J. Chem. Eng. Data **2001,** *46,* 1467−1471

Viscosity Measurements on Gaseous Propane

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A vibrating-wire viscometer was used to measure the viscosity of gaseous propane at subcritical temperatures (298.15, 323.15, 348.15, and 366.15) K and at supercritical temperatures (373.15, 398.15, and 423.15) K. At the subcritical temperatures, the isothermal series of measurements were restricted to 95% of the saturated vapor pressure. The maximum pressure for the supercritical isotherms was 20 MPa. In general, the measurements are characterized by a reproducibility of ±0.05% and a total uncertainty between ±0.25% and ±0.4%. However, close to the critical point, an uncertainty of ±3% had to be accepted, mainly due to the uncertainty of the density. The new data are the most accurate values in the range of the measurements and should be used in a database for the viscosity of fluid propane.

Introduction

In principle, a vibrating-wire viscometer is an absolute instrument if the wire radius R is accurately given by the supplier, but this is not the case. To calibrate the wire, one measurement on a gas with a viscosity η known as accurately as possible for the given thermodynamic state is sufficient to determine the radius.

Several isothermal series of measurements on argon and krypton were carried out to verify the performance of the new viscometer. The results of these measurements and a discussion thereof were published in a previous paper.[1]

The viscosity measurements on propane, which is an important reference gas for industrial applications, are meant to give a contribution to the development of a more accurate database.

Experimental Section

Several improvements of the usual vibrating-wire technique were implemented to design a new viscometer for highly accurate measurements on dilute and dense gases.[2]

The vibrating wire is a Chromel wire with a nominal radius $R_{\mathrm{nom}} = 12.5\ \mu$m and a length $L = 90$ mm. Its upper end is clamped between glass blocks, and a brass weight with a mass $m = 1.1$ g is suspended from the lower end. The wire is placed in a magnetic field with a 10 mm distance between the magnets and with a flux density $B = 0.35$ T. The vertical length L_{magn} of the field is 60 mm. The optimum ratio between L and L_{magn} was found to be 1.5 with regard to the suppression of the third harmonic mode of oscillation. As the arrangement is symmetric, the even harmonics are expected neither to be initiated nor to be observed. The oscillation of the wire is initiated with a sinusoidal voltage pulse, which has a frequency close to the resonance frequency of the wire. Because the wire oscillates in a magnetic field, the velocity of the oscillation can be detected by amplifying the induced voltage and measuring it as a function of time.

An important parameter of the amplifier circuit is its electrical resistance. According to the Lentzian rule, a force acts on a conductor in a magnetic field opposite to its velocity and proportional to the current. This magnetic damping can be expressed by a magnetic decrement, which appears as a part of Δ_0, the logarithmic decrement of the oscillation in a vacuum. To prevent the magnetic part of this damping from becoming too high, the amplifier circuit has a resistance $R_\Omega = 100$ kΩ. Offset suppression filters were left out, because they would decrease the dynamic qualities of the amplifier. Although the oscillation curve is visibly deformed by small bandwidth amplifiers, distortions by wide bandwidth amplifiers are not immediately obvious but appear as an error in the logarithmic decrement Δ of the oscillation. The oscillation curve is undistorted without filters, but the offset voltage must be subtracted by software.

To improve the signal-to-noise ratio, every measurement was carried out 100 times, and the measured oscillation curves were averaged. This procedure requires that the oscillation curves are strictly synchronous, which is achieved by the simultaneous start of initiation pulse and data acquisition.

An essential condition for the validity of the measuring theory is an oscillation amplitude much smaller than the wire radius R. However, with such a small displacement, the signal-to-noise ratio would be unreasonably low. Therefore, the decrement Δ and the angular frequency ω of the oscillation are determined as functions of the square of the amplitude. Their correct values are deduced by extrapolation to zero displacement.

Chromel was chosen as the wire material because of its very smooth surface. It was shown that the rough surface of conventionally used tungsten wire leads to systematic errors.[2]

The experimental equipment is intended for measurements at pressures p up to 40 MPa and temperatures T up to 500 K. Four pressure transmitters are used to measure p. They are characterized by an uncertainty of 0.01% of the measured value plus 0.01% of the working range. The working ranges are (0.69, 2.76, 13.8, and 41.4) MPa. Temperature measurements are carried out with an ITS-90 thermometer and a six and a half digit multimeter. Additional sensors are used to verify the isothermal temperature distribution inside the thermostat.

