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Temperature and Density Dependence of the Viscosity of Cyclopentane

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New measurements have been made for the viscosity of cyclopentane between 258 K and 298 K at pressures up to approximately 380 MPa with a self-centering falling-body viscometer. These extend earlier high-pressure measurements made below 25 MPa by Assael and Dalaouti. A correlation function is used to represent the results as a function of temperature and molar volume with a standard deviation of ±0.3%. The uncertainty in the measurements is estimated at ±1%.

Introduction

New measurements have been made for the viscosity of cyclopentane between 258 K and 298 K at pressures up to approximately 380 MPa using a self-centering falling-body viscometer. The work forms part of a project of the International Association for Transport Properties (http:/transp.eng.auth.gr/iatp.html) to provide high-quality viscosity data for substances that are liquid over broad ranges of temperature and pressure that can be used as reference fluids, particularly where it might not be possible to use water. To this end, measurements have been made for toluene with several different types of viscometer and a correlation was derived from them.[1] The cyclopentane viscosity data presented here complement recent high-pressure vibrating wire measurements made to 25 MPa by Assael and Dalaouti[2] and will be used similarly.

Experimental Section

The cyclopentane was Aldrich 99+% dried over sodium wire. Analysis by GCMS (using a Shimadzu GC17A gas chromatograph fitted with a J.W. Scientific DB5-MS 30 m × 0.25 mm column and employing a Shimadzu QP5000 mass spectroscopic detector) detected an impurity, 2,2-dimethylbutane. By using the method of standard additions, doping cyclopentane with 2,2-dimethylbutane (Chemical Samples Co., 99%), the purity was estimated at 99.89%.

Densities at atmospheric pressure were obtained using an Anton-Paar model DMNA5000 vibrating tube densimeter calibrated with dry air (BOC Gases, Instrument grade, ≤25 ppm water) and purified water (MilliQ ion exchange system, Waters-Millipore Ltd.). The density of the cyclopentane sample at 25 °C was $0.739\ 92_2$ g/cm^3. The reproducibility is ±10 μg/cm^3. From the density of 2,2-dimethylbutane,[3] 0.657 02 g/cm^3, and that recommended for cyclopentane,[4] $0.740\ 39_8$ g/cm^3, one obtains a purity of 99.95 mol %. The molar mass was taken as 70.1329 g/mol.

Viscosities (η) at atmospheric pressure were determined with a reproducibility of ±0.2% in a glass Ubbelohde viscometer mounted in a water thermostat controlled to ±1 mK. This viscometer was calibrated at 25 °C using a set of calibration standards from the Cannon Instrument Co. (State College, PA). The results were found to fit the working equation

$$\eta/\rho = At + B/t \tag{1}$$

(where ρ is the density and t is the flowtime) with the classical kinetic energy correction as the second term (A and B are fitted constants).[5] The alternative equation

$$\eta/\rho = At + B/t^2 \tag{2}$$

recommended by Bauer and Meerlender[6] for long capillary Ubbelohde viscometers was tested but resulted in a poor fit.

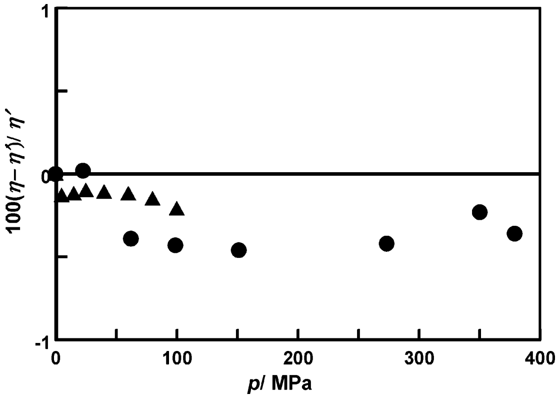

Figure 1. Relative deviations of the viscosity of water at 25 °C (η) reported by Harlow (ref 18) (●, uncertainty of 1.4%) and those recommended in the 1985 IAPS tables (ref 19) (▲, standard uncertainty of 1%) from the results of this work, η'. η'/(mPa·s) = $0.8909 - 2.263\ 027 \times 10^{-4}(p/\text{MPa}) + 2.683\ 453 \times 10^{-6}(p/\text{MPa})^2 - 4.055\ 610 \times 10^{-9}(p/\text{MPa})^3 + 3.168\ 239 \times 10^{-12}(p/\text{MPa})$.[4]

