

# Viscosity Measurements on Water Vapor and Their Evaluation

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Results of new high-precision measurements of the viscosity of water vapor at low densities are reported. The measurements were performed using an all-quartz oscillating-disk viscometer with small gaps. Ten isochoric series were carried out at temperatures between (298 and 438) K and at densities from (0.001 to 0.013) mol·L<sup>-1</sup>. The uncertainty is estimated to be ± 0.2 % at ambient temperature increasing up to ± 0.3 % at higher temperatures. Isothermal values were analyzed with a density series for the viscosity in which only a linear contribution is considered. Values for the viscosity of the saturated vapor were also obtained at low temperatures. The new results and reliable data sets from literature are used to represent the viscosity of water vapor at moderately low densities. The second viscosity virial coefficient was modeled by means of the Rainwater–Friend theory. An individual correlation according to the extended theorem of corresponding states was necessary to describe the zero-density viscosity coefficient within its uncertainty and is particularly reliable at temperatures down to 280 K. The good agreement between the new values and older data from literature, not considered in the IAPWS formulation, requires the improvement of this correlation at low temperatures.

## Introduction

Water and steam are used in electric power generation and in many other technological fields for the transfer of heat and momentum. In addition, water has often been applied as a calibration standard for the development of commercial and scientific instruments. Due to the large number of possible applications and the high requirements on reliable data, the transport properties of this fluid have been determined by many different measuring techniques throughout the twentieth century. Although the need for internationally accepted values for the thermodynamic properties of water substance has already been recognized in the 1920s, the demand for accurate transport properties was not stated until 1954. Ten years later, the first internationally accepted formulation for the transport properties of water substance was given. The International Association for the Properties of Steam (IAPS) and recently the re-named International Association for the Properties of Water and Steam (IAPWS) have coordinated the development of standardized tables and formulations for the viscosity and thermal conductivity of water and steam since the 1970s. The current standard for the viscosity is described in the Revised Release on the IAPS Formulation 1985 for the Viscosity of Ordinary Water Substance,<sup>1</sup> which takes into account some minor revisions consistent with the equations contained in the Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use<sup>2</sup> and with the International Temperature Scale of 1990. Sengers and Kamgar-Parsi<sup>3</sup> as well as Sengers and Watson<sup>4</sup> discussed the background and the development of the viscosity formulation, whereas Wagner and Pruss<sup>5</sup> provided information on selected experimental data of thermodynamic properties of water and on the development of the IAPWS-95 Formulation. Despite the recommendation given by the IAPWS, there exist some regions in the formulation

for the viscosity that could be improved on the basis of new precise data. The present paper has been intended to deliver new experimental values at comparably low densities at temperatures as low as possible for water vapor.

The correlation and prediction of the transport properties of fluids over a wide range of thermodynamic states could be based on the residual viscosity concept given as a function of temperature ( $T$ ) and molar density ( $\rho$ ) by

$$\eta(T, \rho) = \eta^{(0)}(T) + \eta^{(1)}(T) \rho + \Delta\eta_h(T, \rho) + \Delta\eta_c(T, \rho) \quad (1)$$

Here,  $\eta^{(0)}$  is the viscosity coefficient in the limit of zero density, and  $\eta^{(1)}$  is the initial density viscosity coefficient.  $\Delta\eta_h$  represents the so-called residual contribution, which accounts for the effect of increasing density outside the critical region, whereas  $\Delta\eta_c$  is the critical enhancement of the viscosity arising from long-range fluctuations. Apart from the residual contribution, the individual terms of eq 1 are theoretically founded so that they can separately be evaluated in an appropriate manner. A theoretically based correlation and prediction scheme for the transport properties of a fluid should start in the region of the moderately dense gas considering  $\eta^{(0)}$  and  $\eta^{(1)}$ . In practice, measurements at very low densities or even in the limit of zero density are not feasible, so that  $\eta^{(0)}$  has to be determined by extrapolating isotherms with a sufficient number of experimental points at moderately low densities to the limit of zero density. The slope of the isotherms corresponds to the initial-density viscosity coefficient  $\eta^{(1)}$ .

## Experimental Section

The measurements were carried out by means of an all-quartz oscillating-disk viscometer with small gaps. The construction of the apparatus as well as its calibration, the performance of the relative measurements, and their evaluation have been described in previous papers.<sup>6–8</sup> The viscometer was calibrated using a reference value by Kestin et al.<sup>9</sup> for argon at room temperature since only one calibration point is needed in the theory of Newell<sup>10</sup> in the

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Table 1. Viscosity of Water Vapor

