Table IV. Ternary System Constants

	Equation 3a						Equation 3b		
System	B_{123}	C_{123}	D_{123}	E_{123}	F_{123}	G_{123}	B_{123}	C_{123}	D_{123}
Cyclohexane-benzene-naphthalene	2.5907	−4.5198	−4.7043	1.8113	2.3196	4.2806	0.9763	−1.0664	−0.7895
Cyclohexane-toluene-naphthalene	2.9673	−5.5511	−5.4788	2.5181	2.6979	5.2945	1.0205	−1.1092	−0.8600
Cyclohexane-ethylbenzene-naphthalene	2.7167	−4.8873	−4.9902	2.0938	2.5301	4.4972	1.0100	−1.1220	−0.8365
Cyclohexane–carbon tetrachloride–naphthalene	5.4585	−10.1942	−11.3500	4.7299	6.1260	10.7561	1.3594	−1.3802	−1.3127
Hexane-benzene-naphthalene	3.1835	−6.7509	−6.2560	3.6274	3.2043	6.5781	0.8402	−0.9703	−0.7633
Hexane-toluene-naphthalene	1.5487	−2.8260	−2.9444	1.2195	1.5036	2.7235	0.5160	−0.5800	−0.4395
Hexane-ethylbenzene-naphthalene	1.2323	−2.2293	−2.1376	0.9425	0.9983	1.9447	0.5049	−0.5726	−0.4261
Hexane–carbon tetrachloride–naphthalene	6.7871	−13.1284	−15.4595	6.4527	8.9758	14.8240	1.0988	−1.0474	−1.2149
Cyclohexane-hexane-naphthalene	10.9516	−23.0937	−22.3052	12.2495	11.4918	23.7388	1.0097	−1.0103	−0.9092

In applying these constants in Equation 3a or 3b to a system, subscripts 1, 2, 3, refer to the components in the order listed in column 1 of this table.

ACKNOWLEDGMENT

The University of Georgia Institute of Statistics provided vital assistance in computation.

NOMENCLATURE

A_{ij} = function defined in Equation 2
A_{ijk} = function defined in Equation 4
B_{ij}, C_{ij}, D_{ij} = constants in Equation 2
$B_{ijk}, C_{ijk}, D_{ijk}, E_{ijk}, F_{ijk}, G_{ijk}$ = constants in Equation 4
n = refractive index
n_i = refractive index of pure component i
x_i = mole fraction of component i

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RECEIVED for review August 22, 1966. Accepted November 10, 1966.

Viscosity of a Mixture of Methane and *n*-Butane

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Measurements of the viscosity of a mixture of methane and *n*-butane containing 0.394 mole fraction methane have been carried out with a couette-type instrument at pressures up to 5000 p.s.i. in the temperature interval between 40° and 400° F. Good agreement with an earlier investigation involving an effusion-type instrument was realized. The present results and comparisons with the earlier data are depicted in both graphical and tabular form.

THE VISCOSITY of the paraffin hydrocarbons at atmospheric and elevated pressure has been the subject of many investigations over the past two decades. In the case of methane, the viscosity has been investigated experimentally in some detail (*1-4, 6, 7, 10, 13, 14*). Likewise, the viscosity of *n*-butane has been investigated rather completely (*5, 9, 11, 15-18*). Satisfactory agreement for both methane and *n*-butane was obtained between effusion and couette-flow equipment. The agreement as to the viscosity of a particular state as measured with widely different types of equipment lends credence to the accuracy of the absolute values for these compounds.

Recently, the viscosity of four mixtures of methane and *n*-butane was established by Dolan, Ellington, and Lee (*8*) at pressures as high as 5000 p.s.i.a. in the temperature interval between 70° and 340° F. The measurements upon each of the mixtures did not, for the most part, extend throughout all of the above-mentioned range of pressures and temperatures. A summary of the range of states investigated by Dolan, Ellington, and Lee (*8*) and the authors is set forth in Table I.

Dolan, Ellington, and Lee (*8*) carried out their measurements with an effusion type of instrument. To extend the data for the methane-*n*-butane system to another type of flow, measurements were undertaken upon a single mixture of methane and *n*-butane containing 0.394 mole fraction methane with a rotating cylinder instrument (*12*). The effect of pressure upon the viscosity of the mixture of methane and *n*-butane for each of the temperatures investigated is presented in Figure 1. The authors' and Dolan's experimental data are included. Values of the experimental measurements, together with the calibration of the equipment, are available in Table II. Recorded pressures are carried to one more significant figure than is justified by the accuracy, in contradistinction to the precision, of the pressure measurements. Likewise, the viscosities have been carried to at least one, and possibly two, more significant figures in the interest of indicating the reproducibility of the measurements at a given state.

