

Engineering Model for Predicting the Intradiffusion Coefficients of Hydrogen and Oxygen in Vapor, Liquid, and Supercritical Water based on Molecular Dynamics Simulations

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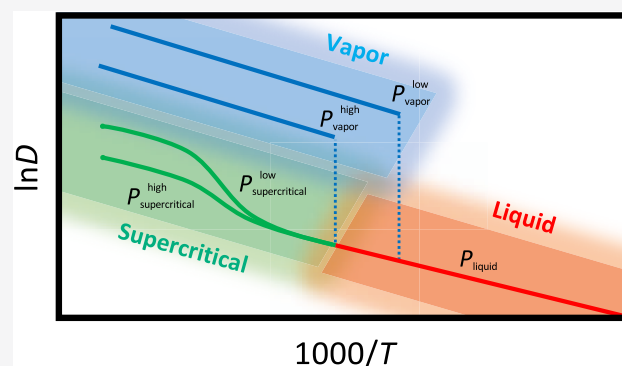
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ABSTRACT: Molecular dynamics simulations are carried out to compute the intradiffusion coefficients of H₂ and O₂ in H₂O for temperatures ranging from 275.15 to 975.15 K and pressures ranging from 0.1 to 200 MPa. These conditions span vapor, liquid, and supercritical conditions. For the vast majority of the state points examined, experimental data are not available. The accuracy of six H₂ and six O₂ force fields is tested in reproducing the available experimentally measured densities, self-diffusivities, and shear viscosities of the pure gas and the intradiffusivity of the gas in H₂O. Namely, we screen the H₂ force fields developed by Buch, Vrabec and co-workers, Hirschfelder et al., Cracknell, a modified Silvera–Goldman, and Marx and Nielaba. For O₂, the force fields by Bohn et al., Miyano, Coon et al., Hansen et al., Vrabec et al., and Watanabe are tested. Overall, the force fields by Buch and Bohn for H₂ and O₂, respectively, were found to perform the best, and combined with the TIP4P/2005 H₂O force field are used to compute the intradiffusivities in the entire temperature and pressure range. The new data are used to develop an engineering model that can predict the H₂ and O₂ intradiffusivity in vapor, liquid, and supercritical H₂O. The new model uses 11 parameters and has an accuracy of 4–11%. The model is validated with other available experimental and simulation data for H₂ and O₂ in H₂O and pure H₂O. Aside from the extensive collection of new data for the intradiffusivities of H₂ and O₂ in H₂O, we present new data for the densities, shear viscosities, and self-diffusivities of pure TIP4P/2005 H₂O in the same wide temperature and pressure range. The new data and the engineering model presented here can be used for the design and optimization of chemical processes, for which the knowledge of H₂ and O₂ diffusivities in H₂O is important.



1. INTRODUCTION

The diffusivity of H₂ and O₂ in H₂O is encountered in numerous environmental, geological, industrial, and biological systems. For example, the diffusion process of light, sparingly soluble gas in H₂O is the major controlling parameter during the air–water gas exchange.¹ Typical applications of industrial interest involving H₂ and/or O₂ diffusion in H₂O are the low-to-moderate temperature processes encountered in fuel cells² and H₂O electrolysis,³ the low⁴ and moderate/high^{5,6} temperature water–gas shift reactions taking place during biomass gasification, and the supercritical H₂O oxidation, which is considered an innovative green technology for the treatment of industrial waste and sludge.^{7,8}

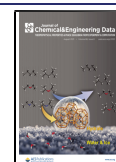
The design and optimization of these processes require the knowledge of the intradiffusion coefficients of H₂ and/or O₂ in H₂O in a wide range of conditions, covering the gas, liquid, and supercritical regions. Experimental measurements are often available, albeit only for a limited number of state points, usually at atmospheric pressure.⁹ For this reason, semi-empirical correlations have been extensively used for obtaining the diffusivity values at conditions outside the range of

experimental measurements.^{10–17} For an extensive discussion on the various correlations, the reader is referred elsewhere.^{11,15,18} Despite being fast and easy to use, these correlations depend on the quality of the available experimental data, while they provide limited physical insight into the transport mechanisms taking place. To this end, molecular dynamics (MD) simulations are used as a complementary approach for computing diffusivities when experimental data are not available.^{19,20} In the past few decades, MD simulations have played a pivotal role in science and engineering since they provide a fundamental understanding of phenomena and processes at the molecular level.^{21,22} The advent of faster computers and more efficient algorithms has resulted in the extensive use of MD simulations

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for computing the thermodynamic, transport, and structural properties of pure components and mixtures relevant to industrial applications.²³ A number of MD simulation studies of the intradiffusivity of H₂^{24–27} and O₂^{24,28–33} in H₂O have been reported. However, these studies are mostly limited to supercritical H₂O conditions, with only a few considering lower pressures and temperatures, e.g., the study by Thapa and Adhikari on O₂ diffusivity in H₂O at 0.1 MPa and temperatures up to 306 K.³⁴

Thus, a dataset of H₂ and O₂ intradiffusivities in H₂O spanning the liquid, vapor, and supercritical conditions is largely lacking. The main objective of this study is twofold: (a) to provide a reliable set of intradiffusivity data for infinitely diluted H₂ and O₂ in H₂O for temperatures and pressures in the range of 275.15–975.15 K and 0.1–200 MPa, respectively, and (b) to establish an engineering model with few parameters that can be used to accurately predict these diffusivities for any pressure and temperature. To this purpose, a screening of six H₂ and six O₂ force fields is performed. One force field for each gas is selected based on their performance in predicting the available experimentally measured densities, shear viscosities and self-diffusion coefficients of the pure gas, and the intradiffusion coefficients of gas into H₂O. The selected force fields are then combined with the widely used TIP4P/2005 force field³⁵ to compute the intradiffusion coefficients of H₂ and O₂ in H₂O, at conditions spanning the vapor, liquid, and supercritical regions, for which experimental data are mostly lacking. Due to the extensive number of MD simulations performed in this study, the densities, shear viscosities, and self-diffusivities of the pure TIP4P/2005 H₂O force field are also reported for the whole temperature and pressure range and used to validate the proposed engineering model. The use of the TIP4P/2005 force field to compute the self-diffusion coefficients of pure H₂O has been reviewed in recent studies.^{36,37}

The paper is organized as follows. In Section 2, the methods and computational details are described. In Section 3, we discuss the force field validation, the MD results for the diffusivity of H₂ and O₂ in H₂O, and the details of the proposed engineering method. In Section 4, the conclusions are presented.

2. METHODOLOGY

2.1. Force Fields. For modeling H₂, the single-site force fields developed by Buch,³⁸ Vrabec and co-workers,³⁹ and Hirschfelder et al.,⁴⁰ the two-site force field by Cracknell,⁴¹ and the modified three-site Silvera–Goldman by Alavi et al.,⁴² and Marx and Nielaba⁴³ force fields are tested (for brevity these force fields are referred to as Buch, Vrabec, Hirschfelder, Cracknell, Silvera–Goldman, and Marx hereafter). These H₂ force fields have been recently used in the literature to predict the thermophysical properties of H₂O/H₂ mixtures in a wide range of temperatures and pressures.^{39,44,45} Furthermore, the modified Silvera–Goldman force field has been used extensively in MD^{42,46} and Monte Carlo^{47–49} studies related to H₂ storage in clathrate hydrate structures. For additional information on the performance of the H₂ force fields for various mixtures, conditions, and properties, the reader is referred to the recent studies by Yang et al.⁵⁰ and Bartolomeu et al.^{51,52} For O₂, the two-site force fields developed by Bohn et al.,⁵³ Miyano,⁵⁴ and Coon et al.,⁵⁵ and the three-site models developed by Hansen et al.,⁵⁶ Vrabec et al.,⁵⁷ and Watanabe⁵⁸ are used (for brevity these force fields are referred to as Bohn,

Table 1. Chemical Formulas and Force Fields of the Components Simulated in this Work

component	chemical formula	CAS number	force field
water	H ₂ O	7732-18-5	TIP4P/2005 ³⁵
hydrogen	H ₂	133-74-0	Buch ³⁸
hydrogen	H ₂	133-74-0	Vrabec ³⁹
hydrogen	H ₂	133-74-0	Hirschfelder ⁴⁰
hydrogen	H ₂	133-74-0	Cracknell ⁴¹
hydrogen	H ₂	133-74-0	Silvera–Goldman (modified) ⁴²
hydrogen	H ₂	133-74-0	Marx ⁴³
oxygen	O ₂	7782-44-7	Bohn ⁵³
oxygen	O ₂	7782-44-7	Miyano ⁵⁴
oxygen	O ₂	7782-44-7	Coon ⁵⁵
oxygen	O ₂	7782-44-7	Hansen ⁵⁶
oxygen	O ₂	7782-44-7	Vrabec ⁵⁷
oxygen	O ₂	7782-44-7	Watanabe ⁵⁸

Miyano, Coon, Hansen, Vrabec, and Watanabe hereafter). The TIP4P/2005 model³⁵ is used to model H₂O. Previous studies have shown that the TIP4P/2005 force field can accurately capture the transport properties of pure H₂O and aqueous solutions for a broad range of conditions.^{36,59–66} Table 1 lists all of the components simulated in this study and the force fields used for each one component. All force field details are provided in the Supporting Information (Tables S1–S3).

