

LETTER

Assessment of Some Density Functional Theory Methods and Force Field Models in Describing Various Interaction Modes of Benzene DimerYu-wei Zhou^a, Igor Ying Zhang^{a,b}, Jian-ming Wu^b, An-an Wu^{a*}, Xin Xu^{a,b*}

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Benzene dimer (bz2) is the simplest prototype of the π - π interactions. Such interactions are ubiquitous in diverse areas of science and molecular engineering. In the present work, we have made assessment on some modern density functional methods including B97-D, BLYP-D3, M06-2X, XYG3, and force field models including CHARMM, AMBER, MM3, AMOEBA on six important interaction modes of bz2. Our results not only highlight the usefulness of these cost-effective methods, which can be used as economic substitutes of the expensive CCSD(T) for complex real-world systems, but also indicate their weakness in the description of the π - π interactions, which points to the future direction for further improvements.

Key words: π - π interaction, Benzene dimer, van der Waals, Dispersion, XYG3

It is well-known that π - π interactions play a significant role in self-assembly, protein folding, drug binding and crystal packing, *etc.*, where interacting aromatic species are involved. Such interactions are also fundamental in various carbon-based materials of graphene, fullerenes, and nanotubes, *etc.* It is therefore not surprising to see that benzene dimer (bz2), the simplest prototype of π - π interactions, has stimulated continuing interest for more than three decades [1–8]. Nevertheless, proper description of π - π interactions in bz2 still presents a great challenge for both experiment and theory due to its small binding energy (8.36–12.54 kJ/mol) and the shallowness of the potential energy surface.

Theoretically, high-level wavefunction based methods, such as CCSD(T) (*i.e.* coupled-cluster with single and double and perturbative triple excitations) extrapolated to complete basis set (CBS) limit, are generally required to set up results which are accurate enough as benchmark [1, 2]. For real applications, density functional theory (DFT) methods are the only affordable first principle methods, while force field (FF) models are even more efficient methods and have been widely used. However, it has to be emphasized that, to make such applications reliable, either DFT or FF methods have to be first characterized and calibrated [5, 6]. In the present work, we have made an assessment on some modern DFT methods including B97-D [9], BLYP-D3 [10], M06-2X [11], and XYG3 [12], as well as some FF

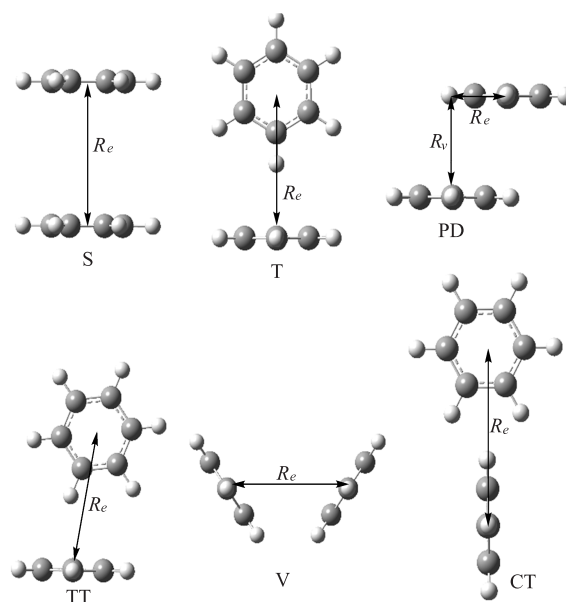


FIG. 1 Sandwich (S), T-shaped (T), parallel-displaced (PD), tilted T-shaped (TT), V-shaped (V) and crossed T-shaped (CT) configurations of benzene dimer.

models including CHARMM [13], AMBER [14], MM3 [15], and AMOEBA [16] on six important interacting configurations of bz2 (see Fig.1). Our results not only highlight the usefulness of these cost-effective methods, which can be used as economic substitutes of the expensive CCSD(T) for complex real-world systems, but also indicate their weakness in the accurate description

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TABLE I Performance of some DFT and FF methods models in describing various interaction modes of benzene dimer^a.