$T$	$\eta$	$T$	$\eta$	$T$	$\eta$	$T$	$\eta$	$T$	$\eta$
K	$\mu\text{Pa}\cdot\text{s}$	K	$\mu\text{Pa}\cdot\text{s}$	K	$\mu\text{Pa}\cdot\text{s}$	K	$\mu\text{Pa}\cdot\text{s}$	K	$\mu\text{Pa}\cdot\text{s}$
series 1		series 2		series 3		series 4		series 5	
$\rho = 0.00103 \text{ mol}\cdot\text{L}^{-1}$		$\rho = 0.00137 \text{ mol}\cdot\text{L}^{-1}$		$\rho = 0.00204 \text{ mol}\cdot\text{L}^{-1}$		$\rho = 0.00223 \text{ mol}\cdot\text{L}^{-1}$		$\rho = 0.00371 \text{ mol}\cdot\text{L}^{-1}$	
298.30	9.700	298.02	9.675	298.08	9.683	297.39	9.665	297.88	9.654
310.80	10.129	311.77	10.151	310.87	10.126	311.45	10.146	310.96	10.112
331.18	10.833	324.54	10.597	325.96	10.651	325.00	10.616	324.45	10.591
338.83	11.105	338.47	11.084	338.71	11.097	339.39	11.124	341.28	11.169
352.75	11.602	352.91	11.600	353.60	11.627	352.77	11.603	352.17	11.561
367.84	12.157	366.37	12.087	368.22	12.164	367.03	12.119	367.10	12.099
380.80	12.627	380.42	12.601	382.14	12.677	381.09	12.633	380.59	12.590
394.39	13.135	394.72	13.128	396.61	13.223	395.38	13.160	394.29	13.101
408.87	13.688	409.76	13.709	411.18	13.788	409.46	13.693	408.32	13.635
423.26	14.243	422.75	14.215	423.80	14.285	423.70	14.257	422.72	14.199
438.77	14.852	440.41	14.919	438.48	14.869	438.99	14.857	438.04	14.807
series 6		series 7		series 8		series 9		series 10	
$\rho = 0.00440 \text{ mol}\cdot\text{L}^{-1}$		$\rho = 0.00600 \text{ mol}\cdot\text{L}^{-1}$		$\rho = 0.00918 \text{ mol}\cdot\text{L}^{-1}$		$\rho = 0.01095 \text{ mol}\cdot\text{L}^{-1}$		$\rho = 0.01305 \text{ mol}\cdot\text{L}^{-1}$	
299.06	9.709	298.38	9.686	298.17	9.693	298.57	9.684	300.07	9.725
311.30	10.127	311.39	10.128	311.24	10.138	313.01	10.167	312.25	10.145
331.47	10.837	325.42	10.616	324.54	10.596	325.15	10.593	324.74	10.580
338.79	11.079	340.17	11.131	339.97	$\alpha$	338.02	11.032	338.38	11.048
352.79	11.588	353.16	11.596	352.05	11.537	352.03	11.527	352.37	11.543
366.96	12.106	366.77	12.094	366.48	12.068	366.29	12.046	365.86	12.029
381.09	12.628	381.33	12.629	380.60	12.581	380.43	12.570	381.70	12.619
395.87	13.189	395.00	13.144	393.95	13.086	394.43	13.102	394.48	13.107
409.39	13.704	409.37	13.690	408.30	13.650	408.76	13.663	408.34	13.647
423.44	14.251	423.62	14.247	422.69	14.215	422.94	14.224	422.56	14.213
438.71	14.858	438.05	14.834	437.71	14.827	437.84	14.838	437.27	14.825

<sup>a</sup> An outlier had to be left out.

range of moderately low densities. The performance was checked by further measurements on argon at higher temperatures up to 600 K.

The ranges of temperature and density had to be restricted to avoid irreversible reactions between water vapor and quartz glass. Some experimental points at low temperatures correspond to measurements in the saturated vapor. The uncertainty is estimated to be  $\pm 0.2\%$  at ambient temperature increasing up to  $\pm 0.3\%$  at higher temperatures, whereas the reproducibility does not exceed  $\pm 0.1\%$  in the whole temperature range.

In a special glass apparatus, 2-fold distilled water was degassed and filled into small glass ampules. Ten series, each differing in density, were performed at temperatures between (298 and 438) K and at densities from (0.001 to 0.013)  $\text{mol}\cdot\text{L}^{-1}$ . The densities were determined from the mass of the sample and the volume of the viscometer body. The experimental results are summarized in Table 1. Isothermal values had to be recalculated from the original isochoric data using a first-order Taylor series in terms of temperature:

$$\eta(T_{\text{int}}) = \eta(T_{\text{exp}}) + \left(\frac{\partial\eta}{\partial T}\right)_{\rho} \Delta T + R_N \quad (2)$$

$$\Delta T = T_{\text{int}} - T_{\text{exp}} \quad (3)$$

The interpolation temperature ( $T_{\text{int}}$ ) was obtained by averaging the corresponding temperatures of the 10 series of measurements. The remainder ( $R_N$ ) in eq 2 was proven to be negligible in comparison with the experimental uncertainty. The temperature derivative of viscosity ( $\partial\eta/\partial T$ ) <sub>$\rho$</sub>  was calculated using eq 4 with the respective coefficients, which were derived from a fit to the original isochoric data:

