



CHAPTER IV

CYCLEN-METHANOL POTENTIAL FUNCTION

4.1 Analytical Form of Potential Functions

To develop the potential function by means of quantum chemical calculations, the following steps were required :

- (i) selection of representative geometries of the pairs ,
 - (ii) performance of the *ab initio* MO SCF calculations,
 - (iii) fitting of the computed interaction energies to the functional form,
- and (iv) testing of the quality of the function.

In the energy fitting step, a suitable mathematical function is selected. Among the many possible analytical forms of potential functions, one needs to construct the most reliable one in order to use in Monte Carlo simulation. Given two molecules P and Q, the pair interaction potential $V(P,Q)$ might contain both angular and radial dependencies. In practical way, however, one selects to use only the radial functions depending on the interatomic distance $r(i,j)$ where i and j are atoms belonging to molecules P and Q, respectively. For accuracy and flexibility, one would like to use a fairly long series of terms. On the other hand, the longer the series, the larger the number of associated fitting parameters, and the larger the number of machine cycles required to compute interaction energies in the simulation.

In general, there are two general forms of potential functions which can be expressed as :

$$(1) \quad V(P,Q) = \sum_{ij} \left[- \frac{A_{ij}}{r_{ij}^x} + \frac{B_{ij}}{r_{ij}^y} + \frac{Dq_i q_j}{r_{ij}} \right]$$

$$(2) \quad V(P,Q) = \sum_{ij} \left[- \frac{A_{ij}}{r_{ij}^x} + B_{ij} \exp(-C_{ij} r_{ij}) + \frac{D q_i q_j}{r_{ij}} \right]$$

where A , B and C are fitting parameters for the i th atom of molecule P and the j th atom of molecule Q . The parameter D (often equal to 1) represents an average correction to the atomic net charges q_i and q_j obtained from computation of molecular wave functions of molecules P and Q at infinite separation, respectively. The first two terms formally describe the short-range attractive and repulsive interactions, respectively, and the last term describe the long-range Coulomb interaction.

Generally, the first form is used for the weak interactions (the stabilization energy is not lower than -20 kcal/mol) such as ligand-ligand or ligand-solvent system. The second one is used for the strong interactions such as ion-ion, ion-ligand or ion-solvent system.

Once the analytical form of the potential has been chosen, the fitting procedure will be carried out. The form of the selected analytical function and the algorithm used in the fitting procedure are both important.

4.2 Development of Cyclen-Methanol Potential Function

It has been shown in the work reported by Udomsub, S. [35] that STO-3G is the most suitable basis set for the cyclen-water and cyclen-ammonia systems from which the acceptable values of molecular dipole moments, stabilization energies and intermolecular distances were derived. Since the present system i.e., cyclen-methanol is not much different from those reported in ref. 35 and the parameters under study are the same, it is therefore justified to employ STO-3G as a basis set in this work. Besides, the CPU time required for the same computation is much less than that required if a bigger basis set e.g. DZP is used (180 and 60 times higher, with and without corrections, for DZP than that required in STO-3G).

In this work, an intermolecular potential function for cyclen-methanol has been derived based on STO-3G/SCF level. An effective procedure to obtain and test the quality of the function, as proposed above, has been employed. Calculations, details specific for the cyclen-methanol system, are the following.

4.2.1 Selection of Pair Geometries

The cyclen and methanol molecules were treated as rigid throughout the calculations. The optimized geometry of cyclen molecule (the alternate form as shown in Fig. 4.1) based on quantum chemical calculations, was taken from the literature [11], and for the methanol molecule experimental data [28] was used. The fixed Cartesian coordinates of cyclen molecule and the experimental geometries of methanol molecule are given in Tables 4.1 and 4.2, respectively. The center of cyclen was fixed at the origin of Cartesian coordinate system. Then, methanol molecule was placed at numerous positions around cyclen, where $0^\circ \leq \theta \leq 180^\circ$ and $0^\circ \leq \phi \leq 90^\circ$ (Fig. 4.2). Due to the symmetry of the cyclen molecule, it is unnecessary to generate methanol molecule around the whole space, only one-fourth is required. The selected θ and ϕ angles given in Table 4.3 were kept constant while varying the distance (r) from 2.0 Å to 10.0 Å. The frequency of chosen points in the space is dependent on the "*chemical importance*" of those regions. A region around the minimum energy has a strong influence not only for the potential function, but also for the simulation results, therefore more points are needed in that zone.

