

This article was downloaded by:

On: 14 January 2011

Access details: *Access Details: Free Access*

Publisher *Taylor & Francis*

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Molecular Simulation

Publication details, including instructions for authors and subscription information:

<http://www.informaworld.com/smpp/title~content=t713644482>

Evaluation of various water models for simulation of adsorption in hydrophobic zeolites

J. M. Castillo^{ab}; D. Dubbeldam^c; T. J. H. Vlugt^b; B. Smit^d; S. Calero^a

^a Department of Physical, Chemical, and Natural Systems, University Pablo de Olavide, Seville, Spain ^b Process and Energy Laboratory, Delft University of Technology, Delft, The Netherlands ^c Chemical and Biological Engineering Department, Northwestern University, Evanston, IL, USA ^d Department of Chemical Engineering, University of California at Berkeley, Berkeley, CA, USA

To cite this Article Castillo, J. M. , Dubbeldam, D. , Vlugt, T. J. H. , Smit, B. and Calero, S.(2009) 'Evaluation of various water models for simulation of adsorption in hydrophobic zeolites', *Molecular Simulation*, 35: 12, 1067 – 1076

To link to this Article: DOI: 10.1080/08927020902865923

URL: <http://dx.doi.org/10.1080/08927020902865923>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.informaworld.com/terms-and-conditions-of-access.pdf>

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Evaluation of various water models for simulation of adsorption in hydrophobic zeolites

J.M. Castillo^{ab}, D. Dubbeldam^c, T.J.H. Vlugt^b, B. Smit^d and S. Calero^{a*}

^aDepartment of Physical, Chemical, and Natural Systems, University Pablo de Olavide, Ctra. Utrera km. 1, 41013 Seville, Spain;

^bProcess and Energy Laboratory, Delft University of Technology, Leeghwaterstraat 44, 2628CA Delft, The Netherlands; ^cChemical and Biological Engineering Department, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA; ^dDepartment of Chemical Engineering, University of California at Berkeley, 101B Gilman Hall #1462, Berkeley, CA 94720, USA

(Received 22 December 2008; final version received 22 February 2009)

We have performed a molecular simulation study on water adsorption in hydrophobic zeolites. The framework structures are truly periodic and therefore the Ewald summation is the natural choice for computing the Coulombic interactions. However, a few water models have been parameterised using this method. The adsorption results are extremely sensitive to the water model used, the framework positions in the orthorhombic structure and the atomic charges of the zeolite framework. This work provides insight into the identification of the potential limitations of the available force fields and models, and into the point charges used for the zeolite atoms, when they are applied to a highly hydrophobic system. We discuss feasible routes to conciliate simulation and experimental results.

Keywords: adsorption; water; zeolites; simulation

1. Introduction

Zeolites nowadays have a great importance in industries, as they have wide applications such as catalysis, molecular sieve and gas storage [1]. In addition, water is probably the most important compound on earth, as it is present in most biological and geological processes. Currently, the main use of zeolites in the presence of water is the removal of a wide range of pollutants from water, for example industrial dyes, heavy metals, hydrocarbons and waste oils [2,3]. The zeolites selected for this use are usually cheap natural zeolites such as clinoptilolite (CLI) or mordenite, although synthetic materials have also been used. Interestingly, it has been suggested that water can be present in the Mars rocks that contain zeolites [4]. Although there are many studies on water in zeolites, many of the phenomena related to the presence of water in these structures, such as adsorption or cation exchange, have not been well described nor have they been yet fully understood. Experimental data obtained by different authors or using different techniques lead to different results, as is the case with adsorption isotherms [5,6]. The most likely reason for this void is the exceptional nature of water. Water is a very simple molecule only composed of three atoms, and yet its behaviour is quite extraordinary and not completely understood. The behaviour of water is quite different from what is found for other materials, although deciding whether these properties are anomalous depends on the materials used to compare [7,8].

Classical molecular simulations are normally used to calculate adsorption isotherms and diffusion in porous

materials. In the search for speed and simplicity in the calculations, simple force fields are desirable. Hydrocarbons and common molecules such as nitrogen or carbon dioxide adsorbed in zeolites are examples of systems that can easily be studied with this kind of methods, obtaining adsorption data that match the experimental data [9,10]. Similar approaches have been used for water in zeolites, but with less success [11,12]. This is attributed to the need for long equilibration cycles, and to the fact that small changes in the potential parameters largely influence the computed values [13].

Many different water models have been proposed during the last decades in an effort to reproduce its most important properties. As an example, one single review gathers 46 different water models [14]. None of these models is completely satisfactory when trying to reproduce simultaneously different properties of water, such as the location of the density maximum and the critical point. Water models have become more and more complex with time in a search for correctly predicting the largest number of properties. Some models include multipoles or polarisation in different ways with moderate success, and it is worth to mention non-atomistic models and models fitted after *ab initio* simulations that are obtaining promising results, as they account for most of the abnormalities of water [15–17].

Molecular simulations of water in zeolites generally use simple models for water, mainly SPC and Tip4p. Furthermore, most of the studies concentrate on two types of zeolites: faujasite (FAU) and silicalite (MFI). Most simulation efforts have been focused on the study of the

*Corresponding author. Email: scalero@upo.es

interaction of water with pure siliceous zeolite or alumina-exchanged zeolite [11–13,18–25]. The first type of zeolite is known to be hydrophobic, while the second is hydrophilic. The interaction between the different atoms is usually modelled with Coulombic interactions plus a simple attractive–dispersive potential such as the Lennard-Jones or Buckingham potentials.

Adsorption and diffusion of water in MFI- and FAU-type zeolites have been reported by a variety of authors using several models for water. The most popular model is Tip4p [26], which has been used by Beauvais et al. [18] to describe the location of the sodium cations in FAU in the presence of water; by Di Lella et al. [19] to calculate the adsorption isotherms and cation distribution in FAU and MFI; by Trzpit et al. [20] and Yang et al. [21] to study water diffusion in MFI or by Cailliez et al. [22] to study the interaction of water with the possible defects of the zeolite MFI. Desbiens et al. [11,23] computed adsorption isotherms in MFI with different partial charges for the framework atoms not only with the Tip4p water model [26], but also with the Tip5p [27], MSPC/E [28] and the polarisable DEC [29] model. Ramachandran et al. [13] simulated adsorption of water in MFI with Tip4p [26] and SPC/E [30], trying to reproduce small defects in the framework with extra water molecules. The SPC [31] water model has also been widely used for adsorption of water in zeolites. Hence, Pellenq et al. [24] used this model in MFI, including polarisation in all the atoms of the system, to study polarisation effects, configuration energy and heats of adsorption, and Puibasset et al. [12] used this simple model of water in conjunction with a more complex, polarisable potential for the interactions of water–zeolite in MFI to study the adsorption and formation of water clusters [31]. Other models for water such as Tips2 [32] have also been used by Halasz et al. [25] to compute the adsorption isotherms of water in different FAUs, and similar studies with similar techniques and models have been performed in other types of zeolites, for example in zeolite A (LTA) [33], heulandite and CLI [34].