2.2. Molecular Dynamics Simulation Details. The open-source Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS)⁶⁷ is used for the MD simulations. Periodic boundary conditions are imposed in all directions. The velocity-Verlet algorithm is used to integrate the equations of motion with a time step of 1 fs. For the two-site H₂, two-site O₂, and H₂O force fields, the bond lengths and the angle in H₂O are fixed using the SHAKE algorithm in LAMMPS.^{67,68} The three-site H₂ and O₂ force fields are modeled as rigid bodies using the technique developed by Zhang and Glotzer.⁶⁹ Thus, in all simulations, the intramolecular interactions are neglected. Only Lennard-Jones (LJ) and Coulombic potentials are used to describe the intermolecular interactions. The cutoff radii for both the LJ and electrostatic energies are set according to the original H₂, O₂, and H₂O force fields. The particle–particle–particle–mesh (PPPM)^{22,70} method with a relative error of 10^{−5} is used to compute the long-range electrostatic energies. Analytic tail corrections are applied to the energy and pressure. The Lorentz–Berthelot combining rules are used for the interactions between unlike species.^{21,22}

The MD simulations are carried out following the procedure described in detail in the Supporting Information of ref 71, i.e., initially, the system is energy minimized, consequently, equilibration runs are performed in the NpT and NVT ensembles for 1–2 ns, and finally the properties are sampled from production runs in the NVE ensemble. The total simulation time of the production runs is in the range of 2–200 ns for obtaining properly converged mean-squared-displacements (MSD) for the computation of the transport coefficients.⁷¹ The temperature and pressure are maintained constant using the Nosé–Hoover thermostat and barostat^{21,22} with coupling constants equal to 100 and 1000 fs, respectively. The modifications to the Nosé–Hoover thermostat and the barostat proposed by Kamberaj⁷² are used in LAMMPS for the simulations of rigid bodies. All initial configurations are created using PACKMOL software.⁷³

2.3. Computation of Transport Properties. The OCTP (On-the-fly computation of transport properties) plugin⁷¹ in LAMMPS is used to compute the self- and intradiffusivities and shear viscosities from the Einstein relations^{20–22,71,74–76} shown in eqs 1 and 2, combined with the order- n algorithm as implemented by Dubbeldam et al.⁷⁷

$$D_i = \lim_{t \rightarrow \infty} \frac{1}{6N_i t} \left\langle \sum_{j=1}^{N_i} (\mathbf{r}_{j,i}(t) - \mathbf{r}_{j,i}(0))^2 \right\rangle \quad (1)$$

where D_i is the self-diffusivity (or intradiffusivity in the case of mixtures) of species i , $\mathbf{r}_{j,i}(t)$ is the position of the j th molecule of species i at time t , and N_i is the number of molecules of species i in the system.

$$\eta = \lim_{t \rightarrow \infty} \frac{1}{10 \cdot 2t} \frac{V}{k_B T} \left\langle \sum_{\alpha\beta} \left(\int_0^t P_{\alpha\beta}^{\text{os}}(t') dt' \right)^2 \right\rangle \quad (2)$$

where^{76,78}

$$P_{\alpha\beta}^{\text{os}} = \frac{P_{\alpha\beta} + P_{\beta\alpha}}{2} - \delta_{\alpha\beta} \left(\frac{1}{3} \sum_k P_{kk} \right) \quad (3)$$

where η is the shear viscosity, V is the volume of the system, k_B is the Boltzmann constant, $P_{\alpha\beta}^{\text{os}}$ denotes the components of the traceless pressure tensor, $P_{\alpha\beta}$ denotes the off-diagonal components of the pressure tensor, and $\delta_{\alpha\beta}$ is the Kronecker delta. (...) indicates an ensemble average. Although diffusivities and viscosities can also be computed using the Green–Kubo method,^{21,22} the use of the Einstein framework has the practical advantage of offering a criterion for specifying the minimum simulation length for obtaining a transport property, i.e., the linear relationship between time and the mean-squared displacement of the dynamical properties of interest is valid at timescales where the slope is 1 in a log–log plot. Such a criterion is not present in the Green–Kubo method, where a time–correlation function slowly converges to zero regardless of the simulation length.^{71,79}

In all MD simulations, 1000 H₂O and 5 solute molecules (i.e., H₂ or O₂) are used, corresponding to infinite dilution conditions. As can be seen in Figure S1 in the Supporting Information, the variation in the number of solute molecules (both H₂ and O₂) from 1 to 5 practically yields the same diffusivity values, while the error is reduced by a factor of ca. 2. As shown by Janzen et al.⁸⁰ and Guevarra-Carrion et al.,⁸¹ intradiffusion coefficients of mixtures at the infinite dilution limit can also be computed by performing MD simulations at several compositions near the infinite dilution, e.g., $x_i = 0.5, 1, 3,$ and 5 mol %, and extrapolating to $x_i \rightarrow 0$. Such an approach may yield relatively low statistical uncertainties since the computation of intradiffusivity is performed using a larger number of solute molecules.

In this work, all diffusivities are corrected for finite-size effects using the Yeh–Hummer equation^{82–84}

$$D_i^\infty = D_i + \frac{k_B T \xi}{6\pi\eta L} \quad (4)$$

where D_i^∞ is the finite-size corrected self- (and intra-) diffusion coefficients, T is the absolute temperature, ξ is a dimensionless constant equal to 2.837298, and L is the length of the simulation box. The computation of η does not depend on the system size.^{85,86} As recently shown by Jamali et al.,^{84,87} eq 4 is

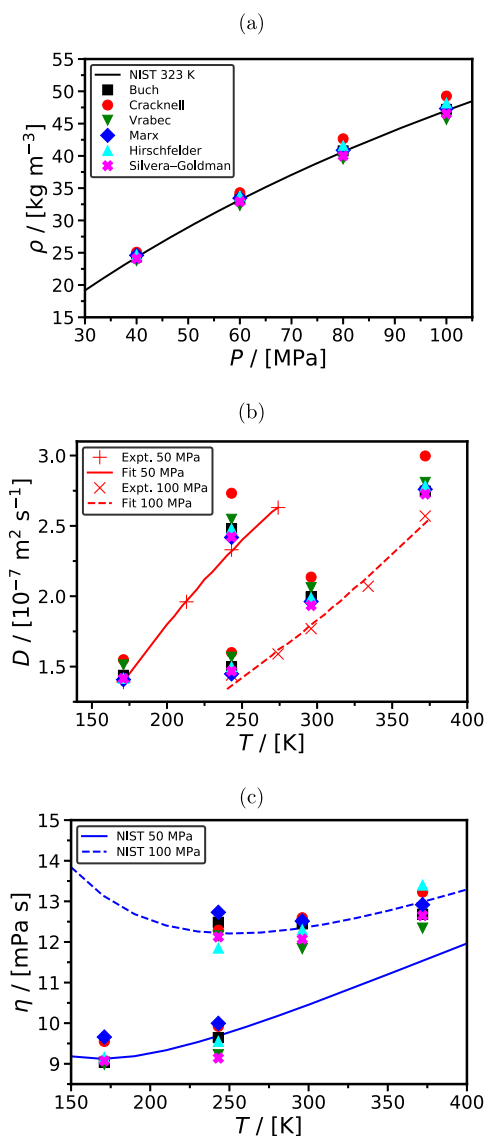


Figure 1. Properties of pure H₂: (a) density as a function of pressure at 323 K, (b) self-diffusion coefficient, and (c) shear viscosity as a function of temperature at 50 and 100 MPa computed in MD simulations using the Buch,³⁸ Cracknell,⁴¹ Vrabc,³⁹ Marx,⁴³ Hirschfelder,⁴⁰ and Silvera–Goldman⁴² H₂ force fields. The experimental data are taken from the NIST database⁹⁰ and Chen et al.⁹¹ The self-diffusion coefficients are corrected for system-size effects using eq 4. The error bars have been omitted for clarity. The raw MD data along with the error bars are listed in Tables 2 and S4 in the Supporting Information. The symbols denoting the different force fields are the same in (a)–(c).

valid for correcting the intradiffusion coefficients in binary and multicomponent mixtures. As can be seen in Figure S2, eq 4 can be used to correct the intradiffusivities of infinitely diluted H₂ in liquid (Figure S2a), vapor (Figure S2b), and supercritical (Figure S2c) H₂O computed in MD simulations. In all cases, D_i computed using different numbers of H₂O molecules (solvent) scale linearly with $1/L$ (where $L \propto N^{1/3}$ and N is the number of molecules). The magnitude of the finite-size correction strongly depends on the system and thermodynamic conditions.^{36,82,86–89} For example, in the liquid phase (Figure S2a), the absolute deviation between D_i and D_i^∞ is 3.5, 4.4, and 5.3% for MD simulations using 1000, 2000, and 4000 H₂O

Table 2. Self-Diffusion Coefficients, Shear Viscosities, and Densities of Pure H₂ Computed Using Different Force Fields for Various Temperatures and Pressures^a

T	P	Buch		Cracknell		Vrabec		Hirschfelder		Marx		Silvera–Goldman		NIST
		D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	
171	50	1.44	0.03	1.55	0.03	1.51	0.03	1.42	0.03	1.41	0.02	1.42	0.02	
243	50	2.48	0.04	2.73	0.04	2.55	0.04	2.48	0.04	2.42	0.02	2.42	0.02	
243	100	1.50	0.03	1.60	0.04	1.57	0.04	1.50	0.04	1.45	0.03	1.47	0.03	
296	100	2.00	0.04	2.14	0.04	2.06	0.04	1.99	0.04	1.96	0.02	1.93	0.02	
372	100	2.75	0.03	3.00	0.05	2.81	0.05	2.78	0.05	2.76	0.02	2.73	0.02	
		η	σ_η	η	σ_η	η	σ_η	η	σ_η	η	σ_η	η	σ_η	η
171	50	9.04	0.84	9.55	1.02	9.0	0.7	9.16	1.01	9.7	1.3	9.1	0.5	9.121
243	50	9.65	0.55	9.92	1.04	9.2	0.7	9.55	0.81	10.0	1.5	9.1	0.8	9.686
243	100	12.48	0.67	12.3	1.1	12.2	1.3	11.19	0.99	12.7	1.5	12.1	1.0	12.215
296	100	12.45	0.59	12.60	0.91	11.8	1.1	12.3	1.2	12.5	1.6	11.1	1.1	12.344
372	100	12.68	0.37	13.2	1.6	12.3	0.9	13.4	1.3	12.9	0.9	12.0	1.8	12.987
		ρ	σ_ρ	ρ	σ_ρ	ρ	σ_ρ	ρ	σ_ρ	ρ	σ_ρ	ρ	σ_ρ	ρ
323	40	24.4	0.1	25.08	0.08	23.77	0.06	24.68	0.09	24.6	0.2	24.10	0.08	24.547
323	60	33.28	0.09	34.3	0.2	32.32	0.12	33.8	0.2	33.45	0.23	32.91	0.11	33.495
323	80	40.78	0.23	42.65	0.07	39.51	0.09	41.57	0.08	40.87	0.36	39.99	0.23	40.992
323	100	47.21	0.28	49.27	0.06	45.65	0.22	48.18	0.21	47.33	0.13	46.53	0.12	47.210

^aT is in units of K, P in MPa, D in 10⁻⁹ m² s⁻¹, η in mPa·s, and ρ in kg m⁻³. σ_x is the uncertainty of quantity x (95% confidence interval of the standard deviation). The values from NIST⁹⁰ are shown for comparison.