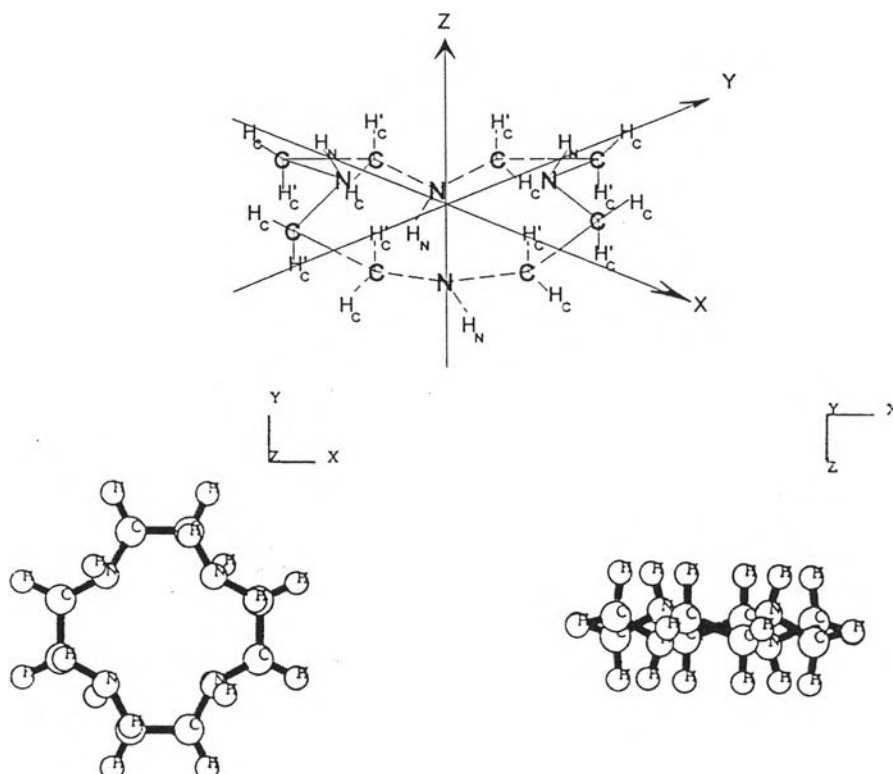


Figure 4.1 Three dimensional plots of the optimized alternate form of cyclen molecule (1,4,7,10-tetraazacyclododecane).

Table 4.1 Optimized coordinates of cyclen (in atomic unit) and the atomic net charges, (q^a) used in the Monte Carlo simulation.

