



Computational investigation on interaction of magnesium ion and cyclen  
การคำนวณเกี่ยวกับอันตรกิริยาของแมกนีเซียมไอออนและสารประกอบไซคลิน



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### Abstract

B3LYP/6-311++G(d,p)-optimized structures of cyclen (1,4,7,10-tetraazacyclododecane) complex with magnesium ion (Mg/cyclen complex) and its interaction complexes with water, chloride ion and nitrate ions were obtained. Each of all complexes are composed of six conformations. Relative energies and formation energies for all studied complexes were calculated. The Mg/cyclen complex with high symmetry interacting with two water molecules with chloride ion lead to the MD (molecular dynamics) simulation of which comprises 500 water molecules, one cyclen, one magnesium ion and two chloride ions compared with the same simulation condition without cyclen ligand. Radial distribution functions of atoms of waters with magnesium and chloride ions were computed and analyzed. Two water molecules solvation with  $Mg^{2+}$  ion of the Mg/cyclen complex at above and below  $Mg^{2+}$  ion along its principal axis. Chloride ion solvated with six water molecules was found and distorted octahedral as the possible solvation structure was expected.

**Keywords:** Magnesium cyclen complexes, DFT, DFTB , macrocyclic, radial distribution function, MD simulation

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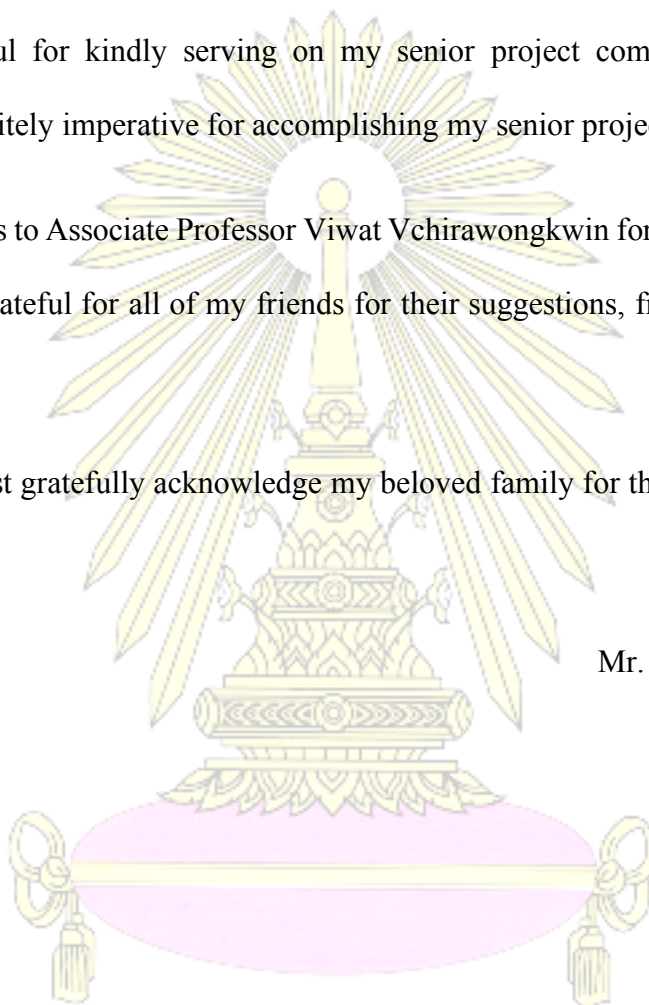
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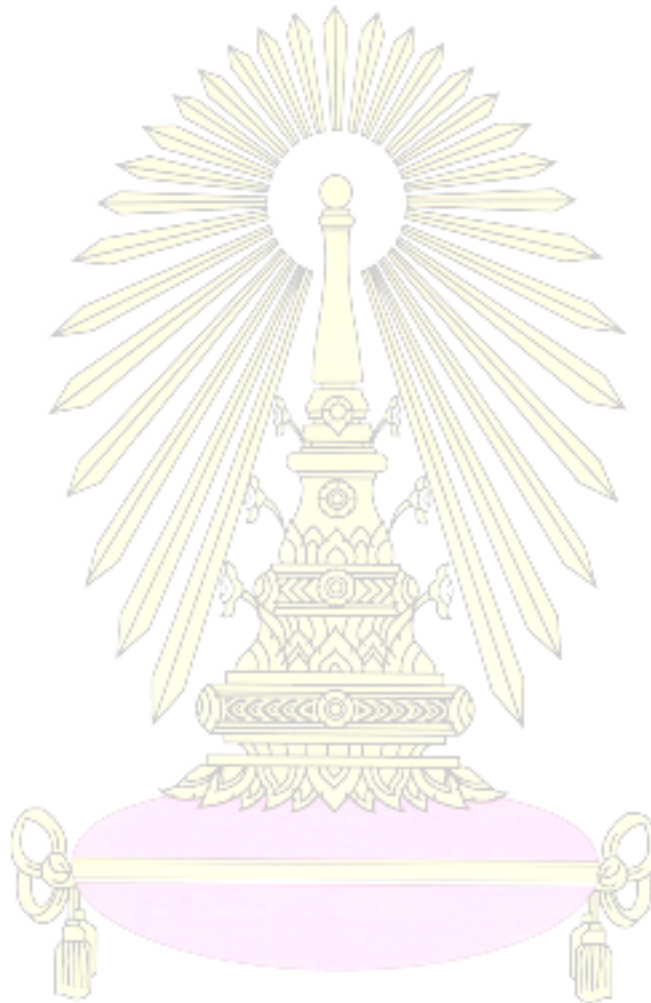
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## CHAPTER I

### INTRODUCTION

#### 1.1 Background and Literature review

1,4,7,10-tetraazacyclododecane (Cyclen) is a macrocycle and the aza analogue of the crown ether, 12-crown-4. The availability of crown ethers possessing various sizes of an intramolecular cavity permits highly selective chelation of cations of matching size, including all existing alkali metal ions. Several theoretical studies on the alkali earth metal ion complexes with cyclen were performed in order to reveal energetic and hydration related effects contributing to macrocyclic effect and the stabilization energies of these complexes<sup>1-4</sup>. The hydration of the magnesium/cyclen complex studies of a molecular dynamics (MD) simulations based on the assumption of additivity of ion-water and complex-water potentials. Bhakhoa<sup>5</sup> studied the geometric and electronic structures of the alkali metal azide-cyclen  $[M(\text{cyclen})\text{N}_3]$  complexes using density functional theory (DFT). The effects of adding a second cyclen ring to form the sandwich give two structures are end-on and side-on. For all the alkali metals, the  $\text{N}_3$ -side-on structure was lowest in energy. Addition of a second cyclen unit to  $[M(\text{cyclen})\text{N}_3]$  to form the sandwich compounds  $[M(\text{cyclen})_2\text{N}_3]$  causes the bond strength between the metal and the  $\text{N}_3$  unit to decrease. Bouazizi<sup>6</sup> studied MD simulations on sodium chloride solutions in water-methanol mixtures under ambient conditions with methanol mole fractions ranging from 0.09 to 0.87. MD simulations were performed with the flexible SPC water model and the flexible six-site model for methanol. The ions were modeled as charged Lennard-Jones spheres. The structural properties of the solutions were discussed on the basis of radial distribution functions. Gong<sup>7</sup> developed a coarse-grained force field (CGFF) for  $\text{MgCl}_2$  and  $\text{CaCl}_2$  aqueous solutions. The ions were modeled by CG beads with characteristics

of hydration shells. The result CGFF accurately reproduces experimental osmotic coefficients, densities, surface tensions, and cation-anion separations of calcium chloride and magnesium chloride solutions at molalities up to 3.0 mol/kg.

Density-functional tight-binding (DFTB) is a semi-empirical method which based on density-functional theory (DFT). DFTB is therefore an appropriate method for calculations in large system compound with the DFT method.

In the present work, interactions of magnesium/cyclen and hydration of magnesium/cyclen have been studied using DFT for structure optimizations of related compounds and DFTB for MD simulations.

## 1.2 Theoretical background

Quantum chemical calculation has been used to calculate structures, properties and interaction of molecules<sup>8</sup>. Density-functional tight-binding (DFTB), one of quantum mechanics method based on density functional theory was employed to calculate in the present work.

### 1.2.1 Ab initio method

Ab initio calculation methods<sup>9</sup> are method of computational chemistry based on quantum mechanics. This method associate with Schrödinger equation as shown in equation

$$-\frac{\hbar^2}{2m}\nabla^2\Psi(r,t) + V(r)\Psi(r,t) = i\hbar\frac{\partial\Psi(r,t)}{\partial t} \quad (1.1)$$

$\hbar = \frac{h}{2\pi}$  and h is Planck's constant, m is particle's mass.  $\nabla^2$  is the Laplacian's operator which is given by  $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$  in Cartesian coordinates.  $V(r)$  is the potential energy function and  $\Psi(r,t)$  is a time-dependent wave function.

This equation needs the same time and position independent constants to resolve. The constant could be energy of the particle, the left-hand side of the equation is thus set equal to the constant. After the modification of equation (1.1), yields in equation (1.2).

$$-\frac{\hbar^2}{2m}\nabla^2\Psi(r) + V(r)\Psi(r) = E\Psi(r) \quad (1.2)$$

The time-independent Schrödinger equation, which depends on position. The left-hand side is the Hamiltonian operator

$$\hat{H}\Psi(r) = E\Psi(r) \quad (1.3)$$

where

$$\hat{H} = -\frac{\hbar^2}{2m} + V(r) \quad (1.4)$$

## 1.2.2 Density functional theory (DFT) method

Density functional theory (DFT) methods are constructed by the Hohenberg-Kohn (HK) theorems<sup>10</sup>. The HK theorems make the electronic density as variable to electronic-structure calculations and the energy of a molecule is obtained from electron density instead of a wave function.

### 1.2.2.1 Kohn-Sham equations

Kohn and Sham method was used to solve the problem of interacting electrons onto a fictitious system of non-interacting electrons<sup>11</sup>. The solution starts from using mono-electronic orbitals to calculate the kinetic energy. In a system of N non-interacting electrons and the external potential  $v_s$  with Hamiltonian.

$$\hat{H}_s = \sum_i^N \frac{1}{2} \nabla_i^2 + \sum_i^N V_s(\vec{r}_i) = \sum_i^N \hat{h}_s \quad (1.5)$$

where

$$\hat{h}_s = -\frac{1}{2}\nabla_i^2 + v_s(\vec{r}_i) \quad (1.6)$$

In which there are no electron repulsion terms and electronic density is exactly the same as in the system of interacting electrons. All electronic densities for the system of the single particle orbital  $\Psi_i(\vec{r})$  can be written as

$$\rho(\vec{r}) = \sum_i^N |\Psi_i(\vec{r})|^2 \quad (1.7)$$

And the Hohenberg-Kohn functional can be written as

$$F_{HK}[\rho] = T_s[\rho] + J[\rho] + E_{xc}[\rho] \quad (1.8)$$

$T_s$  is the kinetic-energy functional, given by

$$T_s[\rho] = \sum_i^N \langle \Psi_i | -\frac{1}{2}\nabla_i^2 | \Psi_i \rangle \quad (1.9)$$

$J$  is the classic Coulomb interaction functional

$$J[\rho] = \frac{1}{2} \iint \frac{\rho(\vec{r})\rho(\vec{r}')}{|\vec{r} - \vec{r}'|} d\vec{r}d\vec{r}' \quad (1.10)$$

$E_{xc}$  is exchange-correlation functional, which defined by the difference between the exact kinetic energy  $T$  and  $T_s$  and the between the non-classic part of the Coulomb interaction ( $V_{ee}$ ) and the classic Coulomb interaction.

$$E_{xc}[\rho] = T[\rho] - T_s[\rho] + V_{ee}[\rho] - J[\rho] \quad (1.11)$$

And the chemical potential can be written as

$$\mu = V_{KS}(\vec{r}) + \frac{\delta T_s[\rho]}{\delta \rho(\vec{r})} \quad (1.12)$$

$V_{KS}$  is the Kohn-Sham effective potential, which is defined as

$$V_{KS}(\vec{r}) = V_{ext}(\vec{r}) + \frac{\delta J[\rho]}{\delta \rho(\vec{r})} + \frac{\delta E_{xc}[\rho]}{\delta \rho(\vec{r})} = V_{ext}(\vec{r}) + \int \frac{\rho(\vec{r}')}{|\vec{r} - \vec{r}'|} d\vec{r}' + V_{xc}(\vec{r}) \quad (1.13)$$

$V_{KS}$  is the external potential and the exchange-correlation potential  $V_{KS}$  is defined as



$$V_{xc}(\vec{r}) = \frac{\delta E_{xc}[\rho]}{\delta \rho(\vec{r})} \quad (1.14)$$