Table 3. Self-Diffusion Coefficients and Shear Viscosities of Pure O₂ Computed Using Different Force Fields for Various Temperatures and Pressures^a

T	P	Bohn		Miyano		Coon		NIST
		D	σ_D	D	σ_D	D	σ_D	
77.65	0.1	0.0016	0.0002	0.0022	0.0002	0.0020	0.0002	
194.65	0.1	9.47	0.22	9.72	0.47	9.60	0.31	
273.15	0.1	17.63	0.44	18.12	0.58	17.93	0.29	
298.15	0.1	20.81	0.30	21.11	0.60	21.00	0.68	
318	0.1	23.26	0.42	23.59	0.51	23.73	0.29	
353.15	0.1	28.75	0.51	28.67	0.37	28.69	0.38	
		η	σ_η	η	σ_η	η	σ_η	η
77.65	0.1	284	10	303	11	295	11	292.080
94.65	0.1	13.6	1.6	14.0	1.1	13.8	0.7	14.308
273.15	0.1	16.5	2.0	17.2	2.0	16.9	1.3	19.055
298.15	0.1	17.0	1.7	18.0	1.9	17.7	1.0	20.459
318	0.1	19.8	2.1	20.9	2.1	20.6	2.2	21.542
353.15	0.1	20.8	2.0	21.9	1.7	21.7	2.0	23.394

^aT is in units of K, P in MPa, D in 10⁻⁹ m² s⁻¹, and η in mPa·s. σ_x is the uncertainty of quantity x (95% confidence interval of the standard deviation). D and η at 77.65 K and 0.1 MPa for the Hansen force field is (0.00248 ± 0.00012) 10⁻⁹ m² s⁻¹ and 295 ± 13 mPa·s, respectively. The values from NIST⁹⁰ are shown for comparison.

molecules, respectively. In the supercritical and vapor phases, the deviations between D_i and D_i^∞ are found to be one and two orders of magnitude lower, respectively. In this study, the vast majority of diffusivities computed at the supercritical and vapor conditions require finite-size corrections smaller than the uncertainties of the simulations.

For clarity, in the remainder of this manuscript (and the Supporting Information), the symbol D is used for representing the finite-size corrected diffusivities. The uncertainties of the reported densities, shear viscosities, and diffusivities are calculated as standard deviations from at least five independent runs, each one starting from a different initial configuration. The confidence level of all reported uncertainties in this work is 95%.

3. RESULTS AND DISCUSSION

3.1. Force Field Validation and Selection. The following procedure is adopted for selecting accurate force fields to be used for the computation of the intradiffusivities of H₂ and O₂ in H₂O. The six H₂ and six O₂ force fields, described in Section 2.1, are evaluated based on their performance in predicting the density, self-diffusion coefficient, and shear viscosity of the pure gas and the intradiffusion coefficient of the gas in H₂O at low pressures. These properties and conditions are chosen because these force fields are primarily fitted to pure gas experimental data. For more details on the force field parametrization procedure, the reader is referred to the original studies, i.e., for H₂^{38–43} and O₂^{53–58}. Selected typical comparisons with the available experimental data are shown in Figures 1–4. All of the MD data with the corresponding uncertainties are provided in Table 2 (density, self-diffusion coefficient, and shear viscosity of pure H₂), Table

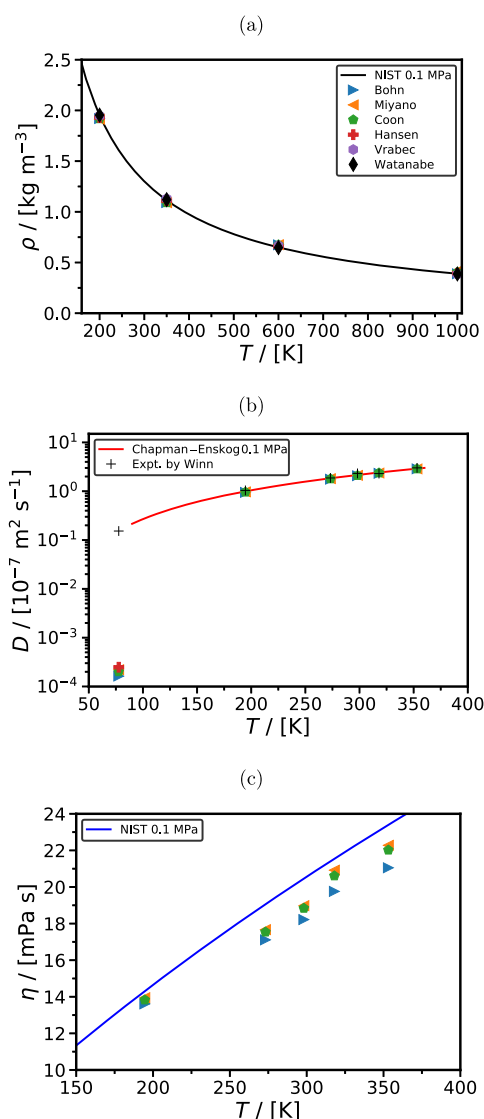


Figure 2. Properties of pure O_2 : (a) density, (b) self-diffusion coefficient, and (c) shear viscosity as a function of temperature at 0.1 MPa computed in MD simulations using the Bohn,⁵³ Miyano,⁵⁴ Coon,⁵⁵ Hansen,⁵⁶ Vrabec,⁵⁷ and Watanabe⁵⁸ O_2 force fields. The experimental data are taken from the NIST database⁹⁰ and Winn.⁹² The self-diffusion coefficients are corrected for system-size effects using eq 4. The error bars have been omitted for clarity. The raw MD data along with the error bars are listed in Tables 3 and S5 in the Supporting Information. The symbols denoting the different force fields are the same in (a)–(c).

3 (self-diffusion coefficient and shear viscosity of pure O_2), as well as Table S4 (density of pure H_2) and Table S5 (density of pure O_2) in the Supporting Information.

Figure 1 shows the comparison of the computed densities (Figure 1a), self-diffusivities (Figure 1b), and shear viscosities (Figure 1c) of pure H_2 with the available experimental data.^{90,91} The respective comparisons with the available experimental data^{90,92} for pure O_2 are shown in Figure 2. As shown in Figure 1a, in Table 2 and Table S4 in the Supporting Information, five of the H_2 force fields can accurately predict the density (within 2.5% absolute deviation) at high temperatures and low pressure, while the Cracknell⁴¹ force field deviates from experiments by ca. 8%. At low temperatures and high pressures, four of the H_2 force fields can accurately predict

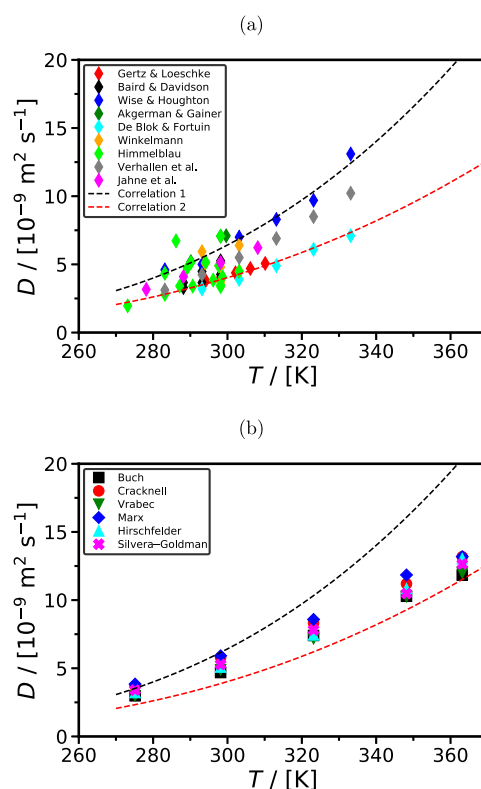


Figure 3. Intradiffusion coefficients of H_2 in H_2O as a function of temperature at 0.1 MPa from (a) experiments, and (b) MD simulations using the Buch,³⁸ Cracknell,⁴¹ Vrabec,³⁹ Marx,⁴³ Hirschfelder,⁴⁰ and Silvera–Goldman⁴² H_2 force fields combined with the TIP4P/2005 H_2O ³⁵ force field. The experimental data are taken from Gertz and Loeschke,⁹⁴ Baird and Davidson,⁹⁵ Wise and Houghton,⁹⁶ Akgerman and Gainer,⁹⁷ de Blok and Fortuin,⁹⁸ Winkelmann,⁹³ Himmelblau,⁹ Verhallen et al.,⁹⁹ and Jahne et al.¹ Correlations 1 and 2 are fits to the experimental data using eq 5 (the parameters of the fits are listed in Table 4). The computed intradiffusion coefficients are corrected for system-size effects using eq 4. The error bars have been omitted for clarity. The raw MD data along with the error bars are listed in Table 5.

Table 4. Parameters of the Arrhenius Fit (equation 5) to the Experimental Data of H_2 in H_2O at 1 Atm^a

	$\ln(D_0)$	α
correlation 1	-12.22 ± 0.48	$(-0.199 \pm 0.014) \times 10^4$
correlation 2	-13.29 ± 0.37	$(-0.181 \pm 0.011) \times 10^4$

^aThe curves representing the correlations are shown in Figure 3a.

the density (within 2.3% absolute deviation), while for the case of Hirschfelder⁴⁰ and Cracknell⁴¹ force fields, the absolute deviation is within 7.5%. For pure O_2 , as shown in Figure 2a and in the additional data provided in the Supporting Information (Table S5), four force fields show high accuracy under all conditions studied (absolute average deviations from the experimental data up to 1.5%), while for the case of Miyano⁵⁴ and Coon⁵⁵ force fields, the absolute average deviation is within 2.4–3.0%. Based on their overall performance in reproducing the experimental density in the temperature range of 200–1000 K, at pressures of 0.1 and 50 MPa (see Table S5 in the Supporting Information), only the force fields by Bohn,⁵³ Miyano,⁵⁴ and Coon⁵⁵ are further considered in this study. Nevertheless, the difference in the performance of

Table 5. Intradiffusion coefficients of H₂ in H₂O and O₂ in H₂O computed using different force field combinations for various temperatures at a pressure of 0.1 MPa^a

T	P	H ₂ in H ₂ O		O ₂ in H ₂ O	
		D	σ_D	D	σ_D
		Buch + TIP4P/2005		Bohn + TIP4P/2005	
275.15	0.1	3.0	0.3	1.5	0.1
298.15	0.1	4.7	0.7	2.6	0.2
323.15	0.1	7.4	0.5	4.16	0.22
348.15	0.1	10.3	1.5	6.09	0.27
363.15	0.1	11.8	1.1	7.39	0.43
		Cracknell + TIP4P/2005		Miyano + TIP4P/2005	
275.15	0.1	3.70	0.35	1.60	0.12
298.15	0.1	5.80	0.54	2.78	0.11
323.15	0.1	8.3	0.6	4.42	0.26
348.15	0.1	11.20	0.94	6.2	0.3
363.15	0.1	13.18	0.99	7.47	0.47
		Vrabec + TIP4P/2005		Coon + TIP4P/2005	
275.15	0.1	2.97	0.26	1.58	0.11
298.15	0.1	4.9	0.3	2.73	0.18
323.15	0.1	7.16	0.46	4.3	0.2
348.15	0.1	10.25	0.43	6.23	0.29
363.15	0.1	12.0	0.6	7.3	0.3
		Hirschfelder + TIP4P/2005		Hansen + TIP4P/2005	
275.15	0.1	3.22	0.16	1.89	0.11
298.15	0.1	5.09	0.46	3.41	0.21
323.15	0.1	7.45	0.46	5.07	0.38
348.15	0.1	10.84	0.37	6.87	0.28
363.15	0.1	13.05	0.71	7.94	0.29
		Marx + TIP4P/2005		Vrabec + TIP4P/2005	
275.15	0.1	3.8	0.2	2.0	0.1
298.15	0.1	5.9	1.8	3.29	0.11
323.15	0.1	8.6	0.8	4.89	0.23
348.15	0.1	12	1	6.6	0.3
363.15	0.1	13.2	1.8	7.84	0.29
		Silvera–Goldman + TIP4P/2005		Watanabe + TIP4P/2005	
275.15	0.1	3.40	0.81	2.01	0.12
298.15	0.1	5.28	0.79	3.34	0.22
323.15	0.1	7.81	0.76	4.4	0.3
348.15	0.1	10.48	0.69	7.01	0.36
363.15	0.1	12.65	0.79	8.49	0.36

^aT is in units of K, P in MPa, and D in 10⁻⁹ m² s⁻¹. σ_x is the uncertainty of quantity x (95% confidence interval of the standard deviation).

the chosen force fields with the ones by Hansen,⁵⁶ Vrabec,⁵⁷ and Watanabe⁵⁸ is not very significant.