atom	X	Y	Z	q^a
N	-2.53625	-2.53625	-0.74461	-0.31521
N	2.53624	-2.53625	0.74462	-0.31521
N	2.53625	2.53623	-0.74462	-0.31521
N	-2.53622	2.53625	0.74461	-0.31521
C	-1.37279	-4.74032	0.48239	-0.00570
C	1.37283	-4.74032	-0.48239	-0.00464
C	4.74031	-1.37285	-0.48239	-0.00569
C	4.74032	1.37281	0.48238	-0.00464
C	1.37285	4.74030	0.48238	-0.00570
C	-1.37280	4.74031	-0.48240	-0.00464
C	-4.74030	1.37286	-0.48239	-0.00570
C	-4.74032	-1.37280	0.48239	-0.00464
H _C	-2.29600	-6.50688	-0.06634	0.03203
H _C	2.29605	-6.50688	0.06635	0.03343
H _C	6.50687	-2.29606	0.06634	0.03203
H _C	6.50688	2.29602	-0.06635	0.03343
H _C	2.29608	6.50685	-0.06636	0.03203
H _C	-2.29601	6.50688	0.06633	0.03343
H _C	-6.50685	2.29607	0.06634	0.03203
H _C	-6.50688	-2.29600	-0.06633	0.03343
H' _C	-1.37920	-4.57044	2.54278	0.05872
H' _C	1.37923	-4.57044	-2.54278	0.06015
H' _C	4.57043	-1.37925	-2.54280	0.05873
H' _C	4.57045	1.37922	2.54278	0.06016
H' _C	1.37926	4.57043	2.54278	0.05872
H' _C	-1.37921	4.57043	-2.54280	0.06016
H' _C	-4.57042	1.37925	-2.54280	0.05872
H' _C	-4.57043	-1.37920	2.54280	0.06015
H _N	3.14135	-3.02567	2.49547	0.14124
H _N	3.02568	3.14193	-2.49548	0.14120
H _N	-3.14192	3.32567	2.49546	0.14120
H _N	-3.02569	-3.24194	-2.49547	0.14120

^a Values obtained from the Mulliken population analysis in the quantum chemical calculations of single molecule.

Table 4.2 Internal coordinates and the atomic net charges of methanol molecule

A_0	A_1	R^a	A_2	θ^b	A_3	ϕ^c	q
C							-0.0602
O	C	1.428					-0.3130
H_O	O	0.960	C	112.00			0.1906
H'	C	1.094	O	109.47	H_O	-60.0	0.0542
H'	C	1.094	O	109.47	H_O	60.0	0.0542
H	C	1.094	O	109.47	H_O	180.0	0.0741

^aBond length A_0-A_1 in angstrom. ^bBond angle $A_0-A_1-A_2$ in degrees. ^cDihedral angle $A_0-A_1-A_2-A_3$ in degrees.

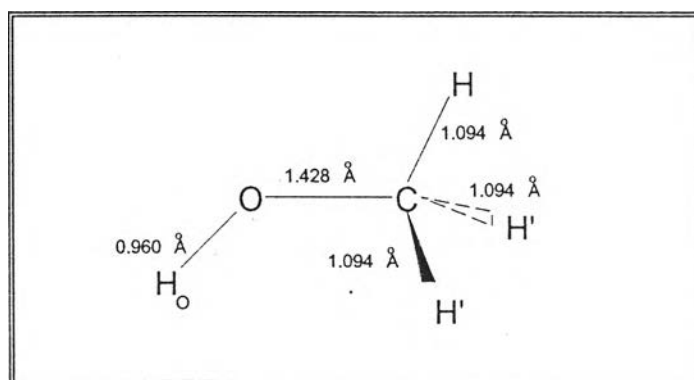


Figure 4.2 Classification of atoms of the methanol molecule according to their atomic net charge obtained from the Mulliken population analysis in the SCF calculations.

