Density functional theory study of the adsorption of elemental mercury on a 1T-MoS$_2$ monolayer

Xue-liang MU$^1$, Xiang GAO$^2$, Hai-tao ZHAO$^{1,2}$, Michael GEORGE$^3$, Tao WU$^{1,1}$

$^1$Municipal Key Laboratory of Clean Energy Conversion Technologies, The University of Nottingham Ningbo China, Ningbo 315100, China
$^2$College of Energy Engineering, Zhejiang University, Hangzhou 310027, China
$^3$School of Chemistry, The University of Nottingham, Nottingham NG7 2RD, UK

$^†$E-mail: tao.wu@nottingham.edu.cn

Received Feb. 13, 2017; Revision accepted Oct. 17, 2017; Crosschecked Dec. 15, 2017

Abstract: Elemental mercury has become a global concern because of its significant impact on human health and the ecosystem. A lot of effort has been put towards the removal of elemental mercury from the 2H-MoS$_2$ (prismatic structure of MoS$_2$). However, the mechanism of 1T-MoS$_2$ (polytype structure of MoS$_2$) in Hg$^0$ capture remains unexplored. In this study, density functional theory (DFT) was adopted to investigate the adsorption mechanism of Hg on a 1T-MoS$_2$ monolayer. The different possible adsorption positions on the 1T-MoS$_2$ were examined. For different adsorption configurations, the changes in electronic property were also studied to understand the adsorption process. The results elucidated that chemisorption dominates the adsorption between Hg$^0$ atoms and the 1T-MoS$_2$. It was found that the T$_{Mo}$ (on top of the Mo atom) position is the strongest adsorption configuration among all the possible adsorption positions. The adsorption of Hg$^0$ atoms on the 1T-MoS$_2$ monolayer is influenced by adjacent S and Mo atoms. The adsorbate Hg$^0$ atom is found being oxidized on the T$_{Mo}$ position of the 1T-MoS$_2$ with an adsorption energy of $-1.091$ eV. From the partial density of states (PDOS) analysis of the atoms, the strong interaction between Hg$^0$ and the 1T-MoS$_2$ surface is caused by the significant overlap among the d orbitals of the mercury atom and the s orbital of the S atom and p and d orbitals of the Mo atom.

Key words: 1T-MoS$_2$ monolayer; Mercury capture; Adsorption mechanism; Density functional theory (DFT)

https://doi.org/10.1631/jzus.A1700079

CLC number: X511; TK09

1 Introduction

Elemental mercury (Hg$^0$) is the most toxic form of mercury in flue gas released from industrial activity (Galbreath and Zygarlicke, 1996; Presto and Granite, 2006). Because it is insoluble in water, highly volatile, and chemically inert, it can be transported in air over long distances and periods of time (Gao et al., 2013; Lim and Wilcox, 2013). Once it returns to the biosphere, mercury can bio-accumulate in the ecosystem and become a major threat to human health (UNEP, 2013a, 2013b; Liang et al., 2015). As a consequence, since 1990 a series of policies and legislation on mercury control has been published to prevent the further invasion of mercury, such as Clean Air Act Amendments (1990) (Johansen, 2003), Mercury and Air Toxics Standards (MATS) (2011) (EPA, 2011), and the Minamata Convention (2013) (UNEP, 2013c). Driven by a series of policies, mercury emissions in Canada, for example, were reduced from about 33 t to 6 t per annum between 1990 and 2000 (UNEP, 2002). Nowadays, more stringent emission legislation has been introduced by many
regions worldwide (Jones, 1999; Praveen, 2003). There is therefore an urgent need for the development of new materials for the control of airborne mercury.