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10.1021/je010062k CCC: $20.00

Results

The wire radius R was determined to be 12.770 μm using reference values for argon, which Kestin and Leidenfrost[3] obtained at $T = 298.15$ K and at the pressures 0.79 MPa and 1.48 MPa with an uncertainty of ±0.15%. Measurements on argon at pressures up to 2.8 MPa also agreed with the corresponding data by Kestin and Leidenfrost within ±0.1%. At the time of our measurements, these data were the most reliable reference data in the literature, but with recently published values for the viscosity of helium in the limit of zero density,[4] based on ab initio calculations of the helium−helium interatomic potential, a recalibration of the viscometer, to lower its uncertainty, has to be discussed. However, it is expected that measurements on helium with the vibrating-wire viscometer will be strongly influenced by the slip effect, so that we would be forced to perform the calibration measurements at ~1 MPa. The initial density dependence would have to be taken into account, which would make it impossible to fully exploit the low uncertainty of the new standard.

To prove the performance of the viscometer, measurements on krypton were carried out at $T = 298.15$ K and at $T = 348.15$ K, and the results were compared with values measured by van den Berg with a capillary viscometer.[5] The comparison showed an agreement within ±0.01% in the limit of zero density at $T = 298.15$ K and within ±0.2% in the entire density range at both temperatures.

For propane, the subcritical isotherms at $T = (298.15, 323.15, 348.15, \text{and } 366.15)$ K cover pressure ranges up to 95% of the vapor pressure, and the supercritical isotherms at $T = (373.15, 398.15, \text{and } 423.15)$ K extend up to 20 MPa. Propane with a certified purity of 99.95% (Messer Griesheim) was used. The calculation of the gas density ρ was based on an equation of state by Span and Wagner,[6,7] which was the best available equation of state for propane.[1]

Viscosity values measured at subcritical temperatures and pressures close to the vapor pressure had to be rejected due to their deviations of up to 2% from preliminary correlation curves. Because these deviations had always positive but not reproducible values, an effect of condensation can be assumed.

For the other data, the reproducibility was within ±0.05%. Additionally, systematic errors arising from the uncertainty of the calibration data[3] and the uncertainty of the density calculation have to be taken into account. The uncertainty of the density propagates into the uncertainty of the viscosity in two ways: First, the density is needed to calculate the viscosity from the oscillation parameters of the vibrating wire. Second, the viscosity is represented as a function of the density. The total uncertainties of the $\eta(\rho)$ data are conservatively estimated to be between ±0.25% for $\rho < 2$ mol·L^{-1} and ±0.4% for $\rho > 8$ mol·L^{-1}.

However, the data measured at $T = 373.15$ K and densities near the critical density are characterized by a reproducibility of ±0.2%. Those data also have higher systematic errors, because, close to the critical point, small uncertainties of the equation of state and of the measured pressures and temperatures lead to high uncertainties of the calculated densities. The total uncertainties of $\eta(\rho)$ measured close to the critical point are estimated to be within ±3%. This seems to be rather high in comparison with statements of other authors; however, we believe that our conservative estimation is more realistic because the density is needed for all viscosity experiments, and, in general, the density has been determined via temperature and pressure measurements.

Deviations of the experimental temperatures from the nominal temperatures of the isothermal series of measurements were kept within ±0.1 K. Therefore, the experimental viscosity values could be adjusted to isothermal values by means of a linear correction. The isothermal values are recorded in Table 1, together with the corresponding densities. To save space, the pressures are not shown here. We are aware of the fact that the pressures might be needed to re-evaluate the densities with an improved equation of state that might be available in the future. However, in that case, the viscosities will have to be re-evaluated too, which also requires the parameters of the wire oscillation, the logarithmic decrement and the frequency.

Some viscosity values measured at low densities are influenced by the slip effect. In Table 1, these data are marked to indicate that they should not be used and that they were not included in the correlations described below.

