International Journal of Thermophysics (2022) 43:67
https://doi.org/10.1007/s10765-022-02994-2

Viscosity Measurements on Gaseous Methane: Re-evaluation

Sebastian Herrmann[1] · Eckhard Vogel[2]

Received: 8 February 2022 / Accepted: 10 February 2022 / Published online: 28 February 2022

Abstract

Previous experimental viscosity data for gaseous methane, published by Schley et al. (Int J Thermophys 25:1623, 2004) and originally obtained using a vibrating-wire viscometer in the temperature range between 260 K and 360 K, were re-evaluated after an improved re-calibration. For this purpose, a new reference value for argon at 298.15 K and at zero density, proposed by Vogel et al. (Mol Phys 108:3335, 2010) and further updated by Hellmann (Private Communication, 2020), was applied.

Keywords Methane · Re-evaluation · Viscosity

Previous measurements of the viscosity η for methane, carried out by Schley et al. [1] using a vibrating-wire viscometer with freely suspended weight and additional measurements of temperature T and pressure p for calculating the required density ρ with an equation of state by Setzmann, Wagner, and de Reuck [2, 3], have been re-evaluated. The re-evaluation concerns the specification of the wire radius by means of an improved calibration. The re-evaluated data, given as $\eta\rho pT$ values, are to be used together with other new accurate $\eta\rho pT$ data to generate a prospective viscosity correlation for methane.

The re-calibration of the applied vibrating-wire viscometer was performed in that way that the radius of the wire was newly specified using previous measurements on argon [4]. The original calibration employed an experimentally based reference value of Kestin and Leidenfrost [5] nowadays considered as obsolete. For the re-calibration, we used a today accepted value for the zero-density viscosity coefficient of argon, derived by Vogel et al. [6] from an ab initio potential on the basis of the kinetic theory of dilute gases and upgraded by Hellmann [7], to

✉ Sebastian Herrmann
s.herrmann@hszg.de

1 Fakultät Maschinenwesen, Hochschule Zittau/Görlitz, 02763 Zittau, Germany

2 Institut für Chemie, Universität Rostock, 18059 Rostock, Germany

be $\eta_{0,\mathrm{Ar},298.15\,\mathrm{K}} = 22.5534\,\mu\mathrm{Pa{\cdot}s}$ with a standard uncertainty of $\pm 0.07\,\%$. The wire radius amounts to $12.7548\,\mu\mathrm{m}$ using the new reference value for argon.

The results reported in Table II of the previous paper of Schley et al. [1] were restricted to $\eta\rho p$ triples along the measured isotherms. In this new report, we include more details in order to make the information comparable to that given for the new viscosity measurements by Humberg et al. [8]. They recommended further a re-evaluation of the measurements by Schley et al. The individual points were not exactly measured at the nominal temperature of an isotherm T_{nom}, but could be kept within small deviations from the nominal temperature each. The experimental viscosity data were adjusted to $\eta_{T_{\mathrm{nom}}}$ values at the nominal temperature using a Taylor series expansion restricted to the first power in temperature.

For this, the experimentally determined value of the initial density dependence $(\partial\eta/\partial T)_\rho = (0.030 \text{ to } 0.034)\,\mu\mathrm{Pa{\cdot}s{\cdot}K^{-1}}$ advised by Vogel [9] for methane was used. Further, it is supposed that the density values $\rho_{\mathrm{eos}(T,p)}$, computed from the measured data for T and p using the equation of state by Setzmann, Wagner, and de Reuck [2, 3], and those for the isotherms are the same. As a result of this, the pressures $p_{T_{\mathrm{nom}},\rho_{\mathrm{eos}}}$ at the nominal temperature changed and were recalculated from the densities. The improved experimental $\eta\rho pT$ data of this work for the previous measurements of Schley et al. [1] on methane (six isotherms at 260 K, 280 K, 300 K, 320 K, 340 K, and 360 K) are summarized in Tables 1, 2, 3, 4, 5, and 6, in which the data are given in the sequential arrangement of the original measurements.

