>23</sup> Specifically, hydrogen atoms of thiol groups are able to form stronger hydrogen bonds than those hydrogen atoms of hydroxyl or hydrocarbon groups. These hydrogen bonds concerning the alkoxyl group, hydroxyl group, and carbonyl group have very similar strength. However, the oxygen atoms of alkoxyl groups can affect the electron abundance of the

neighboring carbon atoms. Meanwhile, these functional groups near the alkoxyl ones can form weak hydrogen bonds with MeSH. The tertiary amine shows bigger electron abundance and stronger hydrogen bond than those of either primary amine or secondary amine. Similarly, the adjacent groups under the influence of tertiary amine will form complex weak hydrogen bonds with MeSH.

**3.3. Correlation between the Molecular Structures of Solvents and Their Dissolubility for MeSH.** Both RDG and QTAIM analyses confirm that the unique structure of the solvent molecule allows it to form a stable configuration as interacting with MeSH at a specific location. To quantify the strength of the interaction of different solvent candidates with MeSH, the overall interaction energies ( $E_{int}$ ) for these 20 solvent—solute systems are calculated and shown in Figure 9.



Figure 9. Interaction energies  $(E_{int})$  for 20 MeSH-solvent systems.

The MeSH–DEAPA system shows the most exothermic  $E_{int}$ . A reasonable interpretation is that the tertiary amine group and the nearby branched hydrocarbon chain contribute strong hydrogen bond interactions and large van der Waals area, respectively. The E<sub>int</sub> of MeSH-etheramine (I, J, and K) systems have more negative values than those of MeSHalkanolamine (A, B, C, and D) systems, suggesting that etheramine compounds have stronger attraction to MeSH than alkanolamines. As compared to the hydroxyl groups, the alkoxyl groups can form more complex weak interactions with MeSH. Meanwhile, the hydroxyl groups and the primary amine groups of the alkanolamines exist at the end of molecules, providing a smaller van der Waals area as compared to the alkoxyl groups of etheramines. These amines with cyclic substituents (E, F, G, and H) have stronger interactions with MeSH by presenting more exothermic  $E_{int}$  than alkanolamines.

For BZA and 4MBA molecules, their benzene rings can form strong van der Waals interactions with MeSH. In cases of PPOH and NBEA, the amino groups form a strong hydrogen bond with MeSH. Moreover, the PPOH-MeSH system exhibits more exothermic interaction energy than the NBEA-MeSH system, suggesting that the tertiary amine group is more attractive to MeSH than the secondary amine group. These commercial physical solvents (N, O, P, Q, R, S, and T) contain strong polar centers of sulfur or oxygen atoms, which can interact with MeSH through the hydrogen bond rather than the van der Waals force. E<sub>int</sub> for these systems including NMP, DFM, DLM, and MP are almost at the same level, suggesting that these compounds have a similar strength of attraction to MeSH. PC, SUL, and DMSO exhibit more exothermic energies for interaction with MeSH than other compounds due to their larger van der Waals areas interacting with MeSH as compared to NMP, DFM, DLM, and MP.

To reveal the underlying relationship between MeSHsolvent interaction and MeSH dissolubility, the solubilities of MeSH in 20 selected solvents were measured at 30 °C. All solubility data are presented in Figure S6a, and the solubility curve for DEA is plotted separately due to the much lower solubility value than other solvents. Equilibrium solubility curves with error lines for MEA and 3EOPA are plotted in Figure S6b. The equilibrium solubility shows a linear relationship with the partial pressure (see the correlation coefficients in Table S4). Henry constants,  $H_{K'}$  can be easily calculated using the Henry's law<sup>12</sup> expression:  $P_3 \cdot \varphi = x_L \cdot H_{K_J}$ where  $x_{I}$  is the mole fraction of MeSH in the solution,  $P_3$  is the partial pressure of MeSH in the gas phase, and  $\varphi$  is the fugacity coefficient. In view of the low partial pressure of MeSH for all solubility measurements, the fugacity coefficient  $\varphi$  can be considered as a constant. Observed  $H_{\rm K}$  are demonstrated in Figure 10. Furthermore, five compounds (i.e., 3BOPA, IPOPA,



**Figure 10.** Henry constants ( $H_{\rm K}$ ) for MeSH absorption into different solvents at 30 °C.

DEAPA, NovM, and MEA) having small  $H_{\rm K}$  were further discussed by comparing their  $H_{\rm K}$  at a temperature range of 30 to 60 °C. The dependence of  $H_{\rm K}$  on temperature is presented in Figure S7.