An overwhelming majority of water models use a direct pairwise Coulombic interaction truncated at 9 or 10 Å. This may give reasonable results for pure water as a liquid due to a large effective charge screening but prohibits transferability to multi-component or adsorptive systems where such a screening is absent. Moreover, zeolites are crystalline materials described by a periodic unit cell. For systems that are periodic, the long-range interactions can be computed exactly up to an arbitrary precision [35]. Recently, researchers have become more aware of the special nature of charge interactions in nanoporous materials. Straightforward truncated, pairwise Coulombic calculations including methods such as the Wolf-method turn out to be non-transferable to zeolites because of the non-uniform local density (dense framework with open voids) [36]. This work provides

a simulation study on water adsorption in MFI-type zeolites using classical force fields to identify the possible limitations of available methods and force field parameters when they are applied to this special and highly hydrophobic system. We also explore possible routes to conciliate simulation and experimental results.

2. Simulation details

Adsorption isotherms are calculated in the grand-canonical ensemble, in which the temperature T , the volume V and the chemical potential μ are kept fixed. The imposed chemical potential μ is related to the fugacity and can be computed from the equation of state for a given pressure. The gas phase was treated as an ideal gas, as the pressures considered were low. In the case of liquid water, the NIST database [37] is used to obtain the chemical potential. For water, this database covers a validity range for temperatures from the melting line (lowest temperature 251.2 K at 209.9 MPa) to 1273 K and pressures up to 1000 MPa. The equation of state for a particular molecular model can be computed instead, but this calculation is long and is subject to large error bars. Some studies have shown that the deviation between the calculated and the experimental chemical potential is negligible in a large range far from the critical conditions [11]. For high-density systems, such as liquid water, the probability of successfully inserting one molecule in the system is very low. For that reason, the insertion/deletion of molecules in the system was performed using the configurational-bias Monte Carlo (MC) technique (40% of the MC moves) while other MC moves were attempted during the simulation: regrowth (20%), rotation (20%) and translation (20%) of a randomly selected molecule. The maximum translational and rotational displacements were adjusted to achieve an acceptance probability of 50%. The pore volume in the frameworks was calculated using the Widom particle insertion method [38]. The Henry coefficients and heats of adsorption at zero coverage were computed using MC in the NVT ensemble. The Henry coefficient is related to the excess chemical potential, which is computed using Widom's test particle method. More details can be found in [38].

For calculating the liquid density of water, the NPT ensemble is chosen. In these simulations, a fixed number of particles are initially placed in a cubic box with an initial length of 25 Å, and then the box length is allowed to change. All the potentials were truncated to different cut-off radii and shifted depending on the water model used. At every moment the box length was at least twice the size of the cut-off radius. In our MC simulations, changes in the volume of the system were attempted with a probability of 10%, while regrowth of the molecule, rotation and translation had a probability of 30%. The maximum translational and rotational displacements were adjusted to achieve an acceptance probability of 50%.

Simulations are performed in cycles, and in each cycle MC moves are chosen at random. The number of MC moves per cycle is equal to the number of particles present in the system, with a minimum of 20 moves per cycle. More details on the simulation technique can be found elsewhere [39,40]. In the case of calculations of water density or water adsorbed in zeolites, it has been repeatedly reported that the number of MC or molecular dynamics (MD) steps necessary for equilibration of the system is unusually large [13]. This is especially true when simulating adsorption inside zeolites in the region that is between the inflection point and the saturation zone, as in this region the shape of the isotherm is very steep. Water molecules interact more strongly with themselves than with the zeolite, and form clusters that grow until they fall apart and the process begins again [41]. In this way, to obtain a proper statistic description of the system from the simulation, the number of cycles has to be large. For the critical zone of the isotherm, up to 5×10^5 initialisation cycles are needed; for the other points of the isotherm 1×10^5 initialisation cycles are used and 2×10^5 for production. For the NPT ensemble, 5×10^4 integration steps are used and at least 2×10^5 for production.

The model Tip5pEw [42] is a suitable model for studying adsorption of water in zeolites, because its properties have been refitted using Ewald sums and the adsorption isotherms can be computed with a good precision. There are other models that also have been parameterised with Ewald sums, such as Tip4pEw [43], Tip3p-PME [44], SPC/Fw [45] molecular dynamics (MD) or SWM4-DP [46]. The last two are flexible water models and therefore their use would increase the simulation time. In any case, flexible water models could be interesting when studying mixtures of water with large molecules or interaction with ions, as it has been shown that flexibility and polarisability can be important in this case [14,46,47]. No hydrolysis is observed in the adsorption of water in zeolites due to the weak interaction of water with the zeolite [48,49], so this effect was not included in our simulations.

Hydrocarbons were modelled using a united atom model, in which CH_x groups are considered as single, chargeless interaction centres with their own effective potential [50]. The bond-stretching, bond-bending and torsion potentials of the alkane, as well as the alkane–alkane and alkane–zeolite potentials, were obtained from a recent parameterisation that accurately describes the adsorption isotherms of alkanes [51]. A rigid atomistic model of CO_2 is used [52], with a bond length of 1.16 Å. Every atom of CO_2 has a partial charge and the dispersive interactions between the molecules are described by a Lennard-Jones potential. The interaction with the zeolite is taken from Garcia-Perez et al. [10]. All Lennard-Jones parameters and atomic charges used in this work are listed in Table 1.

Table 1. Lennard-Jones parameters and initial partial charges used in this work.

Atom(s)	ϵ/k_B	σ (Å)	q (e)
Si [39]			2.05
O _{zeo} [56]	93.53	3.0	−1.025
O _{water} [42]	89.516	3.097	
H _{water} [42]			0.241
D _{water} [42]			−0.241
C _{CO₂} [52]	28.129	2.76	0.6512
C _{CO₂} –O _{zeo} [10]	50.2	2.7815	
O _{CO₂} [52]	80.507	3.033	−0.3256
O _{CO₂} –O _{zeo} [10]	84.93	2.9195	
CH ₃ [50]	108.0	3.76	
CH ₃ –O _{zeo} [51]	93.0	3.48	
CH ₂ [50]	56.0	3.96	
CH ₂ –O _{zeo} [51]	60.5	3.58	

Lorentz–Berthelot mixing rules are used for the interaction between water and the zeolite. The water model Tip5pEw has two dummy atoms, labelled as D.

To set the crystallographic positions of the atoms of the zeolite, we considered two different X-ray characterisations of MFI, the first one from Olson et al. [53] and the second one from van Koningsveld et al. [54]. Both of them are orthorhombic with the space group *Pnma*. For both the structures, the simulations were performed using eight unit cells ($2 \times 2 \times 2$) with periodic boundary conditions, with one size at least twice the cut-off radius. Simulations were performed using a rigid framework [55]. The partial charges of the framework atoms were taken from the work of Calero et al. [39]. As the Coulombic interactions between water and zeolite dominate the adsorption properties of the model due to the large dipole moment of the water molecules, during our study we test different charges in the Si atoms, ranging from 0e to 3.5e. To preserve the electrostatic neutrality of the zeolite, every oxygen atom in the zeolite is assigned to half the charge of the silica atoms (with opposite sign). The Coulombic interactions were calculated using the Ewald summation technique [35] with a relative accuracy of 10^{-6} . The non-Coulombic interactions of the adsorbates with the framework are dominated by the dispersive forces between the pseudo-atoms and the oxygen atoms of the zeolite. These interactions are modelled through an effective Lennard-Jones potential that only takes into account the oxygen atoms. The Lennard-Jones parameters of Pascual et al. [56] were implemented together with Lorentz–Berthelot mixing rules. All Lennard-Jones potentials were truncated and shifted at a cut-off radius of 12 Å.

