Two Faces of the Two-Phase Thermodynamic Model

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Abstract:

The quantum harmonic model and the two-phase thermodynamics method (2PT) are widely used to obtain quantum corrected properties such as isobaric heat capacities or molar entropies. 2PT heat capacities were calculated inconsistently in the literature, and the excellent correlations are due to error cancellation for organic liquids. We reanalyzed the performance of different quantum corrections on the heat capacities of common organic solvents against experimental data. The accuracy of the computations was also assessed with the determination of the self-diffusion coefficients.

Accounting for nuclear quantum effects is essential to obtain meaningful thermodynamic properties that are comparable to experimental observations.¹ The most typical example is that zero point energies are indispensable in the determination of reaction free energies. The quantum harmonic oscillator model works quite well for small molecules and solid states, but the anharmonicity becomes significant in macromolecules, interfaces and liquids and the potential energy surfaces must be mapped using molecular dynamics or Monte Carlo simulation. Berens proposed to add quantum correction to the classically calculated properties using the harmonic oscillator model.² Goddard improved this by the separation of different motions like translation rotations and vibrations and using different partition functions for each of them.^{3,4} This was abbreviated as two-phase thermodynamic (2PT) model referring to the gas phase and solid phase motions in contrast to the one-phase thermodynamic (1PT) method where only vibrations were considered. An anharmonic correction was also included in Berens' original idea, and thus we refer to that method as one-phase-thermodynamics with anharmonic correction (1PT+AC).

2PT and 1PT+AC methods were successfully applied for the calculation of thermodynamic properties of several systems such as Lennard-Jones fluids,^{3,5} water,^{2,4,6–15} aqueous solutions,^{16,17} molten salts,¹⁸ organic liquids,^{19–21} carbon dioxide,²² urea,²³ ionic liquids,^{24–27} carbohydrates,²⁸ cellulose,²⁹ mixtures³⁰ and interfaces.^{31–36} Lately, 2PT was used for the definition of the Frenkel line.^{37–40} Both 1PT/2PT methods are still in continuous development in respect of accuracy and applicability.^{41–48}

The 2PT method is the most excellent in the calculation of absolute entropy even from short trajectories. Although the heat capacity is strictly determined from the temperature dependence of entropy according to the laws of thermodynamics, the calculation of the 2PT heat capacity is not as consistent in the literature as the computation of the 2PT entropy. The 2PT abbreviation refers to two conceptually different calculation procedures of the heat capacity in dif-

ferent articles. The classical heat capacities were also taken into account in the calculation of the 2PT heat capacity of water,^{9,10,17,33} but in the case of organic solvents classical heat capacities were discarded.^{19–21} According to refs 19–21 we refer to 1PT and 2PT heat capacities that do not contain anharmonic corrections calculated from classical values. In previous studies there was no systematic comparison of the effect of this anharmonic correction. In this communication we fill this gap and analyse the 2PT and 1PT+AC methods in more details.

Here we focus on heat capacities to evaluate different types of quantum corrections because it contains large nuclear quantum effect and there are accurate experimental data that can be used for the benchmark of force fields.^{6,17,19–21,25–27,29,49–57} In contrast to enthalpy or Gibbs energy, heat capacity is an absolute quantity meaning that there is no need to set the zero point. Additionally, the isobaric heat capacity is a state function, so if we know the c_p as a function of T and p , the other state functions such as the enthalpy and entropy can be calculated as well. Previously, quantum corrected thermodynamic properties of organic solvents were investigated in two systematic studies by Pascal, and Coleman.^{19,20} For the same solvents they found similar results: the 2PT heat capacities were in good agreements with the experimental data. Both studies showed that OPLS force field gave better results than other general force fields such as GAFF or CHARMM. We recalculated the heat capacities of 92 organic solvents from ref 20 to test further the 1PT+AC and 2PT methods.