The experimental data of each nominal isotherm for methane were correlated as a function of the reduced density δ by means of a power-series representation restricted to the fourth power:

$$\eta(\tau,\delta) = \sum_{i=0}^{4} \eta_i(\tau)\,\delta^i, \quad \delta = \frac{\rho}{\rho_{\mathrm{c,CH_4}}}, \quad \tau = \frac{T}{T_{\mathrm{c,CH_4}}}, \quad \text{with } \rho_{\mathrm{c,CH_4}} = 162.66\,\mathrm{kg{\cdot}m^{-3}}, T_{\mathrm{c,CH_4}} = 190.564\,\mathrm{K}. \tag{1}$$

Here, δ is the reduced density, whereas τ is the reduced temperature. The values of the critical density $\rho_{\mathrm{c,CH_4}}$ and of the critical temperature $T_{\mathrm{c,CH_4}}$ are those given by Setzmann, Wagner, and de Reuck [2, 3]. Weighting factors $w_i = 100\,\eta_{\exp,i}^{-2}$ were used in the multiple linear least-squares regression to minimize the weighted sum of squares $\sigma = \sum_i w_i(\eta_{\mathrm{cor},i} - \eta_{\exp,i})^2$ as criterion for the quality of the representation of the considered isotherm. The coefficients $\eta_i(\tau)$ of Eq. 1 including their standard deviations s.d.$_{\eta_i}$ and the weighted sum of squares σ for each isotherm are given in Table 7.

Table 1 Re-evaluated experimental $\eta\rho pT$ data for methane at 260 K

T (K)	p (MPa)	$p_{260\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{260\,\mathrm{K}}$ (μPa·s)
260.13	19.854	19.825	205.16	22.620	22.615
260.10	19.492	19.470	202.55	22.326	22.322
260.07	19.007	18.992	198.92	21.910	21.908
260.04	18.479	18.471	194.80	21.462	21.461
260.01	17.991	17.989	190.81	21.029	21.029
259.99	17.391	17.393	185.65	20.498	20.499
259.97	17.018	17.023	182.32	20.159	20.160
259.96	16.534	16.541	177.81	19.702	19.703
259.96	16.002	16.009	172.61	19.208	19.209
259.96	15.523	15.529	167.73	18.755	18.756
259.96	15.003	15.009	162.23	18.261	18.262
259.97	14.493	14.498	156.61	17.770	17.771
259.97	13.988	13.992	150.85	17.297	17.298
259.97	13.497	13.501	145.09	16.817	16.818
259.97	13.013	13.017	139.25	16.369	16.370
259.97	12.475	12.478	132.60	15.876	15.877
259.98	12.011	12.013	126.76	15.456	15.457
259.98	11.4752	11.4771	119.942	14.979	14.980
259.98	11.0092	11.0110	113.968	14.572	14.573
259.98	10.4966	10.4982	107.385	14.162	14.162
259.99	9.9936	9.9944	100.939	13.769	13.769
260.00	9.4550	9.4550	94.099	13.367	13.367
260.09	9.0135	9.0077	88.499	13.054	13.051
260.07	8.4848	8.4807	82.010	12.708	12.705
260.06	7.9975	7.9943	76.144	12.410	12.408
260.04	7.5015	7.4996	70.312	12.123	12.122
260.02	6.9988	6.9980	64.550	11.8522	11.8515
260.00	6.5024	6.5024	59.013	11.6044	11.6044
259.99	5.9959	5.9962	53.520	11.3753	11.3756
259.97	5.4974	5.4983	48.279	11.1632	11.1643
259.96	4.9940	4.9951	43.144	10.9688	10.9701
259.96	4.7449	4.7459	40.661	10.8774	10.8787
259.96	4.4832	4.4841	38.094	10.7878	10.7892
259.97	4.2613	4.2620	35.949	10.7148	10.7159
259.97	3.9886	3.9893	33.356	10.6234	10.6245
259.97	3.7393	3.7399	31.024	10.5494	10.5504
259.97	3.4825	3.4829	28.659	10.4806	10.4816
259.97	3.2477	3.2482	26.532	10.4108	10.4119
259.96	2.9859	2.9865	24.196	10.3439	10.3453
259.97	2.7329	2.7332	21.972	10.2837	10.2847
259.97	2.5032	2.5036	19.985	10.2308	10.2318
259.97	2.2622	2.2625	17.929	10.1784	10.1794