The total energy can be calculated by the following expression

$$E[\rho] = \sum_i^N n_i \langle \psi_i | -\frac{1}{2} \nabla^2 + V_{ext}(\vec{r}) + \frac{1}{2} \int \frac{\rho(\vec{r}')}{|\vec{r} - \vec{r}'|} d\vec{r}' | \psi_i \rangle + E_{xc}[\rho] + \frac{1}{2} \sum_{\beta}^N \sum_{\alpha \neq \beta}^N \frac{Z_{\alpha} Z_{\beta}}{|\vec{R}_{\alpha} - \vec{R}_{\beta}|} \quad (1.15)$$

### 1.2.3 Density-functional tight-binding (DFTB) method

DFTB can be derived from a Taylor expansion of the Kohn-Sham density functional total energy around a suitably chosen reference density  $\rho(r)$ . A reference  $\rho^0(r)$  is perturbed by density fluctuation.

$$\rho(r) = \rho^0(r) + \delta\rho(r) \quad (1.16)$$

The exchange-correlation energy functional is expanded in a Taylor series and the total energy can be written as

$$E^{DFTB3}[\rho^0 + \delta\rho] = E^0[\rho_0] + E^1[\rho_0, \delta\rho] + E^2[\rho_0, (\delta\rho)^2] + E^3[\rho_0, (\delta\rho)^3] \quad (1.17)$$

#### 1.2.3.1 DFTB1

DFTB1 or non-self-consistent DFTB (non-SCC DFTB) consist of two terms of equation (1.17),  $E^0[\rho_0]$  and  $E^1[\rho_0, \delta\rho]$  that DFTB1 is based on linear combination of atomic orbital (LCAO) ansatz of the KS orbitals.

$$\psi_i = \sum_{\mu} c_{\mu i} \phi_{\mu} \quad (1.18)$$

The AOs are obtained from DFT calculations of the corresponding atoms. The basis is restricted to the valence shell of the atoms. Such restriction requires an orthogonalization to the core orbitals of the atoms, which can be achieved by a Schmidt orthogonalization.

$$|\phi_{\mu}\rangle = |\phi_{\mu}\rangle - \sum_{b \neq a} \sum_k |\phi_k^b\rangle (\phi_k^b | \phi_{\mu}\rangle), \quad \mu \in \{a\} \quad (1.19)$$

where  $|\phi_{\mu}\rangle$  is the valence AO  $\mu$  at atom  $a$  and  $|\phi_k^b\rangle$  is a core orbital at atom  $b$ , as obtained from the corresponding atomic calculations.

Pure AOs would be too diffuse for a minimal AO basis set; therefore, the atomic KS equations are usually solved applying an additional (harmonic) potential to the atomic KS equations.

$$\left[ -\frac{1}{2}\nabla^2 + v^{eff}[\rho^{atom}] + \left(\frac{r}{r_0}\right)^2 \right] \phi_\mu = \epsilon_\mu \phi_\mu \quad (1.20)$$

Now, with AO basis and initial density determined, the KS equations can be solved leading to the energy ( $n_i$ : occupation number of KS orbital  $i$ ).

$$E^1 = \sum_i n_i \sum_{\mu\nu} c_\mu^i c_\nu^i H_{\mu\nu}^0 = \sum_i n_i \epsilon_i \quad (1.21)$$

This is the electronic energy of the DFTB method, i.e. the sum of the occupied KS energies. To get an expression for the total energy, the  $E^0$  term has to be approximated.  $E^0[\rho_0]$  consists of the DFT ‘double counting’ contributions in the first line of equation (1.17) and depends only on the reference density  $\rho_0$ , i.e. the superposition of the neutral atomic densities. In DFTB, this term is approximated by a sum of pair potentials called repulsive energy term.

$$E^0[\rho_0] \approx E_{rep} = \frac{1}{2} \sum_{ab} V_{ab}^{rep} \quad (1.22)$$

The total energy then reads

$$E^{DFTB1} = \sum_i n_i \epsilon_i + \frac{1}{2} \sum_{ab} V_{ab}^{rep} \quad (1.23)$$

### 1.2.3.2 DFTB2

DFTB2 approximates the  $E^2$  term in equation (1.17) further. First, the density fluctuations are written as a superposition of atomic contributions.

$$\delta\rho = \sum_a \delta\rho_a \quad (1.24)$$

and second, the atomic-like density fluctuations are expanded in a multipole expansion, however, only keeping the monopole term.

$$\delta\rho_a = \Delta q_a F_{00}^a \gamma_{00} \quad (1.25)$$

By evaluated assuming an exponentially decaying charge density

$$\delta\rho_a \approx \Delta q_a \frac{\tau_a^3}{8\pi} e^{-r_a|r-R_0|} \quad (1.26)$$

$E^2$  in (1.17) is defined as

$$E^2(\tau_a, \tau_b, R_{ab}) = \frac{1}{2} \sum_{ab} \Delta q_a \Delta q_b \gamma_{ab}(\tau_a, \tau_b, R_{ab}) \quad (1.27)$$

The Hartree term therefore describes the interaction of the charge density fluctuations  $\delta\rho_a$  and  $\delta\rho_b$ , which reduces to a Coulomb interaction of partial charges  $\Delta q_a$  and  $\Delta q_b$  for large distances, i.e.  $\gamma_{ab}$  approaches  $1/R_{ab}$  for large distances.

### 1.2.3.3 DFTB3

For  $E^3$ , the same approximations are introduced as for  $E^2$ . The third-order terms describe the change of the chemical hardness of an atom with its charge state, i.e. in the third order, a new parameter is introduced, the chemical hardness derivative  $U_a^d$ . This parameter can be computed from DFT or fitted in order to improve the performance of the model. A function  $\Gamma_{ab}$  results as the derivative of the  $\gamma$ -function with respect to charge by introducing the Hubbard derivative parameter. In that way, the third-order terms within SCC-DFTB can be rather seen as a robust way to introduce the charge dependence capturing some deficiencies of problematic approximations within the second-order formalism, namely, the small size of the pseudo-AO basis as well as the very simplified density fluctuation scheme.

All these approximations, the SCC-DFTB total energy in the third-order is given by

$$E^{DFTB3} = \sum_{iab} \sum_{\mu \in a} \sum_{\nu \in b} n_i c_{\mu i} c_{\nu i} H_{\mu\nu}^0 + \frac{1}{2} \sum_{ab} \Delta q_a \Delta q_b \gamma_{ab}^h + \frac{1}{3} \sum_{ab} \Delta q_a^2 \Delta q_b \Gamma_{ab} + \frac{1}{2} \sum_{ab} V_{ab}^{rep} \quad (1.28)$$

## 1.2.4 Molecular dynamics (MD) simulation

Molecular dynamics (MD) simulations are useful method to study in physical chemistry. Because, the time evolution of chemical system and many phenomena such as chemical reactions, diffusion described by MD simulation. MD simulations can be calculated by molecular mechanics (MM), quantum mechanics (QM) and hybrid of QM and MM (QQ/MM)<sup>12-14</sup>.

### 1.2.4.1 Canonical (NVT) ensemble

In the canonical ensemble, the quantities of substance (N), volume (V) and temperature (T) are preserved. In NVT ensemble, the energies of endothermic and exothermic processes are exchange with a thermostat<sup>15</sup>.

### 1.2.4.2 Berendsen thermostat

In Berendsen thermostat, the system is weakly coupled to a heat bath with some temperature. The thermostat suppresses fluctuations of the kinetic energy of the system and therefore cannot produce trajectories consistent with the canonical ensemble. The temperature of the system is corrected such that the deviation exponentially decays with some time constant<sup>16</sup>.

## 1.3 Objective

In this work, Studying macrocyclic effect and the stabilization of magnesium/cyclen complex in the hydration of magnesium/cyclen complex by using DFTB and DFTB/MD methods.

## CHAPTER II

### COMPUTATIONAL DETAILS

#### 2.1 DFT energy of magnesium/cyclen complex

Structure optimizations of all related species were performed with the GAUSSIAN 09 using B3LYP/6-311++G(d,p) method. The molecular graphics of all related compounds were generated with the MOLEKEL 4.3 program<sup>17</sup>.

#### 2.2 MD simulations

Full optimizations of magnesium/cyclen complex were carried out using DFTB method. The optimizations of magnesium/cyclen complex show 4 systems that consist of complex-system, chloride-system, hydrated-system and nitrate-system. Molecular dynamics simulation was used to simulate the hydration of chloride-system. All calculations were performed with DFTB+ version 1.3 program<sup>18</sup>.

#### 2.3 The radial distribution function (RDF)

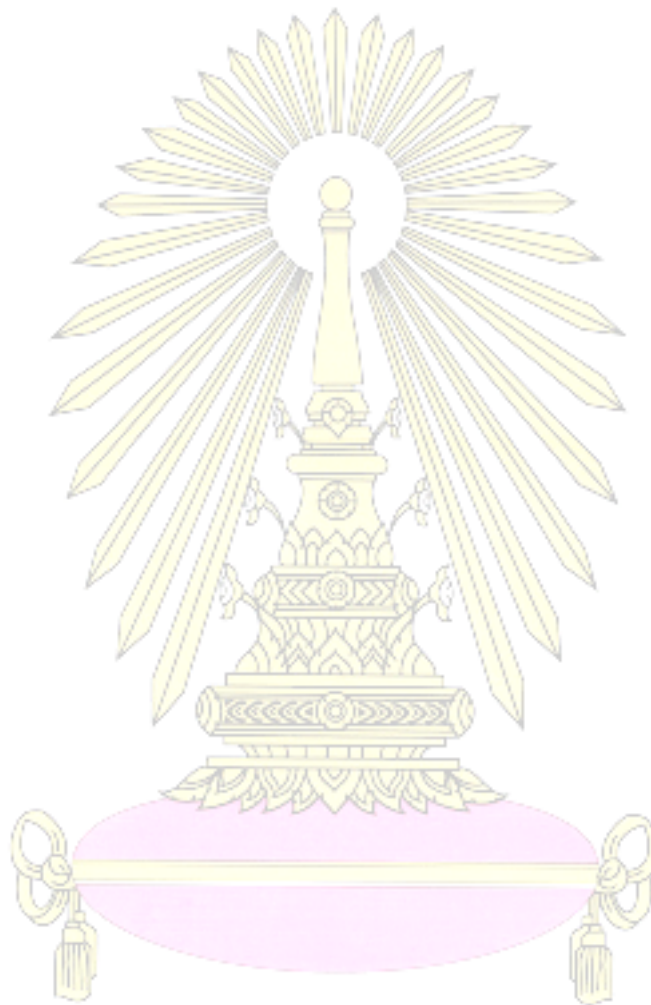
The radial distribution function (RDF) represents by  $g(r)$ . For a system of  $N$  atoms in a volume  $V$  (with number density  $\rho$ ), RDF is defined by the expression

$$\rho g(r) = \frac{1}{N} \left\langle \sum_{i=1}^N \sum_{j \neq i}^N \delta(r - r_{ij}) \right\rangle \quad (2.2)$$

where the bracket indicates time average and  $r_{ij}$  is the distance between atoms  $i$  and  $j$ . If we explicitly consider the time average over the total of  $M$  time steps,  $t_k$  in the MD, we have

$$g(r) = \frac{\sum_{k=1}^M N_k(r, \Delta r)}{M \left(\frac{1}{2}N\right) \rho V(r, \Delta r)} \quad (2.3)$$

where  $N(r, \Delta r)$  and  $V(r, \Delta r)$  are the number of local atoms and volume between the spherical shells of radius  $r$  and  $(r + \Delta r)$  with the shell centered on another atom.