3. Results and discussion

3.1 Choosing water models

Different researchers have used a wide range of classical water models trying to describe the different properties of water in zeolites. The bond length and bond angle of these simple models were usually taken from the experimental

Table 2. Henry coefficients and heats of adsorption of water in MFI, calculated in the Olson and van Koningsveld characterisations of MFI and at different locations in the structure: straight channels, zig-zag channels and intersections.

Location	K_H (mol kg ⁻¹ Pa ⁻¹)		ΔH (kJ mol ⁻¹)	
	van K.	Olson	van K.	Olson
Straight channels	6.2×10^{-6} (6)	1.7×10^{-5} (1)	-24.7 (6)	-27.8 (2)
Zig-zag channels	1.7×10^{-5} (3)	1.7×10^{-5} (1)	-30.3 (9)	-28.9 (2.3)
Intersections	7.9×10^{-7} (5)	6.0×10^{-4} (1.4)	-17.2 (4)	-44.9 (2.1)
Whole structure	2.5×10^{-5} (3)	5.7×10^{-4} (1.0)	-28.9 (1.0)	-44.6 (4.3)

The value obtained for the whole structure is also included for comparison. The values in parentheses indicate the error in the last digits. Van K., van Koningsveld.

gas-phase values, while the interactions were adjusted to reproduce the most important properties of water and particularly the water density at standard conditions. These models were fitted for different cut-off values for the Coulombic and Lennard-Jones interactions. We found large differences between simulations that use the Ewald summation and those that use a direct pairwise potential with spherical cut-off [57]. Some authors claim that particular models of water such as Tip4p/2005 [58] or SPC/Fw [45] are better than others when they are compared at the same simulation conditions (cut-off radius, use of switching functions, method to evaluate the Coulombic energy). However, it has been shown that the particular simulation conditions are vital for the final result of a given simulation [57]. To calculate water properties using one particular water model, the specific simulation conditions used for the parameterisation of that model should be used. If this is not the case, deviations from the expected behaviour can be observed, and therefore the former comparison does not make any sense. To illustrate this point, Figure 1 compares the water density obtained at 1 atm. in the temperature region that spans from -30 to 110°C using a variety of models. The density was computed using MD simulations in the NPT ensemble with SPC [31], Tip4p [26], Tip5p [27] and Tip5pEw [42] models for water. Besides the experimental data, we plot water densities obtained with (a) the parameters that were originally used to fit the particular water model, and (b) the same parameters *but* using Ewald summations and a Lennard-Jones cut-off of 12 Å. Most of the models give a precise estimation of the density at 25°C using the original parameters, as they were adjusted to reproduce this value. Among the models tested, only Tip5p and Tip5pEw reproduce the maximum of densities around 4°C using the originally reported parameters. Note that the Tip5pEw is the only model that also matches the experimental density using conditions other than those considered in the original fitting. This can be easily explained since the Tip5pEw model was originally fitted using Ewald summations and a variable Lennard-Jones cut-off equal to half the box length, which was always close to 12 Å. Furthermore, with Tip5pEw, we obtain the best results for the density as a function of temperature.

Although experimentally the bulk dipole moment of water is reduced upon adsorption in zeolites, the polarisation induced by the zeolite in water is rather small, as well as the influence of the zeolite in the hydrogen bonds of water [59]. Quantum simulations have also found problems describing the polarisation of water molecules in zeolites [24]. As polarity is more important than polarisability in the adsorption of molecules in these materials, in our study, we select the non-polarisable Tip5pEw [42] model for water, which is simply a Tip5p model parameterised for Ewald sums. Similar models such as Tip4pEw [43], Tip3p-PME [44], SPC/Fw [45] or SWM4-DP [46] are also possible candidates, though some of them are flexible or polarisable and they might give a better description of some particular properties of the system at a larger computational cost. The SPC, Tip4p and other similar models can also be used in the study of water adsorption in zeolites, but due to the importance of the

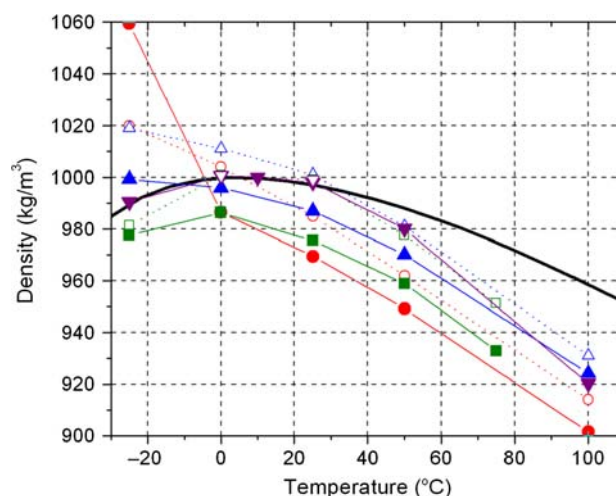


Figure 1. Experimental [37] (black line) and calculated water density as a function of temperature at 1 atm. Simulations were performed using the SPC (●), Tip4p (▲), Tip5p (■) and Tip5pEw (▼) models for water. Simulation data with the original fitting parameters are represented by open symbols, and those using Ewald sums and a Lennard-Jones cut-off of 12 Å are represented by solid symbols. Lines are a guide to the eye.

long-range interactions, their Ewald-fitted versions should be used instead.

3.2 Differences between the two characterisations of MFI

There are two different characterisations of the orthorhombic structure of MFI, one from Olson et al. [53] and another from van Koningsveld et al. [54]. Both structures are similar with slight differences in the atomic positions. Computing the pore volumes using the Widom insertion technique leads to 0.166 and 0.163 cm³/g for the structures of Olson and van Koningsveld, respectively. The two structures differ mainly at the channel intersections. The maximum deviation between equivalent atoms is lower than 0.37 Å. These differences have been shown to be important when simulating tight-fitting molecules such as benzene and xylene, as they can lead to large changes in the computed properties attributed to the different electrostatic potential felt by the molecules at the intersections [60].

Water is a small molecule that does not interact strongly with MFI, so the adsorption in the two structures of MFI is expected to be similar. Figure 2 compares experimental [23,61] and simulation data for water adsorption in both MFI structures at 300 K. For this particular study, we use the Tip4p model at the same simulation conditions as that of previous groups [11,19], assigning a partial charge of 1.4e to the silicon atoms of the framework (and therefore a partial charge of -0.7e to the oxygen atoms). Although the adsorption isotherms for both frameworks have a similar shape, for a given loading the pressure differs up to 60 MPa. This large difference between the isotherms calculated in the two different structures is completely unexpected if compared with the isotherms calculated for other molecules of similar size such as propane (Figure 3) and carbon dioxide (Figure 4) that accurately reproduce the experimental data [10,62]. Differences between isotherms are minor for the non-polar propane and low for the quadrupolar carbon dioxide, indicating that the discrepancies on the adsorption isotherms for water can be mainly attributed to the water dipole moment. Larger, non-polar molecules such as *n*-heptane show similar adsorption for both structures at the lower and higher pressure regions. However, at intermediate pressures, the adsorption in the structure of Olson is notably higher than in the van Koningsveld structure. The calculated and experimental isotherms [63] are shown in Figure 5. The differences are most likely due to the commensurate ‘freezing’ of *n*-heptane in the sinusoidal channels. This affects the adsorption at the channel intersections where the differences between the zeolite structures are the largest [64].