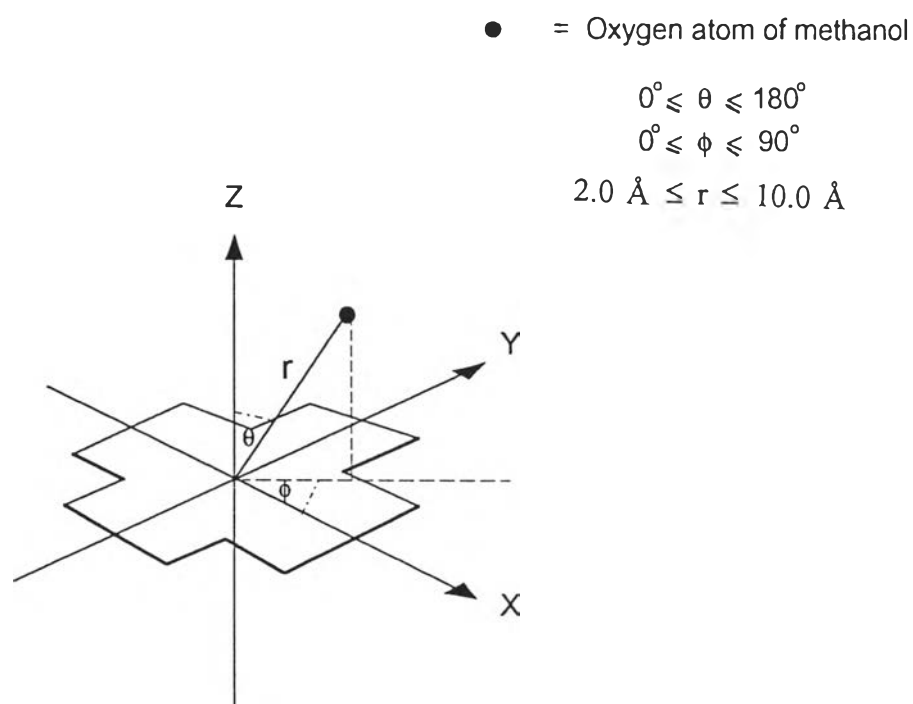


Figure 4.3 Indicating of geometric variables for configurations of cyclen-methanol.

Table 4.3 The selected trajectories, in term of θ and ϕ angles, as defined in Fig. 4.2, for methanol molecule around cyclen.

trajectory	ϕ	θ
1	0	0
2	0	45
3	0	90
4	0	135
5	0	180
6	45	45
7	45	90
8	45	135
9	90	45
10	90	90
11	90	135

4.2.2 Performance of the *Ab Initio* MO SCF Calculations

The calculations were performed based on the LCAO-MO-SCF method, using STO-3G minimal basis set (given in the Appendix) and the HONDO(VII) program [29] on the work station DEC 3100. The calculations have been carried out for all cyclen-methanol configurations chosen in section (4.1.1). The corresponding stabilization energy, ΔE_{SCF} , in kcal/mol (1 Hartree = 627.5 kcal/mol) can be calculated using

$$\Delta E_{\text{SCF}} \text{ (kcal/mol)} = (E_{\text{dimer}} - E_{\text{cyclen}} - E_{\text{methanol}}) \times 627.5 \quad (4.1)$$

where E_{dimer} : Total energy of cyclen-methanol dimer,
 E_{cyclen} : Total energy of cyclen monomer,
 E_{methanol} : Total energy of methanol monomer.

4.2.3 Fitting of the Computed Interaction Energies to the Functional Form

After having 600 SCF energy points in the geometries mentioned in section (4.1.1), 400 of them which are lower than 20 kcal/mol were fitted, using a multidimensional non-linear least-squares procedure, to the analytical function of the form

$$\Delta E \text{ (kcal / mol)} = \sum_{i=1}^6 \sum_{j=1}^{32} \left[-\frac{|A_{ij}|}{r_{ij}^7} + \frac{|B_{ij}|}{r_{ij}^{10}} + \frac{q_i q_j}{r_{ij}} \right] \quad (4.2)$$

where A_{ij} and B_{ij} are fitting parameters and r_{ij} is the distance between the i th atom of methanol and the j th atom of cyclen. q_i and q_j are the net charges of the i th and j th atoms of methanol and cyclen, respectively, obtained from the Mulliken population analysis of the isolated molecules in the SCF calculations. Considering the atomic net charges, the atoms of cyclen can be distinguished into five groups, i.e. N, C, H_N , H_C and H'_C (see Fig. 4.1). H_N are the hydrogen atoms binding to the N atoms, while H_C and H'_C are the hydrogen atoms binding to C atoms in and perpendicular to the molecular plane, respectively. For the methanol molecule, there are five groups of atoms, namely, C, O, H_O , H and H'. H_O is the hydroxyl-hydrogen atom, while H and H' are the hydrogens belonging to C atom, whose C-H and C-H' bonds are in and out of the molecular plane, defined by H_O , O and C atoms.