$$\eta(T) = S \exp\left(A \ln T_R + \frac{B}{T_R} + \frac{C}{T_R^2} + \frac{D}{T_R^3} + E\right) \quad (4)$$

$$T_R = \frac{T}{298.15 \text{ K}} \quad S = 10.0 \mu\text{Pa}\cdot\text{s}$$

Then, the quasi-experimental viscosity values of the isotherms were analyzed with a density series for the viscosity in which only a linear contribution is considered:

$$\eta(T, \rho) = \eta^{(0)}(T) + \eta^{(1)}(T)\rho \quad (5)$$

$$B_{\eta}(T) = \frac{\eta^{(1)}(T)}{\eta^{(0)}(T)} \quad (6)$$

The zero-density and initial-density viscosity coefficients ( $\eta^{(0)}$  and  $\eta^{(1)}$ ) were deduced from the fit of eq 5 and used to calculate the second viscosity virial coefficient ( $B_{\eta}$ ). In addition, values for the viscosity of the saturated vapor were derived at low temperatures. For that purpose, the densities at saturation ( $\rho_s$ ) were calculated from the equation of state.<sup>5</sup> The viscosity coefficient corresponding to the saturated vapor ( $\eta_s$ ) resulted from averaging all viscosity values at densities higher than  $\rho_s$ . All these results are summarized with their individual standard deviations ( $\text{sd}_{\eta_0}$ ,  $\text{sd}_{\eta_1}$ , and  $\text{sd}_{\eta_s}$ ) and with the standard deviations ( $\text{sd}_{\eta}$ ) of each isotherm in Table 2.

Figures 1 and 2 illustrate the initial density dependence of viscosity for all measured isotherms. The open circles represent the quasi-experimental values included in the fit with eq 5, whereas the triangles correspond to the points measured in the saturated vapor. Here it is to take into account that the densities in the figures do not correspond to the densities at which the measurements were performed. The viscosity coefficient at the true density at saturation obtained by averaging is shown as black square. The values calculated according to eq 5 are plotted as straight lines. Uncertainties of  $\pm 0.1\%$  are indicated by error bars.

## Theory

The viscosity coefficient  $\eta(T, \rho)$  of a moderately dense gas at temperature ( $T$ ) and molar density ( $\rho$ ) may be described using a density expansion restricted to the first power according to eq 5.

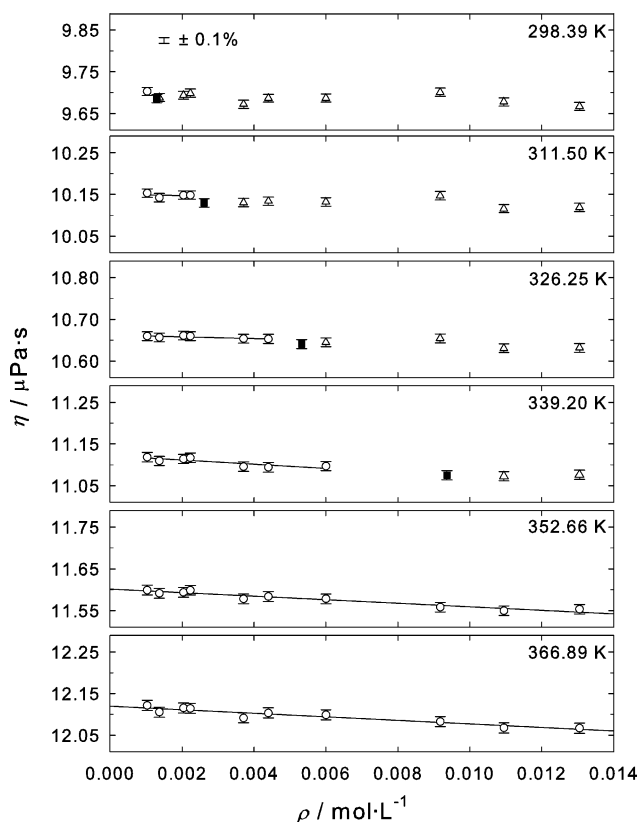
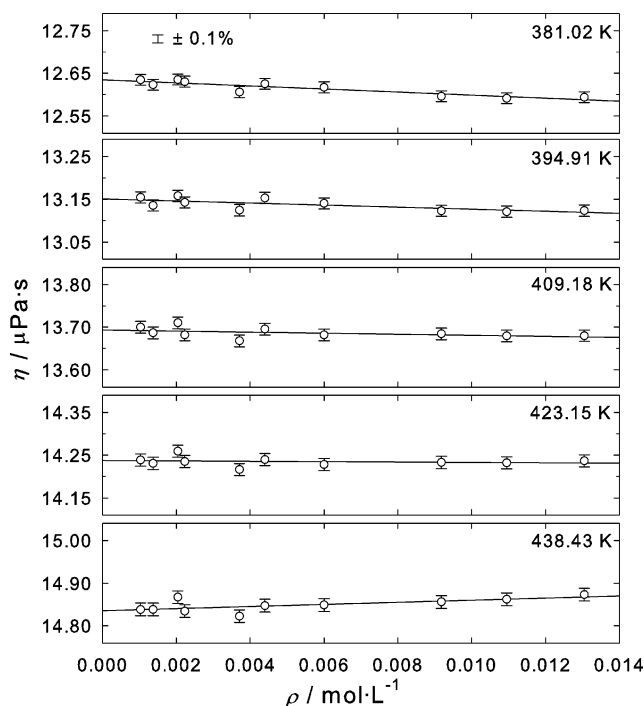
**Table 2.** Zero-Density and Initial-Density Viscosity Coefficients of Water Vapor for All Isotherms and Viscosity Coefficient of the Saturated Vapor

