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Viscosities of *p*-Xylene, Acetic Acid, and *p*-Xylene + Acetic Acid at (313.15 to 473.15) K and (0.10 to 3.20) MPa: Determined by the Rolling-Ball Method

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Experimental liquid viscosities of pure compounds and their mixtures are needed for the design of chemical processes in heat and mass transfers or fluid mechanics. This paper is about partial work supported by SINOPEC (China Petroleum & Chemical Corporation). The results are related to the design calculation of synthesis of purified terephthalic acid (PTA). At temperature (313.15 to 473.15) K, the viscosities of pure *p*-xylene, pure acetic acid, and the *p*-xylene + acetic acid binary system of different concentrations were determined by a rolling-ball viscometer at pressures (0.10 to 3.20) MPa. Then, the viscosity data were fitted by a correlation equation. The AAD of the correlation is 1.21 %.

Introduction

Purified terephthalic acid (PTA) is primarily used in polyester production such as polyester fiber and polyethylene terephthalate (PET) resin production for packaging and film applications. The manufacturing process of PTA comprises two major stages: manufacturing of crude terephthalic acid (CTA) and purification of CTA to PTA. In the first stage, CTA is obtained by homogeneous-phase oxidation of *p*-xylene in acetic acid solution. In this stage, the temperature is about (458.15 to 473.15) K, and pressure is about (0.98 to 1.5) MPa. Currently, only some foreign companies have these patents. To develop the PTA manufacturing technique independently, all the related data especially thermodynamic data are indispensable.[1,2]

Viscosity and density are important properties of a compound, and they are indispensable in the study of fluid, heat transform, mass transform, and engineering calculations. There are many ways to determine the viscosity of a compound at high pressures, such as capillary flow viscometry,[3] rolling- or falling-body viscometry,[4−7] vibrating-quartz viscometry,[8,9] vibrating-wire viscometers,[10,11] and other techniques.

Until now, Et-Tahir et al.[12] have reported densities at (0.1 to 40) MPa and (313.15 to 363.15) K and viscosities at (0.1 to 100) MPa and (313.15 to 353.15) K of *p*-xylene. Our group has measured the densities, viscosities, and heat capacities of *p*-xylene + acetic acid at temperatures ranging from (303.15 to 363.15) K at atmospheric pressure.[13] In this study, an apparatus was designed and manufactured to determine the viscosity using the rolling-ball method, and the viscosities of *p*-xylene, acetic acid, and *p*-xylene + acetic acid were determined at temperatures (313.15 to 473.15) K and pressures (0.10 to 3.20) MPa. Then, the viscosity data were fitted by a correlation equation.

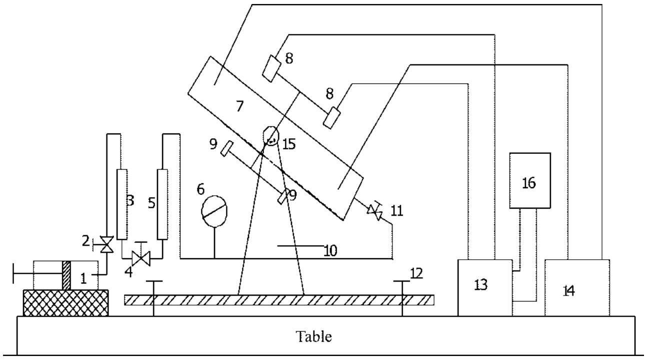

Figure 1. Experiment installation flowchart of viscosity measurement. 1, piston pressure gauge; 2, cutoff valve; 3, oil−mercury separator; 4, needle valve; 5, mercury−sample separator; 6, precision pressure meter; 7, high-pressure part (containing main tube of the viscometer and the heating device); 8, laser emitter; 9, laser accepter; 10, bracket of the viscometer; 11, needle valve; 12, screw to adjust the bracket; 13, magnify circuit; 14, temperature controller; 15, pinhole; 16, the computer currency counter.

Experimental Section

Materials. The *n*-decane and acetic acid were purchased from Kermel Chemical Reagents Development Centre (Tianjin, China), and their purities are both 99.5 %. The toluene was purchased from Guangfu Fine Chemical Research Institute (Tianjin, China) with a purity of 99.95 %. The *p*-xylene was from Dagang Petrochemical Company (Tianjin, China) with a purity of 99.9 %. In the experiment, all samples were degassed using a KQ3200DB ultrasonic cleaner (Kunshan Ultrasonic Instrument Co.) before used. The mixtures used in the experiments were all prepared by mass using a BS 224s balance accurate to within ± 0.01 mg. The average uncertainty in the mole fraction of the mixtures was estimated to be less than ± 0.01 %.