Similar studies have been performed for other water models. For example, calculated adsorption isotherms for the flexible models SPC/Fw and F3C in both structures are shown in Figure 6. These models showed reduced pressure

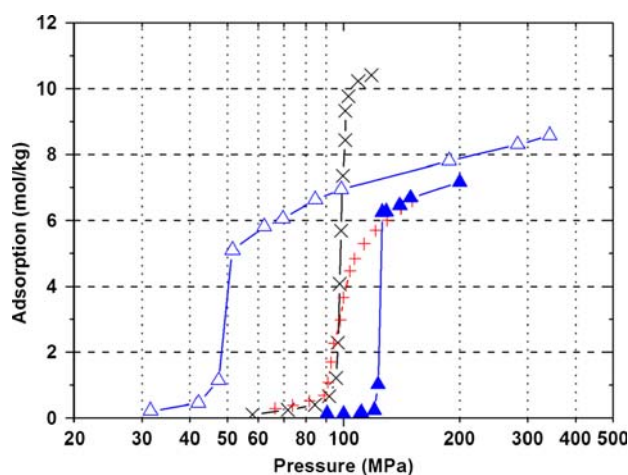


Figure 2. Experimental [23,61] (× and +) and calculated adsorption isotherms of water in MFI structures at 300 K. Simulations were performed using the Tip4p water model for the Olson (Δ) and the van Koningsveld (▲) structures, assigning a partial charge of 1.4e to the Si atoms of the framework. The lines are a guide to the eye.

differences for the condensation point in the two different characterisations of MFI, since condensation takes place at low pressures. Apart from this result, large deviations between the two isotherms are observed as for the other models. Furthermore, the isotherms deviate significantly from the experimental data. The adsorption isotherms obtained for the Tip5pEw model are shown in Figure 7. In this case, the differences are much larger than for the rest of the models tested. The reason is that, for Olson framework, the condensation takes place at low pressures due to a water phase transition. These results suggest that the differences originate from the particular behaviour

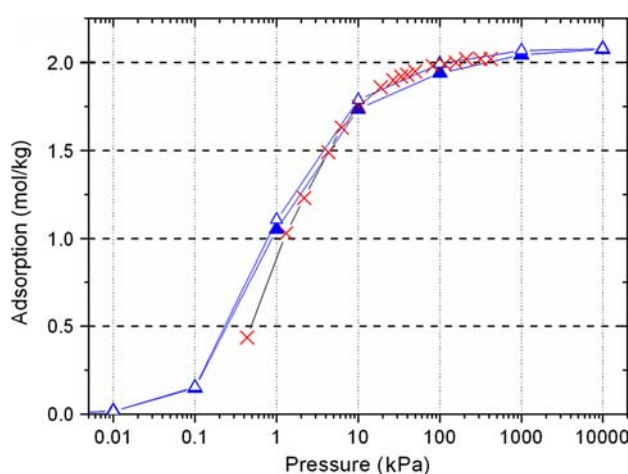


Figure 3. Experimental [62] (×) at 303 K and calculated adsorption isotherms of propane in MFI at 298 K. Simulations were performed using the Olson (Δ) and the van Koningsveld (▲) structures, assigning a partial charge of 2.05e to the Si atoms of the framework. The lines are a guide to the eye.

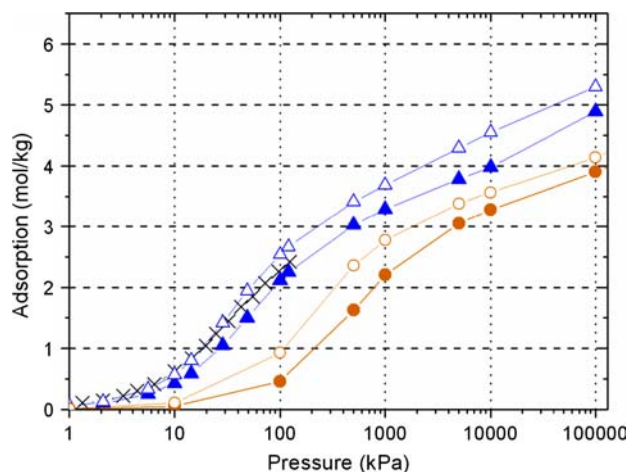


Figure 4. Experimental [10] (+) and calculated adsorption isotherms of carbon dioxide in MFI at 273 K. Simulations were performed for the Olson (open symbols) and the van Koningsveld (solid symbols) structures, assigning partial charges of 2.05 e (\blacktriangle) and 0.5 e (\bullet) to the Si atoms of the framework. The lines are a guide to the eye.

of water in this type of material and not from the details of the force field used. In particular, the large dipolar moment of water must play an important role in the adsorption. The differences in adsorption in both characterisations also increase with the dipole or quadrupolar moment of the molecule, from propane to carbon dioxide and finally water, due to the large differences in the electrostatic energy at the channel intersections of MFI between both the structures. In all cases, the adsorption capacity in the structure of Olson is larger than in the structure of van Koningsveld, since the first has a slightly larger pore volume.

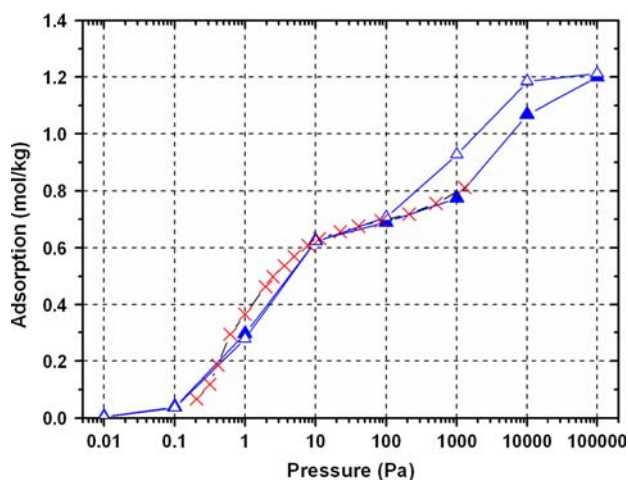


Figure 5. Experimental [63] (\times) and calculated adsorption isotherms of *n*-heptane in MFI at 347 K using the Olson (Δ) and the van Koningsveld (\blacktriangle) structures. The lines are a guide to the eye.

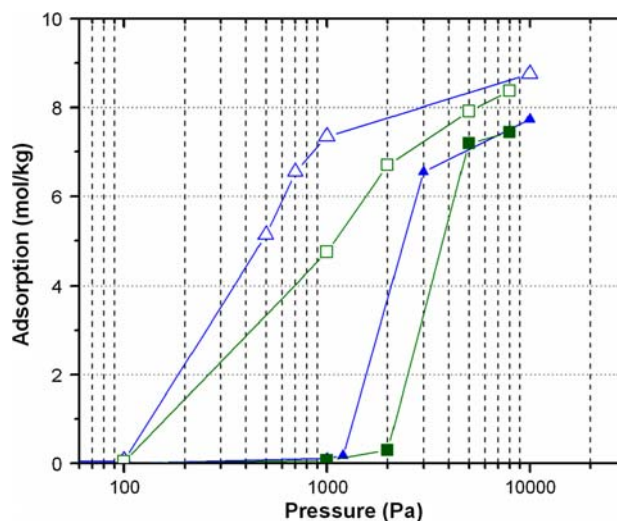


Figure 6. Calculated adsorption isotherms for water in MFI at 300 K using the SPC/Fw (\blacktriangle) and F3C (\blacksquare) models. Simulations were performed for the Olson (open symbols) and the van Koningsveld (solid symbols) structures, assigning a partial charge of 2.05 e to the Si atoms of the framework. The experimental isotherms lie at higher pressures and are not shown. The lines are a guide to the eye.