$T$ K	$\eta_0 \pm \text{sd}_{\eta_0}$ $\mu\text{Pa}\cdot\text{s}$	$\eta_1 \pm \text{sd}_{\eta_1}$ $\mu\text{Pa}\cdot\text{s}\cdot\text{L}\cdot\text{mol}^{-1}$	$\text{sd}_{\eta} \times 10^3$ $\mu\text{Pa}\cdot\text{s}$
298.39	9.703		
311.50	$10.151 \pm 0.010$	$-1.543 \pm 5.598$	5.46
326.25	$10.662 \pm 0.002$	$-2.022 \pm 0.788$	2.34
339.20	$11.122 \pm 0.005$	$-5.026 \pm 1.408$	6.22
352.66	$11.601 \pm 0.003$	$-4.205 \pm 0.417$	5.35
366.89	$12.120 \pm 0.004$	$-4.266 \pm 0.527$	6.76
381.02	$12.635 \pm 0.004$	$-3.602 \pm 0.615$	7.89
394.91	$13.151 \pm 0.006$	$-2.419 \pm 0.817$	10.48
409.18	$13.694 \pm 0.006$	$-1.224 \pm 0.894$	11.46
423.15	$14.237 \pm 0.006$	$-0.424 \pm 0.883$	11.33
438.43	$14.835 \pm 0.007$	$2.470 \pm 0.984$	12.62

$T$ K	$\rho_s$ $\text{mol}\cdot\text{L}^{-1}$	$\eta_s \pm \text{sd}_{\eta_s}$ $\mu\text{Pa}\cdot\text{s}$
298.39	0.001298	$9.686 \pm 0.004$
311.50	0.002617	$10.130 \pm 0.005$
326.25	0.005325	$10.640 \pm 0.006$
339.20	0.009365	$11.075 \pm 0.002$

In comparison with the thermal conductivity, the viscosity is less affected by the existence of internal degrees of freedom and by inelastic collisions. Therefore, the results for the zero-density viscosity coefficient ( $\eta^{(0)}$ ) can be analyzed appropriately using the well-established kinetic theory of dilute monatomic gases by Chapman and Enskog.<sup>11</sup> In principle, the influence of the intermolecular potential energy hypersurface of a polyatomic molecule like water and effects of higher-order terms for the coupling of the velocity and of the angular momentum of the molecules have to be taken into account. This is only possible in a

**Figure 1.** Viscosity of water vapor as a function of molar density.  $\eta = \eta^{(0)} + \eta^{(1)}\rho$ .  $\circ$ , quasi-experimental values;  $\Delta$ , values measured in the saturated vapor;  $\blacksquare$ , value corresponding to the saturated vapor.**Figure 2.** Viscosity of water vapor as a function of molar density.  $\eta = \eta^{(0)} + \eta^{(1)}\rho$ .  $\circ$ , quasi-experimental values.

straightforward procedure for linear molecules such as carbon dioxide<sup>12–14</sup> until now. Hence, the reverse way has to be followed in which only one so-called effective collision cross section is derived in a fit of the theoretical relationships for the first-order approximation of the kinetic theory<sup>15</sup> to experimental viscosity data. Then,  $\eta^{(0)}$  is given by

$$\eta^{(0)}(T) = \frac{0.021357(MT)^{1/2}}{\sigma^2 S_{\eta}^*(T^*)} \quad (7)$$