Solubility measurement results indicate that the promising solvents for MeSH capture are expected to contain a polyamine group (DEAPA and NovM), alkoxyl group (IPOPA and 3BOPA), ring structure along with an amine group (BZA and 4MBA), strong basic amino group (MEA), or strong polar group (DMSO). Significant differences in solubility intrinsically arise from the type and strength of interactions between MeSH and various solvents with diverse molecular structures.

The  $E_{int}$  for each MeSH-solvent system is presented as a function of  $H_K$  (see Figure 11 with DEA being excluded). A



Figure 11. Relationship between  $E_{int}$  and  $H_K$  in different solute-solvent systems.

significant dependence of  $H_K$  for MeSH on  $E_{int}$  is recognized. DEA (C), PC (R), SUL (S), and DMSO (T) do not follow this trend because these simple solvent molecules containing strongly polar groups can form strong solvent-solvent interactions, which hinder the interaction between solvent and MeSH. Understanding the dependence of MeSH solubility on molecular structures of the solvents can guide the design of solvents for efficient capture. These key functional groups that facilitate the uptake of MeSH by solvents were obtained by quantitative analysis. The structures of the solvent compounds except DEA were created as a matrix (see Table S3). Pearson correlation analysis (see eq 5) was performed using the molecular identity columns of the matrix, and the results are shown in the last row. Three functional groups including tertiary amine groups (-NR<sub>2</sub>), primary amines (-NH<sub>2</sub>), and alkoxyl groups (RO-) show strong positive correlation with  $-\ln(H_{\rm K})$ , representing that solvent compounds containing these groups can be expected to have promising dissolubility for MeSH. In addition, the polarizability is positively correlated with  $-\ln(H_{\rm K})$ . Present results suggest that these solvent compounds with larger molecular volume or moderately branched structures are better candidates for MeSH capture.

As a result, an ideal solvent molecule is expected to have the structures in accordance with the following points. (i) Polar atoms like N, S, and O should be contained in the molecule. (ii) More electron donating substituents near polar functional groups can enhance the activity of lone pair electrons of polar atoms. The promotion effects of different functional groups on MeSH solubility rank the order: tertiary amine > alkoxyl group  $\approx$  secondary amine  $\approx$  amide > primary amine  $\approx$  hydroxyl  $\approx$ sulfonyl  $\approx$  benzene ring  $\approx$  carbonyl. (iii) Intermediate substituents of each polar functional group in the molecule should be long enough in order to ensure that the functional groups do not affect the electron density of each other. Substituents of the hydrocarbon chain between two functional groups can reduce the solvent-solvent interaction. As a result, a molecule, 1-(2-(diethylamino)ethoxy)butan-2-amine (DEAEBA), conforming to all above rules was designed using the SMILES (Figure S8). Conformational search and energy calculation were performed with the solute-solvent system using the aforementioned method. The  $E_{int}$  is found to be -31.232 kJ/mol, which is more exothermic than that of the MeSH-DEAPA system (-28.928 kJ/mol). Solvents containing multiple functional groups will form a variety of interaction configurations with MeSH to dominate their dissolving affinity to MeSH. It is indicated that the designed molecule has greater affinity to MeSH than previously screened DEAPA.