To understand better the sensitivity of water to small changes in the zeolite structure, we have generated a series of new structures along a path that continuously transforms the van Koningsveld into the Olson structure. For every generated structure, we have computed the heats of adsorption of water, carbon dioxide and propane, as shown in Figure 8. In the case of propane and carbon dioxide, the heat of adsorption remains practically constant for every structure generated, indicating that the adsorption is barely influenced by small changes in the zeolite structure. This point supports our previous observation that the adsorption isotherms of these molecules in the Olson and van Koningsveld structures do not show large differences. For water, structures which differ less than 0.2 Å from the van Koningsveld structure have a similar heat of adsorption. However, structures that differ more than this value from the van Koningsveld structure (and therefore closer to the Olson structure) have a significant lower heat of adsorption. Apparently, the adsorption of water in the Olson structure is much more sensitive to changes in the atomic positions than the van Koningsveld structure. This could be an indication that the van Koningsveld structure gives a better description of the experimental adsorption isotherm of water in MFI.

To illustrate the importance of the channel intersections of MFI in the adsorption of water, we have calculated the Henry coefficients and heats of adsorption in different locations of the zeolite: straight channels, zig-zag channels and intersections (Table 2). While in both types of channels the values are similar for both structures, in the

Table 3. (a) Henry coefficients in $\text{mol kg}^{-1} \text{Pa}^{-1}$ and (b) heats of adsorption in kJ mol^{-1} of water in MFI, calculated with different water models, the two different orthorhombic characterisations of MFI and different partial charges for the silica atoms of the structure (q).

q (e^-)	Structure	SPC	Tip3p	Tip4p	Tip5p	Tip5pEw	Tip6p
(a)	van K.	2.4×10^{-5} (3)	2.1×10^{-5} (3)	2.0×10^{-5} (3)	2.0×10^{-5} (2)	2.5×10^{-5} (3)	2.2×10^{-5} (2)
	Olson	3.0×10^{-4} (9)	3.7×10^{-4} (1)	1.5×10^{-4} (1.0)	5.2×10^{-4} (5.9)	8.3×10^{-4} (7.2)	1.1×10^{-4} (2)
	van K.	8.0×10^{-7} (1)	8.0×10^{-7} (1)	8.1×10^{-7} (1)	8.1×10^{-7} (1)	9.3×10^{-7} (1)	1.1×10^{-6} (1)
	Olson	1.0×10^{-6} (1)	1.0×10^{-6} (1)	9.9×10^{-7} (1)	1.0×10^{-6} (1)	1.2×10^{-6} (1)	1.3×10^{-6} (1)
(b)	van K.	5.8×10^{-7} (1)	5.8×10^{-7} (1)	6.0×10^{-7} (1)	6.0×10^{-7} (1)	6.9×10^{-7} (1)	8.4×10^{-7} (1)
	Olson	6.3×10^{-7} (1)	6.3×10^{-7} (1)	6.4×10^{-7} (1)	6.5×10^{-7} (1)	7.5×10^{-7} (1)	8.9×10^{-7} (1)
2.05	van K.	-28.5 (8)	-27.8 (8)	-27.4 (9)	-28.3 (9)	-28.9 (1.0)	-27.1 (8)
	Olson	-41.7 (2.1)	-42.0 (2.6)	-36.6 (5.0)	-44.9 (2.5)	-44.6 (4.3)	-35.0 (1.9)
	van K.	-12.8 (1)	-12.8 (1)	-12.8 (1)	-12.8 (1)	-13.2 (1)	-13.6 (1)
	Olson	-13.7 (1)	-13.7 (1)	-13.6 (1)	-13.6 (1)	-14.1 (1)	-14.2 (1)
0.786	van K.	-11.2 (1)	-11.2 (1)	-11.3 (1)	-11.3 (1)	-11.6 (1)	-12.1 (1)
	Olson	-11.5 (1)	-11.6 (1)	-11.6 (1)	-11.5 (1)	-11.9 (1)	-12.3 (1)

The values in parenthesis indicate the error in the last digits. van K., van Koningsveld.

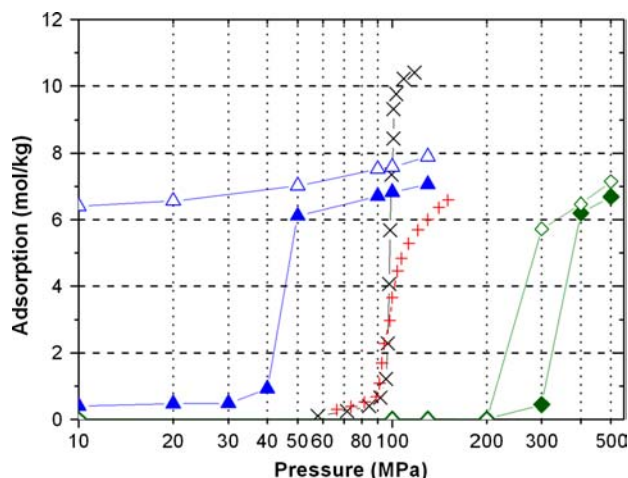


Figure 7. Experimental [23,61] (+ and \times) and calculated adsorption isotherms for water in MFI at 300 K using the Tip5pEw model. Simulations were performed using the Olson (open symbols) and the van Koningsveld (solid symbols) structures for the framework, assigning a partial charge of 2.05 e (\blacktriangle) and 0.5 e (\blacklozenge) to the Si atoms of the framework. The lines are a guide to the eye.

intersections the differences are quite large. The heats of adsorption for the Olson structure are twice than those for the van Koningsveld structure, and the Henry coefficients are three orders of magnitude larger for the Olson structure. Furthermore, the Henry coefficients indicate that the preferential adsorption sites are the zig-zag channels for the van Koningsveld structure, and the intersections for the Olson structure. This explains the large differences in the heat of adsorption found for the whole structure.