$$T^* = k_B T / \epsilon \quad (8)$$

where  $S_{\eta}^*$  represents a reduced effective cross section that contains normally all the dynamic and statistical information about the binary collisions.  $T^*$  is the reduced temperature,  $T$  is the temperature in K, whereas the molar mass  $M$  is in  $\text{g}\cdot\text{mol}^{-1}$ .  $\eta^{(0)}$  is given in units of  $\mu\text{Pa}\cdot\text{s}$  when the length and energy scaling parameters  $\sigma$  and  $\epsilon/k_B$  are in nm and K. Here  $k_B$  is Boltzmann's constant. The temperature dependence of  $S_{\eta}^*$  may be described by the functional form:

$$\ln S_{\eta}^*(T^*) = \sum_{i=0}^4 a_i (\ln T^*)^i \quad (9)$$

The analysis and correlation of the zero-density viscosity coefficient using eqs 7–9 is usually based on the extended corresponding states principle,<sup>11</sup> which is strictly valid only for monatomic molecules such as rare gases. In a first step, a universal correlation is carried out in which the known coefficients  $a_i$  of the functional  $S_{\eta}^*$  for the rare gases reported by Bich et al.<sup>16</sup> are used to derive values of the scaling factors  $\sigma$  and  $\epsilon/k_B$ . It is evident that such a universal correlation cannot describe adequately the experimental viscosity data of a fluid like water. Therefore, in an individual correlation the scaling factors  $\sigma$  and  $\epsilon/k_B$  determined for the universal correlation are kept fixed to derive

new values of the coefficients  $a_i$  by fitting eq 9 again to the experimental viscosity values in the limit of zero density.

The initial density dependence expressed as second viscosity virial coefficient ( $B_\eta$ ) can be described by means of a model for the transport properties of the moderately dense gas proposed by Rainwater and Friend.<sup>17,18</sup> The Rainwater–Friend theory models the moderately dense gas as a mixture of monomers and dimers in which the interactions are represented by a Lennard–Jones (12–6) potential. The relation of the monomer–dimer interaction to that of the monomer–monomer interaction is characterized by the potential ratios  $\delta$  and  $\theta$ . These have been determined by fitting the theoretical expressions to selected experimental second transport virial coefficients. Tables of the reduced second viscosity virial coefficient ( $B_\eta^*$ ) as a function of  $T^*$  for an optimized set of  $\delta$  and  $\theta$  were presented by Bich and Vogel.<sup>19,20</sup> In addition, Vogel et al.<sup>21</sup> recommended an improved empirical equation for reduced temperatures between  $0.5 \leq T^* \leq 100$ , which can safely be extrapolated down to  $T^* \approx 0.3$ :

$$B_\eta^*(T^*) = \frac{B_\eta(T)}{N_A \sigma^3} = \sum_{i=0}^6 b_i T^{*-0.25i} + b_7 T^{*-2.5} + b_8 T^{*-5.5} \quad (10)$$

where  $B_\eta$  is in units  $\text{L}\cdot\text{mol}^{-1}$ , and  $N_A$  is Avogadro's constant. The coefficients  $b_i$  were reported in the same paper.<sup>21</sup> This empirical equation of  $B_\eta^*$  can be used to check the reliability of experimental data for a chosen fluid and possibly to extrapolate the temperature range of the experiments. The formalism for the initial density dependence of viscosity can also be applied to correct experimental  $\eta(T, \rho)$  data at a moderately low density to the limit of zero density using the following equation:

$$\eta^{(0)}(T) = \frac{\eta(T, \rho)}{1 + N_A \sigma^3 B_\eta^*(T^*) \rho} \quad (11)$$

### Analysis Including Literature Data

With regard to a comparison it is to mention that the initial density dependence of viscosity is not taken into account in the IAPWS formulation,<sup>1</sup> which consists of three factors considering the zero-density viscosity, the residual contribution, and the critical enhancement. The viscosity coefficient in the limit of zero density separately correlated is given in the IAPWS formulation for temperatures between (273 and 1173) K.

In principle, the development of an accurate and consistent representation of the viscosity coefficient requires the selection of reliable data sets from the available experimental values in the literature. Such data are qualified by measurements with a high-precision instrument for which a full working equation is available and all necessary corrections can be applied. Our analysis, considering the viscosity of water vapor in the limit of zero density ( $\eta^{(0)}$ ) and the second viscosity virial coefficient ( $B_\eta$ ) requires reliable experimental  $\eta(T, \rho)$  values at moderate densities. For that purpose, the most recent collection of literature data concerning measurements on the viscosity (and thermal conductivity) of water and steam<sup>22</sup> as well as the corresponding electronic database were used. In addition, results for  $\eta^{(0)}$  and  $\eta^{(1)}$  derived by Assael and Metaxa<sup>23</sup> from the isothermal viscosity values at moderate densities in the vapor phase and in the supercritical region could be included in the analysis performed in this paper.