Analysis

A power series representation was assumed for the density dependence of the viscosity:

$$\eta = \sum_{i=0}^{n} \eta_i \rho^i \tag{1}$$

Depending on the considered density range, the order n of the power series was chosen to be 2, 3, or 4. The results of linear fits are not shown here, because in the range of the initial density dependence the quantity of data was too small to obtain reliable fit results. The fits were carried out by means of a multiple linear least-squares analysis. Weighting factors of η^{-2} were chosen to minimize relative deviations instead of absolute deviations and to obtain the standard deviation σ as a dimensionless number. The coefficients η_i generated with the fits of eq 1 are summarized in Table 2. The density $\rho_{\max}$ is the maximum of the evaluated density range. The high values of σ for the supercritical isotherms are caused by the uncertainty of the density determination in the vicinity of the critical density.

Table 2 shows that the temperature dependence of the coefficient η_1 is distinctly positive. This is in agreement with the Rainwater−Friend theory for the initial density dependence of the viscosity.[8] The higher coefficients, η_2, η_3, and η_4, seem to be only weakly temperature dependent.

Comparison

A reference correlation of the viscosity of propane, based on the most reliable data available in the literature at that time, has recently been published by Vogel et al.[9] For the limit of zero density, Figure 1 shows the deviations from the reference correlation for experimental values obtained with oscillating-disk viscometers by Vogel[10] and by Kestin and co-workers.[11−14] All values by Vogel have been used for the reference correlation, whereas only the values by Kestin and co-workers at room temperature were included. Thus, the data by Vogel determine decisively the correlation in the zero-density limit. The new values of this work agree with the data by Vogel within ±0.1% and with the zero-density reference correlation within ±0.2%. This makes evident that it was justified to exclude the data by Kestin and co-workers above room temperature from the correlation. The deviations of these data from the correlation are due to a temperature measurement error in their experiments.