Table 1 (continued)

T (K)	p (MPa)	$p_{260\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{260\,\mathrm{K}}$ (μPa·s)
259.97	1.9976	1.9979	15.707	10.1176	10.1186
259.97	1.7530	1.7532	13.683	10.0703	10.0714
259.97	1.5006	1.5008	11.6262	10.0250	10.0261
260.11	1.2526	1.2521	9.6289	9.9870	9.9833
260.11	1.00295	1.00250	7.6539	9.9406	9.9369
260.11	0.89975	0.89934	6.8461	9.9258	9.9220
260.11	0.80037	0.80007	6.0726	9.9111	9.9073
260.11	0.70073	0.70036	5.3015	9.8932	9.8895
260.11	0.60083	0.60060	4.5327	9.8833	9.8795
260.12	0.49743	0.49725	3.7415	9.8665	9.8625
260.12	0.39841	0.39817	2.9884	9.8524	9.8484
260.12	0.30137	0.30118	2.2544	9.8381	9.8341
260.11	0.20117	0.20113	1.5007	9.8227	9.8189
260.12	0.10188	0.10185	0.75786	9.8026	9.7985

Table 2 Re-evaluated experimental $\eta\rho pT$ data for methane at 280 K

T (K)	p (MPa)	$p_{280\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{280\,\mathrm{K}}$ (μPa·s)
280.00	19.837	19.837	176.38	20.236	20.236
280.01	19.469	19.467	173.62	19.975	19.974
280.02	19.016	19.013	170.14	19.655	19.654
280.02	18.514	18.511	166.19	19.301	19.300
280.02	17.996	17.993	161.99	18.931	18.931
280.01	17.504	17.503	157.90	18.567	18.566
280.01	17.005	17.004	153.63	18.219	18.218
280.01	16.510	16.509	149.28	17.849	17.849
280.00	16.005	16.005	144.74	17.495	17.495
280.00	15.504	15.504	140.13	17.140	17.140
279.99	15.003	15.004	135.43	16.780	16.780
280.06	14.481	14.475	130.37	16.407	16.405
280.08	13.943	13.934	125.10	16.036	16.033
280.07	13.505	13.498	120.79	15.744	15.741
280.05	13.006	13.001	115.838	15.417	15.415
280.03	12.485	12.483	110.624	15.075	15.074
280.01	12.000	11.9991	105.734	14.772	14.771
279.98	11.4938	11.4953	100.625	14.458	14.459
279.96	11.0031	11.0059	95.662	14.167	14.168
279.94	10.4991	10.5031	90.573	13.878	13.880
279.91	9.9988	10.0044	85.551	13.601	13.604
279.90	9.4946	9.5003	80.512	13.336	13.340
279.88	8.9919	8.9982	75.540	13.080	13.084
279.89	8.5157	8.5210	70.868	12.851	12.854
279.88	7.9776	7.9829	65.670	12.603	12.607
279.88	7.4998	7.5047	61.121	12.397	12.401
279.88	7.0039	7.0083	56.475	12.194	12.198
279.88	6.5016	6.5055	51.851	12.004	12.008
279.89	5.9960	5.9993	47.283	11.8222	11.8259
279.90	5.4944	5.4971	42.840	11.6536	11.6569
279.91	4.9837	4.9858	38.410	11.4929	11.4958
279.93	4.7424	4.7439	36.347	11.4196	11.4219
279.95	4.4872	4.4882	34.189	11.3484	11.3501
279.97	4.2319	4.2324	32.054	11.2760	11.2769
279.99	3.9980	3.9981	30.119	11.2164	11.2167
280.00	3.7364	3.7364	27.981	11.1446	11.1446
280.01	3.4973	3.4971	26.047	11.0899	11.0896
280.01	3.2471	3.2469	24.047	11.0308	11.0305
280.02	2.9988	2.9985	22.083	10.9727	10.9721
280.03	2.7428	2.7425	20.081	10.9225	10.9215
280.04	2.4965	2.4961	18.176	10.8711	10.8698
280.04	2.2264	2.2260	16.111	10.8162	10.8149