No.	Structure	Reference		XYG3		M06-2X		B97-D		BLYP-D3	
		R_e	E_{int}	R_e	E_{int}	R_e	E_{int}	R_e	E_{int}	R_e	E_{int}
1	S	3.9 ^b	-7.11 ^b	3.84	-5.27	3.71	-6.48	3.88	-7.86	3.75	-7.86
2	T	5.0 ^b	-11.28 ^b	4.94	-12.04	4.89	-12.12	4.89	-13.63	5.01	-12.87
3	PD(3.2 Å)	1.9 ^b	-8.18 ^b	1.86	-9.15	1.69	-13.08	1.86	-11.79	1.81	-11.29
4	PD(3.4 Å)	1.8 ^b	-11.05 ^b	1.75	-11.54	1.58	-14.50	1.76	-13.38	1.73	-13.50
5	PD(3.6 Å)	1.7 ^b	-11.09 ^b	1.69	-11.08	1.51	-12.79	1.71	-12.71	1.69	-12.50
6	TT	4.93 ^c	-11.79 ^c	4.90	-12.33	4.82	-13.04	4.83	-13.63	4.91	-13.96
7	CT	6.09 ^d	-7.48 ^d	6.09	-7.19	5.95	-7.31	5.94	-8.94	6.10	-9.61
8	V	4.86 ^e	-4.30 ^e	5.22	-2.93	5.25	-1.00	5.11	-4.60	5.08	-4.81
	MAD ^f	—	—	0.08	0.79	0.20	2.05	0.09	1.80	0.07	1.75

No.	Structure	Reference		AMOEBA		CHARMM		AMBER		MM3	
		R_e	E_{int}	R_e	E_{int}	R_e	E_{int}	R_e	E_{int}	R_e	E_{int}
1	S ^b	3.9	-7.11 ^b	3.58	-9.99	3.76	-7.52	3.66	-6.65	3.63	-9.91
2	T ^b	5.0	-11.28 ^b	5.16	-8.61	5.15	-8.78	5.09	-9.03	5.17	-7.56
3	PD(3.2 Å) ^b	1.9	-8.18 ^b	1.74	-10.37	3.74	-8.82	3.47	-9.40	3.09	-9.28
4	PD(3.4 Å) ^b	1.8	-11.05 ^b	1.53	-12.41	3.11	-8.99	2.83	-9.32	2.02	-10.32
5	PD(3.6 Å) ^b	1.7	-11.09 ^b	1.39	-11.58	2.28	-8.94	2.37	-8.69	1.49	-10.37
6	TT ^c	4.93	-11.79 ^c	5.05	-9.91	5.06	-9.40	5.00	-9.65	5.10	-8.15
7	CT ^d	6.09	-7.48 ^d	6.33	-4.39	6.21	-5.89	6.20	-5.22	6.45	-4.26
8	V ^e	4.86	-4.30 ^e	5.13	-3.47	5.11	-4.22	5.12	-3.18	5.20	-4.35
	MAD ^f	—	—	0.23	1.92	0.57	1.46	0.51	1.71	0.37	2.01

^a The equilibrium center-of-mass distance R_e and the corresponding interaction energy E_{int} are given in Å and kJ/mol, respectively. For the PD configurations, interaction energies are calculated for the optimum horizontal displacement of each method at a given vertical separation (R_v) between the rings of 3.2, 3.4, and 3.6 Å, respectively (see Fig.1).

^b CCSD(T)/CBS(Δ ha(DT)Z) values from Sherrill's group [1].

^c CCSD(T)/CBS(aV(DT)Z) values from Hobza and Kim's groups [2].

^d The CCSD(T) corrected PBE geometry with the corresponding CCSD(T)/CBS interaction energy estimated via CCSD(T)/aVDZ+SCS-MP2/CBS-SCS-MP2/aVDZ [3].

^e The MP2/aVDZ optimized geometry with the interaction energy being estimated at the level of MP4(SDTQ)/aVDZ with 90% basis set superposition error (BSSE) correction [4].

^f Mean absolute deviations.

of π - π interactions, which points to the future direction for further improvements.