4.2.4 Testing of the Quality of the Function

The analytical potential function obtained from 400 SCF data points was carefully tested in order to make sure that it is possible to represent interactions of all methanol positions and orientations relative to the cyclen. The resulting function with the best fit for this set of the initial data gave a standard deviation of $\sigma = \pm 0.77$ kcal/mol. Then 50 more points outside the initial data set were added (N_{test}). With the first analytical potential, the energy for these additional 50 points was calculated, leading to a tested standard deviation of $\sigma_{\text{test}} = \pm 3.95$ kcal/mol.

Now, the 50 test points were included into the fitting procedure and a new set of parameters A and B with a standard deviation of $\sigma = \pm 0.72$ kcal/mol was obtained. Another 50 points were again tested and then included. This procedure was repeated until constancy of the fitting parameters was obtained within a range of $\pm 5\%$ [30] and the standard deviation was satisfactory compared with the accuracy of the *ab initio* MO SCF calculations. An additional criterion of convergence is the coincidence of σ_{test} and σ values.

4.3 Results and Discussion

By moving the initial location of the methanol molecule shown in Table 4.4 along the z axis (see Fig.4.1), the minimum interaction energy between cyclen and methanol is found at the O-origin distance of 3.3 Å as given in Table 4.5. Some of the computed energies with different values of θ and ϕ are shown in Table 4.6(a-c) and plotted in Fig. 4.4.

Table 4.4 The initial coordinates of methanol molecule where O is placed at the origin (center of cyclen molecule, see Fig. 4.1), in Å.

atom	X	Y	Z
O	0.00000	0.00000	0.00000
C	1.32402	0.00000	0.53494
Ho	0.00000	0.00000	-0.96000
H	1.27573	0.00000	1.62787
H'	1.85531	-0.89325	0.19337
H'	1.85531	0.89325	0.19337

The results of the test for 5 iterations, see section (4.2.4), are shown in Table 4.7. The σ of ± 0.77 (for 400 initial points of energy) and the σ_{test} of ± 3.95 (for additional 50 tested points) in the first step indicate that the fitting parameters obtained from step 1 are insufficient to converge for other orientations. However, after some iterations the fitting parameters are adjusted (as can be seen from the variation of σ and σ_{test} in Table 4.7 for step 2, 3 and 4). Until step 5 the obtained fitting parameters is in the range of $\pm 5\%$ of the previous step and the standard deviation is satisfactory compared with the accuracy of *ab initio* data. The final values of the fitting parameters are summarized in Table 4.8.

Correlation between ΔE_{SCF} and ΔE_{FIT} for all 600 data points is plotted in Fig. 4.5. It can be clearly seen that they are in good agreement, especially in the low energy ranges.

The standard deviations for different ranges of interaction energies were calculated separately and listed in Table 4.9 in order to illustrate the quality of the fitting. An accuracy of the fit at the attractive ranges has been exhibited.

Table 4.5 The computed energies from *ab initio* calculations (ΔE_{SCF}) and from eq.(4.2) (ΔE_{FIT}), in kcal/mol at the selected values of the O-origin distances (\AA) along z-axis, starting from the configuration given in Table 4.4.

distance	ΔE_{SCF}	ΔE_{FIT}
2.5	11.7210	13.9880
3.0	-1.8114	-1.8132
3.1	-2.4009	-2.3960
3.2	-2.7007	-2.6864
3.3	<u>-2.8045</u>	<u>-2.7847</u>
3.4	-2.7799	-2.7597
3.5	-2.6749	-2.6581
4.0	-1.7992	-1.8061
5.0	-0.64584	-0.65005
6.0	-0.24935	-0.24244
8.0	-0.05501	-0.04721

Table 4.6 Comparison of the computed energies (kcal/mol) from *ab initio* calculation (ΔE_{SCF}) and from eq.(4.2) (ΔE_{FIT}) for (a) $\theta = 45^\circ$ and $\phi = 45^\circ$, (b) $\theta = 90^\circ$ and $\phi = 135^\circ$, (c) $\theta = 135^\circ$ and $\phi = 135^\circ$ by varying the O-origin distances(\AA).