Table I. Range of States Investigated

Temp., ° F.	Pressure, P.S.I.A. Minimum	Pressure, P.S.I.A. Maximum
0.25 Mole Fraction Methane[a]		
100	1000	2500
160	1000	2500
220	1250	2500
340	700	2000
0.50 Mole Fraction Methane[a]		
100	2000	4000
160	2000	3500
220	2000	3000
280	600	3000
0.70 Mole Fraction Methane[a]		
100	1900	6000
160	1750	6000
169	800	1825
171	530	2000
190	540	2500
220	200	2500
0.90 Mole Fraction Methane[a]		
70	2000	3000
100	600	8000
160	600	3000
220	800	5000
0.394 Mole Fraction Methane[b]		
40	1200	5000
100	1250	5100
220	400	5200
340	1000	5000
400	1000	5000

[a] Ref. (*8*). [b] Authors.

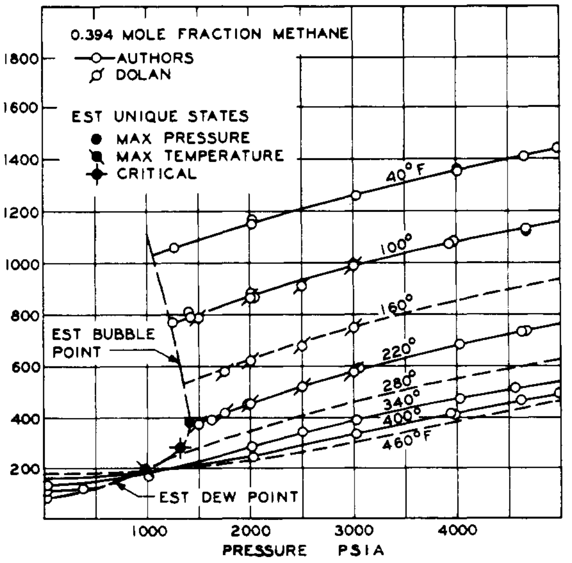

Figure 1. Viscosity of a mixture of methane and *n*-butane

Smooth values of the viscosity for the mixture containing 0.394 mole fraction methane are set forth in Table III. The table includes the standard error of estimate and average deviations of the smoothed data from the authors' measurements. The variation in viscosity with respect to composition for two different temperatures at several even

Table II. Experimental Measurements of Viscosity for a Mixture of Methane and *n*-Butane Containing 0.394 Mole Fraction Methane

Pressure, P.S.I.A.	Viscosity, Micropoises	Pressure, P.S.I.A.	Viscosity, Micropoises	Pressure, P.S.I.A.	Viscosity, Micropoises
40° F.		100° F. (cont.)		220° F. (cont.)	
20.3	83.28	1420.62	798.85	5183.88	776.72
20.3	80.23	1999.97	879.32	5189.51	777.74
20.3	80.61	2000.27	877.14		
20.3	80.35	2001.28	878.02	340° F.	
1210.03	1058.99	2017.24	869.86		
1214.36	1058.71	2028.80	871.54	28.66	131.06
1214.36	1059.24	2031.11	870.44	28.66	131.13
1215.36	1065.72			28.66	131.24
2015.44	1150.12	100° F.		28.66	131.84
2017.44	1165.94			1016.44	169.43
2019.06	1151.92	3008.78	988.24	1016.44	170.24
2019.06	1152.33	3013.50	988.67	1016.44	171.46
3027.27	1258.39	3016.92	988.23	2020.99	287.82
3028.37	1259.12	3926.24	1073.93	2021.09	286.06
3029.88	1259.15	3928.05	1075.20	2022.20	287.81
4005.01	1353.82	3943.63	1079.11	2498.46	344.55
4007.03	1362.53	4669.40	1132.80	2498.46	345.90
4011.45	1359.43	4670.51	1129.19	3021.23	388.81
4633.31	1411.46	4670.81	1127.12	3021.63	389.79
4633.11	1412.26	5126.67	1168.90	4030.64	476.84
4972.36	1447.77	5128.37	1168.55	4032.35	477.22
4974.07	1444.90	5129.48	1166.01	4035.46	478.18
4980.36	1448.25	5133.00	1172.19	4584.40	519.89
				4598.37	519.79
100° F.		220° F.		4604.60	522.13
				5027.48	537.31
22.32	89.43	24.18	109.26	5031.91	539.63
22.42	90.06	24.18	109.24	5037.94	539.62
22.42	90.05	24.18	109.46		
22.42	89.58	398.03	119.40	400° F.	
1180.74	782.76	398.13	119.42		
1180.74	784.28	398.13	119.50	1014.72	166.98
1180.74	784.66	1623.56	393.11	1014.72	167.38
1180.74	785.48	1623.66	392.27	1014.93	167.32
1207.28	757.57	1623.76	390.65	2022.23	242.84
1207.28	773.28	1989.55	454.63	2022.33	250.72
1207.28	777.08	1990.15	458.30	2022.43	259.86
1207.28	779.68	1996.48	460.78	3022.28	338.10
1217.89	768.66	2003.72	461.10	3030.22	339.19
1217.89	768.69	3039.31	591.08	3034.74	339.59
1247.14	772.31	3040.72	591.95	3933.08	419.19
1247.14	772.79	3040.72	592.85	3959.08	417.71
1269.04	776.33	4023.59	684.28	3968.97	420.10
1269.84	784.67	4026.51	682.47	4617.22	470.48
1409.00	806.42	4028.82	684.76	4646.97	473.73
1409.00	809.14	4633.99	735.41	4655.31	474.50
1409.00	811.12	4646.41	736.89	4920.58	487.72
1418.61	797.95	4652.84	733.81	5003.11	498.67
1419.92	795.00	5181.97	777.60	5071.96	503.50