The reference data for the six important configurations of bz2, depicted in Fig.1, are collected in Table I. For the classic sandwich (S), T-shaped (T), and parallel-displaced (PD) configurations which have been intensively studied in the literature [1–6], we use the most recent data of CCSD(T)/CBS(Δ ha(DT)Z) from Sherrill's group [1], where Δ ha(DT)Z denotes the energy difference between CCSD(T) and MP2, evaluated using extrapolated correlation energies determined in the haDZ and haTZ basis sets. Here haDZ is an abbreviation of aug-cc-pVDZ (*i.e.* aVDZ for short) for carbon and cc-pVDZ (VDZ) for hydrogen, while haTZ was constructed following the same rule from the corresponding Dunning's (a) VTZ basis sets [17]. There are other CCSD(T)/CBS data available in the literature. They may differ from these numbers within ± 0.03 Å for the center-to-center dis-

tance between two bz moieties or ± 0.21 kJ/mol for the interaction energies. There are only a few choices for other configurations. For the tilted TT structure, we adopt the CCSD(T)/CBS values from Hobza and Kim's [2], which were based on a two data point (aVDZ and aVTZ) extrapolation scheme with no parameters. For the CT configuration, the best geometry we could find was from the CCSD(T) corrected PBE optimizations [3]. Generally, this PBE/CCSD(T) method gave very good results for S, T, PD, and TT, with errors within ± 0.03 Å for geometries. The corresponding CCSD(T)/CBS value for interaction energy was estimated via CCSD(T)/aVDZ+SCS-MP2/CBS-SCS-MP2/aVDZ, where SCS-MP2 [18] is the spin-component-scaled MP2, and the SCS-MP2/CBS was achieved by employing the aVTZ and aVQZ extrapolation for correlation energy which was added to the HF/haV5Z energy. The reference data for the V structure have to be considered as temporary. The geometry

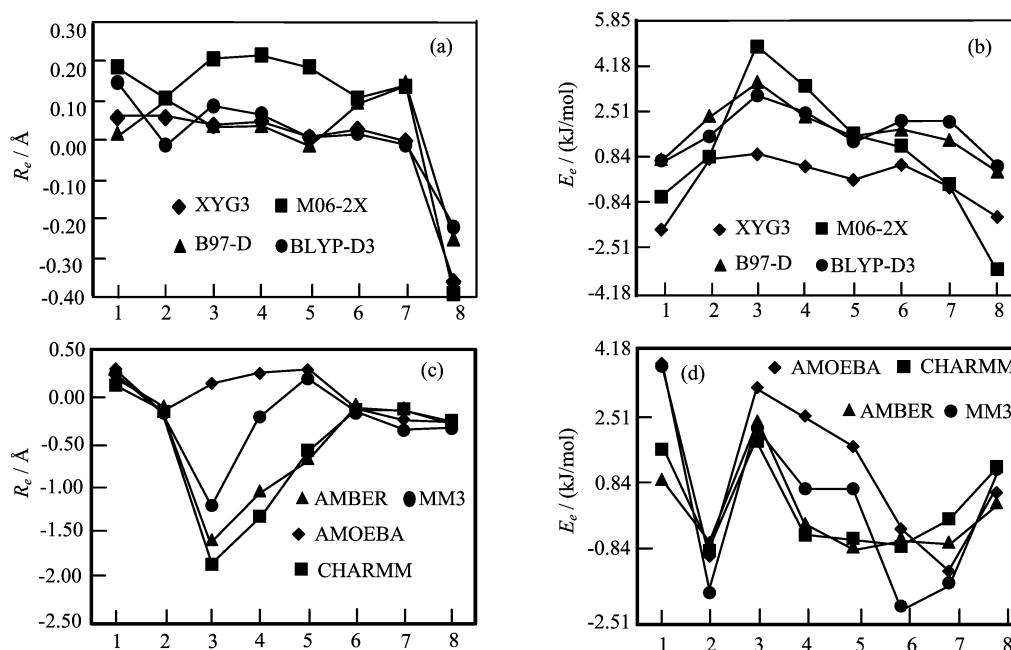


FIG. 2 Deviations from the reference data for some DFT methods (a), (b) and FF (c), (d) models in the description of benzene dimer. No.1–8 correspond to the structures listed in Table I and Fig.1.

was optimized using MP2/aVDZ and the interaction energy was estimated using MP4(SDTQ)/aVDZ with 90% basis set superposition error (BSSE) correction [4].