Table 1. Experimental Data for the Viscosity of Propane

ρ mol·L^{-1}	η μPa·s	ρ mol·L^{-1}	η μPa·s	ρ mol·L^{-1}	η μPa·s	ρ mol·L^{-1}	η μPa·s	ρ mol·L^{-1}	η μPa·s	ρ mol·L^{-1}	η μPa·s
					T = 298.15 K						
0.44478	8.199	0.30987	8.157	0.20200	8.139	0.12666	8.135	0.087280	8.135	0.056003	8.136
0.41074	8.187	0.29016	8.154	0.18622	8.138	0.11889	8.135	0.083393	8.136	0.050109	8.137
0.39094	8.180	0.27247	8.150	0.16935	8.137	0.11131	8.133	0.078799	8.134	0.045374	8.136
0.37019	8.173	0.25297	8.147	0.15446	8.132	0.10608	8.135	0.073807	8.137	0.038296	8.138
0.35024	8.168	0.23494	8.144	0.15048	8.135	0.10025	8.135	0.069283	8.135	0.027286	8.137
0.33032	8.163	0.21969	8.141	0.14483	8.136	0.093916	8.134	0.063985	8.136	0.015982	8.133[a]
					T = 323.15 K						
0.81286	9.188	0.58477	9.009	0.35684	8.885	0.21241	8.839	0.12538	8.818	0.061255	8.812
0.79833	9.172	0.55427	8.991	0.33849	8.876	0.19611	8.833	0.11572	8.819	0.053327	8.814
0.78284	9.158	0.53397	8.979	0.32182	8.871	0.18442	8.830	0.10908	8.817	0.046145	8.813
0.74583	9.126	0.50050	8.960	0.30037	8.862	0.16723	8.826	0.10022	8.817	0.038629	8.811
0.70176	9.091	0.46496	8.942	0.28243	8.858	0.15686	8.822	0.093045	8.817	0.019045	8.795[a]
0.66952	9.067	0.43367	8.923	0.26474	8.851	0.14917	8.823	0.084534	8.815		
0.64868	9.053	0.41643	8.915	0.24805	8.847	0.14032	8.821	0.076295	8.814		
0.61416	9.029	0.37412	8.894	0.23088	8.842	0.13273	8.820	0.069197	8.815		
					T = 348.15 K						
1.5088	10.801	0.89010	10.017	0.52281	9.695	0.30855	9.566	0.13672	9.494	0.049342	9.469
1.4745	10.748	0.83847	9.966	0.49977	9.682	0.29193	9.559	0.12933	9.492	0.042092	9.465
1.4254	10.676	0.79683	9.926	0.47682	9.664	0.27510	9.549	0.12219	9.489	0.037380	9.465
1.3589	10.581	0.76043	9.893	0.45489	9.651	0.25637	9.539	0.11548	9.489	0.021758	9.456[a]
1.3004	10.498	0.73583	9.870	0.43169	9.636	0.23887	9.534	0.10727	9.487		
1.2398	10.418	0.70433	9.841	0.41128	9.623	0.21996	9.525	0.099875	9.485		
1.1853	10.347	0.67203	9.815	0.38981	9.610	0.20675	9.519	0.092271	9.483		
1.1316	10.284	0.64951	9.795	0.37958	9.605	0.19621	9.515	0.085874	9.481		
1.0710	10.213	0.60858	9.761	0.37015	9.598	0.18237	9.511	0.078456	9.477		
1.0285	10.165	0.59141	9.748	0.33862	9.579	0.16913	9.506	0.070562	9.474		
0.97462	10.105	0.57359	9.735	0.33835	9.579	0.15639	9.501	0.063511	9.475		
0.92913	10.056	0.54944	9.716	0.32157	9.572	0.14428	9.495	0.057924	9.472		
					T = 366.15 K						
2.6463	13.618	1.4961	11.329	0.79982	10.443	0.35434	10.084	0.17241	9.992	0.080359	9.957
2.5506	13.389	1.4393	11.239	0.77225	10.415	0.34232	10.076	0.16444	9.987	0.077075	9.956
2.4630	13.192	1.3904	11.169	0.74193	10.387	0.31318	10.065	0.15845	9.984	0.073628	9.956
2.3587	12.958	1.3225	11.074	0.68700	10.337	0.30103	10.055	0.14936	9.982	0.066251	9.951
2.2744	12.786	1.2708	10.999	0.66006	10.312	0.30059	10.054	0.14783	9.983	0.060903	9.949