Apparatus and Procedure. A rolling-ball viscometer which can work at pressures ranging from 0.1 MPa to 3.20 MPa and temperatures ranging from (313.15 to 473.15) K was built as shown in Figure 1. The viscometer contains several parts: high-pressure part, viscometer body, temperature control system

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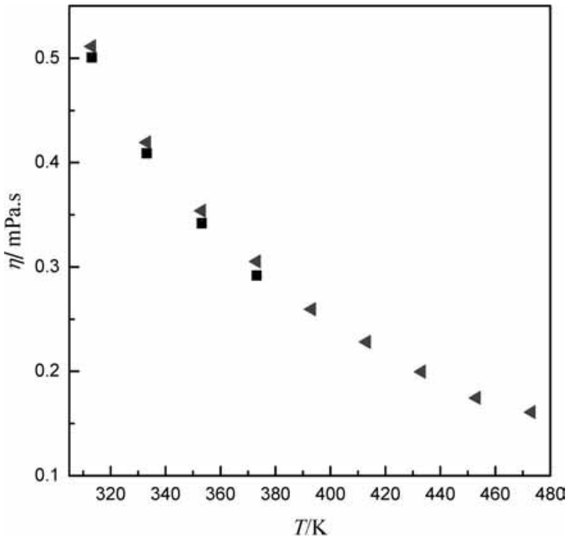

Figure 2. Experimental viscosity data at different temperatures for pure *p*-xylene at constant pressure. ■, 0.10 MPa; triangle pointing left, 3.20 MPa.

Table 1. Determination Time and Estimation Error for Pure *n*-Decane Viscosity

T	p	t	η_{exp}	η_{lit}	
K	MPa	s	mPa·s	mPa·s	dev_i
313.15	0.10	21.6461	0.7051	0.7110	−0.84
323.15	0.10	19.8609	0.6356	0.6302	0.86
333.15	0.10	18.0758	0.5646	0.5624	0.38
333.15	0.80	18.2423	0.5732	0.5666	1.17
333.15	1.60	18.1470	0.5714	0.5715	−0.01
333.15	2.40	18.1966	0.5756	0.5764	−0.14
333.15	3.20	18.2341	0.5792	0.5809	−0.28
343.15	0.10	16.6517	0.5069	0.5049	0.40
353.15	0.10	15.3029	0.4514	0.4559	−0.98
363.15	0.10	14.3902	0.4136	0.4136	0.01
373.15	0.10	13.4207	0.3729	0.3769	−1.06
373.15	0.80	13.4799	0.3773	0.3798	−0.65
373.15	1.60	13.5349	0.3818	0.3833	−0.39
373.15	2.40	13.5619	0.3851	0.3867	−0.41
373.15	3.20	13.6412	0.3906	0.3902	0.12
393.15	1.60	12.1133	0.3216	0.3218	−0.05
413.15	1.60	11.1115	0.2790	0.2735	2.00
433.15	1.60	10.0478	0.2328	0.2346	−0.77
453.15	1.60	9.4526	0.2072	0.2028	2.19
473.15	1.60	8.6976	0.1740	0.1762	−1.23
AAD					0.70

(containing heating apparatus and temperature keeping set), and timer system. The viscometer body contains a main quartz tube (Jingda Quartz Glass Co. Jingzhou, China) which is 310 mm long with an inner diameter of (6.050 ± 0.001) mm and an outer diameter of 17.00 mm, a ZYS ceramic ball (Luoyang Bearing Science and Technology Co. Ltd. Luoyang, China) which is made of ZrO_2 with a diameter of (5.953 ± 0.001) mm in the tube, and a Teflon base of the tube. The temperature of the system was controlled by an XMTA-808 temperature controller (Yuyao Changjiang Merer Co. Ltd., China). The controller and its K thermocouple and the Pt-100 platinum resistance thermometer (Hufeng Electro Thermal Appliances Co., Ltd., Shanghai, China) are all demarcated by the Tianjin Measure Institution. The timer system contains an ST-1670 laser emitter, an ST-JS01A laser accepter, and an MUJ-6B computer time counter (Qingfeng Instrument Plant, Beijing, China), and there is a YU-600A piston pressure gauge (the Forth Shanghai Automation Instrumentation Plant, China) to keep the pressure of the system and an YB-150A precision pressure gauge (Tianlin Pressure Gauge Plant, Shanghai, China) to read the pressure.

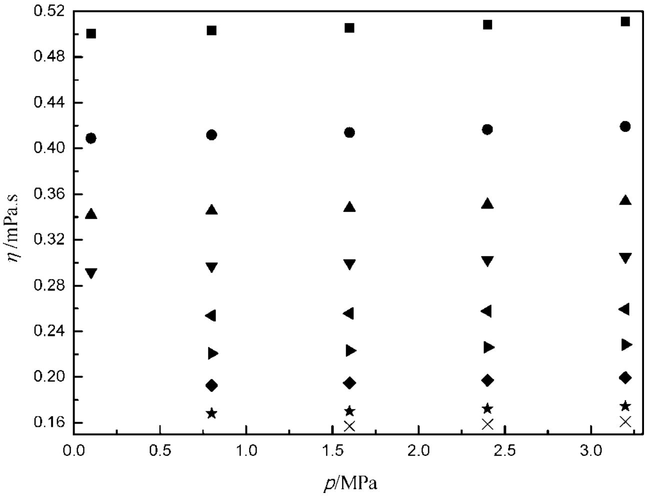

Figure 3. Experimental viscosity data at different pressures for pure *p*-xylene at constant temperature. ■, 313.15 K; ●, 333.15 K; ▲, 353.15 K; ▼, 373.15 K; triangle pointing left, 393.15 K; triangle pointing right, 413.15 K; ◆, 433.15 K; ★, 453.15 K; ×, 473.15 K.