For the case of H₂ self-diffusion coefficients, we compare the computed data with the experimental data reported by Chen et al.⁹¹ at 50 and 100 MPa. It can be clearly seen in Figure 1b (also in Table 2) that the three-site models perform significantly better than the rest. Particularly, the Silvera–Goldman-type⁴² force field has the highest accuracy (absolute average deviation from the experimental data equal to 4.6%), followed by the Marx⁴³ force field (deviation of 4.8%). Among the single and two-site force fields, the Buch³⁸ force field shows an accuracy comparable to the three-site models (6.7%). The force fields show mutual consistency for the majority of temperatures and pressures, with the Silver–Goldman⁴² being the most accurate and Cracknell⁴¹ being the least accurate. For

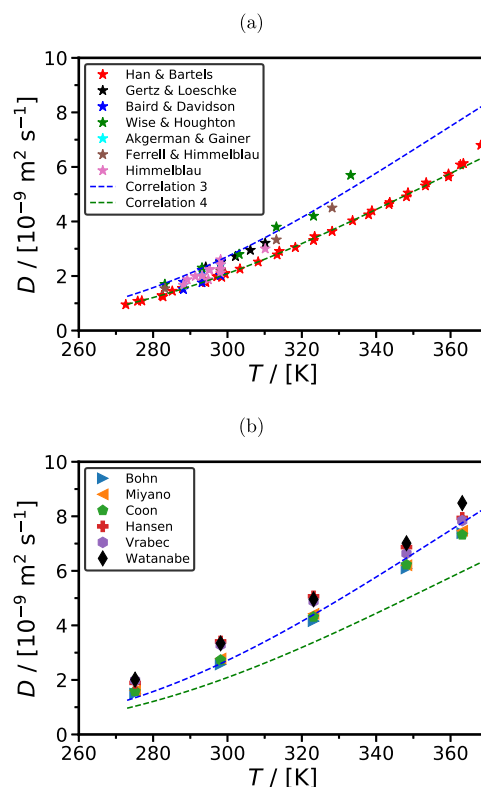


Figure 4. Intradiffusion coefficients of O₂ in H₂O as a function of temperature at 0.1 MPa from (a) experiments, and (b) MD simulations using the Bohn,⁵³ Miyano,⁵⁴ and Coon,⁵⁵ Hansen,⁵⁶ Vrabec,⁵⁷ and Watanabe⁵⁸ O₂ force fields combined with the TIP4P/2005 H₂O³⁵ force field. The experimental data are taken from Han and Bartels,¹⁰¹ Gertz and Loeschke,⁹⁴ Baird and Davidson,⁹⁵ Wise and Houghton,⁹⁶ Akgerman and Gainer,⁹⁷ Ferrell and Himmelblau,¹⁰⁰ and Himmelblau.⁹ Correlation 4 is a fit to experimental data provided by Han and Bartels.¹⁰¹ Correlation 3 is a 25% positive shift of correlation 4. The computed intradiffusion coefficients are corrected for system-size effects using eq 4. The error bars have been omitted for clarity. The raw MD data along with the error bars are listed in Table 5.

the case of O₂ self-diffusion coefficients in the vapor phase, shown in Figure 2b (also in Table 3), the two-site force fields (i.e., Bohn,⁵³ Miyano,⁵⁴ and Coon⁵⁵) are in excellent agreement with the experimental measurements at 0.1 MPa reported by Winn.⁹² In particular, the absolute average deviations are 6.1, 5.2, and 5.8% for the Bohn,⁵³ Miyano,⁵⁴ and Coon⁵⁵ force fields, respectively. In sharp contrast, a strong deviation is observed at 77.65 K, where the experimental point has a “vapor-like” value, while the MD simulations predict “liquid-like” values for the self-diffusion coefficient. It should also be noted that according to NIST,⁹⁰ the corresponding vapor–liquid–equilibrium (VLE) temperature for 0.1 MPa is ca. 90 K. Therefore, the reported experimental value at 77.65 K may be questionable. The self-diffusivities computed with MD are compared with calculations using the Chapman–Enskog¹³ theory for the vapor phase. An almost perfect agreement is found, as can be clearly seen in Figure 2b.

The computed shear viscosities of pure H₂ and O₂ are compared with the values reported by NIST.⁹⁰ As shown in Figure 1c, the Buch³⁸ force field has the best performance (absolute average deviation of 1.3%) in predicting the shear viscosity of pure H₂, clearly reproducing the trend of the NIST

Table 6. Comparison of the Intradiffusivities of O₂ in H₂O (TIP4P/2005 Force Field) Computed Using Different Force Fields with the Available Experimental Data for Various Temperatures and Pressures^a

T	P	D		σ_D
		Bohn + TIP4P/2005		
293.15	1.0	2.29	0.16	
308.15	1.0	3.04	0.11	
283.15	2.5	1.82	0.17	
298.15	2.0	2.62	0.12	
Coon + TIP4P/2005				
293.15	1.0	2.32	0.13	
308.15	1.0	3.16	0.13	
283.15	2.5	1.82	0.13	
298.15	2.0	2.41	0.13	
Miyano + TIP4P/2005				
293.15	1.0	2.43	0.12	
308.15	1.0	3.32	0.12	
283.15	2.5	1.87	0.12	
298.15	2.0	2.67	0.12	

^aT is in units of K, P in MPa, and D in 10⁻⁹ m² s⁻¹. σ_x is the uncertainty of quantity x (95% confidence interval of the standard deviation). The intradiffusion coefficients are corrected for system-size effects using eq 4.

shear viscosity dataset. As shown in Figure 2c, the two-site O₂ force fields are relatively accurate in reproducing the shear viscosity reported by NIST.⁹⁰ Namely, the absolute average deviations are 9.6, 6.3, and 6.7% for the cases of Bohn,⁵³ Miyano,⁵⁴ and Coon⁵⁵ force fields, respectively.

In Figure 3a, we show all of the available experimental values for the H₂ intradiffusion coefficients in H₂O as a function of temperature at 0.1 MPa. For more details on the experiments, the reader is referred to the review papers by Himmelblau⁹ and Winkelmann.⁹³ Additional experimental data for H₂ intradiffusivity in H₂O have been reported by Gertz and Loeschcke,⁹⁴ Baird and Davidson,⁹⁵ Wise and Houghton,⁹⁶ Akgerman and Gainer,⁹⁷ de Blok and Fortuin,⁹⁸ Verhallen et al.,⁹⁹ and Jähne et al.¹ As can be seen in Figure 3a, the majority of the experimental data fall onto two distinct, experimentally based, Arrhenius-type curves (noted as correlations 1 and 2), with some experimental data falling in-between the two curves. The two curves differ by approximately 70%. The Arrhenius-type curves are described as follows:^{10,15}

$$D = D_0 \exp\left(\frac{\alpha}{T}\right) \quad (5)$$

where D_0 and α are the fitting parameters. Often, α is expressed as $\alpha = \frac{-E_a}{R}$, where E_a is the activation energy for diffusion and R is the universal gas constant. The values of the parameters for the two curves are listed in Table 4.

Figure 3b and Table 5 show the MD results for the H₂ intradiffusivities in H₂O at 0.1 MPa as a function of temperature along with correlations 1 and 2. As can be clearly seen, the MD results lie closer to the lower curve (correlation 2), especially for temperatures higher than 310 K. This finding indicates that the experimental data falling onto correlation 1 probably need to be re-evaluated. Among all force field combinations considered for the system H₂–H₂O, the Buch–TIP4P/2005 combination shows the least deviation from correlation 2 for all temperature points (absolute average

deviation of 16.4%), followed by the Vrabec–TIP4P/2005 combination (16.6%), while the absolute average deviation for the remaining four combinations is in the range 24–40%.

A similar procedure is followed for the case of O₂ diffusing in H₂O. Himmelblau⁹ presented an earlier review, while additional experimental data have been reported by Gertz and Loeschcke,⁹⁴ Baird and Davidson,⁹⁵ Wise and Houghton,⁹⁶ Ferrell and Himmelblau,¹⁰⁰ Akgerman and Gainer,⁹⁷ and Han and Bartels.¹⁰¹ Figure 4a shows all of the available experimentally measured O₂ intradiffusion coefficients in H₂O as a function of temperature at 0.1 MPa. Similar to the H₂–H₂O system, the majority of the experimental data fall onto two distinct curves (noted as correlations 3 and 4 in Figure 4), with some data falling in-between the two curves. The two curves differ by approximately 25%. The experimental study by Han and Bartels¹⁰¹ is by far the most extensive for the O₂ intradiffusivity in H₂O spanning temperatures up to 370 K. The data points reported in this study are in excellent agreement with correlation 4, as clearly seen in Figure 4a. Our MD results for the O₂ intradiffusivities in H₂O at 0.1 MPa, along with the two correlations, are shown as a function of temperature in Figure 4b and listed in Table 5. It is evident that the computed intradiffusion coefficients, regardless of the force field used, are in very good agreement with correlation 3, while they systematically deviate from the experimental data reported by Han and Bartels,¹⁰¹ and therefore, correlation 4. Based on this finding, for the remainder of the study, the experimental data falling onto correlation 3 are adopted. The combination of our MD results with the rest of the experiments suggests that the experimental data of Han and Bartels¹⁰¹ probably need to be revisited. Among the six force field combinations considered for the system O₂–H₂O, the Bohn–TIP4P/2005 combination showed the highest agreement with the adopted correlation of experimental values (absolute average deviation of 3.8%), followed by the Coon–TIP4P/2005 combination (6.4%), and the Miyano–TIP4P/2005 combination (7.4%), while the absolute average deviation of the remaining three combinations ranged from 17.6 to 20.1%. The good performance of this force field combination is further confirmed by additional MD simulations of O₂ diffusing in H₂O, performed at higher pressures, i.e., 1.0, 2.0, and 2.5 MPa, for which the experimental data are available.¹⁰² These results are shown in Table 6.

