Thermal Conductivity of Fluids

A Mixture of Methane and *n*-Butane

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Experimental measurements of the thermal conductivity of a mixture of methane and *n*-butane containing 0.394 mole fraction methane were carried out at pressures up to 5000 p.s.i.a. in the temperature interval between 40° and 340° F. At attenuation the experimental results for this mixture of methane and *n*-butane are in satisfactory agreement with existing methods of predicting the thermal conductivity of an attenuated gaseous mixture. The thermal conductivity of this mixture appears to be a single-valued function of the specific weight of the mixture, except possibly in the critical region. No detailed measurements were made in this region. The accuracy of the data obtained upon this mixture is somewhat less than had been obtained earlier with the same equipment, apparently as the result of thermal diffusion which delayed the attainment of steady state.

LITTLE experimental information is available concerning the thermal conductivity of hydrocarbon mixtures even at attenuation (*40*) and only limited data are available for mixtures of nitrogen and hydrocarbons at attenuation (*6*). There exists uncertainty as to whether or not the thermal conductivity of a mixture is a single-valued function of the specific weight as is found for the pure paraffin hydrocarbons except in the critical region (*22, 37–39*).

The prediction of the thermal conductivity of mixtures at attenuation has received significant attention. However, there does not yet appear to be an effective means of predicting with accuracy the thermal conductivity of mixtures at pressures markedly in excess of atmosphere. It appears probable that from the detailed knowledge of the volumetric behavior (*33, 34*) and the viscosity of the mixture (*9, 18, 19*) it may be possible to predict the thermal conductivity. This can be done by utilizing the methods proposed by Chapman and Cowling (*6, 8, 10, 11*), which were based in part upon the early work of Enskog. Studies of the effect of pressure and temperature upon the viscosity of a mixture of methane and *n*-butane containing 0.394 mole fraction methane are available (*3, 9, 19*).

The present measurements were carried out upon a mixture containing 0.394 mole fraction methane in order to permit a direct comparison of methods of predicting the thermal conductivities when the volumetric behavior and the viscosity in the homogeneous region for a particular mixture are known. Furthermore, there exists the possibility of introducing empirical coefficients in the combining rules to permit either the viscosity or the thermal conductivity to be predicted from the volumetric data and the other transport property.

The effort required for thermal conductivity measurements is significantly greater than that associated with corresponding viscosity measurements (*3*). For this reason it did not appear practical to undertake a general investigation of the effect of pressure, temperature, and composition upon the thermal conductivity of the methane–*n*-butane system. However, such an approach would be most desirable if the necessary experimental effort could be made.

EQUIPMENT AND METHODS

The conductivity cell employed was of spherical section (*30–32*) and involved a gold-plated sphere approximately 3.5 inches in diameter placed symmetrically within a slightly larger spherical cavity. A radial transport path of approximately 0.020 inch was provided between the inner and outer spherical surfaces. The inner sphere was provided with a carefully constructed electrical heater that yielded nearly equal flux at all points around the surface of the sphere (*31*). Small thermocouples located near the outer surface of the sphere and the inner surface of the cavity were employed to evaluate the temperature of these spherical surfaces. Corrections were made for the difference in temperature of the thermocouples and of the associated spherical surface. These corrections took into account the radial temperature gradient in the stainless steel as the result of the thermal flux. Appropriate corrections were made for the changes in the length of the radial transport path as a result of changes in pressure and temperature. These corrections, for the most part, did not amount to more than 1% in the resulting value of thermal conductivity.

The thermal conductivity of helium was measured at several different times during this program. The results are set forth in Table I and include, for comparison, the values recommended by Hilsenrath and Touloukian (*12*) as well as the results of measurements by other investigators (*15, 25, 41*). A portion of these comparative data is the same as that reported earlier but has been included for comparison. The values in the lower part of the 130° and 220° F. sections of the table are directly associated with the current program. There has been no significant change in the behavior of the instrument throughout this investigation. The values for the thermal conductivity of helium experimentally measured after the program agreed within 0.8% with those obtained upon the completion of an earlier study upon propane. As had been found earlier (*4*), significant care is necessary in order to obtain pure samples of helium. Diffusion of the hydrocarbons from the interstices of the equipment into the helium causes significant variations in the measured thermal conductivities unless unusual precautions are taken. In the present instance, it was necessary to evacuate the equipment for at least 24 hours at a relatively high temperature in order to remove traces of *n*-butane and probably methane in the interstices of the seals of the spherical vessel (*30*).