Our previous research showed that MoS$_2$ is an elemental Hg trapping agent with a trigonal prismatic (2H) structure (Zhao et al., 2016), wherein the layer of Mo atoms is sandwiched between two layers of S atoms, such that each Mo is coordinated to six S atoms in a trigonal prismatic geometry (Yin et al., 2011; Chhowalla et al., 2013). Experimental and theoretical studies have demonstrated that MoS$_2$, a type of graphene-like 2D material, is an excellent Hg adsorbent (Zhao et al., 2016). In our previous research, the 2H-MoS$_2$, the most stable phase of a MoS$_2$ monolayer, has been examined extensively for the adsorption of mercury on the defect-free to defective surface. However, not much work has been carried out on the adsorption of mercury on the other geometric structure of MoS$_2$, the polytype (1T) with a tetragonal symmetry, which has one MoS$_2$ layer per repeat unit in the octahedral phase.

The 1T-MoS$_2$ monolayer is a metastable phase of MoS$_2$, and this has attracted attention because of its unique properties since it was fabricated for the first time (Wypych and Schollhorn, 1992) and a series of techniques has been developed to characterize the structure of 1T-MoS$_2$ (Wypych et al., 1998). Compared with 2H-MoS$_2$, the metastable phase has a metallic character, and as such, may provide significantly improved catalytic activity compared with its 2H counterpart. Furthermore, one pronounced property of mercury is its affinity to other metals, such as gold, silver, and copper (Aboud et al., 2008). It was reported that Hg atoms can easily bind to sulfurized adsorbents (Asasian and Kaghazchi, 2015). It was also found that the 1T phase could replace noble metals, such as Pt in hydrodesulfurization reactions and hydrogen evolution reaction (HER) processes (Putungan and Kuo, 2014). Therefore, to better understand the potential of MoS$_2$ in mercury capture, in addition to the understanding of mercury adsorption on 2H-MoS$_2$, it is essential to examine the adsorption of mercury on the 1T-MoS$_2$.

Because of the metallic structure of the 1T-MoS$_2$, the 1T phase can transform to the 2H phase at a temperature in the range of around 100–300 °C (Eda et al., 2012). Although there is still no clear consensus on the optimum structural phase transition temperature, there is still a lot of work being carried out on the stabilization of the metallic structure (Gao et al., 2015). However, very little has been done on the adsorption properties of the metallic 1T phase of MoS$_2$, especially the 1T phase of MoS$_2$ material for the adsorption of elemental Hg. In this study, the possible configurations for the adsorption of Hg$^0$ atoms on the 1T-MoS$_2$ were examined by density functional theory (DFT) modelling. The partial density of states (PDOS) and charge transfer for the most stable configuration were studied in detail to show the mechanism of mercury adsorption on the 1T-MoS$_2$ surface.

In the calculation, although ab initio methods such as DFT have been proposed to point out weak interactions, the main difficulty is that weak interactions are long-range. In addition, commonly used approximations such as the local-density approximation (LDA) are suitable for short range and are not appropriate for these long-range interactions. In this simulation work, the overlap of electronic densities around each atom is the basis of all calculation and when this overlap is estimated to be too small, it is not possible to get an accurate result for the system. Therefore, to overcome this problem, a semi-empirical $r^{-6}$ term such as density functional theory-dispersion correction (DFT-D) is adopted (Sato and Nakai, 2009; Hasnip et al., 2014). Because of the great precision and efficiency of simulations of localized d and 2p orbital with plane-waves basis sets, ultrasoft pseudo-potentials (USPPs) are employed in first-row and transition-metal systems (Vanderbilt, 1990).