**Table 3. List of Available Data from Viscosity Measurements on Water Vapor at Low Densities**

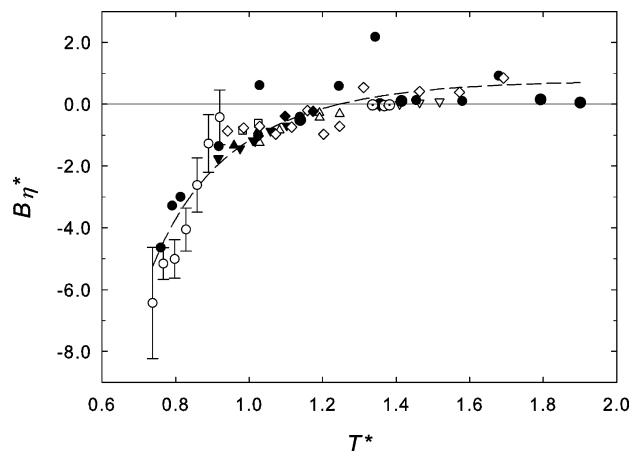
author(s)	$T$	no. pts.	no. iso. <sup>a</sup>	$\delta\eta_r$ <sup>b</sup> %	method <sup>c</sup>
	K				
Shifrin <sup>24</sup>	422–1139	114	15 <sup>d</sup>	2.0	CAP
Kestin and Wang <sup>27</sup>	441–470	12	2	0.5	OSD
Moszynski <sup>28</sup>	471–540	17	3	2.0	OSS
Kestin and Richardson <sup>29</sup>	422–548	36	8	0.8	OSD
Latto <sup>25</sup>	383–1346	555	20 <sup>d</sup>	3.0	CAP
Rivkin and Levin <sup>30</sup>	473–573	23	5	1.5	CAP
Rivkin et al. <sup>31</sup>	548–698	63	4	1.0	CAP
Sato et al. <sup>32</sup>	432–473	14	2	1.0	CAP
Sato et al. <sup>33</sup>	433–778	75	12	1.0	CAP
Yasumoto <sup>26</sup>	280–302	15	5 <sup>d</sup>	0.5	CAP
Timrot et al. <sup>34</sup>	349–772	43	11	0.3	OSD
Nagashima et al. <sup>35</sup>	524–874	21	5	1.5	CAP
Oltermann <sup>36</sup>	614–635	11	3	1.6	OSD
present paper	298–438	109	11	0.3	OSD

<sup>a</sup> Number of isotherms. <sup>b</sup> Ascribed relative uncertainty. <sup>c</sup> CAP, capillary; OSD, oscillating disk; OSS, oscillating sphere. <sup>d</sup> Number of interpolated temperatures.

These results and our new data cover the temperature range between (298 and 874) K. With respect to a comparison with the IAPWS formulation of the zero-density viscosity in the whole temperature range, additional experimental values by Shifrin<sup>24</sup> and Latto<sup>25</sup> at higher temperatures as well as results of Yasumoto<sup>26</sup> at lower temperatures were included in the analysis. Unfortunately, these data sets do not comprise enough experimental points at a constant temperature as a function of pressure or density so that they could not be evaluated with a first-order expansion, in terms of density. In fact, Shifrin<sup>24</sup> and Latto<sup>25</sup> carried out their measurements only at atmospheric pressure, but at a large number of different temperatures. Therefore, the original experimental isobaric values of both data sets were fitted to eq 2 including eq 4 in order to calculate viscosity values for a reduced number of interpolated temperatures. These values had to be corrected to the limit of zero density using the Rainwater–Friend theory (see eq 11). For that purpose, the needed density was deduced from the equation of state.<sup>5</sup> On the contrary, the original data of Yasumoto<sup>26</sup> could be identified with the viscosity in the limit of zero density due to the very small densities applied in the experiments. Hence, these data had only to be reduced to a limited number of interpolated temperatures.

The list of the considered experimental data concerning the viscosity of water vapor at low densities is shown in Table 3. It contains information about the measuring method, the temperature range, the number of data points and of isotherms, and the ascribed relative uncertainty.

With regard to the recalculation of the data by Shifrin<sup>24</sup> and Latto<sup>25</sup> for the limit of zero density with eq 11, values of the second viscosity virial coefficient for the corresponding temperatures or values for the scaling factors  $\sigma$  and  $\epsilon/k_B$  in combination with eq 10 are needed. Therefore, first the correlation of the second viscosity virial coefficient was performed with values derived from suitable data sets. Some of the results of the present paper for the initial density dependence had to be left out. This concerns the unexpected positive value of  $\eta^{(1)}$  for the 438 K isotherm and the results for the (311.50 and 326.25) K isotherms. The latter values are not sufficiently negative, probably due to the small density range accessible to the measurements. In this connection it is to be mentioned that the  $\eta^{(0)}$  values for these three isotherms are reasonable so that they could be used in the further evaluation. In the fitting process of