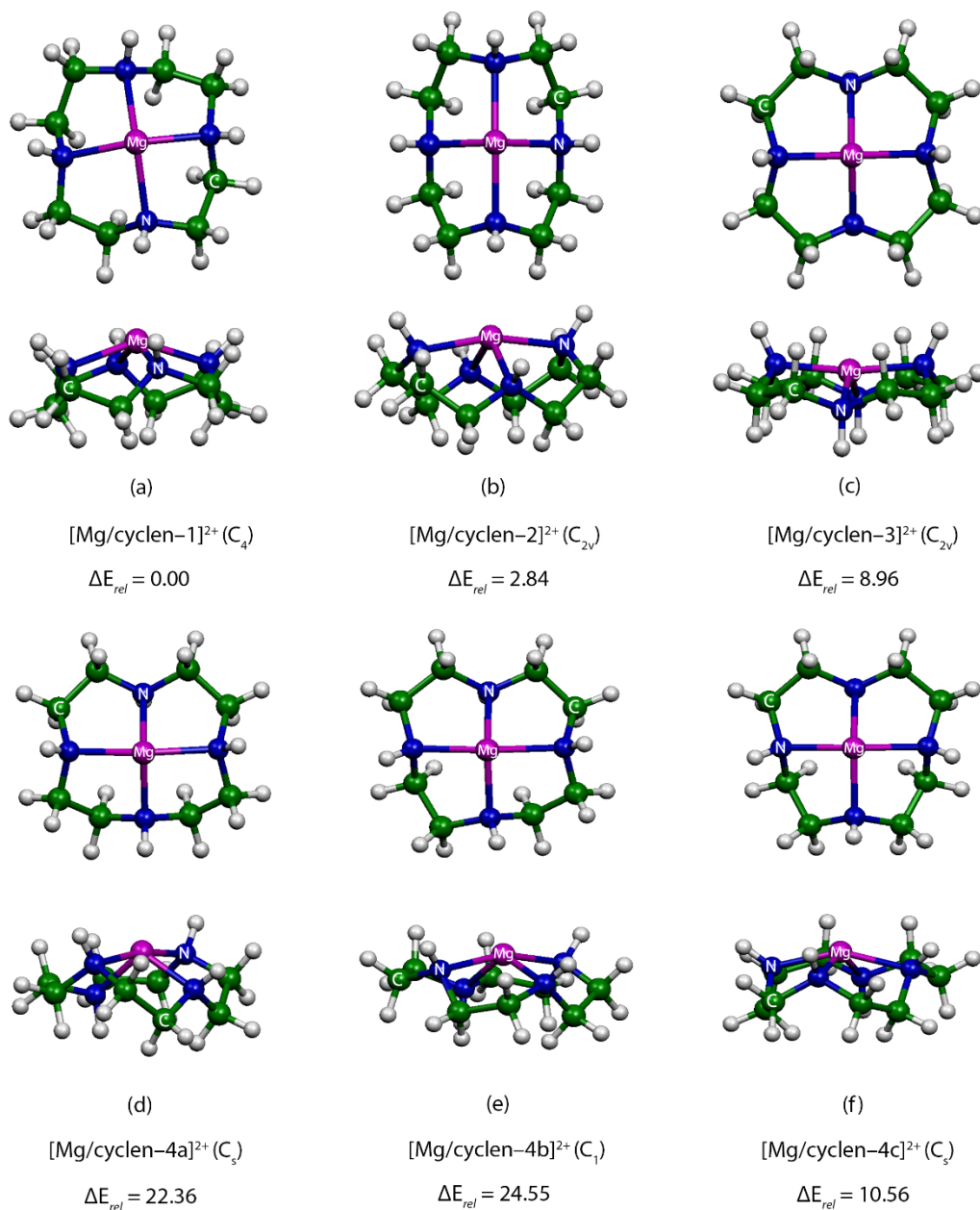


## CHAPTER III

### RESULTS AND DISCUSSIONS

#### 3.1 The optimized structures of Mg/cyclen complexes

The full optimizations of cyclen (1,4,7,10-tetraazacyclododecane) complex with magnesium ion (Mg/cyclen complex) and its interaction complexes with water and anions were carried out with GAUSSIAN 09 using B3LYP/6-311++G(d,p) method. Six conformations of Mg/cyclen complexes were obtained and their structures are shown in Figure 3.1. Total and relative energies of six conformations of Mg/cyclen complexes, computed at B3LYP/6-311++G(d,p) level of theory, are shown in Table 3.1. The [Mg/cyclen-1]<sup>2+</sup> was found to be the most stable conformation and was slightly different from the [Mg/cyclen-2]<sup>2+</sup> of which relative energy ( $\Delta E_{\text{rel}} = 2.84 \text{ kcal mol}^{-1}$ ) was a little bit higher than the [Mg/cyclen-1]<sup>2+</sup>. Figure 3.1 shows that the first three conformations labeled with numbers 1, 2 and 3, are symmetry point groups of  $C_4$ ,  $C_{2v}$ ,  $C_{2v}$ , respectively. The last three conformations labeled with numbers 4a, 4b and 4c, have no symmetry ( $C_1$ ) due to the water molecule interacting at bottom of their molecules are unsymmetrical image. It can be concluded that the first three conformations are all dominant species, but the last three conformations are hardly present in gas phase.

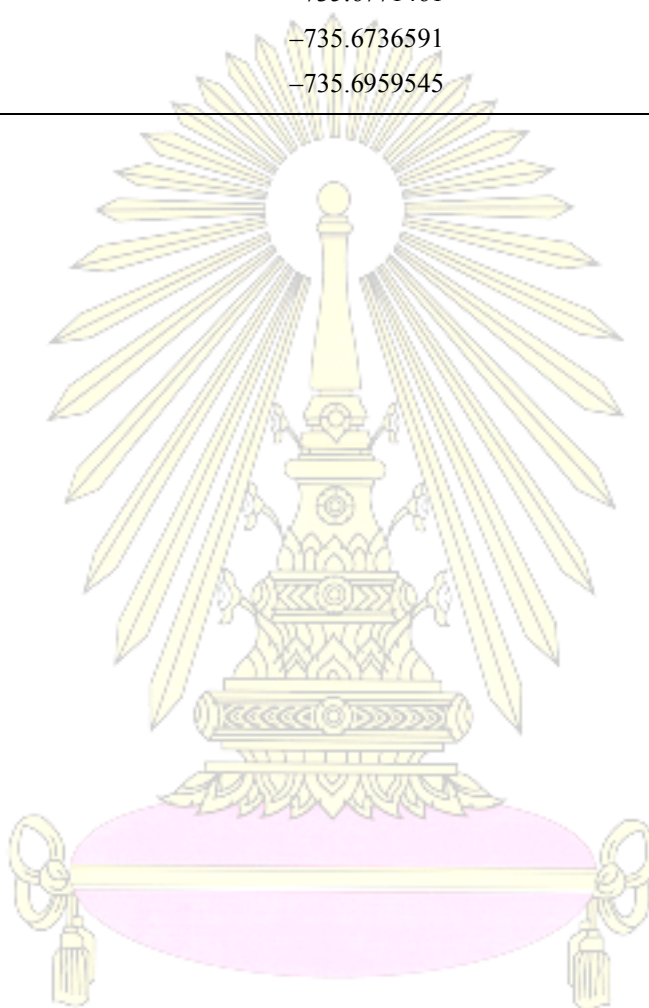


**Figure 3.1** Six conformations of Mg/cyclen complexes. Top and bottom images are top and side views, respectively. The relative energies ( $\Delta E_{\text{rel}}$ ) are in  $\text{kcal mol}^{-1}$ .



**Table 3.1** Total and relative energies of six conformations of Mg/cyclen complexes, computed at B3LP/6-311++G(d,p) level of theory

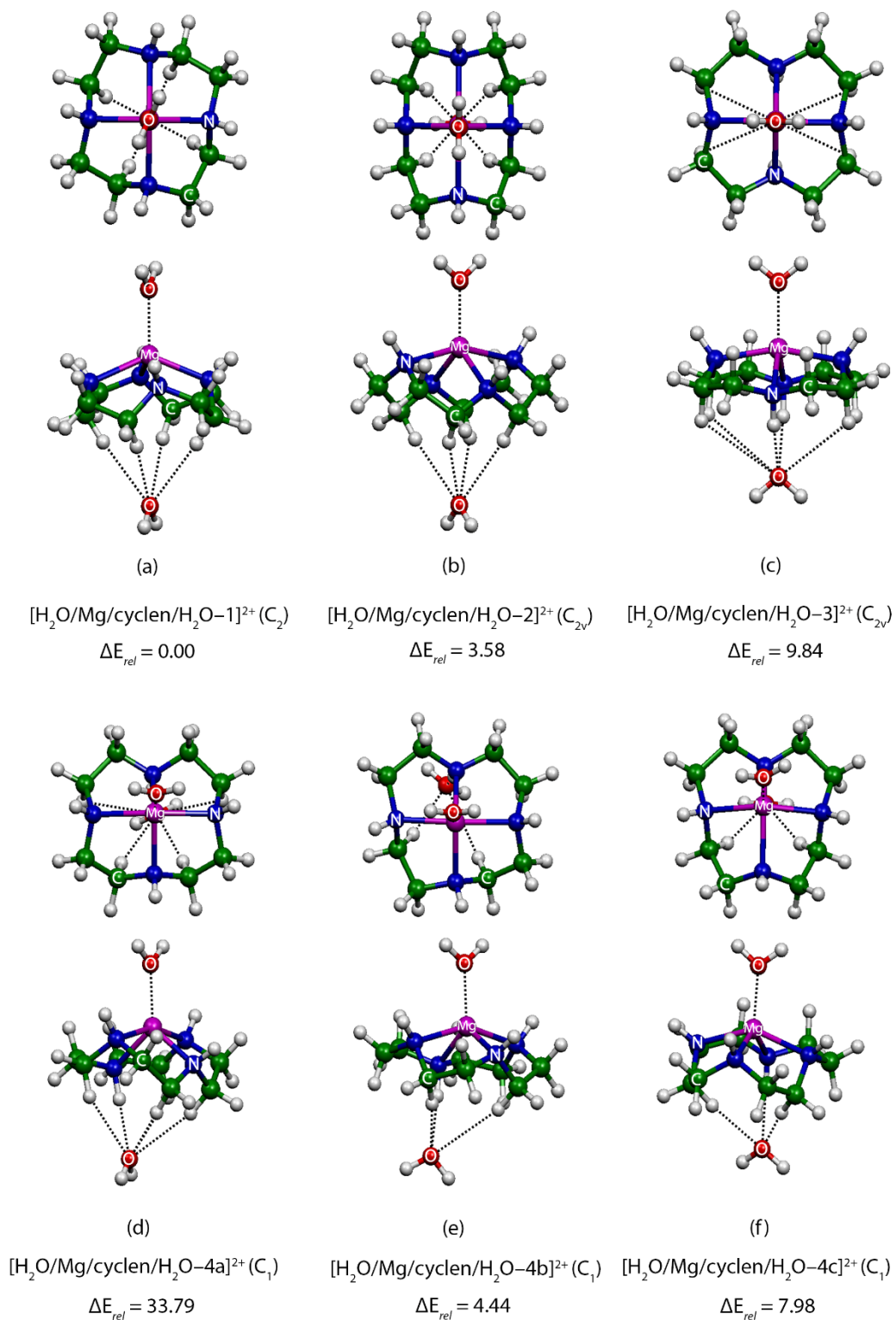
Compounds/ conformers	$E_{\text{total}}$ , au	$\Delta E_{\text{rel}}$ , kcal mol <sup>-1</sup>
<b>[Mg/cyclen]<sup>2+</sup>:</b>		
[Mg/cyclen-1] <sup>2+</sup>	-735.7127989	0.00
[Mg/cyclen-2] <sup>2+</sup>	-735.7082746	2.84
[Mg/cyclen-3] <sup>2+</sup>	-735.6985153	8.96
[Mg/cyclen-4a] <sup>2+</sup>	-735.6771461	22.36
[Mg/cyclen-4b] <sup>2+</sup>	-735.6736591	24.55
[Mg/cyclen-4c] <sup>2+</sup>	-735.6959545	10.56



### 3.2 The optimized structures of Mg/cyclen complex with water

B3LYP/6-311++G(d,p)-optimized structures of Mg/cyclen complex with water ( $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}]^{2+}$ ) are shown in Figure 3.2. Total and relative energies of six conformations of complexes of Mg/cyclen with two water molecules are shown in Table 3.2. The  $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}-3]^{2+}$  was found to be the highest symmetry ( $C_{2v}$ ). The  $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}-1]^{2+}$  was found. Formation energies ( $\Delta E_f$ ) of various conformations of Mg/cyclen complexes with two water molecules are shown in Table 3.3. The formation abilities based on formation energies of all conformations of complexes of Mg/cyclen with two water molecules are in order:  $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}-4b]^{2+}$  ( $\Delta E_f = -67.55 \text{ kcal mol}^{-1}$ )  $\gg$   $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}-4c]^{2+}$  ( $\Delta E_f = -50.02 \text{ kcal mol}^{-1}$ )  $>$   $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}-1]^{2+}$  ( $\Delta E_f = -47.42 \text{ kcal mol}^{-1}$ )  $\sim$   $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}-2]^{2+}$  ( $\Delta E_f = -46.69 \text{ kcal mol}^{-1}$ )  $\sim$   $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}-3]^{2+}$  ( $\Delta E_f = -46.55 \text{ kcal mol}^{-1}$ )  $\gg$   $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}-4a]^{2+}$  ( $\Delta E_f = -36.01 \text{ kcal mol}^{-1}$ ).