2 Methodology

Simulation in this study was conducted using the exchange-correlation functional GGA-PW91-OBS. The DFT-D takes into account the charge of the dispersion forces (Ortmann et al., 2006), as conducted by the CASTEP package (Clark et al., 2005). USPPs were applied to all ion-electron interactions in the system (Vanderbilt, 1990). The valence configurations of Mo, S, and Hg atoms were 4p$^6$4d$^5$5s$^1$, 3s$^2$3p$^4$, and 5d$^{10}$6s$^2$, respectively. To ensure convergence, convergence with respect to both energy cutoff and k-point mesh was set as fine quality (an energy cutoff.


of 310 eV and 2×2×1 k-points mesh). The total energy of the 1T-MoS2 (4×4) was converged to within 1×10⁻⁵ eV/atom using the method of Monkhorst-Pack (Chadi, 1977). In addition, the self-consistent field (SCF) calculation was kept within the energy convergence criterion of 1×10⁻⁶ eV/atom and a smearing width of 0.1 eV was used for the treatment of the metallic system. For supercell calculations, the same modeling parameters were applied.

Since all atomic layers are relaxed in the 1T-MoS2 (4×4) (Liu et al., 2010), to search for the most-stable configuration of the 1T-MoS2 monolayer and the Hg⁰ atoms, the total energy minimization method introduced by Broyden Fletcher Goldfarb Shanno (BFGS) was adopted in this study (Pfrommer et al., 1997). The total-energy difference was set to be within 1×10⁻⁵ eV/atom, and the maximum force was set to be within 0.03 eV/Å, while the maximum stress was set to be within 0.05 GPa, and the maximum atom displacement was set to be within 0.001 Å. For the interactions among periodical slabs, a vacuum region of 25 Å was also applied in the direction perpendicular to the 1T-MoS2 plane. The isolated Hg⁰ atom was calculated in a (10 Å)³ supercell.

The adsorption energy equation (E_{ads}) was determined as

\[ E_{ads} = E_{Hg+1T-MoS2} - (E_{Hg} + E_{1T-MoS2}), \]  

where \( E_{ads} \) is the ground state energy of the free Hg⁰ atom, \( E_{1T-MoS2} \) is the total energy of the 1T-MoS2 monolayer, and \( E_{Hg+1T-MoS2} \) is the total energy of the Hg⁰-1T-MoS2 slab of the stable adsorption configuration. By definition, a more negative adsorption energy suggests a more favorable exothermic Hg adsorption on the 1T-MoS2 surface.

3 Results and discussion

3.1 Geometric structure

The positions of all atoms were fully relaxed in the 1T-MoS2 monolayer to ensure the accuracy of the results. As shown in Fig. 1, the pristine structure of the 1T-MoS2 monolayer is relaxed with the optimized unit cell (lattice constant \( a=b=3.166 \) Å), which is close to the result (\( a=3.169 \) Å) reported by Enyashin and Seifert (2012). There are four possible adsorption positions of an Hg⁰ atom on the 1T-MoS2 monolayer: (1) on top of a Mo atom (T_Mo), (2) on top of the space between neighboring S and Mo atoms (B_Mo-S), (3) on top of an S atom of the top sulphur plane (T_T), and (4) on top of an S atom on the bottom sulphur plane (T_B), and these are shown in Figs. 2a–2d, respectively, after the optimization of the adsorption configuration. It is shown that the Hg⁰ atom is favorably adsorbed at the T_Mo adsorption position with the highest adsorption energy of −1.091 eV, which is the site that was also found as the best site for the adsorption of other transition metals on 2H-MoS2, such as Fe, Co, and Ni (Huang et al., 2013). It is also observed in this study that the Hg⁰ atom is not adsorbed at the position right on top of a Mo atom but with a deviation from Mo atom along the Mo-S bond, as illustrated in Fig. 2a. This is common in the adsorption position of B_Mo-S and T_B. Under the influence of the Hg⁰ atoms adsorbed, the structures of the four adsorption positions on the 1T-MoS2 monolayer are deformed. It suggests that the geometric structure of pristine 1T-MoS2 is unstable and is easily affected by external interference.