Based on our findings for the pure gas (H₂ and O₂) properties and for the gas diffusion in H₂O, we conclude that the Buch–TIP4P/2005 force field combination is the most suitable for modeling H₂ intradiffusion in H₂O, and the Bohn–TIP4P/2005 force field combination is the most suitable for modeling O₂ intradiffusion in H₂O. Therefore, all of the remaining simulations are performed with these two combinations.

3.2. Engineering a Model for Predicting the Intradiffusivities of H₂ and O₂ in H₂O. In this work, extensive MD simulations have been performed for the computation of the intradiffusivities of H₂ and O₂ in H₂O at temperatures in the range 275.15–975.15 K and pressures 0.1–200 MPa. In our simulations, the self-diffusion coefficients of pure H₂O are also computed for the same wide T and P range. All of the results are listed in Tables 7, 8, and 9 for the intradiffusivity of H₂ in H₂O, O₂ in H₂O, and the self-diffusivity of pure H₂O, respectively. Figure 5a shows an Arrhenius-type plot of the computed intradiffusion coefficients for the H₂–H₂O system. The respective results for the O₂–H₂O and pure H₂O systems

Table 7. Intradiffusion Coefficients of H₂ in H₂O Computed for a Wide Range of Temperatures and Pressures^a

T/P	0.1		5.0		7.5		10		12.5		20		30		100		200	
	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D
275.15	2.98	0.31	2.99	0.18		0.24	3.02	0.24			3.11	0.23	2.98	0.18				
298.15	4.69	0.74	4.86	0.37		0.34	4.92	0.34			4.87	0.19	4.85	0.28	4.26	0.24	3.80	0.17
323.15	7.41	0.49	7.48	0.58		0.25	7.24	0.25			7.14	0.54	6.90	0.65				
348.15	10.3	1.5	10.28	0.66		0.42	10.70	0.42			10.27	0.72	10.17	0.99				
363.15	11.8	1.1	12.09	0.41		0.48	12.57	0.48			11.90	0.52	11.73	0.92	10.79	0.78	9.18	0.42
423.15																		
448.15			24.5	1.2		1.1	24.8	1.1			24.89	0.83	25.8	1.4				
473.15															29.9	1.8	27.3	1.8
498.15			38.6	2.0		3.4	35.3	3.4			35.6	2.7	35.5	2.4				
523.15					44.5	5.4									34.2	1.8	29.9	1.8
573.15			5125	670	2470	231	66.5	4.3	63.9	1.9	60.8	3.4	59.2	3.5				
586.15							1967.9	151.3										
623.15							2559.0	202.4	1871	286					60.9	2.4	47.9	2.1
637.15											147	11	103.1	9.1				
641.15											774	23						
657.15																		
673.15			7400	767	4554	389	3212	223	2421	192	1211	68	148	10	72.2	2.5		
723.15											1624	123	814	68	80.8	3.6		
773.15			9260	1259	5881	466	4088	327	3376	293	2000	202	1148	109	105.5	4.9		
823.15													1377	121	205.7	9.2		
873.15			11 196	1599	7329	551	5098	389	4155	277	2562	189	1667	144	274	16		
973.15			14 295	1918	9328	721	6616	403	5066	281	3161	220	1988	227	432	19		

^aThe Buch³⁸ and TIP4P/2005³⁵ force fields are used for H₂ and H₂O, respectively. T is in units of K, P in MPa, and D in 10⁻⁹ m² s⁻¹. σ_x is the uncertainty of quantity x (95% confidence interval of the standard deviation).

Table 8. Intradiffusion Coefficients of O₂ in H₂O Computed for a Wide Range of Temperatures and Pressures^a

T/P	0.1		2.5		5.0		7.5		10		12.5		20		30		100		200		
	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	
275.15	1.50	0.10					1.41	0.17													
298.15	2.57	0.20									2.48	0.24	2.49	0.21	2.46	0.19	2.34	0.18	2.22	0.18	
323.15	4.16	0.22																			
348.15	6.09	0.27	5.80	0.32																	
363.15	7.39	0.43							5.79	0.77											
423.15																					
448.15																					
498.15																					
523.15																					
573.15																					
673.15																					
723.15																					
773.15																					
873.15																					
973.15																					

^aThe Bohn⁵³ and TIP4P/2005³⁵ force fields are used for O₂ and H₂O, respectively. T is in units of K, P in MPa, and D in 10⁻⁹ m² s⁻¹. σ_D is the uncertainty of quantity x (95% confidence interval of the standard deviation).

Table 9. Self-Diffusion Coefficients of Pure H₂O Computed for a Wide Range of Temperatures and Pressures Using the TIP4P/2005 Force Field^a

T/P	0.1		5.0		7.5		10		12.5		20		30		100		200	
	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D	D	σ_D
275.15	1.57	0.02	1.57	0.02			1.56	0.02			1.55	0.02	1.55	0.02				
298.15	2.64	0.05	2.63	0.05			2.62	0.05			2.62	0.04	2.62	0.04	2.58	0.03	2.54	0.03
323.15	4.29	0.05	4.27	0.06			4.23	0.05			4.22	0.06	4.20	0.06				
348.15	6.26	0.07	6.26	0.07			6.24	0.06			6.22	0.07	6.17	0.06				
363.15	7.53	0.07	7.53	0.07			7.52	0.08			7.52	0.08	7.51	0.08	7.30	0.11	6.81	0.72
423.15															12.92	0.15	11.94	0.14
448.15			16.9	1.6			16.9	1.4			16.7	1.5	16.6	1.4				
473.15															18.46	0.17	17.12	0.16
498.15			24.0	2.2			23.9	2.0			23.7	2.1	22.9	1.8				
523.15					28.1	2.4									24.2	2.2	21.35	0.20
573.15			1024	16	458.5	9.8	38.7	3.0	38.4	3.3	37.4	3.3	36.1	3.2				
586.15							432.7	5.2										
623.15							563.4	5.8	409.3	5.0	65.9	4.8	49.7	3.9	38.8	3.2	32.67	0.21
637.15											178.9	7.4	55.4	4.4				
641.15																		
657.15															68.5	4.8	45.2	3.5
673.15			1593	17	972	14	743.1	9.8	569.1	6.9	293.7	6.1	97.1	5.7	48.7	3.9		
723.15											413.8	9.4	231.2	8.6	61.1	4.8		
773.15			2219	27	1466	15	1164	13	875.5	7.6	518.8	8.0	315.6	7.9	76.8	4.8		
823.15													396.0	8.0	97.8	5.7		
873.15			2867	27	1918	23	1481	18	1211.6	8.3	733.0	8.0	472.7	7.1	122.3	6.1		
973.15			3486	29	2385	24	1879	20	1536.1	9.7	955	9	630.4	5.1	176.0	6.2		

^aT is in units of K, P in MPa, and D in 10⁻⁹ m² s⁻¹. σ_x is the uncertainty of quantity x (95% confidence interval of the standard deviation).

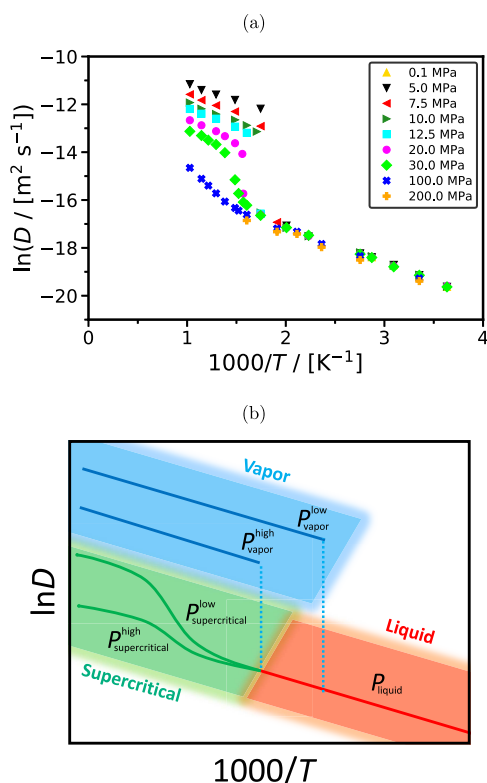


Figure 5. (a) Arrhenius-type plot of the computed intradiffusion coefficients of H₂ in H₂O using the Buch³⁸–TIP4P/2005³⁵ force field combination. The respective results for the O₂–H₂O and pure H₂O systems are shown in Figure S3a,b, and Tables 8 and 9, respectively. The computed intradiffusion coefficients are corrected for system-size effects using eq 4. The error bars have been omitted for clarity. All raw MD data shown here along with the error bars are listed in Table 7. (b) A conceptual schematic representation of the diffusivity patterns of the H₂ in H₂O, O₂ in H₂O, and pure H₂O systems in the vapor, liquid, and supercritical regions.

are shown in Figure S3a,b, respectively, in the Supporting Information. All systems exhibit similar patterns in their Arrhenius plots. A conceptual schematic representation of these patterns is shown in Figure 5b. Since our MD simulations span a wide T and P range, the gas–H₂O systems can be in the vapor, liquid, or supercritical state. We assume that the critical point and the VLE properties are the same as those of the pure H₂O since H₂ and O₂ are present at infinite dilution in the aqueous phase. According to Wagner and Pruss,¹⁰³ the critical temperature T_c and pressure P_c of H₂O are 647.096 K and 22.064 MPa, respectively. According to Vega and Abascal,⁵⁹ the T_c and P_c of the TIP4P/2005 H₂O force field are 640 K and 14.6 MPa, respectively. Our analysis, therefore, is based on the critical point of the TIP4P/2005 H₂O force field. Three distinct zones can be identified in Figure 5b, based on whether the diffusion occurs in the vapor, liquid, or supercritical phase. Each zone has specific characteristics. In particular, the vapor and the liquid zones exhibit Arrhenius behavior as described by eq 5. As can be seen in Figure 5, the slopes of the vapor and liquid zones in the $\ln(D)$ vs $1000/T$ plot have very similar values. A very weak pressure dependence is observed for the case of the liquid zone (Figure 5a), while a strong pressure dependence is observed in the vapor zone. The supercritical zone exhibits a more complex non-Arrhenius behavior. Yet, narrow temperature ranges could

be identified where an Arrhenius behavior is locally present. These characteristics enable us to develop a systematic and generalizable approach for the estimation of the intradiffusion coefficients at the three different zones. To establish the new approach, we examine the gas diffusion in the three zones (i.e., vapor, liquid, and supercritical) separately. Figure 6 shows the overall diffusion behavior of the three systems examined. Namely, the intradiffusion coefficients of H₂ in H₂O, as a function of the inverse temperature, in the vapor (Figure 6a), liquid (Figure 6d), and supercritical (Figure 6g) phases. The respective intradiffusivities of O₂ in H₂O are shown in Figures 6b,e,h. Finally, the respective self-diffusivities for pure H₂O are shown in Figure 6c,f,i.