Table 2 (continued)

T (K)	p (MPa)	$p_{280\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{280\,\mathrm{K}}$ (μPa·s)
280.03	1.9909	1.9906	14.332	10.7728	10.7718
280.02	1.7459	1.7457	12.500	10.7254	10.7248
280.02	1.4976	1.4975	10.6637	10.6821	10.6814
280.01	1.2405	1.2404	8.7835	10.6391	10.6388
280.00	0.99793	0.99789	7.0283	10.6023	10.6023
280.00	0.90042	0.90043	6.3279	10.5874	10.5874
280.00	0.79968	0.79975	5.6075	10.5717	10.5717
279.99	0.70064	0.70073	4.9025	10.5570	10.5573
279.99	0.60094	0.60100	4.1958	10.5466	10.5469
279.99	0.49987	0.49983	3.4824	10.5300	10.5303
279.99	0.40047	0.40050	2.7839	10.5194	10.5197
279.99	0.30068	0.30074	2.0857	10.5018	10.5021
279.99	0.19854	0.19853	1.3741	10.4868	10.4871
279.99	0.10051	0.10049	0.69416	10.4666	10.4669

Table 3 Re-evaluated experimental $\eta\rho pT$ data for methane at 300 K

T (K)	p (MPa)	$p_{300\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{300\,\mathrm{K}}$ (μPa·s)
300.36	20.079	20.028	155.47	19.028	19.016
300.35	19.572	19.525	151.95	18.735	18.723
300.33	18.984	18.941	147.77	18.400	18.390
300.31	18.512	18.473	144.35	18.131	18.121
300.29	18.000	17.965	140.57	17.839	17.830
300.28	17.508	17.476	136.86	17.560	17.551
300.27	17.008	16.978	133.02	17.276	17.267
300.26	16.499	16.471	129.05	16.983	16.974
300.36	15.996	15.959	124.98	16.702	16.690
300.34	15.512	15.479	121.12	16.441	16.430
300.33	15.006	14.975	117.009	16.162	16.151
300.32	14.545	14.517	113.233	15.923	15.912
300.30	14.048	14.023	109.131	15.656	15.646
300.28	13.479	13.457	104.400	15.364	15.355
300.27	12.999	12.979	100.374	15.119	15.110
300.27	12.519	12.500	96.330	14.882	14.873
300.27	12.016	11.9977	92.073	14.642	14.634
300.26	11.5266	11.5101	87.939	14.411	14.403
300.25	10.9621	10.9474	83.171	14.157	14.149
300.25	10.5010	10.4872	79.280	13.953	13.945
300.24	9.9986	9.9862	75.059	13.740	13.732
300.24	9.5112	9.4996	70.981	13.540	13.532
300.23	9.0100	8.9997	66.817	13.342	13.335
300.23	8.4735	8.4640	62.390	13.141	13.133
300.36	7.9941	7.9804	58.430	12.969	12.958
300.35	7.5080	7.4957	54.499	12.803	12.792
300.34	7.0117	7.0008	50.528	12.638	12.627
300.33	6.4804	6.4709	46.328	12.471	12.461
300.32	5.9811	5.9728	42.431	12.322	12.312
300.31	5.5018	5.4945	38.738	12.186	12.176
300.30	5.0006	4.9944	34.929	12.053	12.043
300.30	4.7591	4.7532	33.112	11.9902	11.9805
300.30	4.5009	4.4954	31.184	11.9285	11.9189
300.30	4.2541	4.2490	29.356	11.8682	11.8585
300.31	3.9947	3.9898	27.447	11.8102	11.8002
300.31	3.7562	3.7517	25.707	11.7569	11.7469
300.31	3.5015	3.4972	23.862	11.7009	11.6910
300.31	3.2523	3.2484	22.072	11.6473	11.6373
300.31	2.9960	2.9925	20.246	11.5949	11.5849
300.31	2.7408	2.7375	18.442	11.5479	11.5379
300.31	2.4972	2.4944	16.735	11.5006	11.4906
300.31	2.2534	2.2508	15.039	11.4581	11.4481