#### 4. CONCLUSIONS

In summary, we revealed the structure-interaction-dissolubility relationships within different MeSH-solvent systems through computational investigation coupled with solubility measurement. A series of compounds including alkanolamines, amines with cyclic substituents, etheramines, polyamines, sulfonamides, and several commercial physical solvents were selected, and methyl mercaptan (MeSH) was used as a model of organosulfide for both the quantum chemistry calculation and solubility measurement. Using the RDG and QTAIM analyses, we examined the weak intermolecular interactions in various solvent-solute systems and discussed the influences of the molecular structure (type and distribution of functional group) of the solvent on intermolecular interaction as well as dissolving affinity. Solubility measurement results indicate that the promising solvents for MeSH capture are expected to contain a polyamine group (DEAPA and NovM), alkoxyl group (IPOPA and 3BOPA), ring structure along with an amine group (BZA and 4MBA), strong basic amino group (MEA), or strong polar group (DMSO). Three functional groups including tertiary amine groups, primary amines, and the alkoxyl groups show strong positive correlation with  $-\ln(H_{\rm K})$ . A potentially promising compound with enhanced affinity to MeSH, 1-(2-(diethylamino)ethoxy)butan-2-amine, was generated under the realized guidances. Furthermore, the designed compound exhibits stronger intermolecular interaction with MeSH than the screened compound of DEAPA. The present study enables efficient molecular exploration and design of solvent candidates for absorption capture of diverse environmentally unfriendly compounds and separation applications based on selective dissolving.

#### ASSOCIATED CONTENT

#### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.iecr.2c00321.

Physical and chemical properties of 20 testing solvents, critical point label and topological path, correlation matrix of molecular structure information of solvent compounds with  $H_{\rm K}$  for MeSH, schematic diagram for static absorption equilibrium measurement, RDG- $\rho(r)$  scatter diagram, RDG-sign( $\lambda_2$ ) $\rho$  scatter diagram, QTAIM visualization, extreme point diagram, experimental solubilities of MeSH in 20 solvents at 30 °C, Henry constants ( $H_{\rm K}$ ) for MeSH absorption into five potential solvents, and information on the designed solvent molecule (PDF)

#### AUTHOR INFORMATION

#### **Corresponding Author**

Hui Sun – School of Chemical Engineering and International Joint Research Center of Green Energy Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China; ⊙ orcid.org/0000-0002-8544-756X; Email: sunhui@ecust.edu.cn

#### Authors

- **Chuanlei Liu** School of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China
- Yuxiang Chen School of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China
- Hao Jiang School of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China
- Kongguo Wu School of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China
- **Qilong Peng** School of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China
- Yu Chen School of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China
- Diyi Fang School of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China
- Benxian Shen School of Chemical Engineering and International Joint Research Center of Green Energy Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China
- Di Wu Alexandra Navrotsky Institute for Experimental Thermodynamics, Washington State University, Pullman, Washington 99163, United States; The Gene and Linda Voiland School of Chemical Engineering and Bioengineering, Materials Science and Engineering, and Department of Chemistry, Washington State University, Pullman, Washington 99163, United States; Orcid.org/0000-0001-6879-321X

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.iecr.2c00321

#### Notes

The authors declare no competing financial interest.

#### ACKNOWLEDGMENTS

This work is financially supported by the National Natural Science Foundation of China (Grant 21878097 and 22178109) and the Natural Science Foundation of Shanghai (Grant 21ZR1417700). D.W. acknowledges the institutional funds from the Gene and Linda Voiland School of Chemical Engineering and Bioengineering, and the Alexandra Navrotsky Institute for Experimental Thermodynamics at Washington State University.

#### REFERENCES

(1) Pulhan, A.; Yorucu, V.; Sinan Evcan, N. Global energy market dynamics and natural gas development in the Eastern Mediterranean region. *Util. Policy* **2020**, *64*, 101040.

(2) Awan, J. A.; Tsivintzelis, I.; Valtz, A.; Coquelet, C.; Kontogeorgis, G. M. Vapor-Liquid-Liquid Equilibrium Measurements and Modeling of the Methanethiol + Methane + Water Ternary System at 304, 334, and 364 K. *Ind. Eng. Chem. Res.* **2012**, *51*, 11561–11564.