Table 2. Determination Time and Estimation Error for Pure Toluene Viscosity

T	p	t	η_{exp}	η_{lit}	
K	MPa	s	mPa·s	mPa·s	dev_i
313.15	0.10	16.1367	0.4651	0.4700	−1.05
323.15	0.10	14.9085	0.4158	0.4216	−1.36
333.15	0.10	13.9175	0.3758	0.3814	−1.48
333.15	0.80	14.0712	0.3839	0.3866	−0.69
333.15	1.60	14.1405	0.3889	0.3926	−0.95
333.15	2.40	14.2512	0.3955	0.3987	−0.80
333.15	3.20	14.3306	0.4008	0.4048	−0.98
343.15	0.10	13.1078	0.3428	0.3466	−1.10
353.15	0.10	12.3975	0.3137	0.3180	−1.37
363.15	0.10	11.8228	0.2901	0.2891	0.33
373.15	0.10	11.2890	0.2680	0.2651	1.10
373.15	0.80	11.3070	0.2706	0.2692	0.51
373.15	1.60	11.3455	0.2742	0.2738	0.16
373.15	2.40	11.3867	0.2780	0.2785	−0.17
373.15	3.20	11.4375	0.2822	0.2833	−0.38
393.15	1.60	10.5077	0.2397	0.2324	3.12
413.15	1.60	9.6973	0.2058	0.1987	3.56
433.15	1.60	9.0101	0.1769	0.1711	3.40
453.15	1.60	8.4116	0.1517	0.1487	2.01
473.15	1.60	8.0153	0.1353	0.1310	3.31
AAD					1.39

After the samples are prepared and fed into the viscometer and the temperature is adjusted and stabilized, the piston pressure gauge is turned to change the system pressure. After the temperature and pressure are both stable, the laser emitter, the photoelectric conversion circuit, and the computer timer are turned on. Then, the main tube is turned to a certain obliquity (a constant slope for each measurement) and fixed with a pin. The timer records the ball-rolling time between the two laser beams, and this is written down along with the temperature and pressure. To find the time, it is measured six times at each temperature and pressure, and the average is considered the result. Then, the temperature or pressure are changed, and the steps are repeated to finish the measuring of the samples.

There are three steps to gain the viscosity of a sample:

1. Find the apparatus parameters using known viscosity compounds
2. Do the experiment using the unknown viscosity samples
3. Calculate the viscosity of the samples

Table 3. Experimental Viscosity Data of Pure *p*-Xylene

T K	p MPa	ρ $g \cdot cm^{-3}$	η $mPa \cdot s$	T K	p MPa	ρ $g \cdot cm^{-3}$	η $mPa \cdot s$
313.15	0.10	0.844	0.499	333.15	0.10	0.826	0.409
	0.80	0.845	0.529		0.80	0.827	0.412
	1.60	0.845	0.510		1.60	0.828	0.414
	2.40	0.846	0.516		2.40	0.829	0.417
	3.20	0.847	0.521		3.20	0.830	0.419
353.15	0.10	0.808	0.340	373.15	0.10	0.789	0.292
	0.80	0.809	0.346		0.80	0.791	0.297
	1.60	0.810	0.350		1.60	0.792	0.300
	2.40	0.811	0.356		2.40	0.793	0.303
	3.20	0.812	0.361		3.20	0.794	0.305
393.15	0.80	0.771	0.254	413.15	0.80	0.751	0.221
	1.60	0.773	0.258		1.60	0.753	0.223
	2.40	0.774	0.262		2.40	0.755	0.226
	3.20	0.776	0.266		3.20	0.756	0.228
433.15	0.80	0.730	0.192	453.15	0.80	0.708	0.168
	1.60	0.732	0.197		1.60	0.710	0.170
	2.40	0.734	0.201		2.40	0.713	0.172
	3.20	0.736	0.206		3.20	0.715	0.175
473.15	1.60	0.687	0.159				
	2.40	0.690	0.163				
	3.20	0.693	0.167				