It should be noted that the experimentally measured solubilities of H₂ and O₂ in H₂O are rather low in the entire range of temperatures and pressures examined in this work.^{104–107} For pressures close to the atmospheric and temperatures up to 353 K, the solubility of H₂ in H₂O ranges from 1.3×10^{-5} to 4×10^{-4} . For pressures up to ca. 60 MPa and temperatures up to 373 K, the solubilities increase by an order of magnitude. For higher temperatures and very high pressures, e.g., 100 MPa, the solubilities increase to a maximum of approximately 1×10^{-2} .¹⁰⁶ The solubilities of O₂ in H₂O are in the same range.¹⁰⁷ For high pressures, where the solubility values of the gases in H₂O are significantly higher than in the infinite dilution limit, the computation of mutual diffusivities (Fick and Maxwell–Stefan^{10,11}) would be of practical interest since the mass transport occurs due to gradients in composition (or chemical potential). To this purpose, one can either use Darken equation-based models¹⁴ or can follow the well-established methodology of computing the Maxwell–Stefan diffusivities (D_{MS}) from the Onsager coefficients in MD simulations,^{20,71,84} and the thermodynamic factor (Γ), e.g., from Kirkwood–Buff integrals.^{108,109} Fick diffusivities follow from $D_{Fick} = \Gamma D_{MS}$.^{10,20,71,80} Such an approach is outside the scope of the current work, which is to construct an engineering model for predicting the diffusivities of infinite diluted gases in H₂O (for which $D_{self} = D_{MS} = D_{Fick}$).¹⁰

3.2.1. Gas Diffusivity in H₂O Vapor. MD simulations are performed for four different isobars (i.e., 5.0, 7.5, 10.0, and 12.5 MPa) and various temperatures that correspond to H₂O (TIP4P/2005 force field) being in the vapor phase. From the Arrhenius plots for H₂ in H₂O (Figure 6a), O₂ in H₂O (Figure 6b), and pure H₂O (Figure 6c), a linear behavior and a strong pressure dependence can be observed. The dotted lines in these figures show the linear fits to each isobar. Thus, a value for the slope (α) and the intercept ($\ln(D_0)$) can be calculated for each one. The values for the slope and intercept are plotted as a function of pressure in Figure 7a,b, respectively, where the following linear behavior is established

$$\alpha = m_1 P + m_0 \quad (6)$$

$$\ln(D_0) = n_1 P + n_0 \quad (7)$$

where m_0 , m_1 , n_0 , and n_1 are fitting parameters. The calculated fitting parameters for the three systems considered in the current study are listed in Table 10. These parameters are an important result since they can be used to calculate the self- and intradiffusion coefficients for any conditions where the solute diffusion occurs in the gaseous phase by combining eqs 5–7 into the following equation

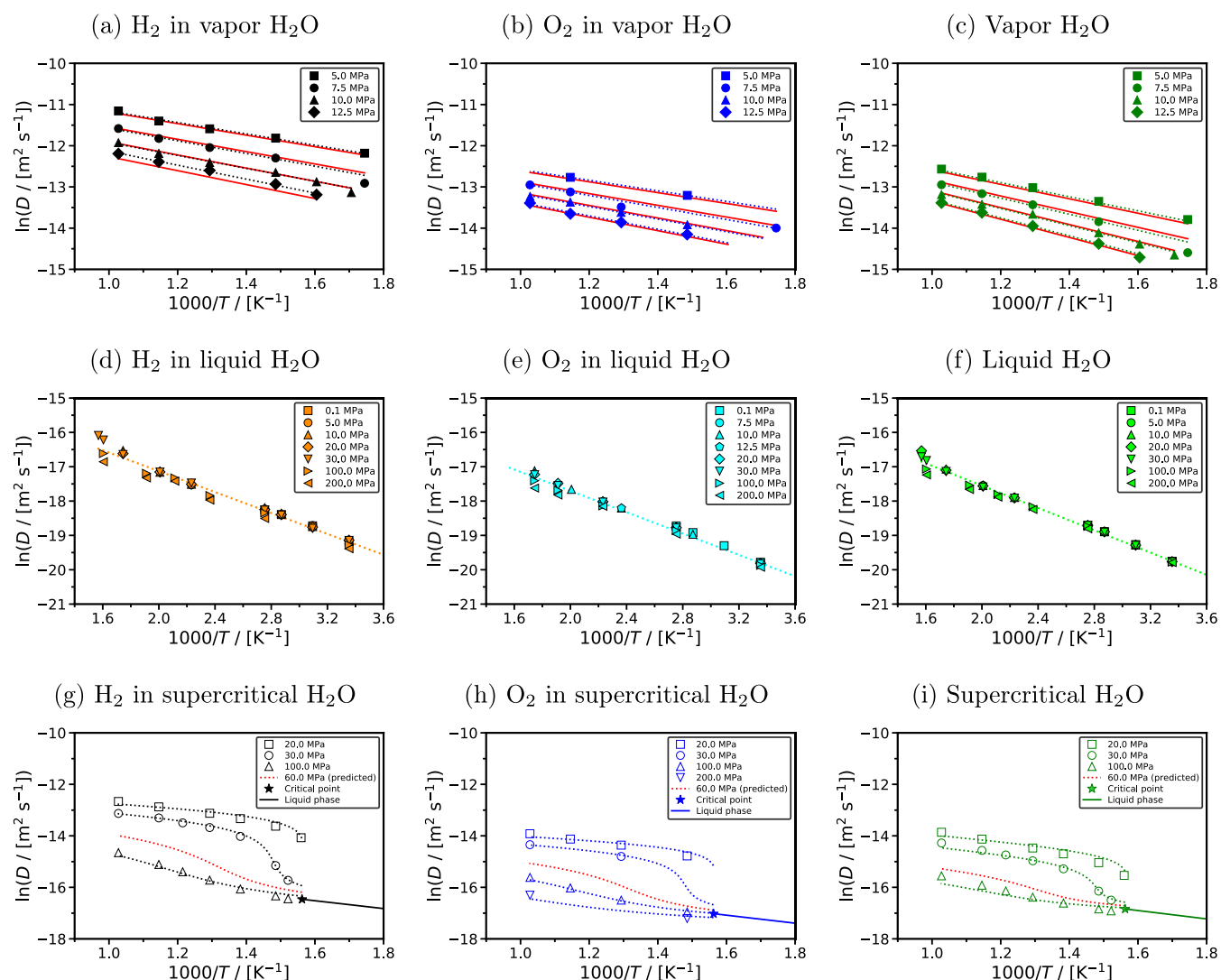


Figure 6. Arrhenius-type plots of the computed intradiffusion coefficients of H₂ in H₂O, O₂ in H₂O, and pure H₂O in the vapor (a–c), liquid (d–f), and supercritical phase (g–i), respectively. The dotted lines in (a)–(c) are pressure specific Arrhenius fits using eq 5. The red solid lines show the generalized fits using eq 8 (the parameters of the fit are listed in Table 10). The dotted lines in (d)–(f) are unified Arrhenius fits using eq 5 (the parameters are listed in Table 11). The dotted lines in (g)–(i) are fits using eq 9 (the parameters are listed in Table 13). The Buch,³⁸ Bohn,⁵³ and TIP4P/2005⁵⁵ force fields are used for H₂, O₂, and H₂O, respectively. The computed intradiffusion coefficients are corrected for system-size effects using eq 4. Error bars have been omitted for clarity. The raw MD data along with the error bars are listed in Tables 7, 8, and 9.

Table 10. Parameters of the Generalized Equation 8 for Predicting the Diffusivities in the Vapor Phase

	H ₂ in H ₂ O	O ₂ in H ₂ O	pure H ₂ O
m_0	$(-1.21 \pm 0.06) \times 10^3$	$(-1.10 \pm 0.06) \times 10^3$	$(-1.45 \pm 0.09) \times 10^3$
m_1	$(-0.39 \pm 0.07) \times 10^1$	$(-0.43 \pm 0.07) \times 10^1$	$(-0.61 \pm 0.09) \times 10^1$
n_0	-9.35 ± 0.12	-10.98 ± 0.04	-10.63 ± 0.01
n_1	$(-0.92 \pm 0.13) \times 10^{-2}$	$(-0.63 \pm 0.05) \times 10^{-2}$	$(-0.40 \pm 0.01) \times 10^{-2}$

$$D = \exp\left[(n_1 P + n_0) + (m_1 P + m_0) \frac{1}{T}\right] \quad (8)$$

As can be seen in Figure 6a–c, the MD results and the calculations using eq 8 (solid red lines) are in very good agreement. In particular, eq 8 can fit the MD data with an absolute average deviation of 6.7, 3.9, and 7.1% for the H₂ in H₂O, O₂ in H₂O, and pure H₂O systems, respectively.

3.2.2. Gas Diffusivity in Liquid H₂O. MD simulations are performed for eight different isobars (i.e., 0.1, 5.0, 10.0, 12.5, 20.0, 30.0, 100.0, and 200.0 MPa) and various temperatures

that correspond to H₂O (TIP4P/2005 force field) being in the liquid phase. Contrary to the strong pressure dependence that is observed for the case of gas diffusivity in the vapor phase, a weak pressure dependence is observed for the liquid phase. This is expected since liquid H₂O is almost incompressible. As shown in Figure 6d–f, single curves (dotted lines) can fit the MD data in the pressure range of 0.1–200 MPa with an absolute average deviation of 9.3, 9.1, and 7.1% for the cases of H₂ in H₂O, O₂ in H₂O, and pure H₂O, respectively. The corresponding parameters for the Arrhenius fit are shown in Table 11. However, to increase the accuracy of the proposed