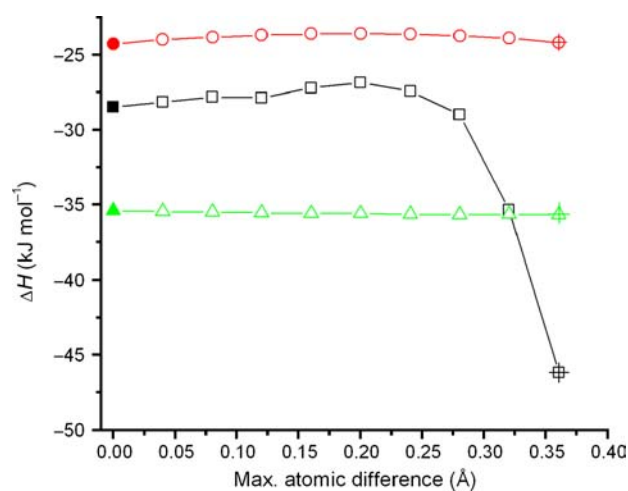


Figure 8. Calculated heats of adsorption of water (\square), carbon dioxide (\circ) and propane (\triangle) in different test structures of MFI at 298 K, where the partial charge of the Si atoms of the framework is 2.05 e . The maximum difference between the atom positions of the van Koningsveld and the test structures is represented at the horizontal axis. The generated structures (open symbols) perform a continuous change from the van Koningsveld (filled symbols) to the Olson structure (crossed symbols).

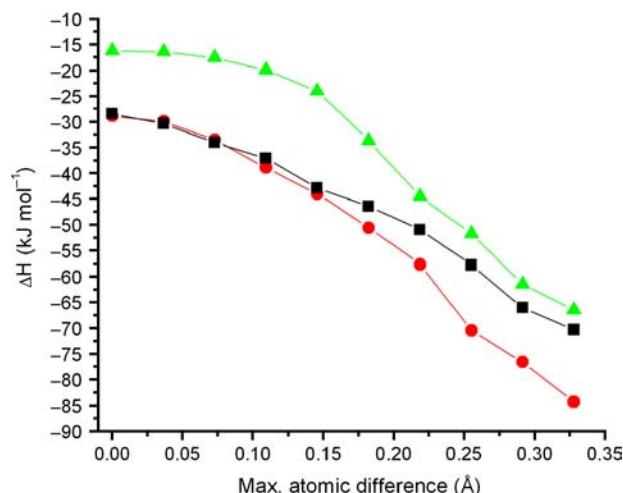


Figure 9. Calculated heats of adsorption for water in test structures of pure siliceous MFI (■), DDR (●) and LTA (▲) at 298 K, where the partial charge of the Si atoms of the framework is 2.05 e. The maximum difference between the atom positions of the original and the test structures is represented at the horizontal axis. For each structure, the atoms are progressively displaced independently along a random direction until a random maximum displacement is reached. Random directions and random maximum displacements are generated for each atom.

The sensitivity of water to the force field parameters can be attributed to the hydrophobic character of all-silica zeolites and not only to the MFI structure; we have performed a parallel study with all-silica deca-dodecasil 3 rhombohedral (DDR), MFI and LTA zeolites. While MFI is a system of intersecting channels, DDR is formed only by longitudinal channels and LTA is a cage-like structure. For every atom of the structures, we defined a random direction of translation and a random displacement, keeping the size of the unit cell fixed. The maximum displacement was set to be shorter than the maximum difference between the two characterisations of MFI, and a continuous series of structures were generated in line with the previous study. The heats of adsorption of water in the resulting structures are shown in Figure 9. The general trend of the heat of adsorption with the increasing distortion is the same for all structures. It is important to note that the gradient of the curves for all the zeolites considered is similar, which could be indicative of a general behaviour for all-silica zeolites. As in the former study, the structures closer to the initial one have a heat of adsorption very similar to the original value, although the displacement at which the drop in the heat of adsorption takes place is shorter.

3.3 Choosing atomic charges for the framework

The influence of the electrostatic interactions in the adsorption of polar molecules was studied, progressively reducing the point charge of the Si atoms in the structure

from 2.05 e to 0.5 e. To keep the electrostatic neutrality of the structure, the charge of the oxygen atoms were changed accordingly and made equal to half the charge of the silica atoms with opposite sign. In the case of non-polar molecules such as alkanes, no effect is observed, as electrostatic interactions between the adsorbed molecules and the framework are not present in the force field. In Figure 4, it is shown that for carbon dioxide a small shift of the isotherm at high pressure is observed when decreasing the silicon charge. This shift can be explained by the lower interaction of the host molecules with the structure, although the differences on adsorption for the two characterisations remain similar. We found a completely different behaviour for the Tip5pEw water model (Figure 7), where the decrease in the silicon charge induces a large shift of the complete isotherm to much higher pressures and reduces adsorption differences between the structures.

The influence of charge and structure was studied for different water models. The Henry coefficients and heat of adsorption of the SPC, Tip3p, Tip4p, Tip5p, Tip5pEw and Tip6p models were calculated for the Olson and the van Koningsveld structures with a partial charge for the silica atoms of 2.05 e, 0.786 e, and 0.5 e. The obtained results are presented in Table 3 showing little differences between different models at the same simulation conditions. This is consistent with our previous assumption that the particular behaviour of water in zeolites is due to its large dipole moment. The differences between the Olson and the van Koningsveld structures are remarkable when we use a larger charge for the silicon atoms: there is a difference of one order of magnitude in the Henry coefficient, and the heats of adsorption in the Olson structure are around 50% larger than those in the van Koningsveld structure. When we decrease the charge of the silicon atoms, these differences also decrease, indicating, again, the importance of the electrostatic interactions for the special behaviour of water.

The importance of the framework charges in the adsorption of water inspired us to try to fit the water–zeolite interaction parameters, as well as the point charges of the atoms of the framework, aiming to reproduce the experimental adsorption isotherms. However, we failed to find such a set of parameters since the shape of the experimental isotherm is very steep in the inflection region, and therefore very sensitive to the parameters of the interaction potential.

4. Conclusions

The adsorption properties of water in zeolites are difficult to describe both experimentally and by molecular simulations. The experiments are complicated by the fact that water adsorbs at very low pressure at the defects. Therefore, the pressure where the sharp increase in adsorption occurs is sensitive to defects, as well as to the

structural crystallographic positions (in addition to pore blockage/collapse, etc.). On the simulation side, there are only a few water models that are suitably calibrated for studying water adsorption in zeolites. The Tip5pEw model is calibrated using the Ewald summation and reproduces well the bulk properties of water. Therefore, it is a suitable candidate to describe water in a periodic environment, though there is still much uncertainty in the proper magnitude of the charges, especially of the framework atoms. The dipole moment of water results in a behaviour that is completely different from other molecules of similar size but without dipole moment, so the partial charge of the zeolite atoms is a critical parameter that has to be chosen carefully. The adsorption of water is also very sensitive to small changes in the precise location of the zeolite atoms. We provided evidence that this sensitivity is directly related to the coupling of the dipole of the water molecules with the electric field induced by the zeolite. Therefore, one has to be cautious when computing the properties of water and highly polar molecules in these hydrophobic structures.

Acknowledgements

This work is supported by the Spanish 'Ministerio de Educación y Ciencia (MEC)' (CTQ2007-63229), the Junta de Andalucía (P07-FQM-02595) and the National Science Foundation (CTS-0507013). T.J.H. Vlugt acknowledges financial support from The Netherlands Organization for Scientific Research (NWO-CW) through a VIDI Grant. J.M. Castillo thanks EuroSim for his PhD fellowship.