3.2 Adsorption energy

The results of DFT-D and DFT methods are listed in Table 1. Because the DFT-D mainly focuses on the dispersion force between adsorbent and the adsorbate system, the adsorption behavior of a single Hg⁰ atom can be calculated more accurately. Therefore, the following discussion is mainly focused around DFT-D method. Based on Eq. (1), the stability of the adsorption configurations is found to be of the order of \( T_Mo>B_{Mo-S}>T_T>B_B \), as shown in Table 1. All the four stable adsorption positions show
sufficient adsorption energy to allow the Hg$^0$ atoms to be chemically adsorbed on the 1T-MoS$_2$ monolayer (Atkins, 2001). Comparing Figs. 2a, 2b, and 2c, it can be seen that for the stable adsorption positions with Hg$^0$ atoms adsorbed, the Hg$^0$ atoms are adsorbed at the positions of T$_{Mo}$, B$_{Mo-S}$, and T$_{BS}$, but deviated along the bond of Mo and S atoms. However, the adsorption position of T$_{Mo}$ is very close to the Mo atom with the shortest distance between the Hg$^0$ atom and the nearest adjacent (NA) S atom (4.822 Å). Furthermore, the distance between the Hg$^0$ atom and the NA Mo/S atom is the shortest among the four potential adsorption sites. That means the Mo atoms of the 1T-MoS$_2$ monolayer may affect the behavior of Hg adsorption. The adsorption site of T$_{TS}$ shows a shorter distance between the Hg$^0$ atom and the NA S atom than that of the T$_{BS}$, which means that the adsorption of Hg$^0$ atom on the 1T-MoS$_2$ monolayer is also possibly contributed to by the NA S atoms in the top sulphur plane.

### 3.3 Electronic structure

The adsorption mechanism is mainly determined by the change of electronic structure in the Hg-1T-MoS$_2$ slab. The charge transfer of all atoms and the relevant PDOS analysis were conducted in this study. The Hirshfeld charge analysis is based on the variation of density of the free atomic electron density (Delley, 1986). The atomic charges for the pristine 1T-MoS$_2$ monolayer, the free Hg$^0$ atom, and the Hg-1T-MoS$_2$ slab were calculated by the Hirshfeld method. The charge transfer is in accordance with the difference of the electron state in each individual atom before and after adsorption (Table 2), the atomic indices of which are labeled in Fig. 3. A

### Table 1 Adsorption properties of Hg$^0$ atom on stable adsorption configuration of 1T-MoS$_2$ monolayer with DFT-D and DFT methods

| Position | $E_{ads}$ (eV) | Frequency (cm$^{-1}$)$^a$ | $d_{Hg-NA S}$ (Å)$^b$ | $d_{Hg-NA Mo}$ (Å)$^c$ |
|----------|---------------|-----------------|-----------------|-----------------|
| T$_{Mo}$ | -1.091 | -0.982 | 949.653 | 3767.507 |
| B$_{Mo-S}$ | -1.085 | -0.455 | 3579.327 | 6110.059 |
| T$_{TS}$ | -1.074 | -0.967 | 2686.095 | 1668.000 |
| T$_{BS}$ | -1.067 | -0.583 | 1996.348 | 4164.766 |

Note: a: optimized geometry of final frequency; b: optimized distance between Hg$^0$ atom and the nearest adjacent (NA) S atom; c: optimized distance between Hg$^0$ atom and the NA Mo atom

---

Fig. 2 Optimized stable structure of 1T-MoS$_2$ monolayer with adsorbed Hg$^0$ atom

(a) Hg$^0$ atom adsorbed on the top site of a Mo atom (T$_{Mo}$); (b) Hg$^0$ atom adsorbed on the top site of the bridge site between a S-Mo bond (B$_{Mo-S}$); (c) Hg$^0$ atom adsorbed on the top site of a S atom in top sulphur plane (T$_{TS}$); (d) Hg$^0$ atom adsorbed on the top site of a S atom in bottom sulphur plane (T$_{BS}$). Yellow atom is S atom, and aquamarine atom is Mo atom

Note: for interpretation of the references to color in this figure, the reader is referred to the web version of this article
positive value of charge transfer means the atom gains electrons after adsorption, while a negative value of that means the atom donates electrons after adsorption.