Table 3 (continued)

T (K)	p (MPa)	$p_{300\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{300\,\mathrm{K}}$ (μPa·s)
300.31	2.0059	2.0037	13.332	11.4137	11.4037
300.30	1.7534	1.7514	11.6043	11.3724	11.3627
300.30	1.4930	1.4914	9.8376	11.3321	11.3224
300.30	1.2532	1.2520	8.2245	11.2955	11.2859
300.30	0.99661	0.99556	6.5121	11.2574	11.2477
300.30	0.89862	0.89767	5.8620	11.2424	11.2327
300.31	0.79654	0.79568	5.1870	11.2284	11.2184
300.31	0.69734	0.69653	4.5334	11.2177	11.2077
300.31	0.60073	0.60009	3.8990	11.2062	11.1962
300.31	0.50093	0.50043	3.2458	11.1940	11.1840
300.31	0.40241	0.40197	2.6031	11.1802	11.1702
300.31	0.30029	0.29995	1.9392	11.1622	11.1522
300.32	0.20117	0.20097	1.2968	11.1503	11.1400
300.32	0.099667	0.099496	0.64141	11.1309	11.1206

Table 4 Re-evaluated experimental $\eta\rho pT$ data for methane at 320 K

T (K)	p (MPa)	$p_{320\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{320\,\mathrm{K}}$ (μPa·s)
320.06	19.936	19.929	137.78	18.266	18.264
320.04	19.508	19.503	135.04	18.065	18.063
320.02	19.019	19.017	131.86	17.832	17.831
320.01	18.525	18.524	128.60	17.594	17.594
320.00	18.011	18.011	125.15	17.357	17.357
319.99	17.539	17.540	121.96	17.131	17.131
319.98	17.033	17.035	118.488	16.900	16.901
319.97	16.525	16.528	114.963	16.677	16.678
319.97	16.017	16.020	111.394	16.437	16.438
319.96	15.495	15.498	107.700	16.205	16.206
319.95	14.998	15.002	104.152	15.983	15.984
319.94	14.500	14.505	100.573	15.775	15.777
319.96	14.000	14.003	96.939	15.563	15.564
319.95	13.493	13.496	93.254	15.353	15.355
319.95	12.977	12.980	89.484	15.142	15.144
319.95	12.482	12.485	85.852	14.940	14.942
320.08	11.8703	11.8657	81.305	14.712	14.710
320.07	11.5003	11.4964	78.591	14.565	14.563
320.06	11.0000	10.9969	74.921	14.381	14.379
320.05	10.4933	10.4909	71.208	14.201	14.199
320.03	10.0023	10.0009	67.621	14.030	14.029
320.02	9.4991	9.4983	63.952	13.858	13.858
320.01	8.9947	8.9943	60.289	13.693	13.693
320.00	8.4947	8.4947	56.676	13.538	13.538
319.99	8.0047	8.0050	53.155	13.389	13.389
319.98	7.4801	7.4807	49.410	13.235	13.236
319.97	6.9969	6.9977	45.986	13.103	13.104
319.96	6.4848	6.4859	42.386	12.965	12.966
319.95	5.9993	6.0005	39.002	12.837	12.839
319.95	5.4892	5.4902	35.477	12.713	12.714
319.94	4.9997	5.0008	32.130	12.599	12.600
319.94	4.7526	4.7538	30.453	12.543	12.544
319.95	4.5079	4.5087	28.798	12.492	12.493
319.96	4.2485	4.2491	27.055	12.434	12.436
319.96	4.0085	4.0091	25.452	12.385	12.387
319.96	3.7591	3.7597	23.795	12.333	12.334
319.97	3.4921	3.4925	22.031	12.283	12.284
319.97	3.2600	3.2604	20.507	12.240	12.241
319.97	2.9995	2.9997	18.806	12.190	12.191
319.98	2.7428	2.7431	17.141	12.147	12.148
319.98	2.4932	2.4933	15.531	12.103	12.104
319.98	2.2531	2.2533	13.993	12.064	12.065

Table 4 (continued)