References

- [1] M. Guisnet and J.-P. Gilson, *Zeolites for Cleaner Technologies*, Vol. 3, Imperial College Press, New York, 2002.
- [2] H. Kusic, A.L. Bozic, N. Koprivanac, and S. Papic, *Fenton type processes for minimization of organic content in coloured wastewaters. Part II: combination with zeolites*, *Dyes Pigments* 74 (2007), pp. 388–395.
- [3] V. Rajakovic, G. Aleksic, M. Radetic, and L. Rajakovic, *Efficiency of oil removal from real wastewater with different sorbent materials*, *J. Hazard. Mater.* 143 (2007), pp. 494–499.
- [4] J. Janchen, D.L. Bish, D.T.F. Mohlmann, and H. Stach, *Investigation of the water sorption properties of Mars-relevant micro- and mesoporous minerals*, *Icarus* 180 (2006), pp. 353–358.
- [5] R.B. Bjorklund, J. Hedlund, J. Sterte, and H. Arwin, *Vapor adsorption in thin silicalite-1 films studied by spectroscopic ellipsometry*, *J. Phys. Chem. B* 102 (1998), pp. 2245–2250.
- [6] D.H. Olson, W.O. Haag, and W.S. Borghard, *Use of water as a probe of zeolitic properties: Interaction of water with HZSM-5*, *Micropor. Mesopor. Mater.* 35–36 (2000), pp. 435–446.
- [7] P. Ball, *Water: Water – An enduring mystery*, *Nature* 452 (2008), pp. 291–292.
- [8] D. Kivelson and G. Tarjus, *H₂O below 277 K: a novel picture*, *J. Phys. Chem. B* 105 (2001), pp. 6620–6627.
- [9] B. Liu, B. Smit, F. Rey, S. Valencia, and S. Calero, *A new united atom force field for adsorption of alkenes in zeolites*, *J. Phys. Chem. C* 112 (2008), pp. 2492–2498.
- [10] E. Garcia-Perez, J.B. Parra, C.O. Ania, A. Garcia-Sanchez, J.M. Van Baten, R. Krishna, D. Dubbeldam, and S. Calero, *A computational study of CO₂, N₂, and CH₄ adsorption in zeolites*, *Adsorp. – J. Int. Adsorp. Soc.* 13 (2007), pp. 469–476.
- [11] N. Desbiens, A. Boutin, and I. Demachy, *Water condensation in hydrophobic silicalite-1 zeolite: a molecular simulation study*, *J. Phys. Chem. B* 109 (2005), pp. 24071–24076.
- [12] J. Puibasset and R.J.M. Pellenq, *Grand canonical Monte Carlo simulation study of water adsorption in silicalite at 300 K*, *J. Phys. Chem. B* 112 (2008), pp. 6390–6397.
- [13] C.E. Ramachandran, S. Chempath, L.J. Broadbelt, and R.Q. Snurr, *Water adsorption in hydrophobic nanopores: Monte Carlo simulations of water in silicalite*, *Micropor. Mesopor. Mater.* 90 (2006), pp. 293–298.
- [14] B. Guillot, *A reappraisal of what we have learnt during three decades of computer simulations on water*, *J. Mol. Liq.* 101 (2002), pp. 219–260.
- [15] A. Bizjak, T. Urbi, V. Vlachy, and K.A. Dill, *The three-dimensional 'Mercedes Benz' model of water*, *Acta Chim. Sloven.* 54 (2007), pp. 532–537.
- [16] H. Tanaka, *Simple physical model of liquid water*, *J. Chem. Phys.* 112 (2000), pp. 799–809.
- [17] R. Bukowski, K. Szalewicz, G.C. Groenenboom, and A. van der Avoird, *Predictions of the properties of water from first principles*, *Science* 315 (2007), pp. 1249–1252.
- [18] C. Beauvais, A. Boutin, and A.H. Fuchs, *Adsorption of water and aromatics in faujasite zeolites: a molecular simulation study*, *Adsorp. – J. Int. Adsorp. Soc.* 11 (2005), pp. 279–282.
- [19] A. Di Lella, N. Desbiens, A. Boutin, I. Demachy, P. Ungerer, J.P. Bellat, and A.H. Fuchs, *Molecular simulation studies of water physisorption in zeolites*, *Phys. Chem. Chem. Phys.* 8 (2006), pp. 5396–5406.
- [20] M. Trzpit, M. Soulard, J. Patarin, N. Desbiens, F. Cailliez, A. Boutin, I. Demachy, and A.H. Fuchs, *The effect of local defects on water adsorption in silicalite-1 zeolite: a joint experimental and molecular simulation study*, *Langmuir* 23 (2007), pp. 10131–10139.
- [21] J.Z. Yang, Y. Chen, A.M. Zhu, Q.L. Liu, and J.Y. Wu, *Analyzing diffusion behaviors of methanol/water through MFI membranes by molecular simulation*, *J. Membr. Sci.* 318 (2008), pp. 327–333.
- [22] F. Cailliez, G. Stirnemann, A. Boutin, I. Demachy, and A.H. Fuchs, *Does water condense in hydrophobic cavities? A molecular simulation study of hydration in heterogeneous nanopores*, *J. Phys. Chem. C* 112 (2008), pp. 10435–10445.
- [23] N. Desbiens, I. Demachy, A.H. Fuchs, H. Kirsch-Rodeschini, M. Soulard, and J. Patarin, *Water condensation in hydrophobic nanopores*, *Angew. Chem. Int. Ed.* 44 (2005), pp. 5310–5313.
- [24] R.J.M. Pellenq, T. Roussel, and J. Puibasset, *Molecular simulation of water in hydrophobic microporous solids*, *Adsorp. – J. Int. Adsorp. Soc.* 14 (2008), pp. 733–742.
- [25] I. Halasz, S. Kim, and B. Marcus, *Hydrophilic and hydrophobic adsorption on Y zeolites*, *Mol. Phys.* 100 (2002), pp. 3123–3132.
- [26] W.L. Jorgensen, J. Chandrasekhar, J.D. Madura, R.W. Impey, and M.L. Klein, *Comparison of simple potential functions for simulating liquid water*, *J. Chem. Phys.* 79 (1983), pp. 926–935.
- [27] M.W. Mahoney and W.L. Jorgensen, *A five-site model for liquid water and the reproduction of the density anomaly by rigid, nonpolarizable potential functions*, *J. Chem. Phys.* 112 (2000), pp. 8910–8922.
- [28] G.C. Boulougouris, I.G. Economou, and D.N. Theodorou, *Engineering a molecular model for water phase equilibrium over a wide temperature range*, *J. Phys. Chem. B* 102 (1998), pp. 1029–1035.
- [29] B. Guillot and Y. Guissani, *How to build a better pair potential for water*, *J. Chem. Phys.* 114 (2001), pp. 6720–6733.
- [30] H.J.C. Berendsen, J.R. Grigera, and T.P. Straatsma, *The missing term in effective pair potentials*, *J. Phys. Chem.* 91 (1987), pp. 6269–6271.
- [31] H.J.C. Berendsen, J.P.M. Postma, W.F. van Gunsteren, and J. Hermans, *Intermolecular Forces*, Reidel, Dordrecht, 1981.
- [32] W.L. Jorgensen, *Quantum and statistical mechanical studies of liquids. 24. Revised tips for simulations of liquid water and aqueous solutions*, *J. Chem. Phys.* 77 (1982), pp. 4156–4163.
- [33] E. Jaramillo and M. Chandross, *Adsorption of small molecules in LTA zeolites. I. NH₃, CO₂, and H₂O in zeolite 4A*, *J. Phys. Chem. B* 108 (2004), pp. 20155–20159.
- [34] N.W. Ockwig, R.T. Cygan, L.J. Criscenti, and T.M. Nenoff, *Molecular dynamics studies of nanoconfined water in clinoptilolite*