(a) $\theta = 45^\circ$ and $\phi = 45^\circ$

distance	ΔE_{SCF}	ΔE_{FIT}
4.5	5.8717	6.0960
5.0	1.0829	0.94665
5.2	0.49558	0.41099
5.4	0.20576	0.14843
5.6	0.07104	0.02292
5.8	0.01335	-0.03352
6.0	-0.00815	-0.05533
6.2	-0.01389	-0.06015
6.4	-0.01349	-0.05705
6.6	-0.01112	-0.05067
8.0	-0.00021	-0.01199
10.0	0.00194	0.00056

(b) $\theta = 90^\circ$ and $\phi = 135^\circ$

distance	ΔE_{SCF}	ΔE_{FIT}
4.8	9.4465	10.5290
5.0	5.0108	4.6173
5.2	2.6200	2.0717
5.4	1.3556	0.92328
5.6	0.70054	0.38803
5.8	0.36847	0.13470
6.0	0.20362	0.01577
6.2	0.12296	-0.03754
6.4	0.08345	-0.05853
6.6	0.06337	-0.06370
6.8	0.05217	-0.06142
8.0	0.02493	-0.02678
10.0	0.00850	-0.00558

(c) $\theta = 135^\circ$ and $\phi = 135^\circ$

distance	ΔE_{SCF}	ΔE_{FIT}
5.8	8.0270	6.6325
6.0	4.0780	2.9789
6.2	2.0059	1.4079
6.4	0.94728	0.68065
6.6	0.42418	0.32698
6.8	0.17558	0.14927
7.0	0.06293	0.05832
8.0	-0.01076	-0.02860
10.0	-0.004090	-0.01180

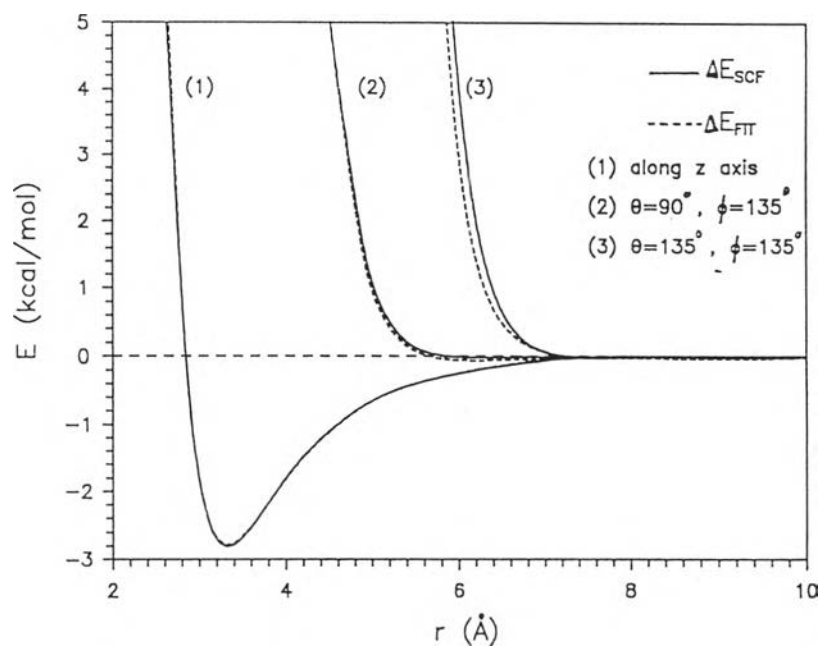


Figure 4.4 The stabilization energies obtained from *ab initio* calculations (ΔE_{SCF}) and from eq. (4.2) (ΔE_{FIT}) as a function of the oxygen-origin distances.