As shown in Table 2, the order of the Hg charge transfer is recognized as TMo>BMo-S>TBS>TTS, which is in a similar order to that of the stability of the four adsorption configurations, except for the TBS and TTs positions. The Hg\textsuperscript{0} atom adsorbed on the TMo adsorption site has the largest charge transfer of $-0.04 \text{ eV}$ after adsorption, while the Hg\textsuperscript{0} atoms on the other three potential adsorption positions donate different electrons to the 1T-MoS\textsubscript{2} monolayer. It indicates that the Hg is oxidized after it is adsorbed on the 1T-MoS\textsubscript{2} monolayer. For the four stable adsorption configurations, the Mo atoms have negative charge transfer ($-0.01 \text{ eV}$) in those different potential adsorption positions. It is worth noting that the TMo adsorption site has the most Mo atoms, i.e. Mo (8), Mo (9), Mo (11), Mo (12), and Mo (16), that participate in the adsorption process. As for the TMo adsorption position, the S atoms in the top S plane, i.e. S (21), S (29) and S(31), show positive charge transfer ($0.01 \text{ eV}$) in the Hg-1T-MoS\textsubscript{2} monolayer system. In addition, the S atoms in the bottom S plane, i.e. S (2), S (4), and S (12), also show negative charge transfer ($-0.01 \text{ eV}$) in the Hg-1T-MoS\textsubscript{2} monolayer system. Consequently, the oxidized Hg\textsuperscript{0} atoms with positive charge are bonded with S atoms in the top S plane that accept electrons from neighboring Mo atoms, the Hg\textsuperscript{0} atoms, and the S atoms in the bottom S plane. Hence, the adsorption of Hg at the TMo position is very stable.

To further understand the electronic interactions of the adsorbate Hg\textsuperscript{0} atom with the 1T-MoS\textsubscript{2} monolayer at the TMo adsorption site, the density of state (DOS) of the system was investigated by analyzing the electron change of each individual orbital and the

### Table 2 Hirshfeld charge analysis for different adsorption positions on 1T-MoS\textsubscript{2}

| Position | Charge analysis (eV) | Atomic index | After adsorption | Before adsorption | Charge transfer |
|----------|---------------------|--------------|------------------|-------------------|-----------------|
| TMo      |                     | S (2)        | -0.10            | -0.11             | -0.01           |
|          |                     | S (4)        | -0.10            | -0.11             | -0.01           |
|          |                     | S (8)        | -0.11            | -0.10             | 0.01            |
|          |                     | S (12)       | -0.10            | -0.11             | -0.01           |
|          |                     | S (20)       | -0.11            | -0.10             | 0.01            |
|          |                     | S (21)       | -0.10            | -0.09             | 0.01            |
|          |                     | S (29)       | -0.10            | -0.09             | 0.01            |
|          |                     | S (31)       | -0.10            | -0.09             | 0.01            |
|          |                     | Mo (8)       | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (9)       | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (11)      | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (12)      | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (16)      | 0.21             | 0.20              | -0.01           |
|          |                     | Hg           | 0.04             | 0                 | -0.04           |
| BMo-S    |                     | S (2)        | -0.10            | -0.11             | -0.01           |
|          |                     | S (4)        | -0.10            | -0.11             | -0.01           |
|          |                     | S (8)        | -0.11            | -0.10             | 0.01            |
|          |                     | S (12)       | -0.10            | -0.11             | -0.01           |
|          |                     | S (20)       | -0.11            | -0.10             | 0.01            |
|          |                     | S (21)       | -0.10            | -0.09             | 0.01            |
|          |                     | S (29)       | -0.10            | -0.09             | 0.01            |
|          |                     | S (31)       | -0.10            | -0.09             | 0.01            |
|          |                     | Mo (11)      | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (12)      | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (16)      | 0.21             | 0.20              | -0.01           |
|          |                     | Hg           | 0.03             | 0                 | -0.03           |
| TBs      |                     | S (4)        | -0.10            | -0.11             | -0.01           |
|          |                     | S (8)        | -0.11            | -0.10             | 0.01            |
|          |                     | S (11)       | -0.10            | -0.09             | 0.01            |
|          |                     | S (20)       | -0.11            | -0.10             | 0.01            |
|          |                     | S (21)       | -0.10            | -0.09             | 0.01            |
|          |                     | S (24)       | -0.10            | -0.11             | -0.01           |
|          |                     | S (31)       | -0.10            | -0.09             | 0.01            |
|          |                     | Mo (1)       | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (6)       | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (11)      | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (16)      | 0.21             | 0.20              | -0.01           |
|          |                     | Hg           | 0.02             | 0                 | -0.02           |
| TTs      |                     | S (8)        | -0.11            | -0.10             | 0.01            |
|          |                     | Mo (3)       | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (4)       | 0.21             | 0.20              | -0.01           |
|          |                     | Mo (8)       | 0.21             | 0.20              | -0.01           |
|          |                     | Hg           | 0.01             | 0                 | -0.01           |