Table III. Viscosity for a Mixture of Methane and *n*-Butane Containing 0.394 Mole Fraction Methane

Pressure, P.S.I.A.	Temperature, ° F. 40	100	160	220	280	340	400	460
	(15)[a]	(90)	(216)	(465)				
Dew Point	83[b]	88	102	121				
	(1050)	(1241)	(1387)	(1439)				
Bubble Point	1033	761	540	348				
200	...	...	99[c]	112	...	130	144	162[d]
400	...	...	...	120	...	132	145	163
600	...	...	...	...	...	138	148	165
800	...	...	...	...	...	148	155	168
1000	...	...	...	...	193[c]	162	165	174
1250	1059[b]	763	...	...	235	190	186	190
1500	1092	800	558	381	280	221	209	204
1750	1124	838	595	421	315	257	228	216
2000	1155	868	630	457	348	289	248	228
2250	1184	901	667	490	380	312	270	244
2500	1212	931	698	522	408	336	290	263
2750	1237	960	728	552	434	360	311	280
3000	1262	988	757	580	459	384	334	300
3500	1308	1037	811	633	512	430	378	340
4000	1353	1082	856	680	559	475	418	381
4500	1399	1122	898	724	594	508	458	424
5000	1446	1160	940	762	627	539	494	466
σ[e]	5.9	9.6		3.4		4.8	3.8	

[a] Values in parentheses represent dew-point or bubble-point pressure expressed in p.s.i.a. [b] Viscosity expressed in micropoises. [c] Values at this temperature interpolated from experimental data at higher and lower temperatures. [d] Values at this temperature extrapolated from experimental data at lower temperatures. [e] Standard error of estimate expressed in micropoises.

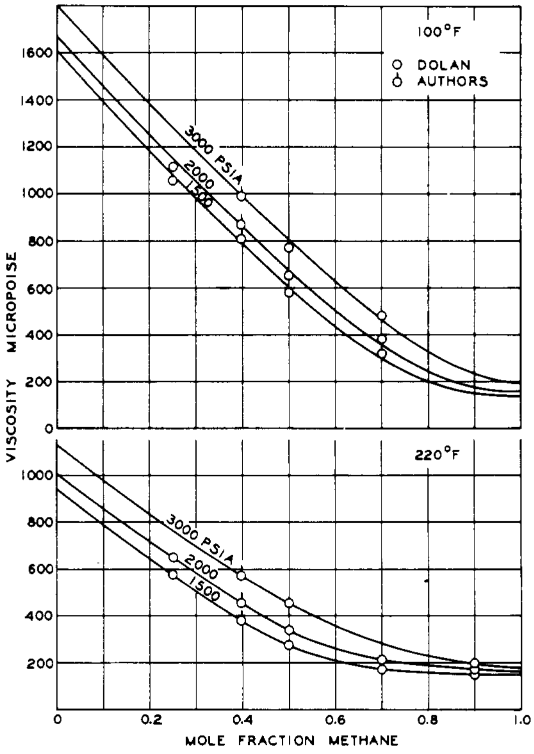

Figure 2. Viscosity of methane–*n*-butane system

Table IV. Comparison of Viscosity[a] from Two Sources

Pressure, P.S.I.A.	Viscosity, Micropoises Authors	Dolan (*8*)
	100° F.	
1500	800	790
2000	867	852
2500	930	910
	160° F.	
1750	594	582
2000	632	619
2500	699	682
3000	755	748
	220° F.	
1500	382	382
1750	411	411
2000	456	456
2500	521	525
3000	581	581

Relative standards error of estimate, $\sigma = 1.4\%$

$$\sigma = 100 \left[\left\{\sum_{1}^{N} \left[(\eta_A - \eta_D)/\eta_A\right]^2\right\}/N\right]^{1/2}$$