Table 4. Experimental Viscosity Data of Pure Acetic Acid

T K	p MPa	ρ $g \cdot cm^{-3}$	η $mPa \cdot s$	T K	p MPa	ρ $g \cdot cm^{-3}$	η $mPa \cdot s$
313.15	0.10	1.028	0.903	333.15	0.10	1.006	0.713
	0.80	1.028	0.910		0.80	1.007	0.720
	1.60	1.029	0.917		1.60	1.008	0.727
	2.40	1.030	0.924		2.40	1.009	0.735
	3.20	1.030	0.932		3.20	1.009	0.743
353.15	0.10	0.984	0.574	373.15	0.10	0.961	0.471
	0.80	0.985	0.582		0.80	0.962	0.478
	1.60	0.986	0.590		1.60	0.963	0.486
	2.40	0.987	0.598		2.40	0.964	0.494
	3.20	0.988	0.605		3.20	0.965	0.502
393.15	0.80	0.938	0.394	413.15	0.80	0.913	0.333
	1.60	0.939	0.402		1.60	0.914	0.340
	2.40	0.941	0.410		2.40	0.916	0.347
	3.20	0.942	0.418		3.20	0.917	0.354
433.15	0.80	0.886	0.281	453.15	0.80	0.857	0.244
	1.60	0.888	0.287		1.60	0.859	0.251
	2.40	0.890	0.294		2.40	0.862	0.258
	3.20	0.891	0.302		3.20	0.864	0.264
473.15	1.60	0.829	0.213				
	2.40	0.831	0.220				
	3.20	0.834	0.226				

Table 5. Experimental Viscosity Data for the Binary Mixture of *p*-Xylene (1) + Acetic Acid (2) (x_1 = 0.1001)

T K	p MPa	ρ $g \cdot cm^{-3}$	η $mPa \cdot s$	T K	p MPa	ρ $g \cdot cm^{-3}$	η $mPa \cdot s$
313.15	0.10	1.002	0.725	333.15	0.10	0.980	0.587
	0.80	1.003	0.731		0.80	0.981	0.592
	1.60	1.003	0.737		1.60	0.982	0.598
	2.40	1.004	0.743		2.40	0.983	0.605
	3.20	1.004	0.749		3.20	0.983	0.611
353.15	0.10	0.958	0.481	373.15	0.10	0.935	0.399
	0.80	0.959	0.487		0.80	0.936	0.405
	1.60	0.960	0.493		1.60	0.937	0.412
	2.40	0.961	0.499		2.40	0.938	0.418
	3.20	0.961	0.505		3.20	0.939	0.424
393.15	0.80	0.911	0.340	413.15	0.80	0.886	0.294
	1.60	0.913	0.345		1.60	0.887	0.300
	2.40	0.914	0.352		2.40	0.889	0.307
	3.20	0.915	0.358		3.20	0.890	0.313
433.15	0.80	0.959	0.245	453.15	0.80	0.830	0.221
	1.60	0.861	0.260		1.60	0.832	0.227
	2.40	0.862	0.267		2.40	0.834	0.233
	3.20	0.864	0.273		3.20	0.836	0.240
473.15	1.60	0.800	0.190				
	2.40	0.803	0.196				
	3.20	0.806	0.202				

Table 6. Experimental Viscosity Data for the Binary Mixture of *p*-Xylene (1) + Acetic Acid (2) (x_1 = 0.1997)

T K	p MPa	ρ $g \cdot cm^{-3}$	η $mPa \cdot s$	T K	p MPa	ρ $g \cdot cm^{-3}$	η $mPa \cdot s$
313.15	0.10	0.978	0.630	333.15	0.10	0.957	0.508
	0.80	0.979	0.635		0.80	0.957	0.514
	1.60	0.979	0.641		1.60	0.958	0.520
	2.40	0.980	0.647		2.40	0.959	0.526
	3.20	0.981	0.653		3.20	0.960	0.532
353.15	0.10	0.934	0.419	373.15	0.10	0.911	0.353
	0.80	0.935	0.425		0.80	0.912	0.359
	1.60	0.936	0.431		1.60	0.913	0.365
	2.40	0.937	0.437		2.40	0.914	0.372
	3.20	0.938	0.444		3.20	0.915	0.378
393.15	0.80	0.888	0.294	413.15	0.80	0.862	0.255
	1.60	0.889	0.300		1.60	0.864	0.260
	2.40	0.890	0.306		2.40	0.865	0.265
	3.20	0.892	0.313		3.20	0.867	0.271
433.15	0.80	0.835	0.223	453.15	0.80	0.806	0.196
	1.60	0.837	0.228		1.60	0.808	0.201
	2.40	0.839	0.233		2.40	0.810	0.206
	3.20	0.841	0.239		3.20	0.813	0.211
473.15	1.60	0.777	0.170				
	2.40	0.779	0.175				
	3.20	0.782	0.181				

The viscosity of a sample is relative to the ball-falling time and the pressure of the system. In this study, we choose formula (1) gained according to the literature[14,15] to calculate the viscosity.

$$\eta = k_1 + k_2 t(\rho_s - \rho_l) + k_3 t^2(\rho_s - \rho_l)^2 + k_4 p \qquad (1)$$