Note: the missing atom index means no charge transfer before and after adsorption.

Fig. 3 Atomic indices for 1T-MoS\textsubscript{2} monolayer (yellow atom is S atom, aquamarine atom is Mo atom)

Note: for interpretation of the references to color in this figure, the reader is referred to the web version of this article.
energy levels. There are obvious changes for orbitals of the Hg, Mo, and S atoms at the PDOS and energy level, as shown in Fig. 4. The PDOS peaks of d, s, and p orbitals of an isolated Hg$^0$ atom are approximately −3.1, 0, and 5.7 eV before adsorption, respectively. However, after adsorption, all the PDOS peaks of the Hg$^0$ atom shift left while the state of the s and p orbitals significantly decreases in energy level. All these changes confirm that strong interactions occur between Hg$^0$ and the 1T-MoS$_2$ monolayer. The orbitals of the NA Mo atom and the NA S atom were analyzed to show possible co-interaction with the Hg$^0$ atom. As illustrated in Figs. 4a and 4c, the s, p, and d orbitals of the NA Mo atom and the s and p orbitals of the S atom change slightly after adsorption. In particular, the p orbitals of the NA Mo atom and of the NA S atom become higher in PDOS value and overlap with the s and d orbitals of the Hg$^0$ atom. It indicates the bonding of s orbital of the Hg$^0$ atom and p orbitals of the S atom. The d orbitals of the Hg$^0$ atom interact with the p and d orbitals of the Mo atom and the s orbital of the S atom strongly. It therefore suggests that there are strong interactions between the 1T-MoS$_2$ monolayer and the adsorbate Hg$^0$ atoms. It can also be concluded that the 1T-MoS$_2$ monolayer can oxidize the adsorbate Hg$^0$ atoms. Both the chemisorption and the oxidation ability of the 1T-MoS$_2$ monolayer contribute to its good performance in Hg adsorption.

4 Conclusions

The DFT modelling of the adsorption of Hg$^0$ atom on the 1T-MoS$_2$ monolayer showed that the Hg$^0$ atoms are favorably adsorbed on the T$_{Mo}$ of the 1T-MoS$_2$ slab with an adsorption energy of −1.091 eV. The most stable adsorption configuration in the Hg-1T-MoS$_2$ slab is chemisorption. The PDOS and charge transfer analyses also show that the Hg$^0$ atoms adsorbed on the T$_{Mo}$ position are oxidized and interact with the 1T-MoS$_2$ slab strongly with a number of Mo atoms and S atoms from both the top and bottom S planes participating in the adsorption. It is evident in this study that the 1T-MoS$_2$ is an excellent adsorbent for Hg$^0$ capture.