For the determination of the quantum corrected thermodynamic properties the velocity autocorrelation functions (VACF) are computed from molecular dynamics simulations that can be defined as follows:

$$\text{VACF}(t) = \frac{\int_0^\infty m v(t + \tau) \cdot v(\tau) d\tau}{\int_0^\infty m v(\tau) \cdot v(\tau) d\tau} \quad (1)$$

where m is the atomic mass and v is the velocity as a function of time (t). The vibrational density of states (VDOS) is the Fourier transform of the autocorrelation function (VACF)

$$\text{VDOS}(\nu) = \mathcal{F}_t \{ \text{VACF}(t) \} (\nu) = 2 \int_0^{+\infty} \text{VACF}(t) \cdot \cos(2\pi\nu t) dt \quad (2)$$

where ν is the frequency.

Originally Berens proposed that the quantum corrected density of states can be determined by the multiplication of VDOS with an appropriate weight function w :²

$$\text{VDOS}^q(\nu) = \text{VDOS}(\nu) \cdot w(\nu) \quad (3)$$

In the 1PT method there is no separation of motions, all

are considered as vibrations. The weight function for the heat capacity is⁵⁸

$$w_{\text{vib}}^{cV}(\nu) = \exp(\beta h \nu) \left(\frac{\beta h \nu}{1 - \exp(\beta h \nu)} \right)^2, \quad (4)$$

where $\beta = (k_B T)^{-1}$, k_B is the Boltzmann constant, T is the temperature, h is the Planck constant. Thus the isochoric heat capacity can be calculated as

$$c_V^{1PT} = 2fR \int_0^\infty \text{VDOS}(\nu) \cdot w_{\text{vib}}^{cV}(\nu) d\nu, \quad (5)$$

where R is the universal gas constant, and $f = 3N$ is the number of degrees of freedom of an N -atomic molecule.

Gaseous motions like translation and rotation are separated from vibrations in the 2PT method. The total VDOS is decomposed into two terms, solid and gaseous components:

$$\text{VDOS}(\nu) = \text{VDOS}_{\text{sol}}(\nu) + \text{VDOS}_{\text{gas}}(\nu) \quad (6)$$

Different weight functions are used for the different motions in the calculation of 2PT heat capacity:^{19,20}

$$c_V^{2PT} = 2fR \int_0^\infty [\text{VDOS}_{\text{sol}}(\nu) w_{\text{vib}}^{cV}(\nu) + \text{VDOS}_{\text{gas}} w_{\text{gas}}^{cV}(\nu)] d\nu \quad (7)$$

The weight function of the gaseous component is 1/2 for the heat capacity. One limitation of 2PT is that the molecular topology needs to remain the same, so bond breaking/formation, thus chemical reactions, cannot be modeled.

In the 1PT+AC method a quantum correction (c_V^{QC}) is added to the classical isochoric heat capacity (c_V^{cl}):²

$$c_V^{1PT+AC} = c_V^{\text{cl}} + c^{\text{QC}} = fR + c^{\text{AC}} + c^{\text{QC}} = c_V^{1PT} + c^{\text{AC}} \quad (8)$$

where c^{AC} is the anharmonic correction. From eq 8 it can be seen that the 1PT+AC heat capacity is actually a sum of three terms: the heat capacity of f classical harmonic oscillators plus an anharmonic- and a quantum correction.

Jorgensen proposed to correct the classical heat capacity by the estimation of the intramolecular component using the ideal gas value taken from experiments or ab initio calculations.^{49,50} If a given force field reproduces the experimental heat capacity of the gas accurately then Jorgensen's approach should give a similar value to the 1PT+AC method. Some deviation may occur if the frequencies of the intramolecular vibrations differ in the liquid and gas phases.