In the formula, t is the ball-falling time; p is the pressure of the system; k_1, k_2, k_3, and k_4 are apparatus parameters related to the size of the ball, the diameter of the tube, the obliquity of the tube, and so on and have no relation to the sample; and ρ_s and ρ_l are densities of the rolling ball and the sample, respectively. In the experiment, ρ_s is 5.90 $g \cdot cm^{-3}$. Since the experimental density data of the samples cannot be found in the literature, they must be estimated first. After several methods have been tested, the method of the literature[16] was chosen to estimate the densities of the samples. The estimation is a corresponding-states correlation, originally developed by Iglesias-Silave and Hall[17] and known as ISH correlation for the prediction of the saturated liquid densities, and Hossein et al. employed the Tait equation into it and extended it successfully to the compressed state. The AADs (average absolute deviations) of *p*-xylene and acetic acid density of the method are reported as 0.26 % and 0.15 %, respectively, while the overall AAD of the method is reported as 0.77 %.

First *n*-decane was measured as a known viscosity compound with the density data from the literature[18] and compared to the literature[19] to obtain the apparatus parameters. Then we can use formula (2) to calculate the viscosity of the samples. In the formula, the units of η, ρ_l, t, and p are $mPa \cdot s$, $g \cdot cm^{-3}$, s, and MPa, respectively. Then, the viscosity of toluene was measured with densities from the literature[20] first and compared to the viscosity results from the literature. The results of these two compounds are shown in Tables 1 and 2. In the tables, AADs were calculated by formulas (3) and (4). In the formula, NP means the number of data points. From the tables, we can find that the parameters are suitable to the measurement.

$$\eta/(\mathrm{mPa \cdot s}) = -0.248772 + 0.00943984(t/\mathrm{s})(5.90 - [\rho_l/(\mathrm{g \cdot cm^{-3}})]) - 8.41187 \cdot 10^{-6}(t/\mathrm{s})^2(5.90 - [\rho_l/(\mathrm{g \cdot cm^{-3}})])^2 + 0.00278507(p/\mathrm{MPa}) \qquad (2)$$

$$\mathrm{dev}_i = \left(\frac{\eta_{\mathrm{exp},i} - \eta_{\mathrm{lit},i}}{\eta_{\mathrm{exp},i}}\right) \cdot 100\ \% \tag{3}$$

$$\mathrm{AAD} = \frac{1}{\mathrm{NP}} \sum_{i=1}^{\mathrm{NP}} |\mathrm{dev}_i| \tag{4}$$

The measurement accuracy of temperature and pressure are 0.4 K and 0.01 MPa, respectively. The uncertainty of time is 0.001 %. Take decane as an example. The relative error caused by temperature and pressure is 0.71 % and 0.01 %, respectively, and the estimated density relative error is less than 3.64 % and may cause 0.83 % error of viscosity. Totally speaking, the maximum relative error of the measurement is 1.55 %.

Results and Discussion

Results of Measurement. The results of the measured viscosities are shown in Tables 3 to 13, in which Table 3 shows viscosities of pure *p*-xylene, Table 4 is for pure acetic acid, and Tables 5 to 13 are about the *p*-xylene + acetic acid binary system. To illustrate the veracity of the experiment, the viscosities at atmospheric pressure of pure *p*-xylene, acetic acid, and water were compared with the reported results in Table 14. The relative deviations are also shown in Figure 4. In the comparison, it is found that the relative deviations are less than 1.9 % compared to data from ref 21 but much more compared to ref 12. In ref 21, the measurement was carried out by an Ubbelohde viscometer, and the densities used to calculate the viscosity are all measured; however, in ref 12, the pressure range of the experiment is very large. So, the results of ref 21 are thought to be more accurate, and considering the pressure of our experiment, the deviation of the results is acceptable.

Table 7. Experimental Viscosity Data for the Binary Mixture of *p*-Xylene (1) + Acetic Acid (2) ($x_1 = 0.3001$)

T	p	ρ	η	T	p	ρ	η
K	MPa	$\mathrm{g \cdot cm^{-3}}$	$\mathrm{mPa \cdot s}$	K	MPa	$\mathrm{g \cdot cm^{-3}}$	$\mathrm{mPa \cdot s}$
313.15	0.10	0.956	0.571	333.15	0.10	0.934	0.459
	0.80	0.957	0.576		0.80	0.935	0.464
	1.60	0.957	0.583		1.60	0.936	0.470
	2.40	0.958	0.585		2.40	0.937	0.476
	3.20	0.959	0.591		3.20	0.938	0.482
353.15	0.10	0.912	0.378	373.15	0.10	0.889	0.314
	0.80	0.913	0.384		0.80	0.890	0.319
	1.60	0.914	0.390		1.60	0.891	0.326
	2.40	0.915	0.396		2.40	0.893	0.332
	3.20	0.916	0.402		3.20	0.894	0.338
393.15	0.80	0.866	0.269	413.15	0.80	0.841	0.237
	1.60	0.868	0.275		1.60	0.843	0.243
	2.40	0.869	0.281		2.40	0.844	0.249
	3.20	0.870	0.287		3.20	0.846	0.255
433.15	0.80	0.814	0.208	453.15	0.80	0.785	0.181
	1.60	0.816	0.213		1.60	0.787	0.186
	2.40	0.818	0.219		2.40	0.79	0.192
	3.20	0.82	0.226		3.20	0.792	0.198
473.15	1.60	0.756	0.162				
	2.40	0.759	0.168				
	3.20	0.762	0.173				