Acknowledgements

The University of Nottingham Ningbo China is acknowledged for the provision of a full scholarship to the first author.

References

Aboud S, Sasmaz E, Wilcox J, 2008. Mercury adsorption on PdAu, PdAg and PdCu alloys. Main Group Chemistry, 7(3):205-215.
Enyashin AN, Seifert G, 2012. Density-functional study of their mercury adsorption/desorption behavior in aqueous phase. *International Journal of Environmental Science and Technology*, 12(8):2511-2522.  
https://doi.org/10.1007/s13762-015-0818-x

Atkins PW, 2001. Physical Chemistry. Oxford University Press, UK.

Chadi DJ, 1977. Special points for Brillouin-zone integrations. *Physical Review B*, 13:5188-5192.

Chhewalla M, Shin HS, Eda G, et al., 2013. The chemistry of two-dimensional layered transition metal dichalcogenide nanosheets. *Nature Chemistry*, 5(4):263-275.  
https://doi.org/10.1038/nchem.1589

Clark SJ, Segall MD, Pickard CJ, et al., 2005. First principles methods using CASTEP. *Zeitschrift Fur Kristallographie*, 220:567-570.

Delley B, 1986. Calculated electron distribution for terefluoroterephthalonitrile (TFT). *Chemical Physics*, 110(2-3):329-338.  
https://doi.org/10.1016/0301-0104(86)87089-6

EPA (Environmental Protection Agency), 2011. National Emission Standards for Hazardous Air Pollutants from Coal-and Oil-fired Electric Utility Steam Generating Units and Standards of Performance for Fossil-Fuel-Fired Electric Utility, Industrial-Commercial-Institutional, and Small Industrial-Commercial-Institutional Steam Generating Units. https://www.federalregister.gov/articles/2016/04/06/2016-06563/national-emission-standards-for-hazardous-air-pollutants-from-coal-and-oil-fired-electric-utility [Accessed on Feb. 15, 2016].

Enyashin AN, Seifert G, 2012. Density-functional study of Li2MoO4 intercalates (0≤x≤1). *Computational and Theoretical Chemistry*, 999:13-20.  
https://doi.org/10.1016/j.comptc.2012.08.005

Galbreath KC, Zygarlicke CJ, 1996. Mercury speciation in coal combustion and gasification fuel gases. *Environmental Science & Technology*, 30(8):2421-2426.  
https://doi.org/10.1021/es950935t

Gao G, Jiao Y, Ma F, et al., 2015. Charge mediated semiconducting-to-metallic phase transition in molybdenum disulfide monolayer and hydrogen evolution reaction in new 1T' phase. *The Journal of Physical Chemistry C*, 119(23):13124-13128.  
https://doi.org/10.1021/acs.jpcc.5b04658

Gao Y, Zhang Z, Wu J, et al., 2013. A critical review on the heterogeneous catalytic oxidation of elemental mercury in flue gases. *Environmental Science & Technology*, 47(19):10813-10823.  
https://doi.org/10.1021/es402495h

Hada G, Fujita T, Yamaguchi H, et al., 2012. Coherent atomic and electronic heterostructures of single-layer MoS2. *ACS Nano*, 6(8):7311-7317.  
https://doi.org/10.1021/nn302422x

Hasnip PJ, Refson K, Probert MI, et al., 2014. Density functional theory in the solid state. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372:20130270.  
https://doi.org/10.1098/rsta.2013.0270

Huang Z, Hao G, He C, et al., 2013. Density functional theory study of Fe adatoms adsorbed monolayer and bilayer MoS2 sheets. *Journal of Applied Physics*, 114:083706.  
https://doi.org/10.1063/1.4818952

Johnson VC, 2003. Mercury speciation in other combustion sources: a literature review. *Portland Cement Association*, 2578:20.