In all our calculations we adopted the frozen monomer approximation as commonly used in the literatures [1–3, 5, 6]. The bz monomer geometries were set to those as suggested by Gauss and Stanton [19], $R(\text{C}-\text{C})=1.3915 \text{ \AA}$ and $R(\text{C}-\text{H})=1.0800 \text{ \AA}$. This actually facilitates the comparison to most of the reference data [1–3, 5, 6], where the same frozen monomer geometries were adopted. It is well-known that the traditional DFT methods within the generalized gradient approximation (GGA) fail in the description of the dispersion interactions. This has brought about the dispersion add-on methods such as B97-D [9], and BLYP-D3 [10] that explicitly introduced the long-range terms of C_6R^{-6} and C_8R^{-8} , etc. Even though it was believed that *meta*-GGAs, just as GGAs, do not incorporate the physics of dispersion correlations [20], some recently developed hybrid *meta*-GGA functionals, such as M06-2X [11], show very impressive performance for some dispersion-dominated systems. XYG3 [12], on the other hand, represents one class of new generation of functionals [21, 22]. As XYG3 mixes in Hartree-Fock exchange as well as contributions from unoccupied orbitals via second-order perturbation theory, there is a potential that such doubly hybrid functionals can give the right answer for the right reason for dispersion. All DFT calculations, except BLYP-D3, were carried out using Gaussian 09 package [23] with the 6-311+G(3df,2p) basis set. For BLYP-D3, the calculations were performed with CP2K [24]. The D3 scaling

coefficients [10] are set to be 1.000, 1.094, and 1.682, respectively, and the corresponding basis set used is 6-311++G(d,p). No BSSE corrections have been applied to all our DFT calculations, as was commonly done in the literature [1, 5, 6, 12, 21, 22]. In addition, several FF models were tested against the high-quality *ab initio* reference data. We chose CHARMM [13], AMBER [14], and MM3 [15], as was done in Sherrill and co-workers' work [6]. For FF models, we paid more attention to AMOEBA, which is a new generation of polarizable force fields based on distributed multipoles [16]. AMBER calculations were carried out with Gaussian09 package, where the charges were optimized using the restrained electrostatic potential approach for bz, leading to $q(\text{H})=-q(\text{C})=0.127748 \text{ a.u.}$ as reported by Sherrill and co-workers [6]. Other FF calculations were carried out with TINKER 5.0 package [25].

Our calculation results are summarized in Table I and the corresponding error distributions, as compared to the reference data, are depicted in Fig.2. In terms of interaction distances, Fig.2 clearly displays a large deviation for all DFT methods for the V-shaped structure. The reference R_e for V is 4.86 \AA , while the DFT values are between 5.08 \AA (BLYP-D3) and 5.25 \AA (M06-2X), which are too long by more than 0.22 \AA . For other configurations, the XYG3 errors in R_e are less than 0.06 \AA (T), and the maximum errors for other DFTs are 0.22 \AA (PD(3.4 \text{ \AA})) for M06-2X, 0.15 \AA (CT) for B97-D, and 0.15 \AA (S) for BLYP-D3. On average over all eight data points including V, the mean absolute deviations (MADs) for R_e are 0.08 , 0.20 , 0.09 , and 0.07 \AA for XYG3, M06-2X, B97-D and BLYP-D3,

respectively. Excluding the data point of V structure, MADs for R_e are 0.03, 0.15, 0.05, and 0.05 Å for XYG3, M06-2X, B97-D, and BLYP-D3, respectively. Hence the M06-2X geometries are on average inferior to those obtained from the other three DFT methods. Specifically, M06-2X gives too small displacements for the PD configurations. Note that the only available reference R_e for V is from MP2/aug-cc-pVDZ, whereas it has been shown that MP2 has a tendency to consistently underestimate the bond distances [1]. Hence, we believe that this MP2 R_e reference has to be updated in the future and the true value of R_e for V might lie in between 5.08 Å (BLYP-D3) and 5.25 Å (M06-2X).