Average deviation, $s = 1.1\%$

$$s = 100 \left[\left\{\sum_{1}^{N} \left|(\eta_A - \eta_D)/\eta_A\right|\right\}/N\right]$$

[a] Composition 0.394 mole fraction methane.

values of pressure is shown in Figure 2. Again, values interpolated from Dolan (*8*) are included. The smoothed values for a composition of 0.394 mole fraction methane interpolated from the measurements of Dolan (*8*) are presented in Table III. The standard error of estimate of the present experimental measurements from the smoothed values of Dolan and coworkers (*8*) was 9.97 micropoises, or approximately 1.1%. This satisfactory agreement between the measurements upon the viscosity of the methane–*n*-butane system determined with an effusion instrument (*8*) and those established with a couette-type of equipment (*12*) increases the credence which may be placed in the available measurements concerning the viscosity of the methane–*n*-butane system.

These data have been presented in the interest of contributing to the confidence that may be placed in the measurements of Dolan, Ellington, and Lee (*8*) upon the methane–*n*-butane system. Measurements from two widely different types of instruments are an effective check upon the absolute uncertainty in the values of viscosity reported.

ACKNOWLEDGMENT

This work was supported by a grant from the National Science Foundation. Theresa Hubik carried out the graphical operations. June Gray prepared the figures, and B. Lawson Miller assisted in the preparation of the manuscript.

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Received for review May 31, 1966. Accepted August 3, 1966. This paper was accepted as a contribution to this journal by R. L. Pigford, Editor of *Ind Eng. Chem. Fundamentals.*

Latent Heat of Vaporization of Propane

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Calorimetric measurements of the latent heat of vaporization of propane were made in the temperature interval between 100° and 135° F. A critical review of the available calorimetric and volumetric data was made and an analytical expression developed by regression analysis, to describe the latent heat of vaporization for propane from 0° F. to the critical state with a standard error of estimate of 1.5 B.t.u. per pound.

THE latent heat of vaporization of propane has been the subject of a number of investigations. The early work of Dana *et al.* (*3*) was followed by some additional calorimetric measurements of the latent heat of vaporization of this hydrocarbon (*6*). The volumetric behavior of the compound and the vapor pressure have been studied by several investigators (*1, 2, 5, 8, 9*). There existed discrepancies of the order of 5 B.t.u. per pound between the latent heat of vaporization as estimated at 80° F. from the two calorimetric investigations (*3, 6*), and from the more recent volumetric measurements (*1, 2, 5*) and the calorimetric data at a temperature of 100° F.

As a result of this discrepancy, calorimetric measurements were made of the latent heat of vaporization of propane. The technique and equipment employed have been described (*4, 7*) and differ materially from the apparatus used earlier (*6*). The temperatures were measured with a platinum resistance thermometer which was compared recently with the indications of a similar instrument calibrated by the National Bureau of Standards. The temperature within the calorimeter was known within 0.01° F. of the international platinum scale. Temperature differences were established within 0.002° F. The experimental results are set forth in Table I. The measurements were not carried above 135° F. because the large volumetric corrections necessary in the calorimetric measurements made use of the Clapeyron equation based upon volumetric and vapor pressure measurements a preferable approach. The calorimeter is not arranged to permit measurements below 100° F. Direct comparison of the present calorimetric measurements with the data mentioned earlier is presented in Figure 1. In this figure, where data were obtained at nearly the same temperature, a single average value was depicted.

The following analytical expression was used to describe the latent heat of vaporization of propane in the temperature interval between 40° and 206.26° F.:

$$l = A(T_c - T)^{1/3} + B(T_c - T)^{2/3} + C(T_c - T) \qquad (1)$$

The application of least square regression methods yielded the following coefficients: $A = 21.771$; $B = 1.8935$; and $C = -0.10836$, with a standard deviation, σ, of 1.5 B.t.u. per pound from the experimental values depicted in Figure 1. The critical temperature employed was 665.95° R., based on Beattie's (*2*) measurements.

To illustrate the quantitative nature of the disagreement of the several sets of data, residual values of the latent heat of vaporization have been calculated, using Equation 1 as a reference value. The residual latent heat of vaporization is defined as

$$\mathbf{l} = l_r - l_e \qquad (2)$$

and is shown as a function of temperature for each of the experimental points employed in obtaining the points shown in Figure 2. The range of temperatures, the standard error of estimate, and average error are reported in Table II for each set of data from the values obtained from Equation 1.

As can be seen from Figure 2, the data of Dana *et al.* (*3*) yield values of at least 5 B.t.u. per pound above the current data when extrapolated to 100° F. The earlier