Jones DW, 1999. Exposure or absorption and the crucial question of limits for mercury. *Journal of the Canadian Dental Association*, 65(1):42-46.

Liang S, Wang Y, Cinnirella S, et al., 2015. Atmospheric mercury footprints of nations. *Environmental Science & Technology*, 49(6):3566-3574.  
https://doi.org/10.1021/acs.est.5b03977

Lim D, Wilcox J, 2013. Heterogeneous mercury oxidation on Au(111) from first principles. *Environmental Science & Technology*, 47(15):8515-8522.  
https://doi.org/10.1021/es400876e

Liu D, Chen X, Li D, 2010. Simulation of MoS2 crystal structure and the experimental study of thermal decomposition. *Journal of Molecular Structure*, 980(1-3):66-71.  
https://doi.org/10.1016/j.molstruc.2010.06.038

Ortmann F, Bechstedt F, Schmidt WG, 2006. Semiepiempirical van der Waals correction to the density functional description of solids and molecular structures. *Physical Review B*, 73(20):205101.  
https://doi.org/10.1103/PhysRevB.73.205101

Pfrommer BG, Cote M, Louie SG, et al., 1997. Relaxation of crystals with the quasi-Newton method. *Journal of Computational Physics*, 131:233-240.  
https://doi.org/10.1006/jcph.1996.5612

Praveen A, 2003. Mercury Emissions from Coal Fired Power Plants. Northeast States for Coordinated Air Use Management.

Presto AA, Granite EJ, 2006. Survey of Catalysts for Oxidation of Mercury in Flue Gas. *Environmental Science & Technology*, 40(18):5601-5609.  
https://doi.org/10.1021/es060504i

Putungan DB, Kuo JL, 2014. Structural and electronic properties of monolayer 1T-MoS2 phase, and its interaction with water adsorbed on perfect, single S-vacated and MoS2-unit-vacated surface: density functional theory calculations. *Integrated Ferroelectrics*, 156(1):93-101.  
https://doi.org/10.1080/10584587.2014.906790

Sato T, Nakai H, 2009. Density functional method including van der Waals correction to the density functional description of solids and molecular structures. *Physical Review B*, 73(20):205101.  
https://doi.org/10.1103/PhysRevB.73.205101

UNEP (United Nations Environment Programme), 2002. Global Mercury Assessment. http://www.unep.org [Accessed on Jan. 15, 2016].

UNEP (United Nations Environment Programme), 2013a. Final Act of the Conference of Plenipotentiaries on the Minamata Convention on Mercury. http://www.mercuryconvention.org [Accessed on Apr. 15, 2016].
中文摘要

题目：关于单层 1T-MoS2 吸附元素汞的密度泛函理论研究

目的：探索 1T-MoS2（多型结构的二硫化钼）的除汞机制。

方法：1. 采用密度泛函理论（DFT）分析 Hg0 在 1T-MoS2 单层上的吸附机理。2. 考察 1T-MoS2 的不同吸附位置。3. 对不同的吸附构型，研究电子吸附前后的变化，从而进一步了解吸附过程。

结论：1. 化学吸附是 Hg 原子与 1T-MoS2 单层吸附的主导因素。同时，在所有可能的吸附位置中，T Mo（在钼原子上方）的位置是最强烈的吸附构型。2. 汞（Hg）原子在 1T-MoS2 单层上的吸附受邻近的硫（S）和钼（Mo）原子的影响。3. 吸附的汞（Hg0）原子在 1T-MoS2 的 T Mo 位置上会被氧化，其吸附能为 −1.091 eV。4. 从局部态密度（PDOS）分析来看，Hg 原子和 1T-MoS2 表面之间的相互作用是由汞（Hg）原子的 d 轨道与硫（S）原子的 s 轨道及钼（Mo）原子的 p 轨道和 d 轨道重叠所致。

关键词：单层 1T-MoS2；汞捕捉；吸附机制；密度泛函理论（DFT）