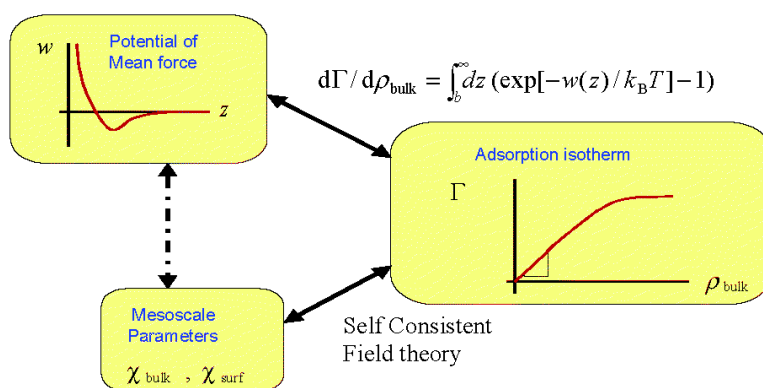


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## Linking Atomistic and Mesoscale Simulations of Water-Soluble Polymers

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Building a link between molecular scales,  $10^{-10}$  m, and mesoscopic scales,  $10^{-6}$  m, is a much sought-after goal in the fields of computational chemistry and molecular biophysics. This would enable very large-scale simulations of multicomponent systems to be performed. One method, for nonaqueous systems, uses the enthalpy of mixing.<sup>1</sup> For aqueous systems though, the enthalpy of mixing may not even be approximately the same as the free-energy of mixing,<sup>2</sup> which is the desired quantity to make the molecular–mesoscale link. It is possible in principle to extract free-energy changes from thermodynamic integration methods,<sup>3</sup> but these are notoriously costly and not always reproducible.

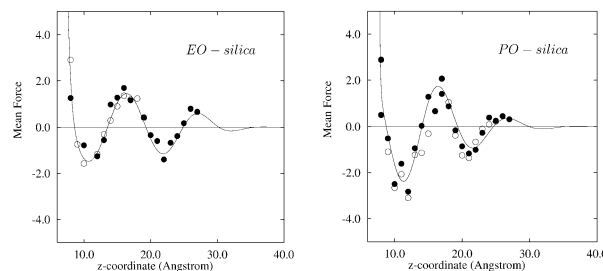
Here we show how potential of mean force (PMF) calculations offer a practical alternative, although one is still faced with extremely long ( $10^{-9}$  s) simulations. We apply PMF methods to the adsorption of poly(ethylene oxide) (PEO) and polypropylene oxide (PPO) onto a silica surface from an aqueous solution. Our study relates to problems of primary industrial importance since PEO, PPO, and PEO–PPO copolymers are commercially available water-soluble polymers, currently used for detergency, colloidal dispersion stabilization, lubrication, and drug delivery.

The method used to establish a link between the molecular and mesoscale models is to determine some thermodynamic properties from atomistic PMF simulations, and the *same* properties from a mesoscale method.<sup>4</sup> Matching the properties allows one to back-calculate a consistent set of mesoscale parameters. For polymer solutions, the obvious thermodynamic property to match is the second virial coefficient  $B_2$  between fragments. For surface effects, we propose to use the limiting slope of the equilibrium adsorption isotherm for fragments, found from

$$\left(\frac{d\Gamma}{d\rho_{\text{bulk}}}\right)_{\rho_{\text{bulk}} \rightarrow 0} = \int_b^\infty dz \left(\exp[-w(z)/k_B T] - 1\right) \quad (1)$$

where  $\Gamma$  is the surface excess,  $\rho_{\text{bulk}}$  is the bulk solute concentration,  $k_B$  the Boltzmann constant,  $w(z)$  the surface PMF,  $z$  the height from the surface, and  $b$  the location of the surface. We regard  $d\Gamma/d\rho_{\text{bulk}}$  in the limit  $\rho_{\text{bulk}} \rightarrow 0$  as the surface analogue of  $B_2$ . Thus, the method proceeds by calculating atomistic PMFs between PEO and PPO fragments, and approaching a surface such as silica, from which  $B_2$  and the limiting adsorption can be found.