Table 1. Viscosity and Density of Cyclopentane at 0.1 MPa

T/K	ρ/(g/cm^3)^a	η/(mPa·s)^b	T/K	ρ/(g/cm^3)^a	η/(mPa·s)^b
278.15	0.759 64	0.5230	293.15	0.744 90	0.4405
283.15	0.754 76	0.4932	298.15	0.739 92	0.4173
288.15	0.749 85	0.4657			

[a] Measured with vibrating tube densimeter. [b] Measured with Ubbelohde viscometer.

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Table 2. Viscosity of Cyclopentane from 258 K to 298 K

T/K	t/s	p/MPa	V/(cm^3/mol)	ρ/(g/cm^3)	η/(mPa·s)	Re[a]
258.01	21.98	0.1	89.9819	0.77941	0.6851	514
257.87	22.04	0.1	89.9667	0.77954	0.6871	511
257.86	22.07	0.1	89.9660	0.77955	0.6878	510
262.99	20.47	0.1	90.5254	0.77473	0.6384	588
262.99	20.49	0.1	90.5254	0.77473	0.6388	587
262.99	21.05	3.1	90.2605	0.77700	0.6562	558
262.99	21.53	5.6	90.0449	0.77887	0.6709	535
262.99	22.01	8.1	89.8316	0.78071	0.6858	513
262.99	22.55	10.8	89.6055	0.78269	0.7025	490
262.99	25.54	25.8	88.4602	0.79282	0.7943	388
262.99	30.86	50.8	86.8352	0.80765	0.9576	271
262.99	36.68	75.7	85.4712	0.82054	1.1362	195
262.99	43.01	100.5	84.2987	0.83196	1.3301	144
262.99	49.97	125.5	83.2532	0.84240	1.5429	108
262.99	57.66	150.5	82.3200	0.85195	1.7779	82
262.99	65.98	175.5	81.4794	0.86074	2.0319	64
262.99	75.00	200.2	80.7196	0.86885	2.3071	50
262.93	20.50	0.1	90.5187	0.77479	0.6392	587
262.93	20.50	0.1	90.5187	0.77479	0.6393	587
262.93	21.09	3.1	90.2531	0.77707	0.6574	556
262.93	21.56	5.6	90.0384	0.77892	0.6719	534
262.93	22.01	7.9	89.8388	0.78065	0.6858	513
262.93	22.43	10.1	89.6612	0.78220	0.6987	495
262.93	25.56	25.8	88.4548	0.79287	0.7950	387
262.93	30.88	50.8	86.8336	0.80767	0.9583	271
262.93	36.71	75.7	85.4697	0.82056	1.1371	195
262.93	43.11	100.7	84.2840	0.83210	1.3330	144
262.93	50.08	125.8	83.2390	0.84255	1.5462	108
262.93	57.79	150.8	82.3083	0.85208	1.7819	82
262.93	66.25	175.8	81.4667	0.86088	2.0402	63
262.93	75.48	200.8	80.6987	0.86907	2.3219	49
262.93	85.58	225.9	79.9926	0.87674	2.6295	39
262.93	96.65	250.9	79.3391	0.88396	2.9667	31
262.93	108.69	275.8	78.7342	0.89076	3.3330	24
262.93	121.58	300.6	78.1713	0.89717	3.7251	20
263.03	20.48	0.1	90.5294	0.77470	0.6386	588
263.03	20.49	0.1	90.5294	0.77470	0.6390	587
263.03	22.49	10.6	89.6245	0.78252	0.7005	493
263.03	24.45	20.6	88.8455	0.78938	0.7608	421
263.03	26.47	30.6	88.1297	0.79579	0.8231	362