Table 8. Experimental Viscosity Data for the Binary Mixture of *p*-Xylene (1) + Acetic Acid (2) ($x_1 = 0.3997$)

T	p	ρ	η	T	p	ρ	η
K	MPa	$\mathrm{g \cdot cm^{-3}}$	$\mathrm{mPa \cdot s}$	K	MPa	$\mathrm{g \cdot cm^{-3}}$	$\mathrm{mPa \cdot s}$
313.15	0.10	0.936	0.522	333.15	0.10	0.914	0.424
	0.80	0.936	0.527		0.80	0.915	0.429
	1.60	0.937	0.532		1.60	0.916	0.434
	2.40	0.938	0.537		2.40	0.917	0.440
	3.20	0.938	0.543		3.20	0.918	0.445
353.15	0.10	0.892	0.351	373.15	0.10	0.870	0.297
	0.80	0.893	0.356		0.80	0.871	0.302
	1.60	0.894	0.361		1.60	0.872	0.307
	2.40	0.896	0.367		2.40	0.873	0.313
	3.20	0.897	0.372		3.20	0.875	0.319
393.15	0.80	0.847	0.252	413.15	0.80	0.822	0.221
	1.60	0.849	0.258		1.60	0.824	0.227
	2.40	0.850	0.263		2.40	0.826	0.233
	3.20	0.852	0.269		3.20	0.827	0.239
433.15	0.80	0.796	0.196	453.15	0.80	0.767	0.177
	1.60	0.798	0.202		1.60	0.769	0.183
	2.40	0.800	0.208		2.40	0.772	0.188
	3.20	0.802	0.213		3.20	0.775	0.194
473.15	1.60	0.739	0.162				
	2.40	0.742	0.167				
	3.20	0.745	0.173				

Table 9. Experimental Viscosity Data for the Binary Mixture of *p*-Xylene (1) + Acetic Acid (2) ($x_1 = 0.5000$)

T	p	ρ	η	T	p	ρ	η
K	MPa	$\mathrm{g \cdot cm^{-3}}$	$\mathrm{mPa \cdot s}$	K	MPa	$\mathrm{g \cdot cm^{-3}}$	$\mathrm{mPa \cdot s}$
313.15	0.10	0.917	0.520	333.15	0.10	0.896	0.419
	0.80	0.917	0.524		0.80	0.897	0.424
	1.60	0.918	0.530		1.60	0.898	0.429
	2.40	0.919	0.535		2.40	0.899	0.435
	3.20	0.92	0.541		3.20	0.899	0.440
353.15	0.10	0.875	0.347	373.15	0.10	0.852	0.293
	0.80	0.875	0.352		0.80	0.853	0.298
	1.60	0.876	0.357		1.60	0.854	0.303
	2.40	0.878	0.363		2.40	0.856	0.309
	3.20	0.879	0.368		3.20	0.857	0.315
393.15	0.80	0.830	0.253	413.15	0.80	0.805	0.217
	1.60	0.831	0.258		1.60	0.807	0.217
	2.40	0.833	0.264		2.40	0.809	0.228
	3.20	0.835	0.270		3.20	0.811	0.233
433.15	0.80	0.780	0.195	453.15	0.80	0.752	0.174
	1.60	0.782	0.201		1.60	0.754	0.180
	2.40	0.784	0.206		2.40	0.757	0.185
	3.20	0.786	0.212		3.20	0.759	0.191
473.15	1.60	0.724	0.161				
	2.40	0.728	0.166				
	3.20	0.731	0.171				

Table 10. Experimental Viscosity Data for the Binary Mixture of *p*-Xylene (1) + Acetic Acid (2) ($x_1 = 0.6002$)