Molecular dynamics simulations (using Discover software<sup>5</sup> and the Compass force-field<sup>6</sup>) were performed<sup>7</sup> for  $\text{EO}_2$  [ $\text{CH}_3\text{-O-CH}_2\text{-CH}_2\text{-O-CH}_3$ ] and  $\text{PO}_2$  [ $\text{CH}_3\text{-O-CH}(\text{CH}_3)\text{-CH}_2\text{-O-CH}(\text{CH}_3)\text{-CH}_3$ ] fragments, both in bulk and approaching a model silica surface.<sup>8</sup> We describe here only the surface simulations, since a parallel methodology was used for the bulk. To access the PMF between a fragment and the surface, the center of mass of the fragment is tied to a specified plane parallel to the surface by a quadratic potential with a spring constant  $K$ . The mean displacement of the center of mass from this plane then provides a direct measure of the force acting on the particle due to the presence of the surface, rather as though we are using a spring balance to “weigh” the fragment. The methodology can be rigorously derived in statistical



**Figure 1.** Computed mean force in kcal/mol Å for  $\text{EO}_2$  and  $\text{PO}_2$  fragments as a function of distance  $z$  from a surface of quartz. At each fixed distance, energy was pre-minimized and initial NVT ( $T = 298$  K) dynamics was run for 100 ps. Data collection was performed for next 200 ps of continued dynamics. The filled circles (●) refer to simulations in a tall simulation box ( $21.5 \times 21.5 \times 57 \text{ Å}^3$ ) and spring constant  $K = 40$  kcal/mol Å<sup>2</sup>, while the open circles (○) refer to a smaller box and spring constant  $K = 20$  kcal/mol Å<sup>2</sup>.

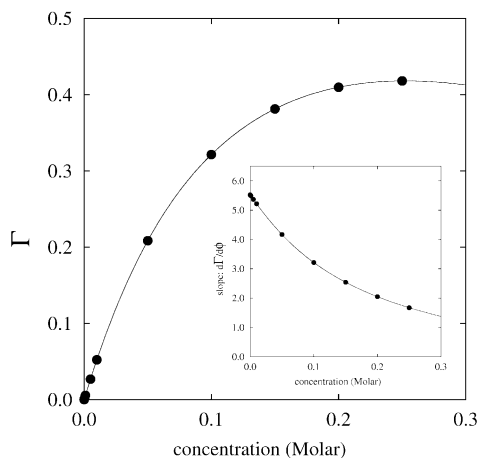
mechanics as an application of the umbrella sampling method.<sup>9</sup> Formally, one needs to be in the limit of infinite  $K$ , so that in practice one needs to perform test simulations for different values of  $K$ . The measurement of the mean force is repeated at different distances. For each distance, the system is equilibrated until the force reaches a steady-state value. The overall length of a run (typically 200 ps for the surface calculations, and up to 1 ns for the bulk) is determined by the need to obtain good statistics for the mean force. Our results are collected in Figure 1. We have used  $K = 20$  and  $40$  kcal/mol Å<sup>2</sup> and two different box sizes, to prove the robustness of these results.

From the whole data set one can calculate the PMF, which represents the free-energy cost to bring a molecule from infinity to a distance  $z$  from the surface, by fitting the mean force simulation data with an appropriate function, and then integrating. This is done by representing the steric repulsion at the surface by a potential barrier diverging at the surface, and adding an exponentially decaying periodic function to represent the solvation force, thus<sup>10</sup>

$$w(z) = 1/[a(z - b)]^m + \exp[-d(z - e)^n] \cos[g(z - e)] \quad (2)$$

We next turn our attention to a mesoscale method appropriate to this class of problem: the Scheutjens–Fleer self-consistent field (SCF) theory.<sup>11</sup> This is a generalization of Flory–Huggins theory for polymer solutions, and is frequently used to calculate the adsorption of polymers from solution.<sup>12</sup> As such, the mesoscale parameters in SCF are Flory–Huggins  $\chi$  parameters, which characterize free-energy changes as the environment of a given monomer is changed. These parameters are also used in some versions of dynamic density functional theory<sup>13</sup> and have been linked to the parameters in the dissipative particle dynamics method;<sup>14</sup> hence, our focus on SCF is not restrictive.<sup>15</sup>

In the present case we deal with a water– $\text{EO}_2$  solution at a model silica surface (or, *mutatis mutandis*, a water– $\text{PO}_2$  solution). We have to deal with three species: water (W),  $\text{EO}_2$  and surface (S).