263.03	28.57	40.5	87.4720	0.80177	0.8873	314
263.03	30.79	50.5	86.8589	0.80743	0.9555	272
263.03	33.03	60.5	86.2841	0.81281	1.0243	238
263.03	35.35	70.5	85.7422	0.81795	1.0955	210
263.03	37.81	80.6	85.2285	0.82288	1.1709	184
263.03	40.26	90.4	84.7592	0.82744	1.2457	164
263.03	42.89	100.4	84.3055	0.83189	1.3265	145
263.03	45.61	110.5	83.8685	0.83622	1.4097	129
263.03	48.43	120.5	83.4563	0.84035	1.4959	115
263.03	51.35	130.5	83.0623	0.84434	1.5851	103
263.03	54.36	140.4	82.6893	0.84815	1.6770	92
263.03	57.52	150.4	82.3261	0.85189	1.7737	83
263.03	60.81	160.5	81.9783	0.85550	1.8742	74
263.03	64.17	170.5	81.6450	0.85900	1.9766	67
263.03	67.65	180.4	81.3261	0.86237	2.0830	61
263.03	71.25	190.3	81.0194	0.86563	2.1927	55
263.03	73.81	200.2	80.7226	0.86881	2.2705	51
268.01	19.28	0.1	91.0842	0.76998	0.6016	659
268.01	19.21	0.1	91.0842	0.76998	0.5994	663
268.01	19.70	3.0	90.8136	0.77227	0.6145	633
268.01	20.16	5.5	90.5844	0.77423	0.6285	606
268.01	20.62	8.1	90.3601	0.77615	0.6428	581
268.01	21.08	10.6	90.1467	0.77799	0.6569	557
268.01	23.95	25.9	88.9372	0.78857	0.7450	439
268.01	28.90	50.9	87.2588	0.80374	0.8969	308
268.01	34.36	75.9	85.8512	0.81691	1.0645	222
268.01	40.20	100.7	84.6459	0.82854	1.2433	164
268.01	46.65	125.7	83.5802	0.83911	1.4405	124
268.01	53.75	150.6	82.6330	0.84873	1.6574	95
268.01	61.55	175.7	81.7727	0.85766	1.8956	73
268.01	69.92	200.7	80.9918	0.86593	2.1508	57
268.01	79.13	225.6	80.2765	0.87364	2.4315	45
268.01	89.32	250.8	79.6080	0.88098	2.7419	36
268.01	100.19	275.3	79.0036	0.88772	3.0726	29
268.01	112.52	301.0	78.4112	0.89443	3.4474	23
268.01	125.22	325.3	77.8853	0.90046	3.8332	19
268.01	140.04	351.2	77.3571	0.90661	4.2832	15
268.01	155.96	378.0	76.8430	0.91268	4.7659	12
273.15	17.94	0.1	91.6698	0.76506	0.5601	756
273.15	17.97	0.1	91.6698	0.76506	0.5610	753
273.15	18.44	3.1	91.3807	0.76748	0.5756	717
273.15	18.87	5.6	91.1444	0.76947	0.5886	688
273.15	19.31	8.1	90.9124	0.77143	0.6022	658
273.15	19.74	10.6	90.6866	0.77335	0.6155	632
273.15	22.42	25.9	89.4362	0.78417	0.6979	497
273.15	27.10	50.8	87.7056	0.79964	0.8418	348
273.15	32.17	75.8	86.2575	0.81306	0.9972	251
273.15	37.69	100.7	85.0199	0.82490	1.1663	186
273.15	43.66	125.5	83.9357	0.83556	1.3491	141
273.15	50.25	150.5	82.9634	0.84535	1.5505	108
273.15	57.39	175.5	82.0905	0.85434	1.7685	84