- and heulandite zeolites, *Phys. Chem. Chem. Phys.* 10 (2008), pp. 800–807.
- [35] D. Frenkel and B. Smit, *Understanding Molecular Simulation*, 2nd ed., Academic Press, London, 2002.
- [36] T.J.H. Vlugt, E. Garcia-Perez, D. Dubbeldam, S. Ban, and S. Calero, *Computing the heat of adsorption using molecular simulations: the effect of strong Coulombic interactions*, *J. Chem. Theor. Comput.* 4 (2008), pp. 1107–1118.
- [37] NIST Chemistry Webbook, Available at <http://webbook.nist.gov/chemistry>.
- [38] A.L. Myers and P.A. Monson, *Adsorption in porous materials at high pressure: Theory and experiment*, *Langmuir* 18 (2002), pp. 10261–10273.
- [39] S. Calero, D. Dubbeldam, R. Krishna, B. Smit, T.J.H. Vlugt, J.F.M. Denayer, J.A. Martens, and T.L.M. Maesen, *Understanding the role of sodium during adsorption: A force field for alkanes in sodium-exchanged faujasites*, *J. Am. Chem. Soc.* 126 (2004), pp. 11377–11386.
- [40] T.J.H. Vlugt, R. Krishna, and B. Smit, *Molecular simulations of adsorption isotherms for linear and branched alkanes and their mixtures in silicalite*, *J. Phys. Chem. B* 103 (1999), pp. 1102–1118.
- [41] D. Bougeard and S. Smirnov, *Modelling studies of water in crystalline nanoporous aluminosilicates*, *Phys. Chem. Chem. Phys.* 9 (2007), pp. 226–245.
- [42] S. Rick, *A reoptimization of the five-site water potential (Tip5p) for use with Ewald sums*, *J. Chem. Phys.* 120 (2004), pp. 6085–6093.
- [43] H.W. Horn, W.C. Swope, J.W. Pitera, J.D. Madura, T.J. Dick, G.L. Hura, and T. Head-Gordon, *Development of an improved four-site water model for biomolecular simulations: TIP4P-EW*, *J. Chem. Phys.* 120 (2004), pp. 9665–9678.
- [44] D.J. Price and C.L. Brooks, *A modified TIP3P water potential for simulation with Ewald summation*, *J. Chem. Phys.* 121 (2004), pp. 10096–10103.
- [45] Y.J. Wu, H.L. Tepper, and G.A. Voth, *Flexible simple point-charge water model with improved liquid-state properties*, *J. Chem. Phys.* 124 (2006), 024503.
- [46] G. Lamoureux, A.D. MacKerell, and B. Roux, *A simple polarizable model of water based on classical Drude oscillators*, *J. Chem. Phys.* 119 (2003), pp. 5185–5197.
- [47] B. Hess, H. Saint-Martin, and H.J.C. Berendsen, *Flexible constraints: An adiabatic treatment of quantum degrees of freedom, with application to the flexible and polarizable mobile charge densities in harmonic oscillators model for water*, *J. Chem. Phys.* 116 (2002), pp. 9602–9610.
- [48] J.C. Moise, J.P. Bellat, and A. Methivier, *Adsorption of water vapor on X and Y zeolites exchanged with barium*, *Micropor. Mesopor. Mater.* 43 (2001), pp. 91–101.
- [49] B. Boddenberg, G.U. Rakhmatkariev, S. Hufnagel, and Z. Salimov, *A calorimetric and statistical mechanics study of water adsorption in zeolite NaY*, *Phys. Chem. Chem. Phys.* 4 (2002), pp. 4172–4180.
- [50] J.B.A. Rychaert, *Molecular dynamics of liquid alkanes*, *Faraday Discuss. Chem. Soc.* 66 (1978), pp. 95–106.
- [51] D. Dubbeldam, S. Calero, T.J.H. Vlugt, R. Krishna, T.L.M. Maesen, and B. Smit, *United atom force field for alkanes in nanoporous materials*, *J. Chem. Phys. B* 108 (2004), pp. 12301–12313.
- [52] J.G. Harris and K.H. Yung, *Carbon dioxides liquid–vapor coexistence curve and critical properties as predicted by a simple molecular model*, *J. Phys. Chem.* 99 (1995), pp. 12021–12024.
- [53] D.H. Olson, G.T. Kokotailo, S.L. Lawton, and W.M. Meier, *Crystal structure and structure-related properties of Zsm-5*, *J. Phys. Chem.* 85 (1981), pp. 2238–2243.
- [54] H. van Koningsveld, H. van Bekkum, and J.C. Jansen, *On the location and disorder of the tetrapropylammonium (Tpa) ion in zeolite Zsm-5 with improved framework accuracy*, *Acta Crystallogr. Sect. B – Struct. Sci.* 43 (1987), pp. 127–132.
- [55] T.J.H. Vlugt and M. Schenk, *Influence of framework flexibility on the adsorption properties of hydrocarbons in the zeolite silicalite*, *J. Phys. Chem. B* 106 (2002), pp. 12757–12763.
- [56] P. Pascual, P. Ungerer, B. Tavitian, P. Pernot, and A. Boutin, *Development of a transferable guest–host force field for adsorption of hydrocarbons in zeolites. I. Reinvestigation of alkane adsorption in silicalite by grand canonical Monte Carlo simulation*, *Phys. Chem. Chem. Phys.* 5 (2003), pp. 3684–3693.
- [57] K.F. Lau, H.E. Alper, T.S. Thacher, and T.R. Stouch, *Effects of switching functions on the behavior of liquid water in molecular dynamics simulations*, *J. Phys. Chem.* 98 (1994), pp. 8785–8792.
- [58] C. Vega, J.L.F. Abascal, M.M. Conde, and J.L. Aragones, *What ice can teach us about water interactions: a critical comparison of the performances of different water models*, *Faraday Discuss.* 141 (2009), pp. 251–276.
- [59] F.X. Coudert, R. Vuilleumier, and A. Boutin, *Dipole moment, hydrogen bonding and IR spectrum of confined water*, *Chemphyschem* 7 (2006), pp. 2464–2467.
- [60] L.A. Clark and R.Q. Snurr, *Adsorption isotherm sensitivity to small changes in zeolite structure*, *Chem. Phys. Lett.* 308 (1999), pp. 155–159.
- [61] V. Eroshenko, R.C. Regis, M. Soulard, and J. Patarin, *Energetics: a new field of applications for hydrophobic zeolites*, *J. Am. Chem. Soc.* 123 (2001), pp. 8129–8130.
- [62] W. Zhu, F. Kapteijn, and J.A. Moulijn, *Equilibrium adsorption of light alkanes in silicalite-1 by the inertial microbalance technique*, *Adsorp. – J. Int. Adsorp. Soc.* 6 (2000), pp. 159–167.
- [63] F. Eder, *Thermodynamic siting of alkane adsorption in molecular sieves*, Ph.D. thesis, University of Twente, The Netherlands, 1996.
- [64] B. Smit and L.M. Maesen, *Commensurate freezing of alkanes in the channels of a zeolite*, *Nature* 374 (1995), pp. 42–44.