Recently we have shown that Berens' original idea about the quantum correction on thermodynamic properties can be extended to structural properties if the quantum correction is applied in time domain instead of frequency domain.^{59,60} Our technique, the generalized smoothed trajectory analysis (GSTA) gives identical results for thermodynamics properties as 1PT+AC. For instance the heat capacity can be obtained from the VACF directly:

$$c_V^{1PT+AC} = 2fR \int_0^{+\infty} \gamma^{cV}(\tau) \cdot \text{VACF}(\tau) d\tau + c_V^{\text{AC}} \quad (9)$$

where γ^{cV} is the Fourier transform of the weight function in eq 4:

$$\gamma^{cV}(\tau) = \frac{2\pi^2}{\beta h} \text{csch}^2 \left(\frac{2\pi^2}{\beta h} \tau \right) \left(\frac{2\pi^2}{\beta h} \tau \coth \left(\frac{2\pi^2}{\beta h} \tau \right) - 1 \right) \quad (10)$$

where csch is the hyperbolic cosecant function. This formal-

ism allows a much more effective calculation, because there is no need to calculate the VDOS.

The isobaric heat capacity can be determined from the isochoric heat capacity by employing the relation

$$c_p = c_V + \frac{TM\alpha_p^2}{\rho\kappa_T}, \quad (11)$$

where α_p denotes the thermal expansion coefficient, M is the relative molar mass, ρ is the density and κ_T is the isothermal compressibility. The isobaric 1PT+AC heat capacity is computed as a sum of the classical isobaric heat capacity and the quantum correction from eq 8 and the latter can be determined from VACF or VDOS according to eqs 5 and 9:

$$c_p^{1PT+AC} = c_p^{\text{cl}} + c^{\text{QC}} \quad (12)$$

We performed 10.6 ns long NpT simulations by using the GROMACS simulation software.⁶¹ The settings and inputs were taken from the ref 20 (more details can be found in the Supporting Information). 2PT heat capacities were calculated with the "dos" analysis tool of GROMACS. The classical heat capacity was determined from the fluctuation of enthalpy

$$c_p^{\text{cl}} = \left(\frac{\langle \partial H^2 \rangle}{RT^2} \right)_p \quad (13)$$

According to the correspondence principle the quantum calculations should agree with the classical results as the h Planck constant formally approaches zero. The 1PT model gives fR for the heat capacity in the classical limit. Applying the classical weight functions of 1/2 and 1 in eq 7 it is easy to see, that the 2PT model can give values between $fR/2$ and fR for the isochoric heat capacities in the classical limit. The 1PT+AC model always satisfies the correspondence principle in contrast with the 1PT or 2PT methods:

$$\lim_{h \rightarrow 0} c_p^{1PT+AC} = c_p^{\text{cl}} \quad (14)$$

This also implies that the technique is able to describe the effects of anharmonic motions. The 1PT and 2PT isochoric heat capacities for a rigid water model with 3 translational and 3 rotational degrees of freedom cannot be higher than $6R = 49.9$ J/mol/K. The fact that in ref 9, 10, 17, 33 the calculated heat capacities are in the range of 57 and 81 J/K/mol which is significantly larger than the theoretical limit of 49.9 J/K/mol implies that anharmonic contribution was also considered. Since the experimental isochoric heat capacity is 74.5 J/K/mol, the anharmonic contribution is at least 24.6 J/K/mol.⁶²

In our previous study we showed that the 1PT+AC heat capacity can be significantly overestimated if the left Riemann sum is used instead of the trapezoidal rule in the computation of VDOS in eq 2.⁵⁹ To check whether this numerical error can occur in the calculation of the 2PT heat capacities, we tested thoroughly the "dos" analysis tool of the GROMACS that was used in ref 20. The default Fast Fourier Transformation routine in GROMACS applies the left Riemann rule but we also implemented a simple trapezoidal integral rule. We analyzed the effect of the different algorithms on methanol. Decreasing the integration time step, the trapezoidal integral converged rapidly at 5 fs, meanwhile the default left Riemann sum gave the correct 2PT heat capacity, 51.6 J/K/mol only in the $\Delta t \rightarrow 0$ limit (see Figure 1). At 4 fs time step, which is generally used in 2PT calculations, the heat capacity of 73.4 J/K/mol is overestimated by 40 %. This agrees well with the result of 75.8 J/K/mol

from ref 20. The convergence of the 1PT method is also shown with the trapezoidal formula, and at 4 fs the 1PT heat capacity is also converged with 60.7 J/K/mol.