Based on the most stable, second and third most conformations of Mg/cyclen complexes (types 1, 2 and 3) which are symmetric structures, the hydration energies by two water molecules were found in the range of  $-47.42$  to  $-46.55 \text{ kcal mole}^{-1}$ . Their upper water bound to Mg/cyclen, mainly interact with  $\text{Mg}^{2+}$  ion but their lower water, mainly interact with hydrogen atoms of the cyclen.



**Figure 3.2** Six conformations of Mg/cyclen complexes with two water molecules. Top and bottom images are top and side views, respectively. The relative energies ( $\Delta E_{\text{rel}}$ ) are in kcal mol<sup>-1</sup>.

**Table 3.2** Total and relative energies of six conformations of Mg/cyclen complexes with two water molecules, computed at B3LP/6–311++G(d,p) level of theory

Compounds/ conformers	$E_{\text{total}}$ , au	$\Delta E_{\text{rel}}$ , kcal mol <sup>-1</sup>
[H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–1] <sup>2+</sup>	–888.7054360	0.00
[H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–2] <sup>2+</sup>	–888.6997373	3.58
[H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–3] <sup>2+</sup>	–888.6897512	9.84
[H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–4a] <sup>2+</sup>	–888.6515945	33.79
[H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–4b] <sup>2+</sup>	–888.6983660	4.44
[H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–4c] <sup>2+</sup>	–888.6927203	7.98

**Table 3.3** Formation energies ( $\Delta E_f$ ) of various conformations of Mg/cyclen complexes with two water molecules

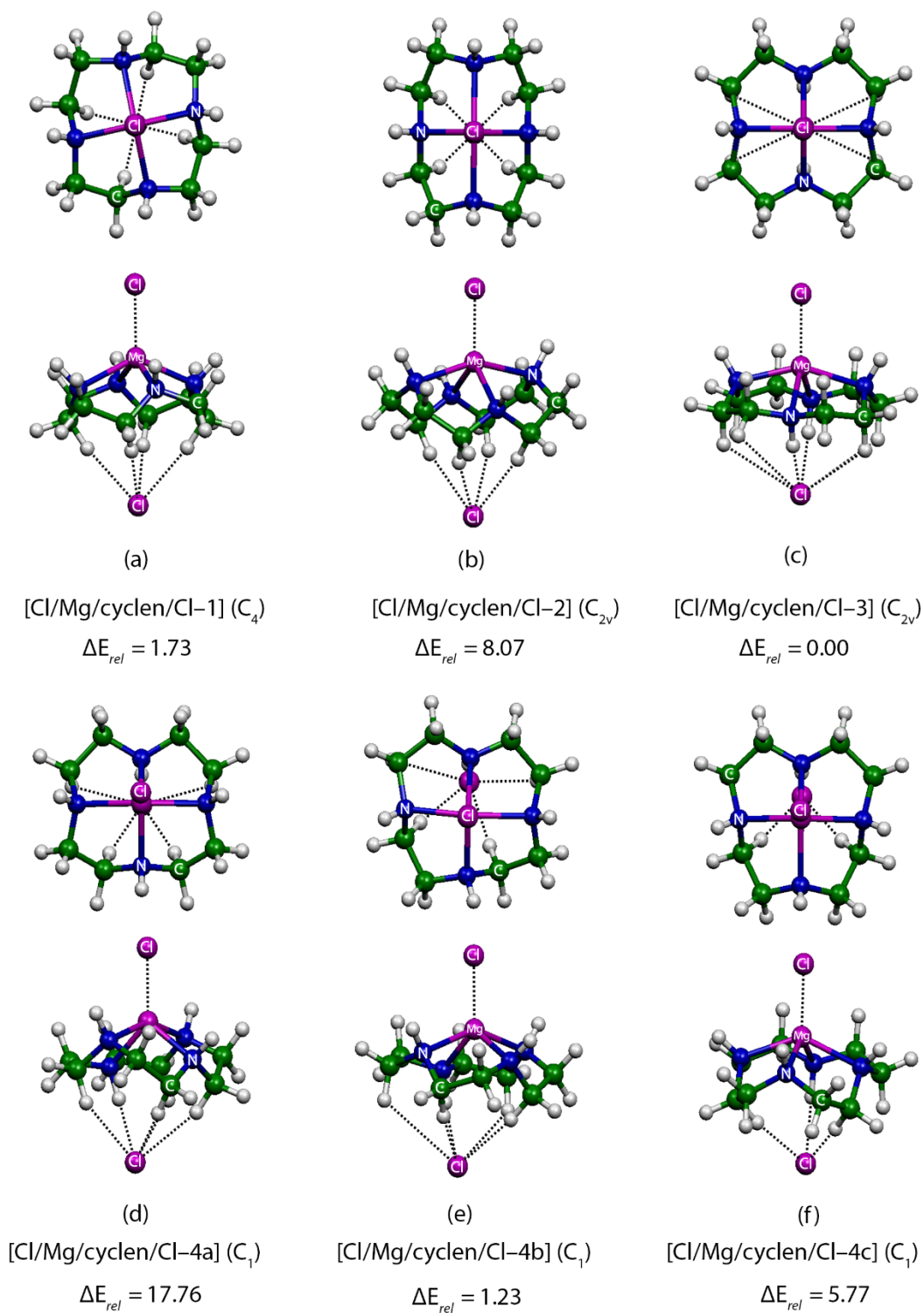
Complexations	$\Delta E_f$ , kcal mol <sup>-1</sup>
[Mg/cyclen–1] <sup>2+</sup> + 2H <sub>2</sub> O → [H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–1] <sup>2+</sup>	–47.42
[Mg/cyclen–2] <sup>2+</sup> + 2H <sub>2</sub> O → [H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–2] <sup>2+</sup>	–46.69
[Mg/cyclen–3] <sup>2+</sup> + 2H <sub>2</sub> O → [H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–3] <sup>2+</sup>	–46.55
[Mg/cyclen–4a] <sup>2+</sup> + 2H <sub>2</sub> O → [H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–4a] <sup>2+</sup>	–36.01
[Mg/cyclen–4b] <sup>2+</sup> + 2H <sub>2</sub> O → [H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–4b] <sup>2+</sup>	–67.55
[Mg/cyclen–4c] <sup>2+</sup> + 2H <sub>2</sub> O → [H <sub>2</sub> O/Mg/cyclen/H <sub>2</sub> O–4c] <sup>2+</sup>	–50.02

### 3.3 The optimized structures of Mg/cyclen complex with anions

#### 3.3.1 The Mg/cyclen complex with chloride ions

B3LYP/6-311++G(d,p)-optimized structures of Mg/cyclen complex with two chloride ions ( $[\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl}]$ ) are shown in Figure 3.3. Total and relative energies of six conformations of complexes of Mg/cyclen with two chloride ions are shown in Table 3.4. The  $[\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl-3}]$ ,  $C_{2v}$  point group was found to be the most stable conformation. Formation energies of various conformations of Mg/cyclen complexes with two chloride ions are shown in Table 3.5. The formation abilities based on formation energies of all conformations of complexes of Mg/cyclen with two chloride ions are in order:  $[\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl-4b}] \gg [\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl-3}] > [\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl-4c}] > [\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl-4a}] > [\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl-1}] \sim [\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl-2}]$ .

As reactions between Mg/cyclen and two chloride ions to form  $[\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl}]$  complexes are neutralization, their formation energies were found to be very stable. Nevertheless, in very dilute solution of  $[\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl}]$  in aqueous solution, chloride ion and water molecule are competitive species to form their complexes with Mg/cyclen. Therefore, the MD simulation of the system containing Mg/cyclen, chloride ions and water molecules was relevant to be studied for determination of existing species between  $[\text{H}_2\text{O}/\text{Mg}/\text{cyclen}/\text{H}_2\text{O}]$  and  $[\text{Cl}/\text{Mg}/\text{cyclen}/\text{Cl}]$ . The next section is then the subtopic for the MD simulation using DFTB calculations.



**Figure 3.3** Six conformations of Mg/cyclen complexes with two chloride ions. Top and bottom images are top and side views, respectively. The relative energies ( $\Delta E_{rel}$ ) are in kcal mol<sup>-1</sup>.

**Table 3.4** Total and relative energies of six conformations of Mg/cyclen complexes with two chloride ions, computed at B3LP/6–311++G(d,p) level of theory

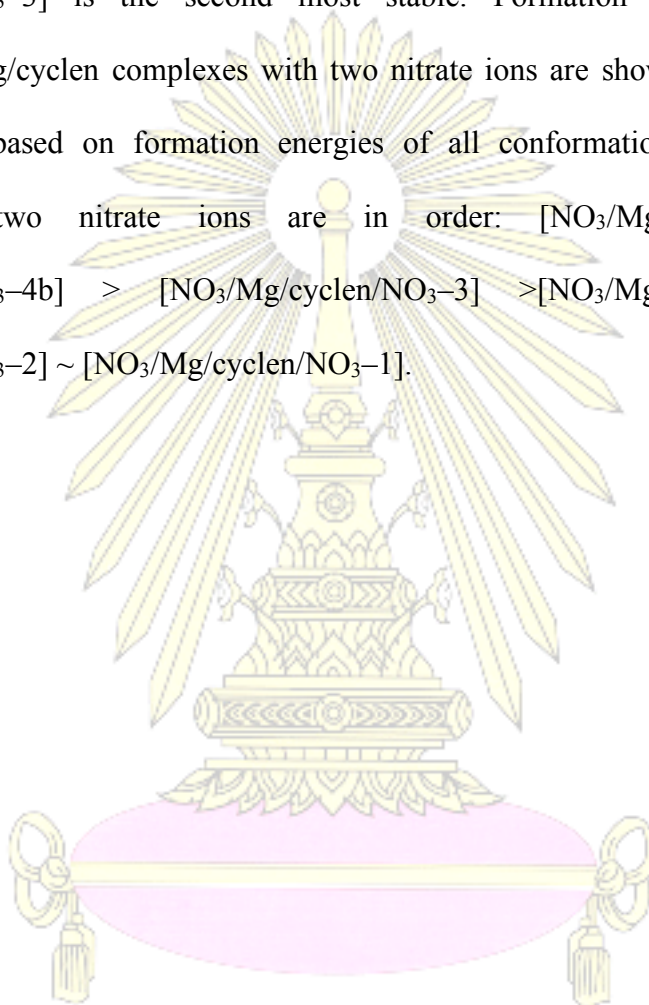
Compounds/ conformers	$E_{\text{total}}$ , au	$\Delta E_{\text{rel}}$ , kcal mol <sup>-1</sup>
[Cl/Mg/cyclen/Cl-1]	-1656.809918	1.73
[Cl/Mg/cyclen/Cl-2]	-1656.799815	8.07
[Cl/Mg/cyclen/Cl-3]	-1656.812682	0.00
[Cl/Mg/cyclen/Cl-4a]	-1656.784375	17.75
[Cl/Mg/cyclen/Cl-4b]	-1656.810722	1.23
[Cl/Mg/cyclen/Cl-4c]	-1656.803486	5.77