Table 4.7 Characteristics of the optimization process (detail see text).

step	N	σ	N_{test}	σ_{test}
1	400	0.77	50	3.95
2	450	0.72	50	3.09
3	500	0.93	50	0.55
4	550	0.90	50	0.91
5	600	0.95		

Table 4.8 Final optimized parameters for interacting atom *j* of 1,4,7,10-tetraazacyclododecane with atom *i* of methanol (interaction energies in kcal/mol, *r* in atomic length unit (alu.)).

atoms		parameter	
<i>i</i>	<i>j</i>	A ((alu.) ⁷ kcal/mol)	B ((alu.) ¹⁰ kcal/mol)
C	N	0.745674536922E-01	0.268672249138E+06
	C	0.378564659524E-06	0.514963881866E+07
	H _C	0.109963893573E-05	0.213758461079E-02
	H' _C	0.279313309247E-06	0.676371950063E+07
	H _N	0.732028608004E-07	0.558647082584E+07
O	N	0.101179419974E+07	0.207420245746E+09
	C	0.777311335349E-06	0.102613452172E+09
	H _C	0.984430974665E-06	0.229217412430E+07
	H' _C	0.280904980779E+05	0.273112399947E+06
	H _N	0.416947670775E+05	0.389371777864E+06
H _O	N	0.752355792566E+05	0.151087626478E+06
	C	0.154875437941E-06	0.144555312682E+08
	H _C	0.651603808350E-02	0.281918220498E-04
	H' _C	0.489787863238E-08	0.743121332915E+05
	H _N	0.251455763739E-07	0.233515086886E+06
H	N	0.252157006330E+05	0.835417612059E-04
	C	0.116305578660E-06	0.155442051093E+08
	H _C	0.817774165078E+04	0.418872034695E-05
	H' _C	0.159567673077E-06	0.369043477432E+05
	H _N	0.485163980745E-07	0.354478000810E+06
H'	N	0.354249710781E-06	0.188969114783E+07
	C	0.396727424184E-06	0.190610306939E+08
	H _C	0.496163638740E+04	0.192801245117E-04
	H' _C	0.717451247231E+03	0.205547656015E+04
	H _N	0.199659975175E-07	0.125017244107E+06

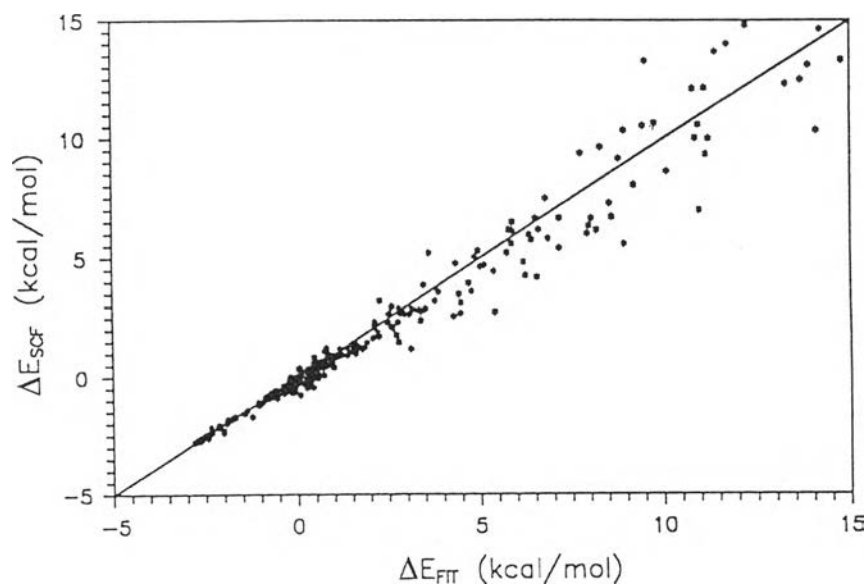


Figure 4.5 Energy data from *ab initio* calculations (ΔE_{SCF}) versus those obtained from eq.(4.2) (ΔE_{FIT}) with optimized parameters