**Figure 2.** Excess adsorbed amount plotted as a function of the molar concentration obtained from SCF calculations for  $\text{EO}_2$  at the model silica surface. Inset shows the slope of the excess adsorbed amount. The zero concentration limit of the slope is the thermodynamic quantity calculated independently via molecular simulations.

Therefore, we need to specify the bulk parameter  $\chi_{\text{W,EO}_2}$  and the difference between two surface parameters,  $\chi_{\text{S,EO}_2}$  and  $\chi_{\text{S,W}}$ .

We now discuss our results. From the bulk molecular simulations we obtain the parameters  $\chi_{\text{W,EO}_2}$  and  $\chi_{\text{W,PO}_2}$ . The calculated  $\chi$  parameters, via the second virial coefficient  $B_2$ , are extremely sensitive to the choice of the fitting function; for the functional form proposed in eq 2 we obtain  $\chi_{\text{W,EO}_2} = 0.4$  and  $\chi_{\text{W,PO}_2} = 1.5$ , respectively (see Supporting Information). Thus, our calculations correctly predict that  $\text{PO}_2$  is less soluble in water than  $\text{EO}_2$ . From the two-state model of Karlström,<sup>17</sup> in the limit of infinite dilution, the values are  $\chi_{\text{W,EO}} = 0.45$  and  $\chi_{\text{W,PO}} = 0.77$ , which compare favorably with our simulation results.

For the surface  $\chi$  parameters, we first calculate from the surface PMF and eq 1 that  $d\Gamma/d\rho_{\text{bulk}} = 33 \text{ \AA}$  for  $\text{EO}_2$ , and  $147 \text{ \AA}$  for  $\text{PO}_2$ , in the limit  $\rho_{\text{bulk}} \rightarrow 0$ . Since we can set  $\chi_{\text{S,W}} = 0$  as a reference, and  $\chi_{\text{W,EO}_2}$  is known from the  $B_2$  calculation (or could be known from elsewhere), the simplest way forward is to match the limiting slope in the SCF adsorption isotherm as the only unknown parameter,  $\chi_{\text{S,EO}_2}$ , is varied. A typical adsorption isotherm for  $\text{EO}_2$  is illustrated in Figure 2 (see also Supporting Information). In the SCF model, we assume each  $\text{EO}_2$  or  $\text{PO}_2$  fragment is represented by one polymer segment, set the lattice spacing  $l = 4 \text{ \AA}$ , and use a cubic lattice, in common with previous work.<sup>12</sup> With this choice, the target dimensionless quantities to be matched are  $(1/l) d\Gamma/d\rho_{\text{bulk}} = 8.25$  for  $\text{EO}_2$ , and  $36.75$  for  $\text{PO}_2$ , in the limit of the infinite dilution. To recover these values, we find  $\chi_{\text{S,EO}_2} = -7.1$  and  $\chi_{\text{S,PO}_2} = -11.15$ , indicating that the surface has a higher tendency to adsorb  $\text{PO}_2$  rather than  $\text{EO}_2$ .

At first sight this is surprising since it is well-known that polymers and surfactants containing  $\text{EO}_2$  groups adsorb onto amorphous silica surfaces, but  $\text{PO}_2$  groups interact less favorably with the same surface.<sup>18</sup> However, it has been shown that silanol groups on the silica surface are essential for the adsorption of  $\text{EO}_2$  to occur, and the proposed mechanism is thought to proceed via hydrogen bonding.<sup>19</sup> These interactions are absent in our case since the model silica surface (a surface of quartz) does not have the

H-bond donor groups that are present in the silanol groups of amorphous silica (nor do the  $\text{EO}_2$  and  $\text{PO}_2$  have H-bond donor groups).

In summary, we have shown here that the potential of mean force (PMF) method together with a suitable choice of thermodynamic quantities can offer a practical route to make the molecular-mesoscale link in aqueous systems.<sup>20</sup> This method can also be used to obtain mesoscale parameters for biopolymers.