T (K)	p (MPa)	$p_{320\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{320\,\mathrm{K}}$ (μPa·s)
319.98	2.0005	2.0007	12.384	12.025	12.025
319.98	1.7492	1.7492	10.7924	11.9839	11.9845
319.98	1.5026	1.5026	9.2415	11.9473	11.9480
319.98	1.2501	1.2501	7.6633	11.9125	11.9131
319.98	1.00008	1.00021	6.1106	11.8788	11.8795
320.06	0.90159	0.90137	5.5003	11.8655	11.8636
320.06	0.80028	0.80017	4.8757	11.8545	11.8526
320.06	0.69957	0.69952	4.2565	11.8418	11.8399
320.06	0.60029	0.60023	3.6477	11.8293	11.8274
320.06	0.50009	0.50003	3.0348	11.8181	11.8162
320.05	0.40013	0.40006	2.4251	11.8044	11.8028
320.05	0.30001	0.29998	1.8159	11.7916	11.7901
320.05	0.20142	0.20146	1.2175	11.7783	11.7767
320.04	0.097179	0.097227	0.58664	11.7561	11.7549

Table 5 Re-evaluated experimental $\eta\rho pT$ data for methane at 340 K

T (K)	p (MPa)	$p_{340\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{340\,\mathrm{K}}$ (μPa·s)
340.04	28.773	28.767	170.47	21.614	21.612
340.02	27.800	27.797	166.02	21.211	21.210
340.01	26.949	26.948	162.00	20.855	20.855
340.04	25.964	25.959	157.19	20.448	20.447
340.02	24.966	24.963	152.19	20.023	20.022
339.99	23.882	23.883	146.59	19.571	19.572
339.97	22.945	22.949	141.60	19.188	19.189
339.95	21.981	21.987	136.32	18.789	18.790
339.93	20.982	20.990	130.70	18.378	18.380
340.04	20.089	20.085	125.48	18.012	18.011
340.02	19.023	19.021	119.187	17.584	17.583
340.00	17.991	17.991	112.958	17.175	17.175
339.97	17.019	17.022	106.987	16.798	16.799
339.95	15.995	15.999	100.573	16.412	16.413
339.92	15.002	15.008	94.274	16.048	16.051
339.92	14.496	14.501	91.024	15.867	15.870
339.94	14.010	14.014	87.890	15.695	15.697
339.97	13.494	13.496	84.535	15.511	15.512
339.98	12.971	12.972	81.138	15.331	15.331
339.98	12.494	12.495	78.033	15.172	15.173
339.98	11.8825	11.8835	74.042	14.970	14.971
339.98	11.4908	11.4918	71.484	14.849	14.850
339.98	10.9859	10.9868	68.186	14.691	14.691
339.98	10.4666	10.4675	64.795	14.533	14.534
339.98	9.9898	9.9906	61.686	14.390	14.391
339.98	9.4977	9.4984	58.481	14.248	14.249
339.98	9.0019	9.0026	55.260	14.109	14.110
339.99	8.4909	8.4912	51.949	13.973	13.974
340.00	8.0050	8.0050	48.812	13.847	13.847
340.00	7.9406	7.9405	48.397	13.828	13.828
340.00	7.4842	7.4843	45.467	13.715	13.715
340.00	7.0060	7.0060	42.410	13.596	13.596
340.00	6.4721	6.4720	39.015	13.470	13.470
340.00	5.9912	5.9912	35.977	13.358	13.358
340.00	5.5006	5.5007	32.897	13.254	13.254
340.00	4.9156	4.9157	29.251	13.136	13.136
340.00	4.7412	4.7411	28.169	13.100	13.100
340.06	4.4865	4.4857	26.591	13.050	13.048
340.06	4.2523	4.2515	25.150	13.007	13.005
340.06	4.0025	4.0017	23.619	12.959	12.957
340.05	3.7476	3.7469	22.063	12.913	12.911
340.05	3.5061	3.5056	20.596	12.871	12.870

Table 5 (continued)