**Table 3.5** Formation energies ( $\Delta E_f$ ) of various conformations of Mg/cyclen complexes with two chloride ions

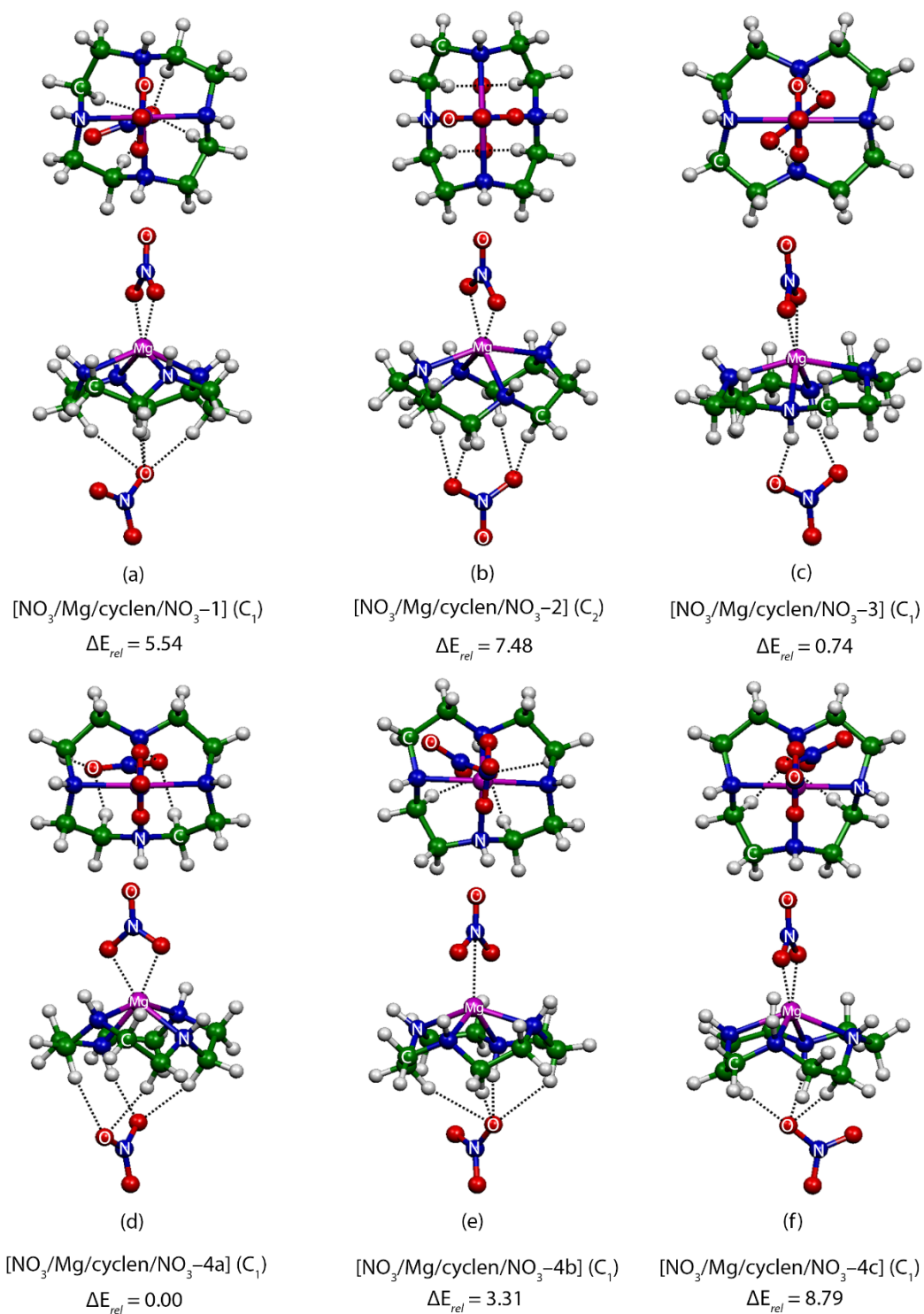
Complexations	$\Delta E_f$ , kcal mol <sup>-1</sup>
$[\text{Mg/cyclen-1}]^{2+} + 2\text{Cl}^- \rightarrow [\text{Cl/Mg/cyclen/Cl-1}]$	-307.27
$[\text{Mg/cyclen-2}]^{2+} + 2\text{Cl}^- \rightarrow [\text{Cl/Mg/cyclen/Cl-2}]$	-303.77
$[\text{Mg/cyclen-3}]^{2+} + 2\text{Cl}^- \rightarrow [\text{Cl/Mg/cyclen/Cl-3}]$	-317.97
$[\text{Mg/cyclen-4a}]^{2+} + 2\text{Cl}^- \rightarrow [\text{Cl/Mg/cyclen/Cl-4a}]$	-313.61
$[\text{Mg/cyclen-4b}]^{2+} + 2\text{Cl}^- \rightarrow [\text{Cl/Mg/cyclen/Cl-4b}]$	-332.33
$[\text{Mg/cyclen-4c}]^{2+} + 2\text{Cl}^- \rightarrow [\text{Cl/Mg/cyclen/Cl-4c}]$	-313.80

### 3.3.2 The Mg/cyclen complex with nitrate ions

B3LYP/6-311++G(d,p)-optimized structures of Mg/cyclen complex with two nitrate ions ( $[\text{NO}_3/\text{Mg}/\text{cyclen}/\text{NO}_3]$ ) are shown in Figure 3.4. Total and relative energies of six conformations of complexes of Mg/cyclen with two nitrate ions are shown in Table 3.6. The  $[\text{NO}_3/\text{Mg}/\text{cyclen}/\text{NO}_3\text{-4a}]$  was found to be the most stable conformation and the  $[\text{NO}_3/\text{Mg}/\text{cyclen}/\text{NO}_3\text{-3}]$  is the second most stable. Formation energies of various conformations of Mg/cyclen complexes with two nitrate ions are shown in Table 3.7. The formation abilities based on formation energies of all conformations of complexes of Mg/cyclen with two nitrate ions are in order:  $[\text{NO}_3/\text{Mg}/\text{cyclen}/\text{NO}_3\text{-4a}] > [\text{NO}_3/\text{Mg}/\text{cyclen}/\text{NO}_3\text{-4b}] > [\text{NO}_3/\text{Mg}/\text{cyclen}/\text{NO}_3\text{-3}] > [\text{NO}_3/\text{Mg}/\text{cyclen}/\text{NO}_3\text{-4c}] > [\text{NO}_3/\text{Mg}/\text{cyclen}/\text{NO}_3\text{-2}] \sim [\text{NO}_3/\text{Mg}/\text{cyclen}/\text{NO}_3\text{-1}]$ .







**Figure 3.4** Six conformations of Mg/cyclen complexes with two nitrate ions. Top and bottom images are top and side views, respectively. The relative energies ( $\Delta E_{\text{rel}}$ ) are in  $\text{kcal mol}^{-1}$ .

**Table 3.6** Total and relative energies of six conformations of Mg/cyclen complexes with two nitrate ions, computed at B3LP/6-311++G(d,p) level of theory

Compounds/ conformers	$E_{\text{total}}$ , au	$\Delta E_{\text{rel}}$ , kcal mol <sup>-1</sup>
[NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -1]	-1297.098246	5.53
[NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -2]	-1297.095141	7.48
[NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -3]	-1297.105891	0.74
[NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -4a]	-1297.107068	0.00
[NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -4b]	-1297.101785	3.31
[NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -4c]	-1297.093054	8.79

**Table 3.7** Formation energies ( $\Delta E_f$ ) of various conformations of Mg/cyclen complexes with two nitrate ions

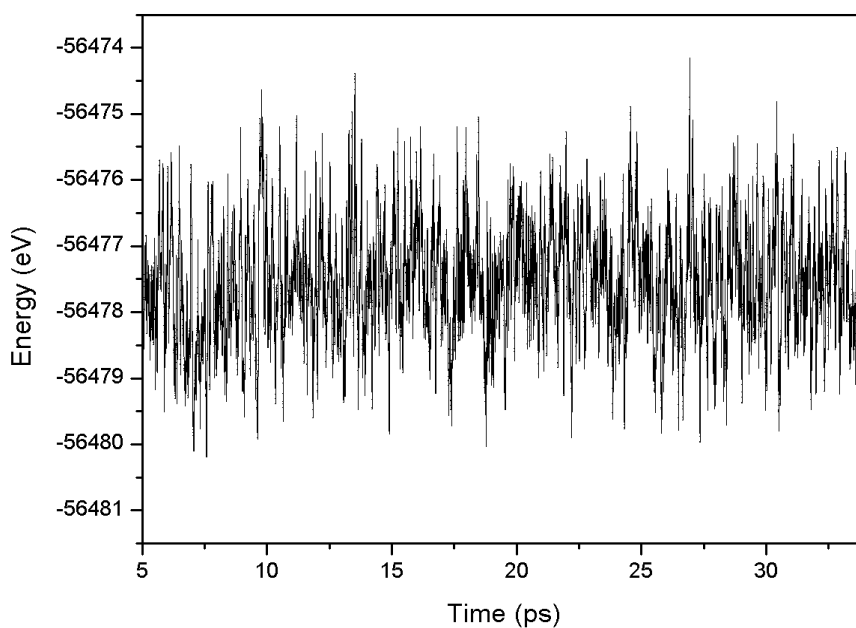
Complexations	$\Delta E_f$ , kcal mol <sup>-1</sup>
[Mg/cyclen-1] <sup>2+</sup> + 2NO <sub>3</sub> <sup>-</sup> → [NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -1]	-295.13
[Mg/cyclen-2] <sup>2+</sup> + 2NO <sub>3</sub> <sup>-</sup> → [NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -2]	-296.02
[Mg/cyclen-3] <sup>2+</sup> + 2NO <sub>3</sub> <sup>-</sup> → [NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -3]	-308.89
[Mg/cyclen-4a] <sup>2+</sup> + 2NO <sub>3</sub> <sup>-</sup> → [NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -4a]	-323.04
[Mg/cyclen-4b] <sup>2+</sup> + 2NO <sub>3</sub> <sup>-</sup> → [NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -4b]	-321.91
[Mg/cyclen-4c] <sup>2+</sup> + 2NO <sub>3</sub> <sup>-</sup> → [NO <sub>3</sub> /Mg/cyclen/NO <sub>3</sub> -4c]	-302.44

### 3.4 MD simulation of Mg/cyclen complexes in aqueous solution

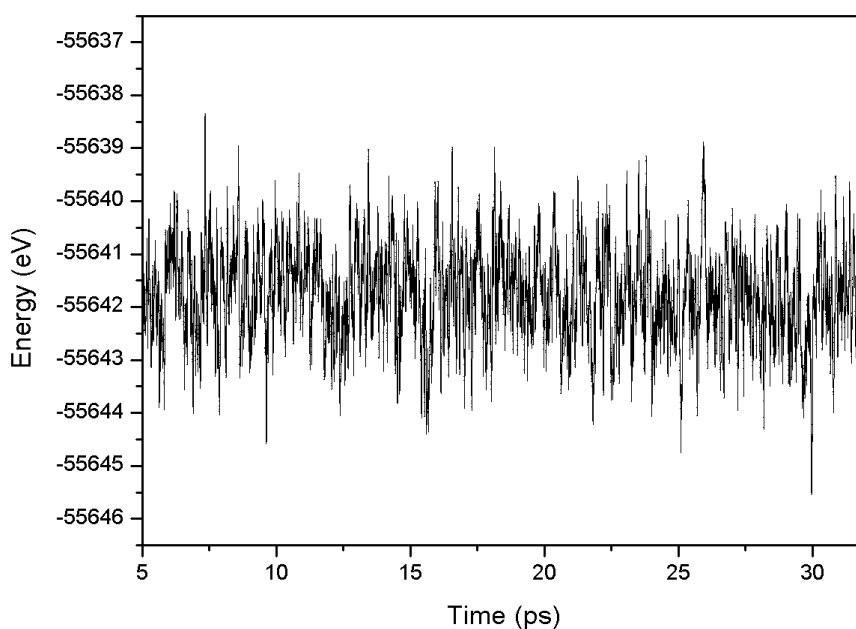
The MD simulation defined as a cubic box with size of  $24.9077 \times 24.9077 \times 24.9077 \text{ \AA}^3$ , based on the density of  $0.997044 \text{ g cm}^{-3}$  at  $298.15 \text{ K}$ ,  $1 \text{ atm}$ ; all parameters were computed as shown in Tables A1 and A2. All MD simulations based on the NVT ensemble using the Berendsen thermostat and calculated using non-SCC DFTB method were performed. The main MD simulation for study of solvation structure of Mg/cyclen complex, contains 500 molecules of water, one  $\text{Mg}^{2+}$ , two  $\text{Cl}^-$  ions and one cyclen molecule of  $[\text{Mg/cyclen-3}]^{2+}$  species. The second MD simulation of one  $\text{Mg}^{2+}$ , two  $\text{Cl}^-$  ions and 500 water molecules was performed to be used for comparison with the relevant MD simulation as mentioned above. The B3LYP/6-311++G(d,p) optimized structure of the Mg/cyclen complex with high symmetry ( $C_{2v}$ ),  $[\text{Mg/cyclen-3}]^{2+}$ , shown in Figure 3.1 (c), was selected to be fixed at the center of simulation box. The  $[\text{Mg/cyclen-3}]^{2+}$  is the third most stable species of which relative energy of  $8.96 \text{ kcal mol}^{-1}$ .

#### 3.4.1 The total energies of MD simulations

The steps of the MD simulation of the system of Mg/cyclen complex with containing 500 molecules of water, one  $\text{Mg}^{2+}$  and two  $\text{Cl}^-$  ions of 350,000 steps were collected after 50,000 steps being processed, as shown in Figure B1. The total energies of the system plotted against time are shown in Figure 3.5. For the system of one  $\text{Mg}^{2+}$  and two  $\text{Cl}^-$  ions in aqueous solution with 500 water molecules of 350,000 steps collected after 50,000 steps being processed, as shown in Figure B2. The total energies of the system plotted against time are shown in Figure 3.6.