Figure 2 shows that, for the interaction energy E_e , XYG3 also displays the best performance, with errors in the range from -1.84 kJ/mol (S) to 0.96 kJ/mol (PD(3.2 Å)). The negative error sign indicates an under-binding, while the positive error sign indicates an over-binding. As dispersion interaction is more significant in the S configuration than other configurations, XYG3 may still fall short of some dispersion interactions. The error range for E_e associated with M06-2X spans from -3.30 kJ/mol (V) to 4.89 kJ/mol (PD(3.2 Å)). These errors are sizable as compared to the net binding energy of 4.18 – 11.70 kJ/mol. The dispersion add-on methods consistently overestimate the binding energy with no negative errors for this bz2 set. The maximum errors again occur at PD(3.2 Å), being 3.59 kJ/mol for B97-D and 3.09 kJ/mol for BLYP-D3. On average, MADs for E_e are 0.79, 2.05, 1.80, and 1.75 kJ/mol for XYG3, M06-2X, B97-D, and BLYP-D3, respectively. Note that nonbonded interactions are not included in the training set of XYG3, while such systems, specifically bz2, are included in the training set of the other three DFT methods. Hence, the good performance of XYG3 comes naturally from its right physics of truly nonlocal correlation in the PT2 term. Nevertheless, XYG3 does not recover 100% PT2 term at the long range for dispersion. Development is in progress along this line.

The performances of the FF models are all inferior to the DFT methods evaluated in the present work. Note that the scale of the vertical axis for R_e has been enlarged for the FF methods. As shown in Fig.2, the widely used FF models, *e.g.* CHARMM, AMBER, and MM3, have met serious problems in predicting R_e for the PD configurations. They all predicted a too long displacement. Encouragingly, the new generation of polarizable AMOEBA force field performed reasonably well in this aspect. On average, MADs for R_e are 0.96, 2.38, 2.13, and 1.55 kJ/mol for AMOEBA, CHARMM, AMBER and MM3, respectively. So far as E_e are concerned, the FF models seem to give similar errors (1.67 – 2.09 kJ/mol) to those of M06-2X, B97-D and BLYP-D3. Nevertheless, the poor geometries on the PD configurations have downplayed the values of using FF in calculating these interaction energies. Development of better polarizable FF models should be a valuable direction to go.

The issue for the configuration of the global minimum of bz2 has not yet been completely settled down by experiments. For example, optical absorption spectroscopy of Bernstein and co-workers [7] suggested that the bz moieties are symmetrically equivalent and favored a PD configuration with C_{2h} symmetry. On the other hand, the rotational spectrum of Arunan and Cutowsky [8], obtained with Fourier transform microwave spectrometer, indicated that two bz molecules are structurally inequivalent, and thus favored a T-shaped configuration. High quality *ab initio* data [1–4] suggested that PD of C_{2h} and T of C_{2v} are isoenergetical ($E_e = -11.29$ kJ/mol), while that TT of C_s may appear to be the global minimum, being 0.42 kJ/mol more stable than PD and T. XYG3, B97-D, and BLYP-D3 all qualitatively support this assignment, whereas M06-2X is in favor of PD(3.4 Å) as the global minimum. Arunan and Cutowsky suggested a center-to-center distance of 4.96 Å [8], which was supported by the high quality *ab initio* calculations (4.93 – 5.0 Å [1–3]), as well as those of XYG3 and BLYP-B3, while R_e from M06-2X and B97-D may seem too short (see Table I).

In summary, the present work highlights the performance of some modern DFT methods as well as FF models in the description of six interacting configurations of bz2. Traditionally, S, T and PD have been intensively studied and high quality *ab initio* data for the whole potential energy curves are available for comparison. For other configurations, such data are not available, but highly desirable. Construction of a high quality *ab initio* bz2 potential energy surface is under way in our lab, which shall be useful in calibrating and testing current DFT methods. XYG3, a new generation doubly hybrid functional, performs quite satisfactory, although it calls for further development of the dispersion interactions. XYG3, which formally scales as $O(N^5)$, where N is proportional to the system size, shows its potential as an economic substitute of the expensive CCSD(T) of $O(N^7)$. We believe that results of XYG3 for more complete information of the bz2 potential energy surface and for systems much larger than bz2 of real biomolecular and carbon-based materials' applications, where CCSD(T)/CBS calculations are infeasible, shall be useful in calibrating and developing new FF models. We anticipate that better polarizable FF models shall provide even more reliable results for nonbonded interactions, which will substantially assist the studies of molecular recognition, crystal engineering, and supramolecular chemistry, *etc.*

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