2.2514	12.720	1.2276	10.947	0.63119	10.286	0.29003	10.051	0.14319	9.979	0.055200	9.949
2.1682	12.551	1.1765	10.876	0.59956	10.261	0.26540	10.034	0.13742	9.976	0.053538	9.948
2.0998	12.404	1.1413	10.832	0.56792	10.235	0.26379	10.035	0.12839	9.973	0.047594	9.944
2.0234	12.245	1.1036	10.785	0.53896	10.211	0.24351	10.024	0.12830	9.974	0.045589	9.954
1.9445	12.099	1.0600	10.732	0.50993	10.188	0.22668	10.018	0.12158	9.971	0.039976	9.943
1.8605	11.943	1.0176	10.681	0.48524	10.170	0.22449	10.015	0.11658	9.969	0.033799	9.941
1.8059	11.849	0.98419	10.637	0.46004	10.154	0.21381	10.015	0.10748	9.966	0.020962	9.932[a]
1.7484	11.736	0.93020	10.581	0.42904	10.131	0.20419	10.006	0.10291	9.965		
1.6902	11.644	0.90657	10.553	0.41482	10.122	0.19278	10.001	0.10107	9.963		
1.6059	11.502	0.87772	10.524	0.39924	10.113	0.19131	10.001	0.093741	9.962		
1.5480	11.417	0.83624	10.477	0.37180	10.093	0.18381	9.997	0.087602	9.957		
					T = 373.15 K						
10.124	73.89	8.4581	48.89	4.9075	21.22	1.5428	11.637	0.65425	10.531	0.16895	10.186
10.068	72.82	8.3271	47.37	4.4963	19.247	1.4720	11.528	0.62888	10.507	0.16736	10.183
10.019	71.93	8.1837	45.79	4.2911	18.588	1.4238	11.455	0.60677	10.489	0.15843	10.181
9.9746	71.08	8.0631	44.51	4.1788	18.291	1.3782	11.392	0.56622	10.454	0.14620	10.176
9.9233	70.14	7.9570	43.42	3.9158	17.369	1.3268	11.314	0.54540	10.437	0.13576	10.169
9.8571	68.98	7.8585	42.44	3.8074	17.206	1.2845	11.255	0.51302	10.410	0.12533	10.165
9.7746	67.55	7.7318	41.22	3.5822	16.385	1.2577	11.216	0.48950	10.393	0.11540	10.162
9.7113	66.46	7.5674	39.68	3.4355	16.012	1.1994	11.134	0.46639	10.374	0.10909	10.158
9.6501	65.43	7.4780	38.85	3.0597	14.925	1.1534	11.082	0.43766	10.353	0.10295	10.156
9.6020	64.65	7.3508	37.72	2.8406	14.369	1.1095	11.023	0.40686	10.331	0.095430	10.152
9.5424	63.67	7.2077	36.50	2.6889	13.974	1.0755	10.982	0.38264	10.314	0.087439	10.149
9.4859	62.78	7.0777	35.45	2.4785	13.465	1.0305	10.928	0.36144	10.300	0.079776	10.145
9.4163	61.71	6.9145	34.16	2.3356	13.148	1.0067	10.901	0.33402	10.281	0.072598	10.142
9.3269	60.35	6.6657	32.35	2.2017	12.858	0.96138	10.847	0.29914	10.256	0.066752	10.138
9.2403	59.08	6.5394	31.47	2.1214	12.689	0.92625	10.807	0.28390	10.247	0.059727	10.136
9.1605	57.91	6.3305	30.04	2.0405	12.536	0.89421	10.772	0.27222	10.240	0.053309	10.135
9.0713	56.69	6.0504	28.34	1.9407	12.336	0.85897	10.736	0.24925	10.227	0.046546	10.129
8.9809	55.42	5.9595	27.75	1.8365	12.132	0.82624	10.702	0.22789	10.219	0.039711	10.128
8.8854	54.18	5.8438	27.11	1.7633	12.007	0.78477	10.657	0.21019	10.209	0.032252	10.121[a]
8.8013	53.07	5.5735	25.31	1.7049	11.904	0.75934	10.633	0.20343	10.205		
8.7085	51.90	5.3606	23.92	1.6439	11.799	0.71712	10.591	0.19108	10.198		
8.5783	50.30	5.1624	22.73	1.5911	11.721	0.69784	10.574	0.17877	10.192		