Figure 1. Convergence of the isochoric heat capacity of methanol as a function of step size

When we recalculated the heat capacities of 9 common solvents from ref 19 and 20 with both integral formulas, we reproduced the literature data but we obtained 45 % lower heat capacities with the correct integral formula (see the Supporting Information). In ref 19 and 20 the 2PT heat capacities are similar to each other for the same solvents with OPLS force field, which implies that in both works the same (incorrect) integration routine was used.

Surprisingly, in these previous works excellent correlations were found between the 2PT and experimental isobaric heat capacities. How is it possible that such a good correlation has been achieved, if the values were overestimated by 45 %? It seems that there was an (un)fortunate error cancellation, where the opposite error is connected to the conversion between the isobaric and isochoric heat capacities in eq 11.

Figure 2. Calculated vs. experimental isobaric heat capacities

In ref 20 the $c_p - c_v$ difference is always smaller than 0.1 J/K/mol, and in ref 19 this correction was not larger than 1.2 J/K/mol. We recalculated the $c_p - c_v$ differences for the organic liquids from ref 20 and we obtained orders of magnitude higher values. In our computations the average difference is 38.4 J/K/mol, and the heat capacity ratio is 1.31. For a few molecules there are direct experimental data for the

isochoric heat capacities (see the Supporting Information). For instance the $c_p - c_v$ differences of methanol and ethanol are 14 and 11 J/K/mol, respectively.^{63,64} This supports that we calculated correctly the $c_p - c_v$ values.

The correctly calculated isobaric heat capacities are shown in Figure 2 as a function of experimental values. The overall correlations are good for the predicted and experimental heat capacities, the R^2 is about 0.9 for all three methods. From the fitted lines it can be seen that the slope of the 1PT and 2PT are almost perfect 1.01, but for 1PT+AC the slope is 1.24. 2PT systematically underestimates, 1PT overestimates the isobaric heat capacities.

The mean absolute deviations for different types of molecules are shown in Figure 3. For all the compounds the error is 20 J/K/mol for the 1PT+AC method. The error is smaller with 1PT and even smaller with the 2PT method. The methods perform differently for different types of compounds, and even their relative goodness is varying. For hydrocarbons, organosulfures, halocarbons and heteroaromatics the 1PT performs the worst, and the 1PT+AC and 2PT performs similarly better. For amines, ethers, alcohols and ketones the 1PT+AC performs the worst, and the 1PT and 2PT methods perform much better. The large errors of the 1PT+AC heat capacities may originate from the deficiency of the force field and/or from the inaccuracy of the 1PT+AC method. To separate these two errors, we investigated the classical limits which characterizes the failure of the method.

Figure 3. Mean absolute errors (MAE) of the calculated isobaric heat capacities compared to experimental data.

As mentioned above the 1PT and 2PT models do not satisfy the correspondence principle, they cannot reproduce the classical heat capacities of anharmonic cases. To quantify these deviations the mean error of the reproduction of the classical heat capacities is shown for the 1PT and 2PT methods in Figure 4. 1PT+AC is not shown because this error is zero according to eq 14. 2PT always underestimates the classical heat capacity, by 21.5 J/mol/K in average which is almost twice as large as the mean absolute error compared to the experiments, 11.8 J/mol/K. The 1PT method overestimates the classical heat capacity for the heteroaromatics, halocarbons, organosulfures and hydrocarbons and underestimates for the other compound groups. This classification correlates perfectly with the relative performance of 1PT and 1PT+AC in Figure 3. If the 1PT heat capacity agrees better with the experiment than the 1PT+AC, then it means that the anharmonicity is described incorrectly by

the force field. The Lennard-Jones potential is known to be too repulsive and this may cause inaccuracies when stronger attractive interactions are also present. The uncertainty of the anharmonicity is too large with the OPLS force field for the aliphatic N and O compounds and this is why the 2PT method estimates the heat capacity of organic liquids more accurately. These results suggest that the effect of anharmonicity is significantly smaller than the quantum effect on the heat capacity of the organic liquids. In the 1PT+AC method this means that the magnitude of the anharmonic correction is smaller than that of the quantum correction in eq 8.