T (K)	p (MPa)	$p_{340\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{340\,\mathrm{K}}$ (μPa·s)
340.04	3.2440	3.2436	19.010	12.825	12.824
340.04	3.0040	3.0035	17.563	12.785	12.784
340.04	2.7531	2.7527	16.058	12.744	12.743
340.03	2.4972	2.4969	14.530	12.709	12.708
340.03	2.2541	2.2539	13.085	12.671	12.670
340.02	1.9946	1.9944	11.5491	12.635	12.634
340.02	1.7492	1.7491	10.1040	12.597	12.596
340.02	1.4925	1.4924	8.5991	12.565	12.564
340.02	1.2636	1.2634	7.2635	12.538	12.538
340.02	1.00122	1.00114	5.7401	12.502	12.502
340.02	0.90554	0.90556	5.1866	12.490	12.489
340.02	0.80276	0.80270	4.5931	12.476	12.476
340.02	0.70130	0.70118	4.0084	12.465	12.465
340.02	0.60212	0.60207	3.4380	12.453	12.452
340.01	0.50192	0.50189	2.8631	12.442	12.441
340.00	0.40440	0.40448	2.3045	12.432	12.432
339.99	0.30053	0.30056	1.7109	12.419	12.419
339.99	0.19776	0.19783	1.12459	12.401	12.401
340.00	0.099605	0.099633	0.56584	12.383	12.383

Table 6 Re-evaluated experimental $\eta\rho pT$ data for methane at 360 K

T (K)	p (MPa)	$p_{360\,\mathrm{K},\rho_{\mathrm{eos}}}$ (MPa)	$\rho_{\mathrm{eos}(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{360\,\mathrm{K}}$ (μPa·s)
360.01	29.185	29.183	158.93	21.191	21.191
360.01	28.029	28.028	153.89	20.767	20.766
360.02	26.906	26.903	148.82	20.348	20.347
360.03	25.978	25.975	144.53	20.021	20.020
360.03	24.996	24.993	139.87	19.659	19.658
360.04	24.027	24.023	135.15	19.298	19.297
360.04	22.887	22.883	129.46	18.900	18.899
360.03	21.983	21.980	124.85	18.576	18.575
360.03	20.985	20.982	119.640	18.220	18.219
360.02	19.942	19.940	114.086	17.854	17.853
360.01	18.990	18.989	108.918	17.522	17.522
360.00	18.015	18.015	103.537	17.195	17.195
359.99	17.036	17.036	98.044	16.869	16.869
359.99	16.004	16.005	92.174	16.535	16.535
359.99	14.993	14.994	86.356	16.214	16.215
359.99	14.494	14.495	83.458	16.056	16.056
359.98	13.983	13.984	80.480	15.901	15.901
359.99	13.481	13.481	77.541	15.753	15.753
359.99	12.985	12.986	74.635	15.607	15.607
359.99	12.488	12.488	71.707	15.462	15.462
360.00	11.9849	11.9849	68.740	15.322	15.322
360.00	11.5041	11.5041	65.901	15.189	15.189
360.00	10.9925	10.9925	62.878	15.051	15.051
360.00	10.4821	10.4821	59.860	14.917	14.917
359.98	9.9973	9.9980	56.998	14.790	14.791
359.98	9.4823	9.4829	53.955	14.660	14.661
359.98	8.9782	8.9788	50.980	14.537	14.538
359.98	8.5100	8.5106	48.222	14.427	14.427
359.97	8.0209	8.0218	45.348	14.309	14.310
359.97	7.4950	7.4959	42.264	14.193	14.194
359.98	7.0014	7.0018	39.376	14.089	14.090
359.97	6.5000	6.5007	36.457	13.981	13.981
359.97	6.0060	6.0065	33.590	13.882	13.883
359.96	5.5031	5.5038	30.686	13.782	13.783
359.96	5.0028	5.0035	27.810	13.692	13.693
359.96	4.7515	4.7520	26.370	13.649	13.650
359.96	4.5021	4.5027	24.946	13.600	13.602
359.97	4.2508	4.2511	23.513	13.557	13.558
359.98	3.9983	3.9986	22.079	13.517	13.517
359.98	3.7513	3.7515	20.680	13.474	13.475
359.99	3.5007	3.5007	19.264	13.432	13.433
359.99	3.2510	3.2510	17.859	13.394	13.394