(3) Suleman, H.; Maulud, A. S.; Man, Z. Review and selection criteria of classical thermodynamic models for acid gas absorption in aqueous alkanolamines. *Rev. Chem. Eng.* **2015**, *31*, 599–639.

pubs.acs.org/IECR

(4) Saha, B.; Vedachalam, S.; Dalai, A. K. Review on recent advances in adsorptive desulfurization. *Fuel Process. Technol.* **2021**, *214*, 106685–106707.

(5) Pullumbi, P. Gas Separation by Polymer Membranes. In *Membrane Reactor Engineering*, Basile, A.; De Falco, M.; Centi, G.; Iaquaniello, G., Ed.; John Wiley & Sons: New York, 2016; p 256.

(6) Chen, C.; Xu, X.-J.; Xie, P.; Yuan, Y.; Zhou, X.; Wang, A.-J.; Lee, D.-J.; Ren, N.-Q. Pyrosequencing reveals microbial community dynamics in integrated simultaneous desulfurization and denitrification process at different influent nitrate concentrations. *Chemosphere* **2017**, *171*, 294–301.

(7) Couvert, A.; Sanchez, C.; Laplanche, A.; Renner, C. Scrubbing intensification for sulphur and ammonia compounds removal. *Chemosphere* **2008**, *70*, 1510–1517.

(8) Shah, M. S.; Tsapatsis, M.; Siepmann, J. I. Hydrogen Sulfide Capture: From Absorption in Polar Liquids to Oxide, Zeolite, and Metal–Organic Framework Adsorbents and Membranes. *Chem. Rev.* **2017**, *117*, 9755–9803.

(9) de Angelis, A. Natural gas removal of hydrogen sulphide and mercaptans. *Appl. Catal., B* **2012**, *113-114*, 37–42.

(10) Rahman, M. A.; Maddox, R. N.; Mains, G. J. Reactions of carbonyl sulfide and methyl mercaptan with ethanolamines. *Ind. Eng. Chem. Res.* **1989**, *28*, 470–475.

(11) Lyddon, B. A Comparison of Physical Solvents for Acid Gas Removal. In 87th Annual Gas Processors Association Convention. Grapevine, Texas, March 2008.

(12) Bedell, S. A.; Miller, M. Aqueous Amines as Reactive Solvents for Mercaptan Removal. *Ind. Eng. Chem. Res.* 2007, 46, 3729–3733.

(13) Charry Prada, I. D.; Rivera-Tinoco, R.; Bouallou, C. Methyl Mercaptan Absorption Study into a Hybrid Solvent Mixture Composed of Diethanolamine/Methanol/Water at Temperatures

from 313.9 to 353.0 K. *Ind. Eng. Chem. Res.* **2017**, *56*, 14410–14418. (14) Yousefinejad, S.; Honarasa, F.; Solhjoo, A. On the Solubility of Ferrocene in Nonaqueous Solvents. *J. Chem. Eng. Data* **2016**, *61*, 614–621.

(15) Kowalski, P. H.; Krzemińska, A.; Pernal, K.; Pastorczak, E. Dispersion Interactions between Molecules in and out of Equilibrium Geometry: Visualization and Analysis. *The Journal of Physical Chemistry A* **2022**, *126*, 1312–1319.

(16) Chen, Y.; Liu, C.; An, Y.; Lou, Y.; Zhao, Y.; Qian, C.; Jiang, H.; Wu, K.; Zhang, X.; Sun, H.; et al. Intelligent Molecular Identification for High Performance Organosulfide Capture Using Active Machine Learning Algorithm. *ChemRxiv* 2021, DOI: 10.26434/chemrxiv-2021hczsl.

(17) Wakchaure, P. D.; Ganguly, B. Unraveling the Role of  $\pi$ -Stacking Interactions in Ligand Binding to the Thiamine Pyrophosphate Riboswitch with High-level Quantum Chemical Calculations and Docking Study. *The Journal of Physical Chemistry B* **2022**, *126*, 1076–1084.