T	p	ρ	η	T	p	ρ	η
K	MPa	$\mathrm{g \cdot cm^{-3}}$	$\mathrm{mPa \cdot s}$	K	MPa	$\mathrm{g \cdot cm^{-3}}$	$\mathrm{mPa \cdot s}$
313.15	0.10	0.899	0.514	333.15	0.10	0.878	0.418
	0.80	0.899	0.519		0.80	0.879	0.423
	1.60	0.900	0.524		1.60	0.880	0.428
	2.40	0.901	0.529		2.40	0.881	0.433
	3.20	0.902	0.534		3.20	0.882	0.438
353.15	0.10	0.857	0.342	373.15	0.10	0.836	0.289
	0.80	0.858	0.347		0.80	0.837	0.293
	1.60	0.860	0.352		1.60	0.838	0.299
	2.40	0.861	0.357		2.40	0.840	0.304
	3.20	0.862	0.363		3.20	0.841	0.309
393.15	0.80	0.814	0.249	413.15	0.80	0.791	0.218
	1.60	0.816	0.254		1.60	0.792	0.223
	2.40	0.817	0.260		2.40	0.794	0.229
	3.20	0.819	0.265		3.20	0.796	0.234
433.15	0.80	0.765	0.194	453.15	0.80	0.738	0.173
	1.60	0.768	0.199		1.60	0.741	0.179
	2.40	0.770	0.205		2.40	0.744	0.184
	3.20	0.772	0.210		3.20	0.746	0.189
473.15	1.60	0.712	0.160				
	2.40	0.716	0.165				
	3.20	0.719	0.170				

From the results in the tables, it can be found that the viscosities decrease while the temperatures increase at a constant pressure and increase while pressure increases at a constant temperature. Take the pure acetic acid as an example to draw a viscosity−temperature curve and a viscosity−pressure curve shown in Figures 2 and 3. The figures show that the viscosity−temperature curve is approximately a parabola and

Table 11. Experimental Viscosity Data for the Binary Mixture of *p*-Xylene (1) + Acetic Acid (2) (x_1 = 0.6988)

T/K	p/MPa	ρ/g·cm^{-3}	η/mPa·s	T/K	p/MPa	ρ/g·cm^{-3}	η/mPa·s
313.15	0.10	0.884	0.508	333.15	0.10	0.864	0.415
	0.80	0.885	0.512		0.80	0.865	0.419
	1.60	0.885	0.517		1.60	0.866	0.424
	2.40	0.886	0.522		2.40	0.867	0.429
	3.20	0.887	0.527		3.20	0.868	0.435
353.15	0.10	0.844	0.341	373.15	0.10	0.822	0.287
	0.80	0.845	0.346		0.80	0.824	0.291
	1.60	0.846	0.351		1.60	0.825	0.296
	2.40	0.847	0.356		2.40	0.826	0.302
	3.20	0.848	0.361		3.20	0.828	0.307
393.15	0.80	0.802	0.256	413.15	0.80	0.779	0.222
	1.60	0.803	0.261		1.60	0.781	0.227
	2.40	0.805	0.266		2.40	0.783	0.232
	3.20	0.806	0.272		3.20	0.784	0.237
433.15	0.80	0.755	0.194	453.15	0.80	0.729	0.173
	1.60	0.757	0.199		1.60	0.731	0.178
	2.40	0.759	0.204		2.40	0.734	0.183
	3.20	0.761	0.209		3.20	0.736	0.188
473.15	1.60	0.704	0.160				
	2.40	0.707	0.164				
	3.20	0.710	0.169				

Table 12. Experimental Viscosity Data for the Binary Mixture of *p*-Xylene (1) + Acetic Acid (2) (x_1 = 0.7994)

T/K	p/MPa	ρ/g·cm^{-3}	η/mPa·s	T/K	p/MPa	ρ/g·cm^{-3}	η/mPa·s
313.15	0.10	0.869	0.505	333.15	0.10	0.850	0.412
	0.80	0.870	0.509		0.80	0.852	0.416
	1.60	0.871	0.514		1.60	0.852	0.422
	2.40	0.872	0.519		2.40	0.853	0.427
	3.20	0.872	0.525		3.20	0.854	0.432
353.15	0.10	0.830	0.339	373.15	0.10	0.810	0.285
	0.80	0.831	0.343		0.80	0.811	0.289
	1.60	0.833	0.349		1.60	0.813	0.294
	2.40	0.834	0.354		2.40	0.814	0.300
	3.20	0.835	0.359		3.20	0.815	0.305
393.15	0.80	0.790	0.254	413.15	0.80	0.768	0.219
	1.60	0.792	0.258		1.60	0.770	0.225
	2.40	0.793	0.264		2.40	0.772	0.230
	3.20	0.795	0.270		3.20	0.774	0.235
433.15	0.80	0.745	0.191	453.15	0.80	0.720	0.170
	1.60	0.747	0.197		1.60	0.723	0.176
	2.40	0.749	0.202		2.40	0.725	0.181
	3.20	0.751	0.208		3.20	0.728	0.187
473.15	1.60	0.697	0.157				
	2.40	0.700	0.162				
	3.20	0.703	0.168				

the viscosity−pressure curve a linear curve for the small change of the pressures.