Table 4.9 Standard deviations, σ , calculated from eq.(4.2) for different interaction energy ranges.

Energy (kcal/mol)	< 0.0	< 5.0	< 10.0	Total
σ	0.12	0.54	0.65	0.95

Table 4.10 Comparison of the computed energies (kcal/mol) from *ab initio* calculations by including and not including the "BSSE" as a function of the oxygen-origin distances.

distance	ΔE_{SCF}	$\Delta E_{\text{SCF}} + \text{BSSE}$
2.5	11.7210	17.3420
3.0	-1.8114	0.3476
3.1	-2.4009	-0.6609
3.2	-2.7007	-1.3088
3.3	<u>-2.8045</u>	-1.6990
3.4	-2.7799	-1.9078
3.5	-2.6749	<u>-1.9913</u>
3.6	-2.5233	-1.9904
3.7	-2.3472	-1.9339
4.0	-1.7992	-1.6114
5.0	-0.6458	-0.6347
6.0	-0.2493	-0.2931
8.0	-0.0550	-0.0550

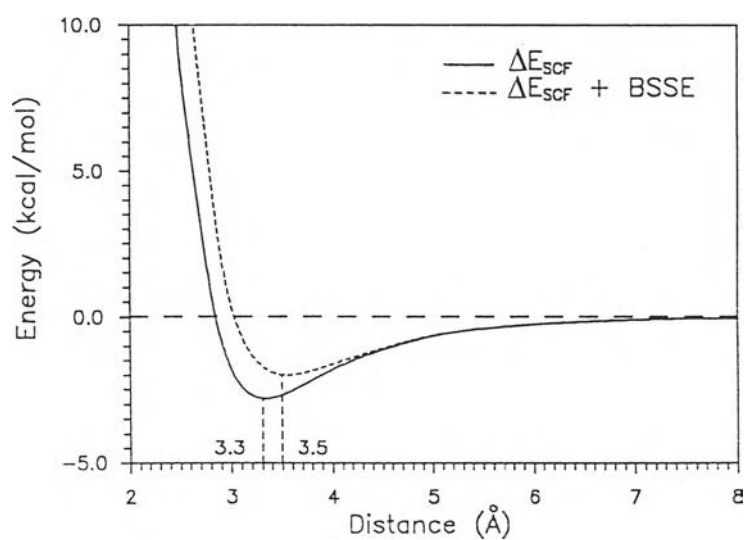


Figure 4.6 Comparison of the energies obtained from *ab initio* calculations by including (—) and not including (---) the "BSSE" as a function of the oxygen-origin distances.

In this work, a minimal basis set was used because the size of the system under consideration obviously do not allow the use of a more extended basis set (because of unreasonable computation times that would have been required).

Investigation of the BSSE

With the definition described in section (2.2), the "Basis Set Superposition Error" for cyclen-methanol has been investigated. The trajectory along z-axis, equivalent to Table 4.5, has been selected. The calculated results are summarized in Table 4.10 and plotted in Fig. 4.6.

It can be seen, as expected, that the influence of the small basis set, used in our SCF calculations, causes a *"too low"* stabilization energy of the cyclen-methanol complex. The shift of the minimum of 3.3 Å to 3.5 Å due to the BSSE is, surely, not effect the simulation results since the curves near to local minima are rather broad, i.e., the energy difference is much lower than Boltzman factor, for example, at room temperature.