273.15	65.19	200.5	81.2915	0.86273	2.0065	65
273.15	73.72	225.3	80.5671	0.87049	2.2665	52
273.15	83.08	250.6	79.8841	0.87793	2.5516	41
273.15	93.35	275.8	79.2534	0.88492	2.8641	33
273.15	104.31	300.7	78.6699	0.89148	3.1977	27
273.15	116.23	325.9	78.1167	0.89780	3.5597	22
273.15	128.97	350.7	77.6032	0.90374	3.9467	18
273.15	145.21	379.2	77.0490	0.91024	4.4399	14
278.16	16.93	0.1	92.2540	0.76022	0.5288	843
278.16	16.94	0.1	92.2540	0.76022	0.5290	842
278.16	17.39	2.9	91.9731	0.76254	0.5430	801
278.16	17.74	5.0	91.7607	0.76430	0.5539	772
278.16	18.26	8.1	91.4636	0.76679	0.5697	732
278.16	18.71	10.8	91.2115	0.76890	0.5838	698
278.16	21.25	25.9	89.9307	0.77986	0.6618	550
278.16	25.68	50.8	88.1454	0.79565	0.7981	385
278.16	30.49	75.8	86.6573	0.80931	0.9456	279
278.16	35.69	100.6	85.3884	0.82134	1.1048	207
278.16	41.40	125.7	84.2688	0.83225	1.2796	156
278.16	47.59	150.7	83.2772	0.84216	1.4689	120
278.16	54.33	175.8	82.3825	0.85131	1.6746	93
278.16	61.56	200.7	81.5743	0.85974	1.8953	73
278.16	69.48	225.8	80.8289	0.86767	2.1366	58
278.16	77.96	250.8	80.1448	0.87508	2.3951	47
278.16	87.30	275.9	79.5048	0.88212	2.6793	37
278.16	97.57	300.8	78.9129	0.88874	2.9917	30
278.16	108.47	325.9	78.3559	0.89506	3.3230	25
278.16	120.33	350.9	77.8310	0.90109	3.6833	20
278.16	135.51	380.1	77.2557	0.90780	4.1439	16
287.93	15.06	0.1	93.4306	0.75064	0.4710	1050
287.93	15.07	0.1	93.4306	0.75064	0.4712	1049
287.93	15.50	3.0	93.1064	0.75326	0.4845	995
287.93	15.86	5.4	92.8527	0.75531	0.4955	954
287.93	16.28	8.1	92.5747	0.75758	0.5084	908
287.93	16.70	10.8	92.3007	0.75983	0.5216	865
287.93	19.00	25.9	90.9217	0.77135	0.5923	680
287.93	23.00	50.9	89.0138	0.78789	0.7153	475
287.93	27.28	75.8	87.4405	0.80206	0.8468	344
287.93	31.91	100.8	86.1048	0.81451	0.9885	256
287.93	36.95	125.7	84.9428	0.82565	1.1428	194
287.93	42.36	150.6	83.9123	0.83579	1.3083	150
287.93	48.24	175.7	82.9835	0.84514	1.4879	117
287.93	54.57	200.6	82.1443	0.85378	1.6810	92
287.93	61.53	225.7	81.3754	0.86184	1.8932	73
287.93	69.00	250.7	80.6673	0.86941	2.1208	59
287.93	76.89	275.7	80.0087	0.87657	2.3608	48
287.93	85.50	300.8	79.3963	0.88333	2.6228	39
287.93	94.66	325.5	78.8302	0.88967	2.9013	32
287.93	104.38	349.5	78.3123	0.89555	3.1964	27
287.93	116.44	376.9	77.7545	0.90198	3.5626	22