Figure 4. Mean unsigned errors (MUE) of the isobaric heat capacities in the classical limit.

Caleman and Pascal concluded from their studies that the reproduction of the experimental heat capacities could be improved by better description of the force constants of bonds and angles.^{19,20} This is true for the quantum correction, but the anharmonic correction can be adjusted with the non-bonding parameters. Our results indicate that the thermodynamic properties are more sensitive to the intermolecular interactions than to the intramolecular interactions. This is in line with the general experiences that in the simulation of the organic liquids the bond lengths and angles can be constrained at room temperature.

To estimate the consistency of the calculations of VACF and VDOS functions we computed the self-diffusion coefficients with two different methods.⁶⁵ First, we determined D_s from the VACF:

$$D_s = \frac{\langle v^2 \rangle}{3} \lim_{t \rightarrow \infty} \int_0^t \text{VACF}(\tau) d\tau \quad (15)$$

The self-diffusion coefficient can also be calculated from the mean square displacement of the atoms using the Einstein equation:

$$D_s = \lim_{t \rightarrow \infty} \frac{\partial \langle (x(t) - x(0))^2 \rangle}{6 \partial t} \quad (16)$$

We computed the self-diffusion coefficients according to these equations at 10 ps. The two complementary approaches gave almost identical results ($\text{MAE} = 0.05 \cdot 10^{-9} \text{m}^2 \text{s}^{-1}$, $R^2 = 0.998$) which validates how we calculated the VACF and VDOS functions (see the Supplementary Information). The self-diffusion coefficients were also determined from the 10 ns simulations using eq 16. Comparing to the available experimental data the mean absolute error

is $0.62 \cdot 10^{-9} \text{m}^2 \text{s}^{-1}$ for 31 liquids, which means significant correlation ($R^2 = 0.79$) (see Figure 5). It looks that the values have not converged at 10 ps but the longer simulation time (10 ns vs. 10 ps) does not improve the accuracy of the estimation of the self-diffusion coefficient. Actually, the mean absolute error is slightly lower, $0.55 \cdot 10^{-9} \text{m}^2 \text{s}^{-1}$ using 10 ps long VACF functions, and the correlation coefficient is almost the same ($R^2 = 0.77$).

Computation of the heat capacity from a converged VDOS function is a memory-intensive calculation since all of the velocities need to be read from several picosecond long trajectories with time intervals of a few femtoseconds. This computational cost can be reduced significantly with the GSTA approach. In the present case, it is enough to compute the VACF 68 fs long, if the VACF function is corrected, instead of the 10 ps length used for the determination of the VDOS.

The calculation of the self-diffusion coefficient from a trajectory is orders of magnitude more expensive with the Green-Kubo method than with the Einstein equation. While in the first case we needed to compute 10 ps long VACF with a resolution of 4 fs, in the latter case it was enough to calculate the mean squared displacement at 8 and 12 ps. Moreover, the calculation of VACF is almost unfeasible after 100 ps, when the self-diffusion coefficient converges.

Figure 5. Calculated vs. experimental self-diffusion coefficients in unit of $10^{-9} \text{m}^2 \text{s}^{-1}$ for 31 organic solvents

As a summary, we compared the 2PT and 1PT+AC heat capacities. We pointed out that previous 2PT heat capacities in the literature were calculated incorrectly.^{19–21} The right program code is given in the Supporting Information to calculate the correct 2PT and 1PT thus the more exact 1PT+AC methods by using the GROMACS software. Based on our benchmark calculations we suggest to use different methods for different purposes. Despite of the theoretical limitation of the 2PT method, it can give reasonable estimation for thermodynamic properties of organic liquids. If someone wants to benchmark force fields, or develop new force field parameters it is recommended to use the 1PT+AC method which accounts the anharmonicity correctly. Our results help to improve the accuracy of the calculated thermodynamic properties of large systems, and with the use of more efficient algorithms even larger systems can be investigated.

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Supporting Information Available

The details of the simulations along with the program codes, input files and results are available in the Supporting Information.

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