Results of Correlation. The viscosity can be correlated with temperature by the equation: lg $\eta_L = A + B/(T/\mathrm{K}) + C(T/\mathrm{K}) + D(T/\mathrm{K})^2$.[22] We take the composition and pressure into account and improved the equation. As a result, eq 5 is used to correlate the viscosities of the *p*-xylene + acetic acid binary system, and in the equation, parameters A, B, C, and D can all be expressed as a polynomial of the mixture composition.

$$\ln[\eta/(\mathrm{mPa \cdot s})] = A + \frac{B}{T/\mathrm{K}} + C(T/\mathrm{K}) + D(p/\mathrm{MPa}) \quad (5)$$

To indicate the effect of the correlation, calculate the average deviation AAD by eq 4 and maximum deviation MxD of the correlation results by eq 6.

$$\mathrm{MxD} = \max |\mathrm{dev}_i| \quad (6)$$

The results of the correlation are as follows

$$A = -2.58187 - 1.91979x + 1.48398x^2 - 1.18253x^3 \quad (7)$$

$$B = 985.32 - 328.389x + 441.112x^2 \quad (8)$$

$$C = -0.00220092 + 0.00220584x \quad (9)$$

$$D = 0.0217812 \quad (10)$$

In these formulas, T and p are temperature and pressure of the mixture, respectively, and x is the mole fraction of *p*-xylene. The average deviation of the correlation results is 1.21 %, and the maximum deviation is 4.66 %.

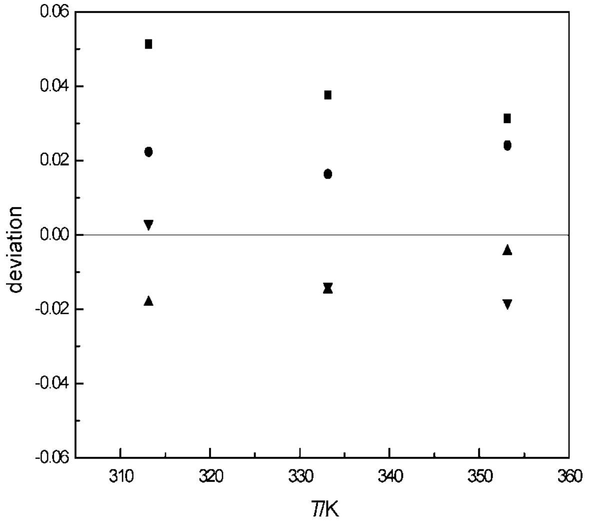

Figure 4. Deviation of the experimental viscosity data from the literature. ■, *p*-xylene from ref 12; ●, *p*-xylene from ref 21; ▲, water from ref 21; ▼, acetic acid from ref 21.

Table 13. Experimental Viscosity Data for the Binary Mixture of *p*-Xylene (1) + Acetic Acid (2) (x_1 = 0.8994)

T/K	p/MPa	ρ/g·cm^{-3}	η/mPa·s	T/K	p/MPa	ρ/g·cm^{-3}	η/mPa·s
313.15	0.10	0.856	0.499	333.15	0.10	0.838	0.407
	0.80	0.857	0.503		0.80	0.839	0.411
	1.60	0.858	0.508		1.60	0.839	0.416
	2.40	0.858	0.513		2.40	0.840	0.421
	3.20	0.859	0.518		3.20	0.841	0.427
353.15	0.10	0.819	0.339	373.15	0.10	0.799	0.288
	0.80	0.820	0.344		0.80	0.800	0.293
	1.60	0.821	0.349		1.60	0.802	0.298
	2.40	0.822	0.354		2.40	0.803	0.303
	3.20	0.823	0.359		3.20	0.804	0.308
393.15	0.80	0.780	0.254	413.15	0.80	0.759	0.220
	1.60	0.782	0.259		1.60	0.761	0.225
	2.40	0.783	0.265		2.40	0.763	0.231
	3.20	0.785	0.270		3.20	0.764	0.236
433.15	0.80	0.737	0.194	453.15	0.80	0.713	0.170
	1.60	0.739	0.199		1.60	0.716	0.175
	2.40	0.741	0.204		2.40	0.718	0.180
	3.20	0.745	0.209		3.20	0.723	0.184
473.15	1.60	0.692	0.159				
	2.40	0.694	0.164				
	3.20	0.700	0.168				

Table 14. Experimental Viscosity Data at Atmospheric Pressure of Pure *p*-Xylene, Acetic Acid, and Water Compared with Literature

	p-xylene			acetic acid		water	
T/K	η_{exp}/mPa·s	η_{lit1}/mPa·s[12]	η_{lit2}/mPa·s[21]	η_{exp}/mPa·s	η_{lit}/mPa·s[21]	η_{exp}/mPa·s	η_{lit}/mPa·s[21]
313.15	0.499	0.526	0.5104	0.903	0.9060	0.668	0.6557
333.15	0.409	0.425	0.4158	0.713	0.7029	0.475	0.4682
353.15	0.340	0.351	0.3484	0.574	0.5640	0.358	0.3564

Conclusion

In this work, a rolling-ball viscometer was built up. The viscosities of pure *p*-xylene, pure acetic acid, and the *p*-xylene + acetic acid binary system were measured and correlated at different temperatures and pressures. The parameters of the correlation are given to convenience the engineering use. In the correlation, the average deviation and the maximum deviation are 1.21 % and 4.66 %, respectively.

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