**Figure 3.** Reduced second viscosity virial coefficient of water vapor  $B_{\eta}^*$  as a function of the reduced temperature  $T^*$ .  $\blacktriangle$ , Kestin and Wang;<sup>27</sup>  $\blacklozenge$ , Moszynski;<sup>28</sup>  $\blacktriangledown$ , Kestin and Richardson;<sup>29</sup>  $\triangle$ , Rivkin and Levin;<sup>30</sup>  $\nabla$ , Rivkin et al.;<sup>31</sup>  $\square$ , Sato et al.;<sup>32</sup>  $\diamond$ , Sato et al.;<sup>33</sup>  $\bullet$ , Timrot et al.;<sup>34</sup>  $\star$ , Nagashima et al.;<sup>35</sup>  $\circ$ , Oltermann;<sup>36</sup>  $\circ$ , present paper;  $- -$ , Rainwater-Friend theory, Vogel et al.<sup>21</sup>

eq 10 to the experimental  $B_{\eta}$  values, the following scaling factors  $\sigma$  and  $\epsilon/k_B$  were deduced:

$$\sigma = 0.48873 \text{ nm} \quad \epsilon/k_B = 459.85 \text{ K}$$

The theoretical curve for the reduced second viscosity virial coefficient and the experimental data included in the fit are illustrated in Figure 3. Uncertainties derived from the standard deviations ( $sd_{\eta}$ ) are indicated by error bars for the results of the present paper. It is obvious that the experimental results are appropriately described by the Rainwater-Friend theory. It is to be pointed out that some values of the present paper and of Timrot et al.<sup>34</sup> show larger deviations at medium reduced temperatures. Both measurements were performed with an all-quartz oscillating-disk viscometer and could be influenced by reactions between water vapor and quartz glass at higher temperatures.

As already mentioned the correlation of the zero-density viscosity coefficient was carried out in two steps. Experimental  $S_{\eta}(S_{\eta} = \pi\sigma^2 S_{\eta}^*)$  values were deduced from the selected primary data for the limit of zero density via eq 7 taking into account appropriate statistical weights  $w_k$  following from

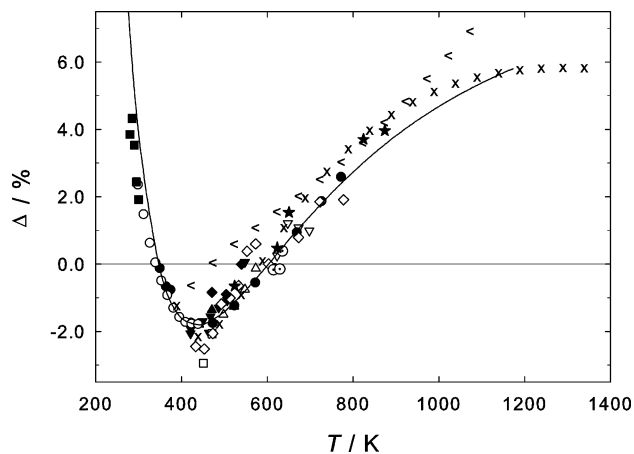
$$w_k = \left( \frac{100}{\eta_{\text{exp},k} \cdot \delta\eta_{r,k}} \right)^2 \quad (12)$$

Here,  $\eta_{\text{exp},k}$  and  $\delta\eta_{r,k}$  are the  $k$ th experimental viscosity value and its ascribed relative uncertainty, respectively.  $\delta\eta_r$  is based on the measurement method, the quoted experimental error, the check on precision of the data, and the discrepancies to other independent data in overlapping thermodynamic ranges.

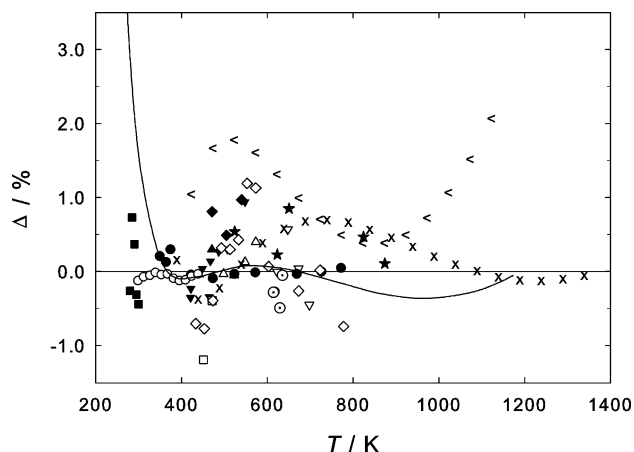
It became obvious in the analysis that the values of Shifrin<sup>24</sup> are characterized by large deviations from the other data, especially at low and high temperatures so that they were not considered in the further evaluation. The following scaling factors were derived from the primary  $\eta^{(0)}$  values of water vapor as the result of the universal correlation:

$$\sigma = 0.26949 \text{ nm} \quad \epsilon/k_B = 768.47 \text{ K}$$

The deviations of the experimental data as well as of the IAPWS formulation<sup>1</sup> from the universal correlation are