Table 1 (Continued)

ρ / mol·L^{-1}	η / μPa·s	ρ / mol·L^{-1}	η / μPa·s	ρ / mol·L^{-1}	η / μPa·s	ρ / mol·L^{-1}	η / μPa·s	ρ / mol·L^{-1}	η / μPa·s	ρ / mol·L^{-1}	η / μPa·s
T = 398.15 K											
9.4301	62.55	7.0782	36.12	3.5729	17.490	1.4193	12.222	0.65491	11.227	0.17005	10.847
9.3525	61.39	6.9258	34.88	3.4089	16.945	1.3819	12.169	0.63013	11.203	0.15221	10.838
9.2911	60.48	6.7650	33.66	3.2710	16.531	1.3169	12.067	0.60207	11.176	0.14331	10.833
9.2215	59.47	6.5908	32.38	3.1191	16.067	1.2254	11.930	0.57395	11.147	0.13504	10.828
9.1902	58.99	6.4183	31.17	3.0014	15.732	1.1913	11.882	0.55846	11.134	0.12839	10.825
9.1174	57.98	6.2806	30.23	2.8941	15.427	1.1496	11.820	0.52082	11.099	0.12170	10.821
9.0571	57.11	6.1273	29.24	2.7606	15.068	1.1199	11.775	0.50297	11.084	0.11198	10.816
8.9639	55.87	6.0021	28.47	2.6098	14.669	1.0963	11.744	0.48163	11.065	0.10564	10.812
8.8979	54.98	5.8289	27.42	2.5045	14.414	1.0730	11.714	0.44644	11.035	0.099760	10.812
8.8042	53.76	5.6855	26.65	2.4023	14.165	1.0321	11.662	0.42308	11.016	0.094156	10.808
8.7008	52.48	5.5148	25.72	2.2852	13.893	0.96251	11.578	0.40861	11.004	0.086450	10.804
8.5892	51.09	5.3649	24.94	2.1483	13.588	0.92743	11.532	0.38421	10.985	0.079558	10.801
8.4534	49.51	5.1830	24.01	2.0878	13.462	0.90412	11.505	0.35411	10.963	0.073079	10.799
8.3157	47.91	5.0596	23.41	2.0168	13.317	0.87992	11.478	0.33740	10.952	0.067135	10.798
8.1985	46.64	4.8764	22.57	1.9169	13.118	0.86223	11.453	0.30683	10.931	0.060842	10.794
8.0828	45.41	4.7029	21.80	1.8438	12.967	0.84493	11.430	0.27699	10.907	0.055796	10.790
7.9302	43.86	4.5455	21.13	1.7712	12.839	0.82182	11.405	0.26413	10.898	0.048381	10.786
7.8216	42.76	4.3793	20.43	1.6927	12.696	0.80542	11.390	0.24626	10.889	0.041877	10.787
7.6617	41.21	4.2228	19.823	1.6245	12.576	0.77234	11.352	0.22907	10.879	0.034298	10.781
7.5297	39.98	4.0571	19.183	1.5750	12.482	0.72857	11.301	0.21184	10.869		
7.3907	38.74	3.9176	18.683	1.5216	12.394	0.71183	11.284	0.20188	10.864		
7.2478	37.53	3.7330	18.021	1.4696	12.306	0.68172	11.256	0.18098	10.853		
T = 423.15 K											
8.5960	51.84	6.0337	29.40	3.0395	16.660	1.1353	12.508	0.54644	11.791	0.17831	11.494
8.5207	50.97	5.8438	28.30	2.9000	16.257	1.0966	12.450	0.53016	11.775	0.16707	11.485
8.4411	50.04	5.7103	27.56	2.7440	15.843	1.0623	12.404	0.51442	11.758	0.15500	11.478
8.3597	49.10	5.5962	26.91	2.5980	15.435	1.0168	12.339	0.48081	11.728	0.14355	11.471
8.2481	47.85	5.4814	26.30	2.4444	15.068	0.96821	12.275	0.45877	11.706	0.13552	11.468
8.1613	46.90	5.3397	25.55	2.3576	14.847	0.92632	12.221	0.44219	11.694	0.12725	11.464
8.0581	45.80	5.1880	24.79	2.2071	14.486	0.89092	12.183	0.41060	11.664	0.11873	11.461
7.9295	44.47	5.0331	24.08	2.0698	14.186	0.86831	12.153	0.38979	11.648	0.11267	11.456
7.8372	43.57	4.9016	23.48	1.9532	13.950	0.83638	12.112	0.36287	11.623	0.10622	11.452
7.7404	42.62	4.7476	22.79	1.8491	13.731	0.81665	12.088	0.34996	11.615	0.097617	11.449
7.6186	41.46	4.5873	22.11	1.7444	13.529	0.79685	12.066	0.32808	11.596	0.091714	11.445
7.4723	40.14	4.3918	21.31	1.6610	13.375	0.76449	12.024	0.31066	11.584	0.085021	11.441
7.3719	39.24	4.1977	20.54	1.5713	13.215	0.73544	11.991	0.29161	11.569	0.078055	11.436
7.2111	37.88	4.0376	19.953	1.4986	13.084	0.71235	11.963	0.25930	11.545	0.070426	11.433
7.0963	36.93	3.8886	19.400	1.4358	12.982	0.69326	11.944	0.24449	11.536	0.062813	11.428
6.8725	35.17	3.7339	18.847	1.3835	12.893	0.67185	11.920	0.23152	11.526	0.055762	11.426
6.7199	34.01	3.5813	18.332	1.3313	12.810	0.65208	11.897	0.21868	11.517	0.049351	11.421
6.5625	32.91	3.4568	17.929	1.2842	12.731	0.62183	11.870	0.20675	11.509	0.043491	11.416
6.3727	31.59	3.3391	17.549	1.2243	12.640	0.60046	11.847	0.19682	11.504	0.035856	11.411
6.2244	30.62	3.1683	17.034	1.1832	12.583	0.58037	11.822	0.18713	11.498		

[a] Influenced by slip effect.

Table 2. Coefficients According to Equation 1

T / K	n	$\rho_{\max}$ / mol·L^{-1}	η_0 / μPa·s	$10^3\ \eta_1$ / μPa·s·L·mol^{-1}	$10^3\ \eta_2$ / μPa·s·L^2·mol^{-2}	$10^3\ \eta_3$ / μPa·s·L^3·mol^{-3}	$10^3\ \eta_4$ / μPa·s·L^4·mol^{-4}	σ / %
298.15	2	0.44	8.1411	−124.4	573.6			0.011
323.15	2	0.81	8.8081	26.5	539.8			0.022
348.15	2	0.76	9.4585	195.3	495.9			0.013
	3	1.51	9.4579	197.1	517.8	−40.08		0.019
366.15	2	0.93	9.9320	269.1	461.4			0.018
	3	2.65	9.9300	282.9	457.3	−14.23		0.031
373.15	2	0.83	10.1135	357.8	429.4			0.012
	3	1.64	10.1127	362.8	435.1	−19.02		0.018
	4	10.12	10.1035	416.9	390.6	−16.64	3.445	0.554
398.15	2	0.82	10.7678	381.2	485.8			0.014
	3	1.58	10.7679	374.5	526.1	−46.69		0.019
	4	9.43	10.7713	367.0	515.1	−43.56	4.927	0.071
423.15	2	0.89	11.3973	453.9	481.2			0.015
	3	1.57	11.3974	446.7	521.8	−45.56		0.020
	4	8.60	11.4017	429.5	526.8	−48.84	5.285	0.063