Table 2 (Continued)

T/K	t/s	p/MPa	V/(cm^3/mol)	ρ/(g/cm^3)	η/(mPa·s)	Re^a	T/K	t/s	p/MPa	V/(cm^3/mol)	ρ/(g/cm^3)	η/(mPa·s)	Re^a
298.03	13.38	0.1	94.7018	0.74057	0.4190	1311	298.00	13.39	0.1	94.6979	0.74060	0.4191	1310
298.03	13.38	0.1	94.7018	0.74057	0.4190	1310	298.00	13.40	0.1	94.6979	0.74060	0.4196	1307
298.03	13.38	0.1	94.7018	0.74057	0.4190	1310	298.00	13.77	3.0	94.3457	0.74336	0.4308	1244
298.03	14.10	5.5	94.0554	0.74566	0.4410	1190	298.00	14.08	5.3	94.0814	0.74545	0.4404	1193
298.03	14.40	7.8	93.8012	0.74768	0.4505	1143	298.00	14.47	8.1	93.7585	0.74802	0.4526	1133
298.03	14.83	10.8	93.4647	0.75037	0.4637	1083	298.00	14.86	10.9	93.4587	0.75042	0.4644	1079
298.03	16.91	25.9	91.9690	0.76257	0.5276	848	298.00	16.95	26.0	91.9617	0.76263	0.5288	844
298.03	20.50	50.9	89.9336	0.77983	0.6379	592	298.00	20.53	50.8	89.9316	0.77985	0.6390	590
298.03	24.30	75.8	88.2673	0.79455	0.7549	430	298.00	24.38	75.8	88.2654	0.79457	0.7572	427
298.03	28.41	100.8	86.8585	0.80744	0.8807	320	298.00	28.52	100.8	86.8585	0.80744	0.8842	318
298.03	32.83	125.8	85.6400	0.81893	1.0159	244	298.00	32.98	125.8	85.6376	0.81895	1.0207	241
298.03	37.64	150.7	84.5642	0.82935	1.1633	188	298.00	37.76	150.7	84.5638	0.82935	1.1669	187
298.03	42.84	175.7	83.6010	0.83890	1.3221	147	298.00	42.91	175.7	83.6012	0.83890	1.3241	147
298.03	48.39	200.7	82.7308	0.84772	1.4914	117	298.00	48.51	200.7	82.7292	0.84774	1.4951	116
298.03	54.34	225.6	81.9380	0.85593	1.6729	93	298.00	54.52	225.7	81.9336	0.85597	1.6784	93
298.03	60.85	250.6	81.2068	0.86363	1.8711	75	298.00	60.95	250.7	81.2031	0.86367	1.8743	75
298.03	67.74	275.6	80.5294	0.87090	2.0809	61	298.00	67.89	275.7	80.5248	0.87095	2.0854	61
298.03	75.12	300.4	79.9028	0.87773	2.3054	50	298.00	75.29	300.6	79.8953	0.87781	2.3106	50
298.03	83.01	325.3	79.3153	0.88423	2.5452	42	298.00	82.89	324.9	79.3222	0.88415	2.5415	42
298.03	91.38	350.1	78.7639	0.89042	2.7995	35	298.00	91.17	349.6	78.7730	0.89032	2.7929	35
298.03	101.68	378.0	78.1834	0.89703	3.1121	28	298.00	100.78	375.7	78.2277	0.89652	3.0845	29

[a] Reynolds number for annular flow: $Re = 2r_1^2\rho v/(r_2 - r_1)\eta)$ where v is the terminal velocity of the sinker and r_1 and r_2 are the radii of the sinker and tube, respectively (ref 9).

The effect of the impurity on the viscosity was checked by adding 0.5 and 1% 2,2-dimethylbutane by mass. There was no discernible effect within the experimental error of ±0.2%: the composition dependence of the viscosity of the mixture is therefore very flat in this composition range.

The high-pressure viscometer and its operation and calibration have been described elsewhere.[7,8] It was also calibrated with the Cannon standards.[8] Platinum resistance thermometers newly recalibrated by the National Measurement Laboratory (CSIRO, West Lindfield, NSW) between (−65 and 100) °C on the ITS-90 to a tolerance of ±8 mK were employed. The viscometer oil-bath temperature was controlled[8] to within ±0.01 K between (−10 and 25) °C and to ±0.02 K below −10 °C. The primary pressure gauge (400 MPa Heise CM) was calibrated[7] against a deadweight tester to ±0.05%, and pressures have an overall uncertainty of ±0.2 MPa.