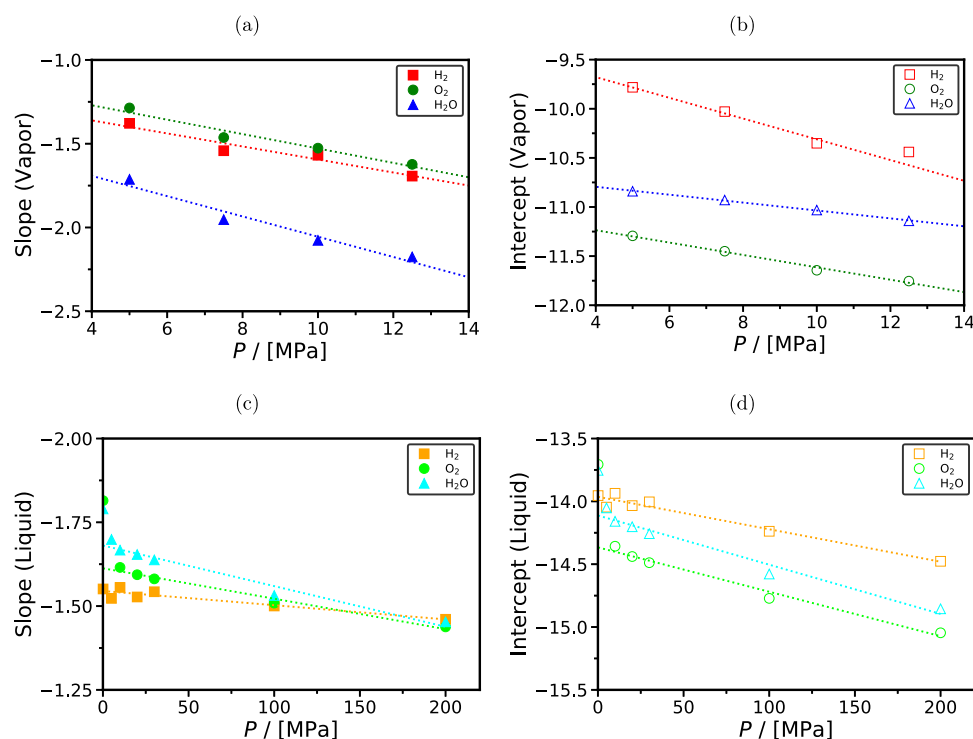


Figure 7. (a) Slopes and (b) intercepts of the linear fits to the MD diffusivity data for the H₂ in H₂O, O₂ in H₂O, and pure H₂O systems in the vapor phase shown in Figure 6a–c as a function of pressure. The dotted lines in (a) and (b) are fits using eqs 6 and 7, respectively (the parameters of the fits are listed in Table 10). The (c) slopes and (d) intercepts of the linear fits to the MD diffusivity data for the H₂ in H₂O, O₂ in H₂O, and pure H₂O systems in the liquid phase shown in Figure 6d–f as a function of pressure. The dotted lines in (c) and (d) are fits using eqs 6 and 7, respectively (the parameters of the fits are listed in Table 12).

Table 11. Parameters of the Unified Arrhenius Fit Equation 5 Using all Diffusivity Data in the Liquid Phase^a

	$\ln(D_0)$	α
H ₂ in H ₂ O	-14.09 ± 0.08	$(-0.152 \pm 0.003) \times 10^4$
O ₂ in H ₂ O	-14.59 ± 0.08	$(-0.155 \pm 0.003) \times 10^4$
pure H ₂ O	-14.30 ± 0.06	$(-0.162 \pm 0.002) \times 10^4$

^aThe curves representing the correlations are shown in Figure 6d–f.

methodology, we follow an approach similar to the one used for the vapor phase. A linear fit is performed for each isobar, and subsequently, the calculated slopes and intercepts are expressed as a function of pressure using eqs 6 and 77. The slopes and intercepts are shown in Figure 7c,d, respectively. Table 12 shows the calculated fitting parameters for the three cases considered in the current study. These parameters can be used in eq 8 to calculate the self- and intradiffusion coefficients for any pressure and temperature below the critical point where the solute diffusion occurs in the liquid phase. Equation 8 can fit the MD data with an absolute average deviation of 5.1, 5.6, and 4.6% for the H₂ in H₂O, O₂ in H₂O, and pure H₂O systems, respectively. The resulting absolute average deviations

are improved when compared to the case of using a single curve for all pressures.

3.2.3. Gas Diffusivity in Supercritical H₂O. MD simulations are performed for three different isobars (i.e., 20.0, 30.0, and 100.0 MPa) and various temperatures that correspond to H₂O (TIP4P/2005 force field) being in the supercritical phase. As can be observed in Figure 6g–i for the cases of H₂ in H₂O, O₂ in H₂O, and pure H₂O, respectively, the supercritical zone exhibits a more complex, non-Arrhenius behavior. Away from the critical point, Arrhenius behavior can be observed in the temperature range of 675–975 K. Such a behavior has also been reported by a number of studies.^{25–27} For example, Zhao et al.²⁶ reported MD simulations following an Arrhenius behavior at 25 MPa and temperatures in the range of 673–973 K. To generalize the methodology developed here, the computed self- and intradiffusivity data for the supercritical region have been collapsed onto a single curve that has the following form

$$\ln(D) = o_2 (\ln(\rho))^2 + o_1 \ln(\rho) + o_0 \quad (9)$$

where ρ is the density of H₂O (in kg/m³), while o_0 , o_1 , and o_2 are fitting parameters. Figure 8 shows the resulting fits, while the calculated parameters for the three cases considered in this

Table 12. Parameters of the Generalized Equation 8 for Predicting the Diffusivities in the Liquid Phase

	H ₂ in H ₂ O	O ₂ in H ₂ O	pure H ₂ O
m_0	$(-1.55 \pm 0.01) \times 10^3$	$(-1.67 \pm 0.05) \times 10^3$	$(-1.71 \pm 0.02) \times 10^3$
m_1	$(0.42 \pm 0.07) \times 10^{-1}$	0.13 ± 0.05	0.14 ± 0.03
n_0	-13.96 ± 0.02	-14.18 ± 0.15	-14.03 ± 0.07
n_1	$(-0.26 \pm 0.02) \times 10^{-3}$	$(-0.49 \pm 0.16) \times 10^{-3}$	$(-0.45 \pm 0.08) \times 10^{-3}$

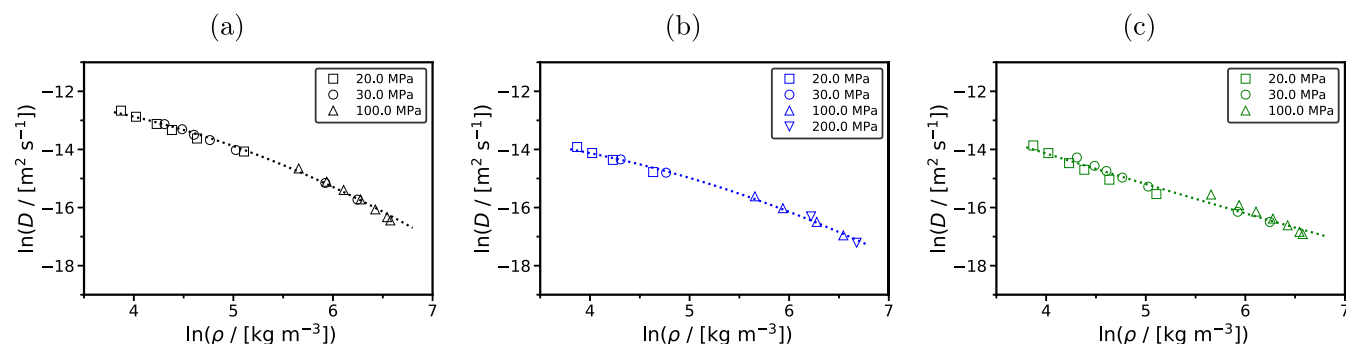


Figure 8. Logarithm of the computed intradiffusivities of (a) H₂ in H₂O, (b) O₂ in H₂O, and (c) pure H₂O in the supercritical region as a function of the logarithm of density. The dotted lines are fits using eq 9 (the parameters for the fits are listed in Table 13). The Buch,³⁸ Bohn,⁵³ and TIP4P/2005³⁵ force fields are used for H₂, O₂, and H₂O, respectively. The computed intradiffusion coefficients are corrected for system-size effects using eq 4. Error bars have been omitted for clarity. All raw MD data shown here along with the error bars are listed in Tables 7, 8, and 9.

Table 13. Parameters of the Generalized Equation 9 for Predicting the Diffusivities in the Supercritical Phase

	H ₂ in H ₂ O	O ₂ in H ₂ O	pure H ₂ O
o_0	-12.76 ± 0.94	-13.83 ± 1.24	-9.54 ± 1.72
o_1	0.76 ± 0.37	0.55 ± 0.49	-1.23 ± 0.67
o_2	-0.197 ± 0.035	-0.156 ± 0.046	0.02 ± 0.06

study are listed in Table 13. Therefore, eq 9 can be used to calculate the self- and intradiffusion coefficients for any pressure and temperature above the critical point where the solute diffusion occurs in the supercritical phase. Density values can be either from MD simulations or from NIST⁹⁰ in case no MD data are available. Equation 9 can fit the MD data with an absolute average deviation of 6.8, 7.1, and 11.3% for the H₂ in H₂O, O₂ in H₂O, and pure H₂O systems, respectively.

3.3. Additional Comparisons with the Literature. The computed densities and shear viscosities of pure H₂O, along with the corresponding uncertainties, are reported in the Supporting Information (Tables S6 and S7 for densities and shear viscosities, respectively). A comparison between the MD values with those reported by NIST⁹⁰ can be seen in the Supporting Information in Figure S4a for density and Figure S4b for shear viscosity. The self-diffusivity of H₂O has been extensively discussed in a recent review.³⁶ The vast majority of the experimental and computational studies discussed in that review are at subcritical conditions (mainly liquid). Therefore, this work provides new data for the pure TIP4P/2005 H₂O in the vapor and supercritical phase. Krynicky et al.¹¹⁰ reported a correlation for the self-diffusivity of H₂O based on the extensive experimental measurements presented in that work in the temperature range of 275–498 K and for pressures up to 150 MPa. The H₂O self-diffusion coefficients calculated with the generalized expression developed in the current study have an absolute average deviation of 12.7% from the correlation of the experimental data of Krynicky et al.¹¹⁰ The absolute average deviation drops to 11.1% when the actual MD values are compared instead.

We also compared the H₂O self-diffusion coefficients computed here with other MD studies that used the TIP4P/2005 H₂O force field. Note that the comparison is limited only to studies reporting diffusivities that have been corrected for system-size effects or have been computed in MD simulations of more than 1000 H₂O molecules (following the recommendation in the review paper by Tsimpanogiannis et al.³⁶).