Table 6 (continued)

T (K)	p (MPa)	$p_{360\,\mathrm{K},\rho_{eos}}$ (MPa)	$\rho_{eos(T,p)}$ (kg·m^{-3})	η (μPa·s)	$\eta_{360\,\mathrm{K}}$ (μPa·s)
359.98	3.0017	3.0018	16.461	13.355	13.356
359.98	2.7436	2.7438	15.018	13.318	13.319
359.98	2.4999	2.5001	13.660	13.289	13.289
359.97	2.2470	2.2471	12.255	13.252	13.253
359.97	1.9996	1.9998	10.886	13.216	13.217
359.96	1.7506	1.7508	9.5131	13.184	13.186
359.95	1.4988	1.4991	8.1296	13.154	13.155
359.95	1.2512	1.2515	6.7736	13.122	13.123
359.96	1.00063	1.00068	5.4064	13.092	13.093
359.96	0.90014	0.90031	4.8596	13.077	13.078
359.99	0.79961	0.79961	4.3131	13.071	13.071
359.99	0.69939	0.69949	3.7695	13.058	13.058
359.99	0.59989	0.59996	3.2307	13.046	13.046
359.98	0.50016	0.50026	2.6916	13.036	13.037
359.97	0.39974	0.39986	2.1495	13.021	13.022
359.97	0.29870	0.29874	1.6049	13.009	13.010
359.93	0.19670	0.19671	1.05611	12.994	12.997
359.92	0.10261	0.10272	0.55056	12.972	12.974

Table 7 Coefficients of Eq. 1 for the re-evaluated viscosity measurements on methane

T (K)	n	ρ_{max} (kg·m^{-3})	η_0 (μPa·s)	η_1 (μPa·s)	η_2 (μPa·s)
260	4	205.16	9.796 ± 0.001	2.712 ± 0.015	7.028 ± 0.060
280	4	176.38	10.465 ± 0.001	2.858 ± 0.016	6.863 ± 0.070
300	4	155.47	11.120 ± 0.001	2.965 ± 0.014	6.724 ± 0.070
320	4	137.78	11.755 ± 0.001	3.034 ± 0.017	6.804 ± 0.096
340	4	170.47	12.386 ± 0.001	2.996 ± 0.015	6.995 ± 0.069
360	4	158.93	12.979 ± 0.001	3.122 ± 0.024	6.557 ± 0.119
T (K)			η_3 (μPa·s)	η_4 (μPa·s)	σ
260			− 2.586 ± 0.080	1.349 ± 0.034	0.023
280			− 2.504 ± 0.108	1.299 ± 0.053	0.020
300			− 2.514 ± 0.122	1.339 ± 0.068	0.015
320			− 2.978 ± 0.186	1.691 ± 0.115	0.015
340			− 3.144 ± 0.111	1.680 ± 0.057	0.017
360			− 2.556 ± 0.205	1.409 ± 0.113	0.025

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

1. P. Schley, M. Jaeschke, C. Küchenmeister, E. Vogel, Int. J. Thermophys. **25**, 1623 (2004)
2. U. Setzmann, W. Wagner, Int. J. Thermophys. **10**, 1103 (1989)
3. W. Wagner, K.M. de Reuck, *Methane. International Thermodynamic Tables of the Fluid State-13* (Blackwell Science, Oxford, 1996)
4. J. Wilhelm, E. Vogel, Int. J. Thermophys. **21**, 301 (2000)
5. J. Kestin, W. Leidenfrost, Physica **25**, 1033 (1959)
6. E. Vogel, B. Jäger, R. Hellmann, E. Bich, Mol. Phys. **108**, 3335 (2010)
7. R. Hellmann, Private communication (Helmut-Schmidt University/University of the Federal Armed Forces Hamburg, Hamburg, Germany, 2020)
8. K. Humberg, M. Richter, J.P.M. Trusler, R. Span, J. Chem. Thermodyn. **147**, 106104 (2020)
9. E. Vogel, Private communication (University of Rostock, Rostock, Germany, 2020)