**Figure 4.** Deviations  $\Delta = 100(\eta_{\text{lit}} - \eta_{\text{cor}})/\eta_{\text{lit}}$  of viscosity data from the universal zero-density viscosity correlation.  $\blacktriangle$ , Kestin and Wang;<sup>27</sup>  $\blacklozenge$ , Moszynski;<sup>28</sup>  $\blacktriangledown$ , Kestin and Richardson;<sup>29</sup>  $\times$ , Latto;<sup>25</sup>  $\triangle$ , Rivkin and Levin;<sup>30</sup>  $\nabla$ , Rivkin et al.;<sup>31</sup>  $\square$ , Sato et al.;<sup>32</sup>  $\diamond$ , Sato et al.;<sup>33</sup>  $\blacksquare$ , Yasumoto;<sup>26</sup>  $\bullet$ , Timrot et al.;<sup>34</sup>  $\star$ , Nagashima et al.;<sup>35</sup>  $\circ$ , Oltermann;<sup>36</sup>  $\circ$ , present paper;  $-$ , IAPWS.<sup>1</sup> Not considered in the correlation:  $<$ , Shifrin.<sup>24</sup>



**Figure 5.** Deviations  $\Delta = 100(\eta_{\text{lit}} - \eta_{\text{cor}})/\eta_{\text{lit}}$  of viscosity data from the present individual zero-density viscosity correlation.  $\blacktriangle$ , Kestin and Wang;<sup>27</sup>  $\blacklozenge$ , Moszynski;<sup>28</sup>  $\blacktriangledown$ , Kestin and Richardson;<sup>29</sup>  $\times$ , Latto;<sup>25</sup>  $\triangle$ , Rivkin and Levin;<sup>30</sup>  $\nabla$ , Rivkin et al.;<sup>31</sup>  $\square$ , Sato et al.;<sup>32</sup>  $\diamond$ , Sato et al.;<sup>33</sup>  $\blacksquare$ , Yasumoto;<sup>26</sup>  $\bullet$ , Timrot et al.;<sup>34</sup>  $\star$ , Nagashima et al.;<sup>35</sup>  $\circ$ , Oltermann;<sup>36</sup>  $\circ$ , present paper;  $-$ , IAPWS.<sup>1</sup> Not considered in the correlation:  $<$ , Shifrin.<sup>24</sup>

shown in Figure 4, which makes evident that the viscosity coefficient in the limit of zero density cannot adequately be represented.

Hence, new coefficients  $a_i$  of the functional  $S_{\eta}^*(T^*)$  were determined in an individual correlation valid for the temperature range (273 to 1350) K:

$$\begin{aligned} a_0 &= 0.19650798 & a_1 &= -0.62020061 \\ a_2 &= 0.14090948 & a_3 &= 0.12764717 \\ a_4 &= -0.005161536 \end{aligned}$$

The deviations from the individual correlation are demonstrated in Figure 5. The figure reveals that the present correlation is suitable to represent the experimental data within their uncertainties. In the temperature range between (298 and 350) K, the new results amend the available experimental data. They are in good agreement with the values of Yasumoto<sup>26</sup> at low temperatures as well as with the results of Timrot et al.<sup>34</sup> at temperatures above 350 K. The data of Yasumoto<sup>26</sup> were obviously not taken

into account for the development of the IAPWS formulation,<sup>1</sup> which explains the deviation of 3.5 % at 273 K between the individual correlation and that of the IAPWS. On the other hand, the values of Timrot et al.<sup>34</sup> are characterized by low deviations from the individual correlation as well as from the IAPWS formulation. They are evidently considered in that formulation. Furthermore, at high temperatures the results of Latto<sup>25</sup> and the IAPWS formulation agree within 1 % so that the temperature range of any zero-density viscosity correlation could be extended to 1350 K with comparably low uncertainty.

## Conclusions

The measurements of the present paper are used together with reliable data sets from literature to represent the viscosity of water vapor at moderately low densities. Such a representation includes the initial density dependence of the viscosity expressed as the second virial coefficient according to the Rainwater–Friend theory and the zero-density viscosity coefficient based on the kinetic theory of dilute gases. The results for the viscosity coefficient in the limit of zero density make clear that an individual correlation within the framework of the extended theorem of corresponding states is necessary to describe the experimental data within their uncertainties.

The good agreement of the new experimental values with the data of Yasumoto<sup>26</sup> and Timrot et al.<sup>34</sup> demonstrates the reliability of the present individual correlation at low temperatures. Since the data of Yasumoto were not considered and the values of the present paper were not available at that time, the IAPWS formulation should be improved by including these data at low temperatures. Considering all values of Latto<sup>25</sup> enables to extend the IAPWS formulation up to 1350 K.

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