(18) Lin, X.; Mo, Y. Partial Double Metal-Carbon Bonding Model in Transition Metal Methyl Compounds. *Inorg. Chem.* **2022**, *61*, 2892–2902.

(19) Cents, A. H. G.; Brilman, D. W. F.; Versteeg, G. F. Gas absorption in an agitated gas-liquid-liquid system. *Chem. Eng. Sci.* **2001**, *56*, 1075–1083.

(20) Adamson, W. In A textbook of physical chemistry, Academic Press: New York, 1973; p 356.

(21) Johnson, E. R.; Keinan, S.; Mori-Sánchez, P.; Contreras-García, J.; Cohen, A. J.; Yang, W. Revealing Noncovalent Interactions. *J. Am. Chem. Soc.* **2010**, *132*, 6498–6506.

(22) Lu, T.; Chen, F. Multiwfn: A multifunctional wavefunction analyzer. J. Comput. Chem. 2012, 33, 580-592.

(23) Bader, R. F. W.; Beddall, P. M. Virial Field Relationship for Molecular Charge Distributions and the Spatial Partitioning of Molecular Properties. *The Journal of Chemical Physics* **1972**, *56*, 3320–3329.

(24) Bader, R. F. W. A quantum theory of molecular structure and its applications. *Chem. Rev.* **1991**, *91*, 893–928.

(25) Zhang, J.; Lu, T. Efficient evaluation of electrostatic potential with computerized optimized code. *Phys. Chem. Chem. Phys.* **2021**, 23, 20323–20328.

(26) Boys, S. F.; Bernardi, F. The calculation of small molecular interactions by the differences of separate total energies. Some procedures with reduced errors. *Mol. Phys.* **1970**, *19*, 553–566.

(27) Overgaard, J.; Iversen, B. B. Charge Density Methods in Hydrogen Bond Studies. In *Electron Density and Chemical Bonding I: Experimental Charge Density Studies*, Stalke, D. Ed.; Springer Berlin Heidelberg, 2012; pp. 53–74.

(28) Rozas, I.; Alkorta, I.; Elguero, J. Behavior of Ylides Containing N, O, and C Atoms as Hydrogen Bond Acceptors. *J. Am. Chem. Soc.* **2000**, *122*, 11154–11161.

(29) Babapulle, M. N.; Joseph, L.; Bélisle, P.; Brophy, J. M.; Eisenberg, M. J. A hierarchical Bayesian meta-analysis of randomised clinical trials of drug-eluting stents. *The Lancet* **2004**, *364*, 583–591.

(30) Emamian, S.; Lu, T.; Kruse, H.; Emamian, H. Exploring Nature and Predicting Strength of Hydrogen Bonds: A Correlation Analysis Between Atoms-in-Molecules Descriptors, Binding Energies, and Energy Components of Symmetry-Adapted Perturbation Theory. J. Comput. Chem. 2019, 40, 2868–2881.

## **Recommended by ACS**

#### Computer-Aided Molecular Design of Double-Salt Ionic Liquid Solvents for Extractive Distillation with the COSMO-SAC and Genetic Algorithm

Shuang Xu, Huisheng Feng, et al. DECEMBER 03, 2021 INDUSTRIAL & ENGINEERING CHEMISTRY RESEARCH

Evaluation of Methanesulfonate-Based Deep Eutectic Solvent for Ammonia Sorption

Alsu I. Akhmetshina, Ilya V. Vorotyntsev, *et al.* MAY 03, 2018 JOURNAL OF CHEMICAL & ENGINEERING DATA

READ 🗹

RFAD

#### COSMO-RS-Based Screening of Antisolvents for the Separation of Sugars from Ionic Liquids: Experimental and Molecular Dynamic Simulations

Mood Mohan, Vaibhav V. Goud, et al. JULY 05, 2018

ACS OMEGA	READ 🗹
Ionic-Liquid-Based Bioisop Design	ene Recovery Process

Yuqiu Chen, John M. Woodley, et al. April 08, 2020 INDUSTRIAL & ENGINEERING CHEMISTRY RESEARCH

Get More Suggestions >