**Figure 3.5.** Total energies of MD simulation for system of Mg/cyclen complex, containing 500 molecules of water, one  $\text{Mg}^{2+}$ , two  $\text{Cl}^-$  ions.

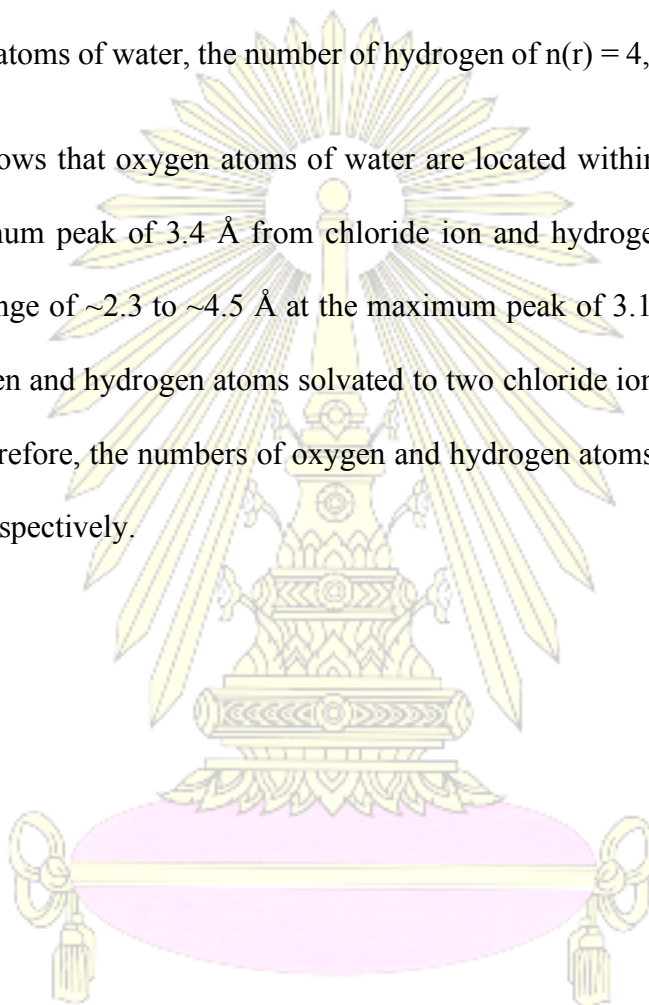


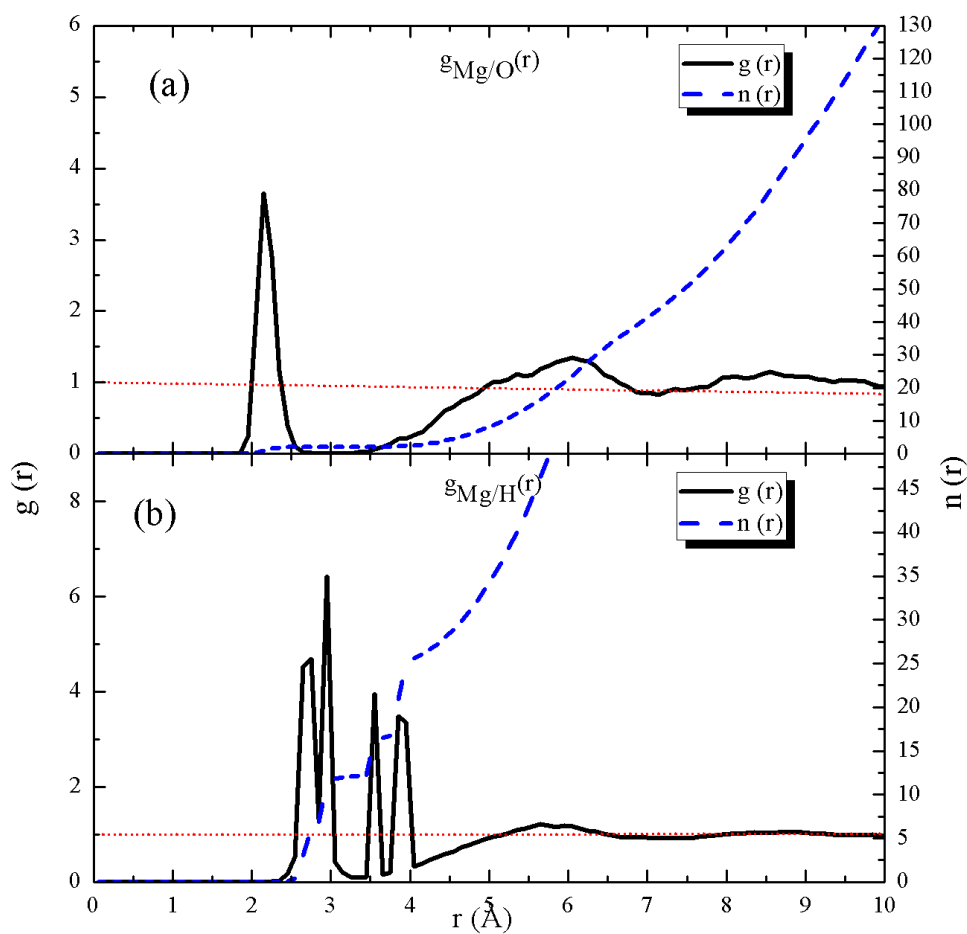
**Figure 3.6** Total energies of MD simulation for system containing 500 molecules of water, one  $\text{Mg}^{2+}$ , two  $\text{Cl}^-$  ions.

### 3.4.2 MD simulation of the system of $\text{MgCl}_2$ with and without a cyclen molecule

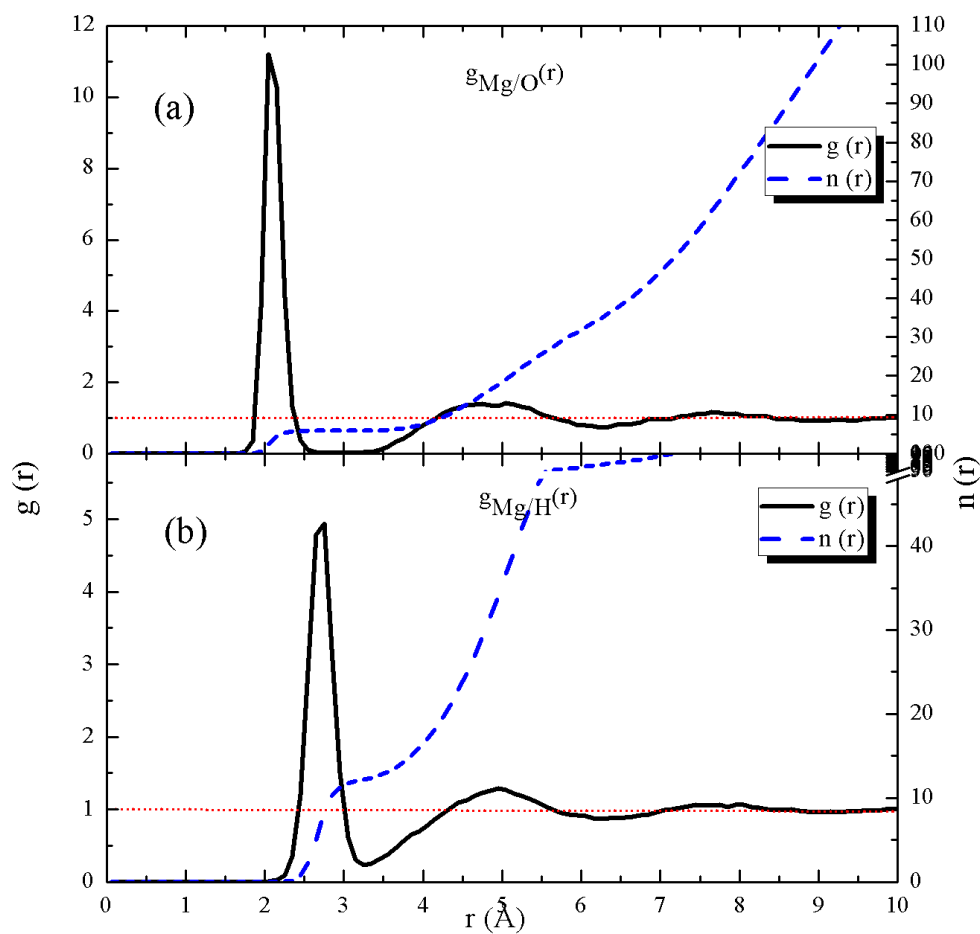
The MD simulation of  $\text{Mg/cyclen}$  complexes with two chloride ions, radial distributions (RDFs) of oxygen atom and hydrogen atom of waters with  $\text{Mg}^{2+}$  ion in the system are shown in Figure 3.7. It shows that oxygen atoms of water are located within the range of 1.8–2.6 Å at the maximum peak of 2.1 Å from magnesium ion and the number of oxygen atom ( $n(r) = 2$ ) is indicated, as shown in Figure 3.7(a). As the first peak of RDF, Figure 3.7(b), belongs to hydrogen atoms of water, the number of hydrogen of  $n(r) = 4$ , is therefore expected.

Figure 3.8 shows that oxygen atoms of water are located within the range of ~2.8 to ~4.3 Å at the maximum peak of 3.4 Å from chloride ion and hydrogen atoms of water are located within the range of ~2.3 to ~4.5 Å at the maximum peak of 3.1 Å from chloride ion. The number of oxygen and hydrogen atoms solvated to two chloride ions are of  $n(r) = 12$  and 24, respectively. Therefore, the numbers of oxygen and hydrogen atoms solvated to one must be  $n(r) = 6$  and 12, respectively.





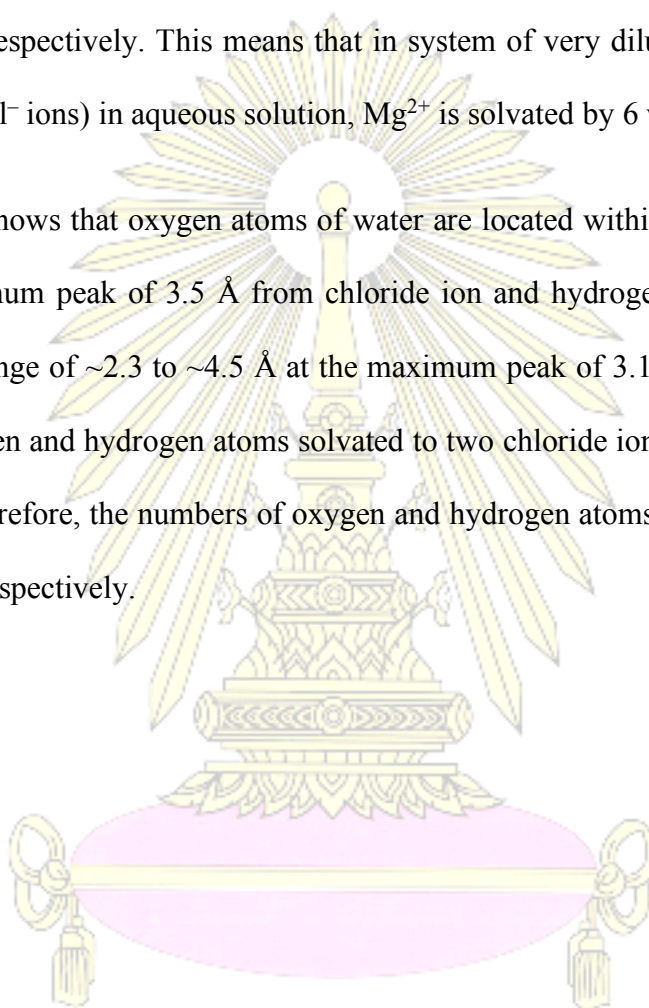
**Figure 3.7** Radial distributions (RDFs) of (a) oxygen atom and (b) hydrogen atom of waters with  $\text{Mg}^{2+}$  ion in the system of Mg/cyclen complexes with two chloride ions. The solid and dashed lines show the  $g(r)$  and  $n(r)$ , respectively.