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**Supporting Information Available:** Figures showing mean force of two  $\text{EO}_2$ 's and  $\text{PO}_2$ 's in bulk water, and figures showing adsorption isotherm for  $\text{PO}_2$  on model silica (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

## References

- (1) Case, F. H.; Honeycutt, D. J. *Trends Polym. Sci.* **1994**, *2*, 259.
- (2) Molyneux, P. In *Water: A Comprehensive Treatise*; Franks, F., Ed.; Plenum Press: New York, 1975; Vol. 4.
- (3) Free-energy calculations using thermodynamic integration are computationally intensive, and in an aqueous system one must use either complex continuum models or accurate interaction potentials for water. Also, the free-energy changes may be many times smaller than the reference free energies, which consequently have to be determined with great precision. Many references exist; see, for example, ref 9 for details of this method.
- (4) Examples of mesoscale methods are self-consistent field (SCF) theory used here, dynamic density functional theory (DDFT) as used in the Mesodyn code, dissipative particle dynamics (DPD).
- (5) Discover is a simulation program of Accelrys Inc.: San Diego, CA.
- (6) (a) Sun, H. *J. Phys. Chem. B* **1998**, *102*, 7338–7364. (b) The compass force-field shows good evidence that the most important structural features of the liquid state of water such as the oxygen–oxygen pair correlation function (Soper, A. K.; Bruni, F.; Ricci, M. A. *J. Chem. Phys.* **1997**, *106*, 247) are reproduced. Such requirements are stringent for our purposes, since the force-field has to be trusted in the calculation of free energies.
- (7) The simulations were run in the NVT protocol, at  $T = 298 \text{ K}$  and  $V$  obtained from a well-equilibrated NPT simulation at zero pressure.
- (8) For a model silica surface, we have used a surface of quartz obtained from its crystal structure, appropriately terminated and satisfying both the stoichiometry of the material and charge neutrality requirements.
- (9) Frenkel, D.; Smit, B. *Understanding Molecular Simulations*; Academic Press: San Diego, 1996.
- (10) The fitting parameters,  $b$  and  $e$ , in eq 2 arise from the fact that the surface is not necessarily located at  $z = 0$  (the model silica surface is nominally located at about  $z = 6 \text{ \AA}$ ).
- (11) Most mesoscale methods readily yield predictions for  $B_2$  and for  $d\Gamma/d\rho_{\text{bulk}}$  in the limit  $\rho_{\text{bulk}} \rightarrow 0$ . Indeed such methods are often based on free energy models from which these quantities can be directly calculated.
- (12) Fleer, G. H.; Cohen Stuart, M. A.; Scheutjens, J. M. H. M.; Cosgrove, T.; Vincent, B. *Polymers at Interfaces*; Chapman and Hall: London, 1993.
- (13) Sevink, G. J. A.; Fraaije, J. G. E. M.; Huinink, H. P. *Macromolecules* **2002**, *35*, 1848–1859.
- (14) Groot, R. D.; Warren, P. B. *J. Chem. Phys.* **1997**, *107*, 4423–4435.
- (15) While the SCF approach is expected to provide the desired molecular-mesoscale link, the numerical values of the mesoscale parameters obtained also depend on implicit details of the mesoscale model (i.e. there are no unique set of values for  $\chi$  parameters). But, just as for the link to the atomistic PMF, these or other thermodynamic quantities can be chosen to bridge between different mesoscale models, for an example for DPD see ref 14.
- (16) The SCF code (ACOPEL) was generously provided by Frans Leermakers of Wageningen University.
- (17) Karlström, G. *J. Chem. Phys.* **1985**, *89*, 4962–4964.
- (18) See Malmsten, M.; Linse, P.; Cosgrove, T. *Macromolecules* **1992**, *25*, 2474–2481 and references therein.
- (19) Rubio, J.; Kitchener, J. A. *J. Colloid Interface Sci.* **1976**, *57*, 132–142.
- (20) Of course, PMF methods may not be so readily useful for matching nonequilibrium quantities such as transport coefficients or viscosities or diffusion coefficients.

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