The working equation for the falling-body viscometer is[7,9,10]

$$\eta(p,T) = \frac{t(1 - \rho/\rho_s)}{A[(1 + 2\alpha(T - T_{ref})][1 - 2\beta(p - p_{ref})/3]} \quad (3)$$

where t is the fall time at temperature T and pressure p, ρ is the density of the fluid, ρ_s is that of the sinker, α is the coefficient of thermal expansion (1.6×10^{-5} K^{-1}), and β is the bulk compressibility (2×10^{-6} MPa^{-1}) of the sinker and tube material, in this case 316 stainless steel. A is the calibration constant, 28 707 Pa^{-1} (±0.17%[8]), obtained at temperature T_{ref} and pressure p_{ref}, valid for $Re < 1000$.[8] The sinker density was corrected for changes in temperature and pressure from the calibration state point, $T_{ref} \equiv$ 298.15 K and $p_{ref} \equiv 0.1$ MPa, using the relation[11]

$$\rho_s = \frac{\rho_s(T_{ref},p_{ref})}{[1 + 3\alpha(T - T_{ref})][1 - \beta(p - p_{ref})]} \quad (4)$$

The overall uncertainty in the viscosity, based on replicate measurements and the sum of the uncertainty in the calibration (±0.2%) and that in the fit to the function of temperature and density described below (±0.25%), is estimated at ±1%.

Calculation of the viscosity from fall times requires knowledge of the density of cyclopentane as a function of T and p. There are three sets of pVT data for cyclopentane in the literature: those of Brazier and Freeman[12] are confined to a single isotherm (303.15 K) but extend to 450 MPa, those of Kuss and Taslimi[13] lie in the pT region (39.2 MPa to 196.1 MPa, 298.15 K to 353.15 K), and those of Baonza et al.[4] lie in the region (0.1 MPa to 104.3 MPa, 192.79 K to 298.15 K). We have used two equations of state based on these data in this work, one given by Cibulka and co-workers,[14] recommended for the region (0.1 MPa to 196 MPa, 192.79 K to 353.15 K), and one based on the method of Malhotra and Woolf[15,16] for extrapolation of modified Tait equation parameters outside the range of experimental data. For the latter method, the Tait parameter C was taken to be 0.2220[13] and Tait parameters $B(T)$ were obtained from the equation

$$B(T) = -p_c + b_1(1 - T_r) + b_2(1 - T_r)^2 \qquad T_r = T/T_c \quad (5)$$

The critical pressure p_c and temperature T_c are the values recommended by Kudchadker et al.[17] (4.508 MPa, 511.65 K), and b_1 and b_2, obtained from a least-squares fit of the B parameters of refs 12 and 13, are 68.2777 MPa and 286.3729 MPa, respectively.

Measurements were made of the viscosity of water at 298.15 K as a test of the instrument and technique. Figure 1 shows a comparison with the results of Harlow[18] (uncertainty given as ±1.4%) and the 1985 International Association for the Properties of Steam (IAPS) recommendations (standard uncertainty, ±1%).[19] The agreement is well within the limits of the combined uncertainties.

Results and Discussion

The results are presented in Tables 1 and 2.

The viscosities were fitted as a function of temperature and molar volume to the empirical Pade approximation used for toluene,[8]

$$\sqrt{T}/\eta = (\zeta_1 + \zeta_2 V_r + \zeta_2 V_r^2)/(1 + \zeta_4 V_r) \quad (6)$$

where the η−V isotherms are mapped onto a single

Table 3. Coefficients of Best Fit: Equations 6 and 7

$10^{-3}\zeta_1/(K^{0.5}/mPa\cdot s)$	0.252 583 2
$10^{-1}\zeta_2/(K^{0.5}\ mol/mPa\cdot s\cdot cm^3)$	−0.710 693 7
$10\zeta_3/(K^{0.5}\ mol^2/mPa\cdot s\cdot cm^6)$	0.502 047 4
$10^2\zeta_4/(mol/cm^3)$[a]	−0.238 253 2
$10\xi_1/(cm^3/K\cdot mol)$	−0.347 809 1
$10^4\ \xi_1/(cm^3/K^2\cdot mol)$	0.474 140 0
standard uncertainty/mPa·s	0.004
standard percentage uncertainty	0.25
maximum percentage deviation	0.8

[a] Incorrect units were given in Table 3 of ref 8 for this parameter.