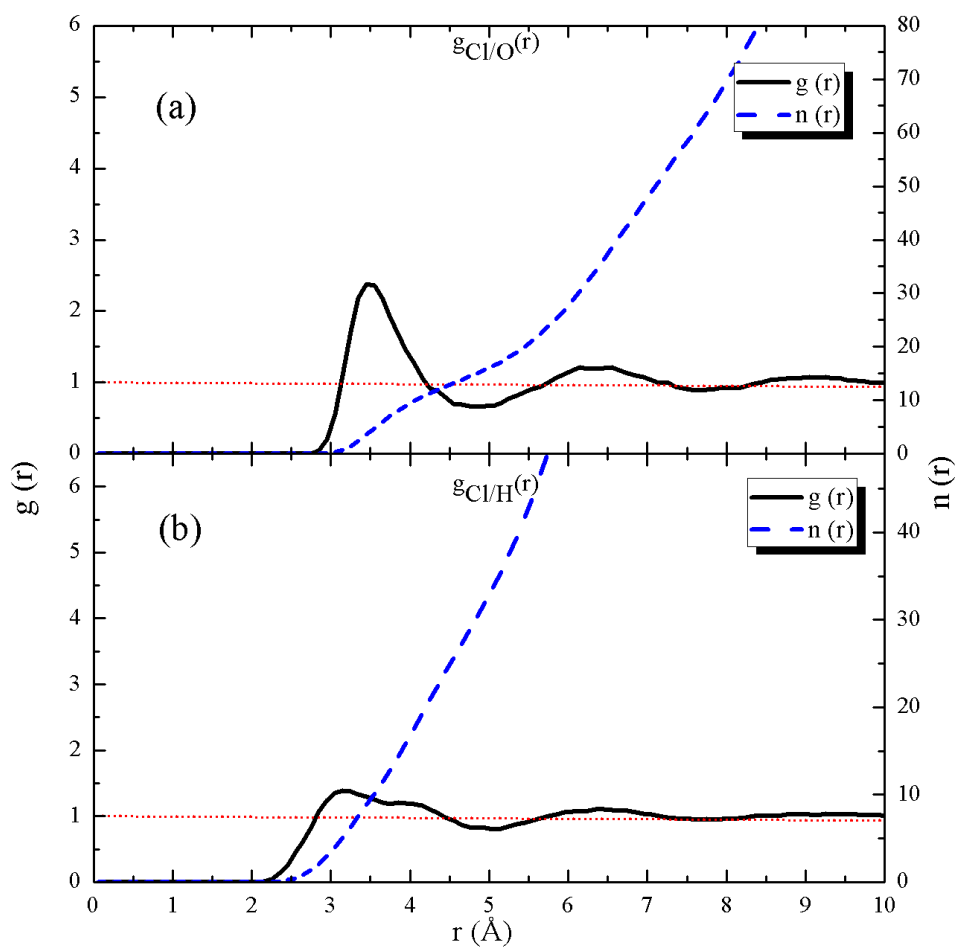
**Figure 3.8** Radial distributions (RDFs) of (a) oxygen atom and (b) hydrogen atom of waters with  $\text{Cl}^-$  ion in the system of Mg ion with two chloride ions. The solid and dashed lines show the  $g(r)$  and  $n(r)$ , respectively.

The comparison of numbers of hydrogen and oxygen atoms of water, related RDFs of the MD simulation for the system of one  $\text{Mg}^{2+}$  and two  $\text{Cl}^-$  ions in aqueous solution with 500 water molecules as shown in Figure 3.9 were computed. Figure 3.9 shows that oxygen atoms of water are located within the range of 1.7 to 2.5 Å at the maximum peak of 2.1 Å from magnesium ion and hydrogen atoms of water are located within the range of 2.2 to 3.2 Å at the maximum peak of 2.8 Å from magnesium ion. The number of oxygen and hydrogen atoms are of  $n(r) = 6$  and 12, respectively. This means that in system of very dilute solution of  $\text{MgCl}_2$  (one  $\text{Mg}^{2+}$  and two  $\text{Cl}^-$  ions) in aqueous solution,  $\text{Mg}^{2+}$  is solvated by 6 water molecules.

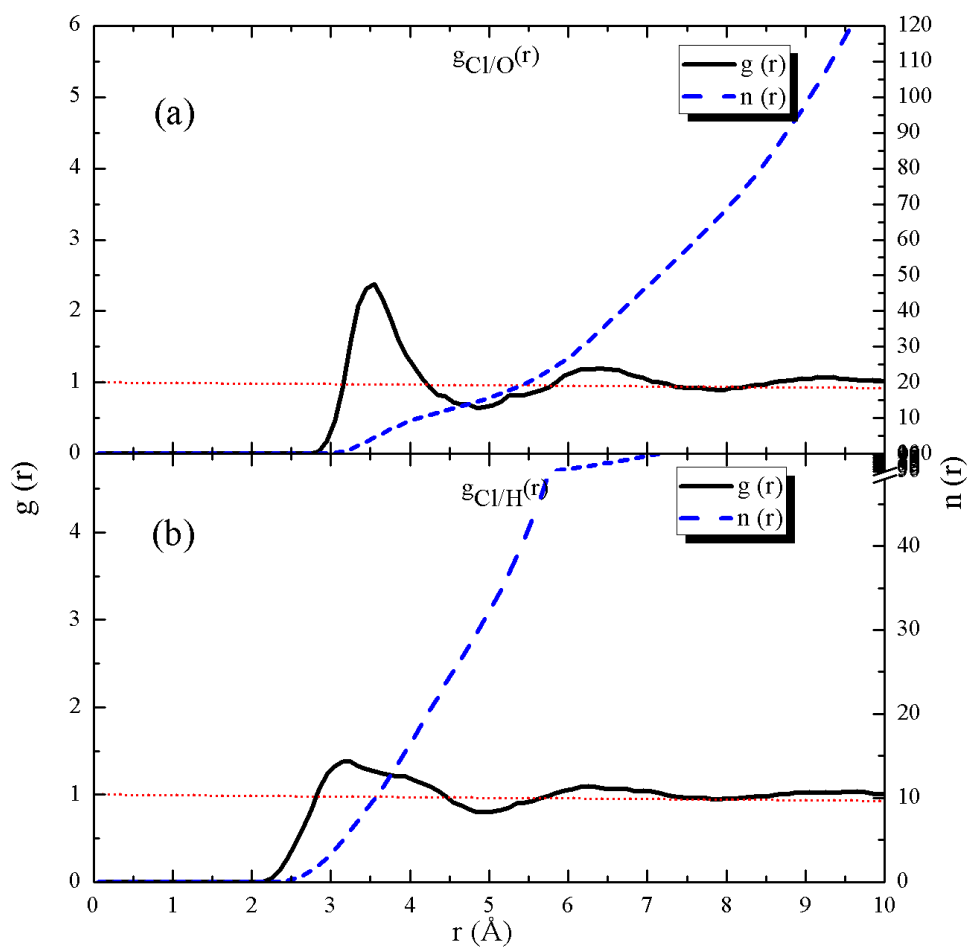
Figure 3.10 shows that oxygen atoms of water are located within the range of ~2.8 to ~4.2 Å at the maximum peak of 3.5 Å from chloride ion and hydrogen atoms of water are located within the range of ~2.3 to ~4.5 Å at the maximum peak of 3.1 Å from chloride ion. The number of oxygen and hydrogen atoms solvated to two chloride ions are of  $n(r) = 12$  and 24, respectively. Therefore, the numbers of oxygen and hydrogen atoms solvated to one must be  $n(r) = 6$  and 12, respectively.







**Figure 3.9** Radial distribution of  $Mg^{2+}$  ion with (a) oxygen atom and (b) hydrogen atom of waters in the system of one Mg/cyclen complexes and two chloride ions in aqueous solution. The solid and dashed lines show the  $g(r)$  and  $n(r)$ , respectively.



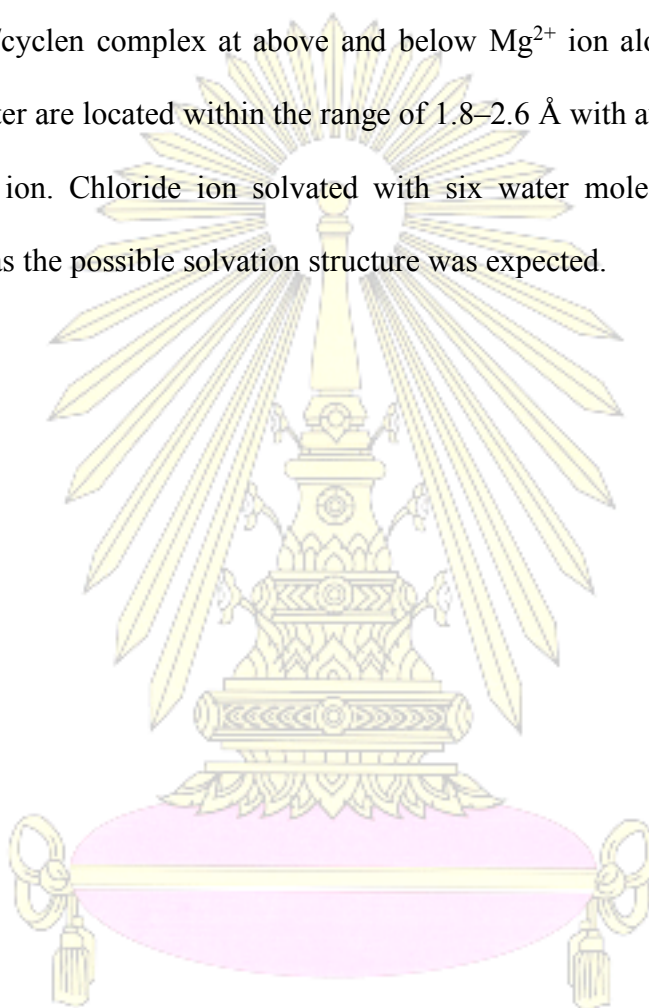
**Figure 3.10** Radial distribution of  $\text{Cl}^-$  ion with (a) oxygen atom and (b) hydrogen atom of waters in the system of one Mg ion and two chloride ions in aqueous solution. The solid and dashed lines show the  $g(r)$  and  $n(r)$ , respectively.

## CHAPTER IV

### CONCLUSIONS

All the structures of cyclen complex with magnesium ions (Mg/cyclen complex), with water molecules, chloride and nitrate ions were obtained using DFT optimization at the B3LYP/6-311++G(d,p) level of theory. Six conformations of Mg/cyclen complexes and six conformations of their complexes with two water molecules, two chloride ions and two nitrate ions were found. The [Mg/cyclen-1]<sup>2+</sup> of C<sub>4</sub> point group, was found to be the most stable conformation and was slightly different from the second ([Mg/cyclen-2]<sup>2+</sup>) and the third [Mg/cyclen-3]<sup>2+</sup> by 2.84 and 8.96 kcal mol<sup>-1</sup>, respectively. The Mg/cyclen complexes with two water, [H<sub>2</sub>O/Mg/cyclen/H<sub>2</sub>O-3]<sup>2+</sup> was found to be the highest symmetry (C<sub>2v</sub>). The formation abilities based on formation energies of all conformations of complexes of Mg/cyclen with two water molecules were in order: [H<sub>2</sub>O/Mg/cyclen/H<sub>2</sub>O-4b]<sup>2+</sup> (ΔE<sub>f</sub>=-67.55 kcal mol<sup>-1</sup>) >> [H<sub>2</sub>O/Mg/cyclen/H<sub>2</sub>O-4c]<sup>2+</sup> (ΔE<sub>f</sub> =-50.02 kcal mol<sup>-1</sup>) > [H<sub>2</sub>O/Mg/cyclen/H<sub>2</sub>O-1]<sup>2+</sup> (ΔE<sub>f</sub>=-47.42 kcal mol<sup>-1</sup>) ~ [H<sub>2</sub>O/Mg/cyclen/H<sub>2</sub>O-2]<sup>2+</sup>(ΔE<sub>f</sub>=-46.69 kcal mol<sup>-1</sup>) ~ [H<sub>2</sub>O/Mg/cyclen/H<sub>2</sub>O-3]<sup>2+</sup> (ΔE<sub>f</sub> =-46.55 kcal mol<sup>-1</sup>) >> [H<sub>2</sub>O/Mg/cyclen/H<sub>2</sub>O-4a]<sup>2+</sup> (ΔE<sub>f</sub> =-36.01 kcal mol<sup>-1</sup>). The hydration energies by two water molecules were found in the range of -47.42 to -46.55 kcal mole<sup>-1</sup>. MD simulation with size of cubic box with side length of 24.9077 Å, based on the NVT ensemble using the Berendsen thermostat and calculated using non-SCC DFTB method were employed. The main MD simulation for study of solvation structure of Mg/cyclen complex, contains 500 molecules of water, one Mg<sup>2+</sup>, two Cl<sup>-</sup> ions and one cyclen molecule of [Mg/cyclen-3]<sup>2+</sup> species. The second MD simulation of one Mg<sup>2+</sup>, two Cl<sup>-</sup> ions and 500 water molecules was performed to be used for comparison with the relevant MD simulation as mentioned above. The B3LYP/6-311++G(d,p) optimized structure of the

Mg/cyclen complex with high symmetry ( $C_{2v}$ ),  $[\text{Mg/cyclen-3}]^{2+}$  was fixed at the center of simulation box. The steps of the MD simulation of the system of Mg/cyclen complex with containing 500 molecules of water, one  $\text{Mg}^{2+}$  and two  $\text{Cl}^-$  ions of 350,000 steps were collected after 50,000 steps being processed. For the system of one  $\text{Mg}^{2+}$  and two  $\text{Cl}^-$  ions in aqueous solution with 500 water molecules of 350,000 steps collected after 50,000 steps being processed. Based on analyses of RDFs, it was found that two water molecules solvation with  $\text{Mg}^{2+}$  ion of the Mg/cyclen complex at above and below  $\text{Mg}^{2+}$  ion along its principal axis. Oxygen atoms of water are located within the range of 1.8–2.6 Å with average distance of 2.1 Å from magnesium ion. Chloride ion solvated with six water molecules was found and distorted octahedral as the possible solvation structure was expected.