Unfortunately, the data at higher densities used for the complete reference correlation, even as primary data, are not characterized by similarly small uncertainties. We believe that the data of this work are better qualified as

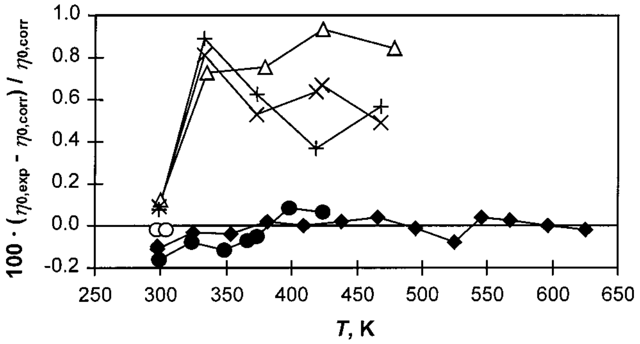

Figure 1. Deviations of experimental zero-density viscosity values from the correlation by Vogel et al.:[9] ●, this work; ♦, Vogel;[10] ○, Kestin et al.;[11] △, Kestin et al.;[12] +, Abe et al.;[13] ×, Abe et al.[14]

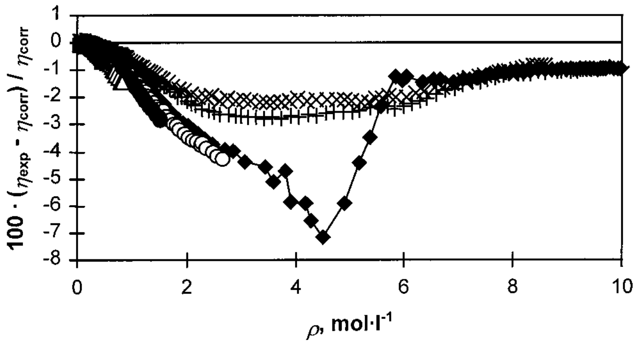

Figure 2. Deviations of the experimental viscosity values of this work from the correlation by Vogel et al.:[9] ■, 298.15 K; △, 323.15 K; ●, 348.15 K; ○, 366.15 K; ♦, 373.15 K; +, 398.15 K; ×, 423.15 K.

primary data than those which had to be used for the development of the reference correlation. Therefore, an agreement or disagreement with the reference correlation can hardly be used for a judgment of the uncertainty of the new data. The measurements reported here were performed with the intention to contribute to a more accurate database. Figure 2 displays the differences between the experimental results of this work and the reference correlation. The figure reveals that the deviations increase the more the density approaches the critical density. At T = 398.15 K and at T = 423.15 K, the deviations almost do not exceed the uncertainty range of ±2.5% that has been claimed for the reference correlation. Near the critical temperature in the region around the critical density, the deviations increase to up to 7.5%. However, it should be noted that the references used by Vogel et al. for the correlation provided only a few data for this region and that the deviations of the primary data from the correlation were within ±2.5%. The secondary data were even characterized by deviations within ±30%. Furthermore, the equation of state by Span and Wagner[6,7] was used to calculate the density values presented here, whereas the reference correlation is based on the equation of state by Younglove and Ely.[15]

Conclusion

Measurements on gaseous propane in wide density ranges were carried out with a new vibrating-wire viscometer. A high accuracy was achieved, except for measurements close to the critical point of propane, at which the determination of the gas density had a high uncertainty. We recommend that the new data be used to develop an improved viscosity database for propane.

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Received for review May 16, 2001. Accepted July 16, 2001. We are grateful to Deutsche Forschungsgemeinschaft, Germany, for financial support.

JE010062K