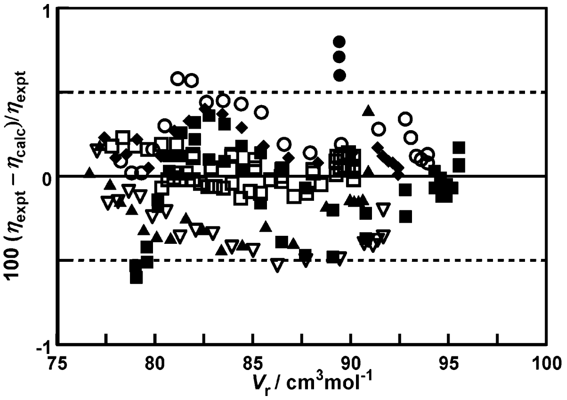

Figure 2. Residuals (experimental − calculated values) for the fit of the experimental high-pressure viscosity results of this work to eqs 6 and 7 plotted as a function of reference molar volume, V_r, for each experimental isotherm. The dashed lines represent the expanded uncertainty of the fit, or 95% confidence limits, that is, the standard uncertainty multiplied by 2. Symbols: ●, 258 K; □, 263 K; ▲, 268 K; ▽, 273 K; ◆, 278 K; ○, 288 K; ■, 298 K.

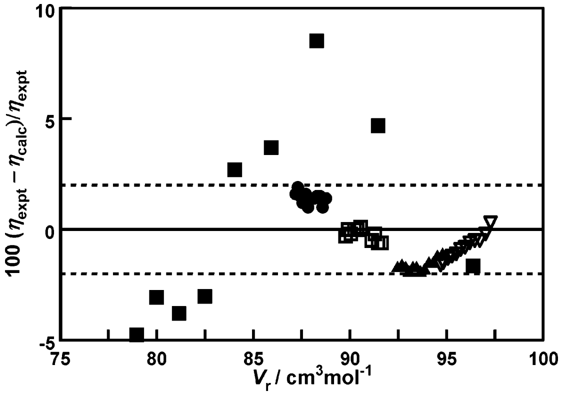

Figure 3. Residuals (literature data − values calculated from eqs 6 and 7 using the coefficients of Table 3) for the comparison of the viscosity results of Assael and Dalaouti (ref 2) (vibrating wire; ●, 253 K; □, 273 K; ▲, 293 K; ▽, 309 K) and of Brazier and Freeman (ref 12) (rolling ball; ■, 303 K) with those of this work as a function of reference molar volume, V_r. The dashed lines represent limits of ±2% about our correlation.

isotherm, T_{ref}, taken as an arbitrary reference, by

$$V_r = V - \xi_1(T - T_{ref}) - \xi_2(T - T_{ref})^2 \qquad (7)$$

In this work, T_{ref} was chosen as 273.15 K. The coefficients of the fit, ζ_i and ξ_j, are given in Table 3. The residual plot is shown as Figure 2. For cyclopentane, this correlation is superior to those based on reduced viscosities employed in earlier studies.[8,20−22]

The viscosity of cyclopentane has been measured under high pressure by Brazier and Freeman[12] using a rolling ball viscometer at the single temperature of 303.15 K to 400 MPa pressure and by Assael and Dalaouti[2] using a vibrating wire technique over the temperature range of (210 to 310) K but to only 25 MPa pressure. Figure 3 shows a comparison with the results of this work. Our results are in satisfactory agreement with those of Assael and Dalaouti (uncertainty, ±0.5 to 1%), but much less so with those of Brazier and Freeman (uncertainty not explicitly stated but gauged at ±2%). A similar lack of agreement with the latter workers' results has been found by other groups for hexane[23] and hexadecane.[11] Lohrenz and co-workers[24] have made an analysis of the rolling ball viscometer showing that it is extremely sensitive to the effects of nonuniform construction and may exhibit random slip and spin that vary with density and viscosity.

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