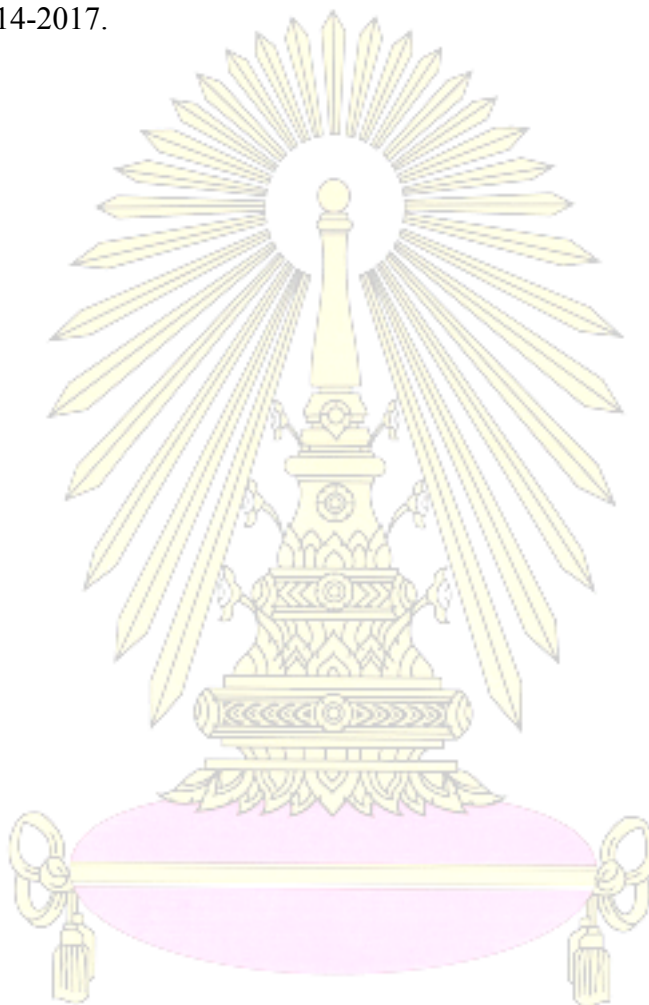
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## VITAE

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## APPENDIX A

**Table A1.** The computational parameters for the MD simulation for system of Mg/cyclen complex, containing 500 molecules of water, one Mg<sup>2+</sup> and two Cl<sup>-</sup> ions.

Species	MW	Numbers	Sum
H <sub>2</sub> O	18.015	500	9007.5
Cyclen	172.271	1	172.271
Mg <sup>2+</sup>	24.305	1	24.305
Cl <sup>-</sup>	35.453	2	70.906
			9,274.982

**Table A2.** The calculation for MD simulation box size, simulation for system of Mg/cyclen complex, containing 500 molecules of water, one Mg<sup>2+</sup> and two Cl<sup>-</sup> ions with total mass of 9,274.982 g (taken from Table A1), based on density of solution of 0.997044 g cm<sup>-3</sup> (D) at 298.15 K.

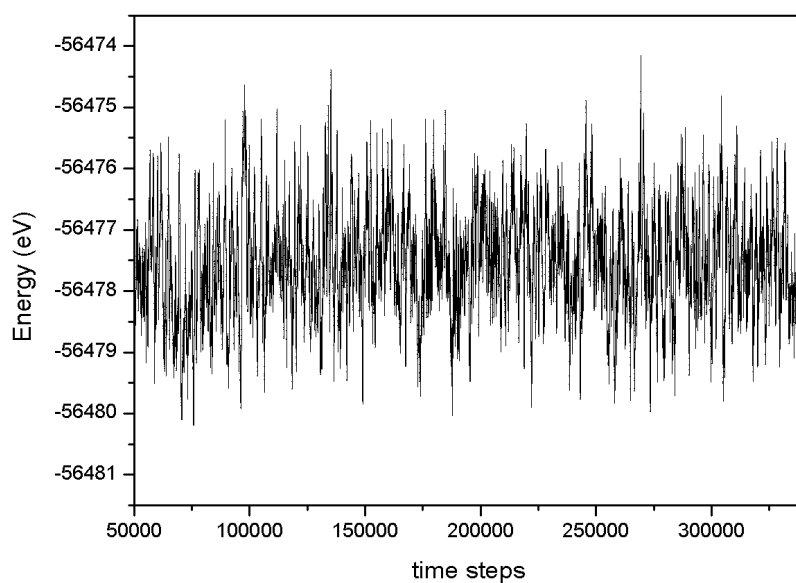
Dimension	Size
V= M/D =	1.55×10 <sup>-20</sup> a
x = y = z = V <sup>1/3</sup>	2.49077×10 <sup>-7</sup> a
	24.9077 b

<sup>a</sup> In cm<sup>3</sup>.

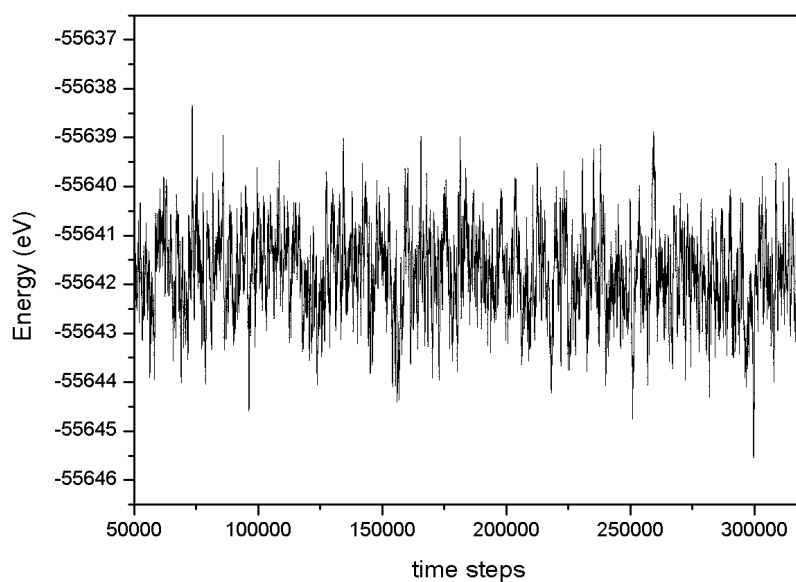
<sup>b</sup> in Å.



## APPENDIX B

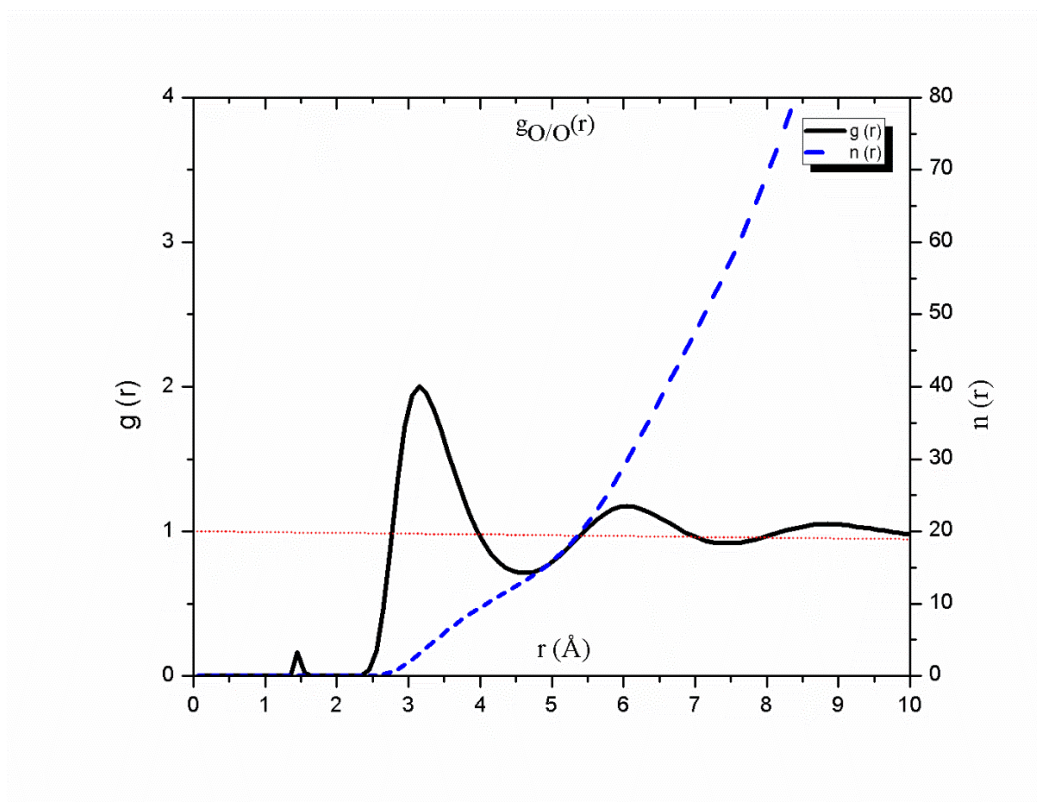


**Figure B1.** Total energies of MD simulation for system of Mg/cyclen complex, containing 500 molecules of water, one  $\text{Mg}^{2+}$ , two  $\text{Cl}^-$  ions, based on time steps.



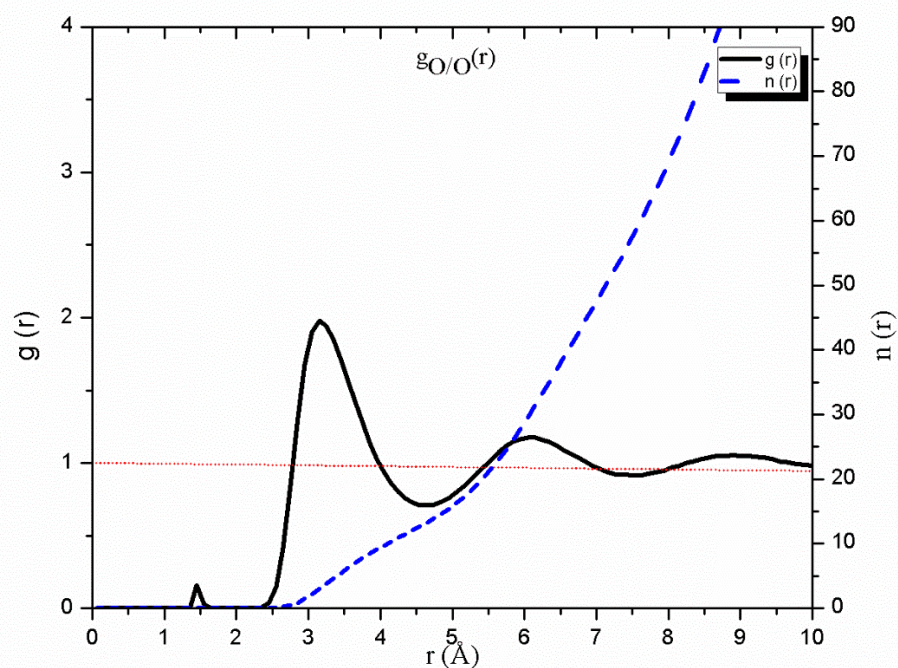
**Figure B2.** Total energies of MD simulation for system containing 500 molecules of water, one  $\text{Mg}^{2+}$ , two  $\text{Cl}^-$  ions, based on time steps

## APPENDIX C



**Figure C1.** Radial distributions (RDFs) of oxygen atom of waters in the system of Mg/cyclen complexes with two chloride ions in aqueous solution. The solid and dashed lines show the  $g(r)$  and  $n(r)$ , respectively.





**Figure C2.** Radial distributions (RDFs) of oxygen atom of waters in the system of two chloride ions in aqueous solution. The solid and dashed lines show the  $g(r)$  and  $n(r)$ , respectively.