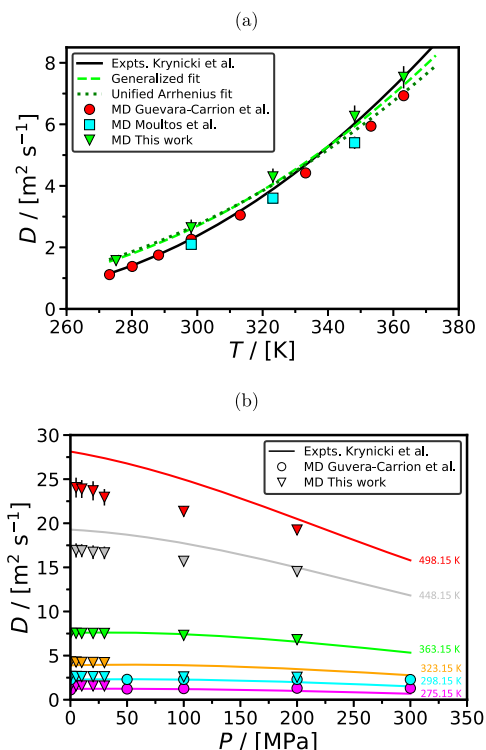


Figure 9. (a) Comparison between the experimentally¹¹⁰ measured self-diffusivities of pure H₂O at 0.1 MPa with MD simulations performed by Guevara-Carrion et al.,¹¹¹ Moultois et al.,⁶⁴ and this study using the TIP4P/2005³⁵ force field. (b) Comparison between the experimentally¹¹⁰ measured self-diffusivities of pure H₂O at various pressures with MD simulations performed by Guevara-Carrion et al. and in this study using the TIP4P/2005 force field. The self-diffusivities computed in this work have been corrected for system-size effects using eq 4, while the ones reported by Guevara-Carrion et al. and Moultois et al. have been computed in MD simulations using 2000 molecules or more. The generalized fit to the MD data of this study is performed using eq 8 (the parameters of the fit are listed in Table 12). The unified Arrhenius fit to the MD data of this study is performed using eq 5 (the parameters are listed in Table 11).

Figure 9a shows the comparison of the H₂O self-diffusion coefficients for the TIP4P/2005 H₂O force field at 0.1 MPa and temperatures up to 363 K, computed here, with the simulations reported by Guevara-Carrion et al.¹¹¹ and Moultois et al.⁶⁴ The MD results are also compared with the correlation

Table 14. Comparison of the Diffusivities Computed in this Work and in Kallikragas et al.²⁴ Expressed as % Absolute Average Deviation (% AAD), Defined as:

$$\%AAD = 100 \times \frac{\sum_{i=1}^{N_{\text{data}}} \left| \frac{D_i^{\text{this work}} - D_i^{\text{Kallikragas}}}{D_i^{\text{this work}}} \right|}{N_{\text{data}}}, \text{ where } N_{\text{data}} \text{ Denotes the Number of Data Points}$$

phase	system	T range (K)	N_{data}	MD correlation eq 8	MD data
vapor	H ₂ in H ₂ O	>460	21	21.4	22.2
	O ₂ in H ₂ O	>460	14	11.8	11.1
	pure H ₂ O	>460	21	18.3	17.7
liquid	H ₂ in H ₂ O	>460	14	17.7	4.6
	H ₂ in H ₂ O	all	50	24.2	20.0
	O ₂ in H ₂ O	>460	15	15.3	12.5
	O ₂ in H ₂ O	all	33	19.5	16.2
	pure H ₂ O	>460	20	16.0	13.6
	pure H ₂ O	all	51	11.2	12.1
supercritical	H ₂ in H ₂ O	>460	20	12.3	6.3
	O ₂ in H ₂ O	>460	12	15.3	8.8
	pure H ₂ O	>460	20	13.5	11.0

of the experimental measurements reported by Krynicky et al.¹¹⁰ Our data deviate from the experimental correlation by 11.8%. Figure 9b shows the comparison of our MD results with the experiments of Krynicky et al. at higher pressures. The minimum deviation from the experimental correlation is 1.4% for the 363.15 K isotherm, while the maximum deviation is 26.9% for the 275.15 K isotherm. The corresponding deviations for the 298.15, 323.15, 448.15, and 498.15 K are, 16.2, 8.1, 10.6, and 13.3%, respectively.

Next, we compared the self-diffusivities computed here with those reported by Kallikragas et al.²⁴ The authors used the SPCE H₂O force field¹¹² and performed simulations using 343 molecules. The self-diffusion coefficients have been correlated for temperatures above 460 K. To this purpose, Kallikragas et al. used an equation with 14 parameters based on a formulation by Kawasaki and Oppenheim.¹¹³ Table 14 shows the comparison of our data with the ones reported by Kallikragas et al. for the H₂ diffusivity in H₂O, O₂ in H₂O, and pure H₂O. Considering that the MD simulations of Kallikragas et al. are performed with less than 1000 H₂O molecules, while no system-size corrections have been reported, a shift to higher values of at least 5% should be expected for the reported MD results. This brings our data even closer to the ones by Kallikragas et al. Although the expression by Kallikragas et al. can fit their MD data with an accuracy of ca. 1%, which is higher than the accuracy of the methodology presented here, it requires the fitting of more parameters, i.e., 14 parameters for $T > 460$ K, while our model has 11 parameters for the temperature range 275.15–975.15 K.

Finally, we report a comparison with MD at supercritical conditions. Figure 10 shows a comparison of our generalized model (eq 8) with MD intradiffusivity data from Zhao et al.^{25–27} for the cases of H₂ in H₂O (Figure 10a), O₂ in H₂O (Figure 10b), and pure H₂O (Figure 10c). The intradiffusion coefficients computed in this work are corrected for system-size effects using eq 4, while the ones reported by Zhao et al. have no system-size corrections; however, they have been computed with 4161, 4125, and 900 H₂O molecules for the cases of H₂ in H₂O, O₂ in H₂O, and pure H₂O, respectively. Very good agreement is observed between the correlations of

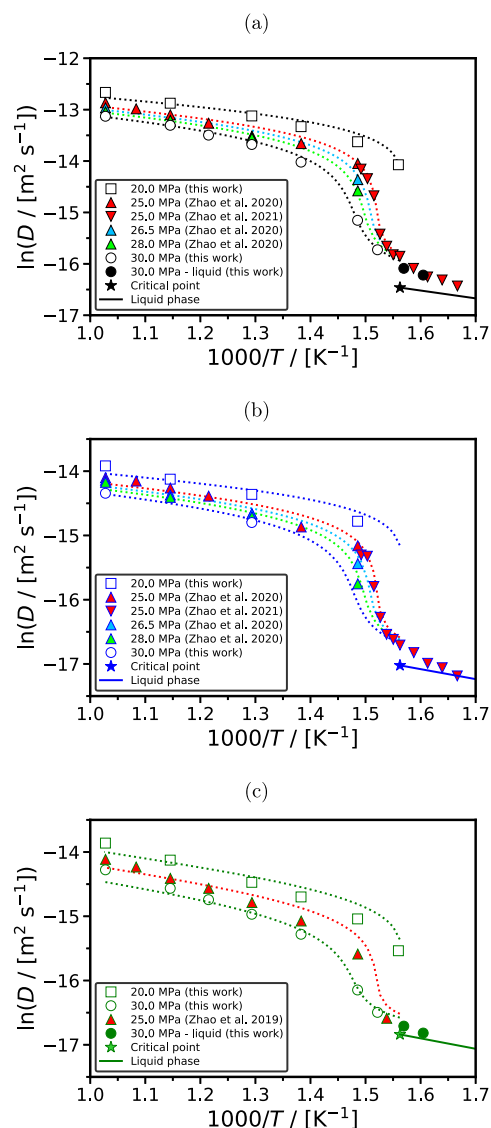


Figure 10. Comparison of our generalized model (eq 8) with MD diffusivity data from Zhao et al.^{25–27} for the cases of (a) H₂ in H₂O, (b) O₂ in H₂O, and (c) pure H₂O. The diffusion coefficients computed in this work are corrected for system-size effects using eq 4, while the ones reported by Zhao et al. have been computed using 900–4161 H₂O, 42 H₂, and 24 O₂. Zhao et al. used the TIP4P/2005,³⁵ Yang and Zhong,¹¹⁴ and CHARMM¹¹⁵ force fields for H₂O, H₂, and O₂, respectively. The statistical uncertainties are in the range of 5–10%. The error bars have been omitted for clarity.

our MD simulations (eq 9) and those reported by Zhao et al.^{25–27} In particular, the absolute average deviations between the values obtained from eq 9 and those reported by Zhao et al. are 7.2, 9.1, and 12.4% for the cases of diffusion of H₂ in H₂O (Figure 10a), O₂ in H₂O (Figure 10b), and pure H₂O (Figure 10c), respectively.

4. CONCLUSIONS

Extensive MD simulations have been performed to compute the intradiffusion coefficients of (i) H₂ and O₂ in H₂O and (ii) the self-diffusion coefficients of pure H₂O in a wide temperature (275.15–975.15 K) and pressure (0.1–200 MPa) range. Initially, the accuracy of six H₂ and six O₂ force fields was tested to select one force field for each gas for further examination. The TIP4P/2005 force field was used for

modeling H₂O. The initial screening was based on the accuracy of the force fields in reproducing the available experimentally measured densities, self-diffusivities, and shear viscosities of the pure gas, and the intradiffusivity of the gas in H₂O. During the screening process, experimental measurements that exhibit problematic behavior were identified and appropriate recommendations were introduced. For H₂ and O₂, the force fields by Buch³⁸ and Bohn et al.⁵³ were selected, respectively. Subsequently, the selected force fields were used for the computation of the intradiffusion coefficients in the wide temperature and pressure range of interest. Finally, the MD simulation results were used to develop an engineering model with 11 parameters that can estimate the intradiffusion coefficients in vapor, liquid, and supercritical H₂O, with an accuracy of 4–11%. It is expected that the current methodology can be extended to the study of the intradiffusivity of other infinite gases in H₂O. In fact, the following road-map, consisting of four steps, can be utilized for the extension to other gas–H₂O systems: (i) Select appropriate force field for the diffusing gas (solute) based on comparison with the available experimental data for densities, self-diffusivities, and shear viscosities of the pure gas and the intradiffusivity of the gas in H₂O, (ii) perform MD simulations at 3–4 temperatures, for each chosen pressure for the cases of diffusion in H₂O, in the vapor (4 pressures) and liquid (6 pressures) phase, (iii) perform MD simulations at 4–5 temperatures, for each chosen pressure for the cases of diffusion in H₂O, in the supercritical (3 pressures) phase, and (iv) correlate the MD data using eq 8 for the case of diffusion in the vapor or liquid H₂O, and eq 9 for the case in supercritical H₂O.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.jced.1c00300>.

Effect of the number of dissolved hydrogen and oxygen molecules in water in the computed intradiffusivity (Figure S1); finite-size dependency of the computed intradiffusion coefficients of H₂ in liquid, supercritical, and vapor H₂O (Figure S2); Arrhenius-type plots of the computed intradiffusivity of H₂ in H₂O and O₂ in H₂O (Figure S3); plots of densities and shear viscosities of pure water computed with the TIP4P/2005 force field as a function of temperature (Figure S4); force field parameters for water (Table S1), hydrogen (Table S2), and oxygen (Table S3); computed densities of pure hydrogen for different force fields, temperatures, and pressures (Table S4); computed densities of pure oxygen for different force fields, temperatures, and pressures (Table S5); and computed densities (Table S6) and shear viscosities (Table S7) of pure water for different force fields, temperatures, and pressures (PDF)

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Notes

The authors declare no competing financial interest.

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