At most of the states investigated, measurements were carried out at four different values of thermal flux. A period of approximately 24 hours was required at the higher pressures in order to obtain steady state. This long period resulted from some thermal diffusion in the transport path. Measurements of samples from the upper and lower part

Table I. Thermal Conductivity of Helium from Several Sources

Date	Pressure, P.S.I.A.	Temp., ° F.	Thermal Conductivity, B.t.u./(Hr.)(Ft.)(° F.) Authors	Keyes[a]	Hilsenrath, Touloukian[b]	Wilson[a]	Powell, Ho, Liley[a]
			ATMOSPHERIC PRESSURE				
1961	16.3	40	0.08204	0.08273	0.08257		0.08165
1959	15.0	100	0.08853	0.08864	0.08854	0.0890	0.08750
1960	18.9	100	0.08854				
1961	16.6	100	0.08859				
1964	18.1	100	0.08824				
1962[c]	17.7	130	0.09169	0.09150	0.09135		0.09064
1963[c]	16.4	130	0.09130				
1964[c]	173	130	0.09094				
1966[c]	17.1	130	0.09108				
1968	17.3	130	0.09179				
1959	17.7	220	0.09947	0.09960	0.09941		0.09878
1960	18.1	220	0.09946				
1968	17.6	220	0.09989				
1959[c]	15.0	340	0.10954	0.10957	0.10936		0.11003
1960[c]	18.4	340	0.10927				
Av. deviation[d]				0.00025	0.00018	0.00052	0.00070

[a] Statistical mechanical calculations and experimental data (*15, 25, 41*). [b] Critical review (*12*). [c] Average value for given year. [d] Average deviation expressed as:

$$s' = \sum_{1}^{N_p} \frac{|(k_e)_{av} - k_r|}{N_p}$$

of the path yielded significantly different compositions. However, as would be expected, the differences in composition decreased in nearly a linear fashion as the temperature gradients were decreased. Therefore, by extrapolating the apparent thermal conductivity (*30*) to zero thermal flux, the effect of the thermal diffusion could be mitigated.

As an indication of the magnitude of this effect for the samples reported, there are shown in Table II measurements of the composition of the sample introduced and that obtained at the bottom and in one instance at the top of the conductivity cell after a reasonable period of applying a thermal gradient to the spherical transport path. It was recognized that the spherical transport path is not particularly desirable for mixtures, but the magnitude of the effects after a number of measurements was larger than expected. The limiting value of the apparent thermal conductivity, defined as $(q_m/d\theta)/\Delta t_m$, was established for each thermocouple for zero thermal flux. Individual corrections for the location of the thermocouple below the surface of the sphere and shell were applied after the limiting value at zero flux of the aforementioned derivative was obtained by linear regression analysis to all the experimental points as a group. In the above-described regression analysis it was assumed that the apparent thermal conductivity changed with respect to thermal flux in the same fashion for all six thermocouples employed.

As the fluxes increased, there was a change in the average temperature of the transport path. The possibility of some local convection particularly near the equator of the sphere cannot be ruled out. As a result there is a significant variation in the apparent thermal conductivity with flux. The onset of gross convection within the transport path could be established easily by rapid increases in the apparent thermal conductivity with a small increase in the radial temperature gradient. Data in this region were discarded.

Table II. Composition of Sample

Sample Date	 Methane Mole Fraction	Cell[a] Date	 Methane Mole Fraction
12-9-66	0.394		
2-14-67	0.394		
4-3-67	0.400	4-5-67	0.375
		4-6-67	0.400
		4-10-67	0.410
		4-12-67	0.395
5-1-67	0.394	5-9-67	0.400
		5-10-67	0.403
		5-15-67	0.370
		5-16-67	0.369
		5-16-67	0.420[b]
		5-17-67	0.403
		5-18-67	0.402
		5-22-67	0.385
8-3-67	0.394	8-3-67	0.403
		8-4-67	0.390
Standard deviation, s[c] 0.002			0.015

[a] Taken from lowest point in cell. [b] Taken from highest point in cell. [c] Standard deviation, *s*, defined as:

$$s = \left[\sum_{1}^{N_p} (x_{av} - x)^2 / N_p \right]^{1/2}$$

In introducing the sample of methane and *n*-butane into the thermal conductivity cell, a somewhat more complicated procedure was necessary than in the case of pure substances. The desired mixture of methane and *n*-butane was prepared in equipment utilized for the study of the volumetric behavior of fluids (*35*). A magnetically driven mechanical agitator permitted the attainment of equilibrium between the methane and *n*-butane. The quantity of *n*-butane added was determined gravimetrically, while the quantity of methane was introduced by volumetric measurements from a second piece of equipment (*28*) which is also used for determining the volumetric behavior of fluids. From a knowledge of the volumetric behavior of methane at elevated pressures (*24*) it was possible to determine the composition of the sample prepared. Such samples were withdrawn and their actual composition was determined by partial condensation (*26*) and chromatographic techniques. The measured composition of each of the several samples employed is recorded in a part of Table II.

The samples were introduced into the thermal conductivity cell at temperatures and pressures well above those of the heterogenous region (*33, 34*). In fact, all the samples but one were introduced at pressures above 4000 p.s.i. and temperatures of 340° F. Conventional high vacuum techniques were employed in connection with the introduction of samples into the thermal conductivity cell. As a check upon the behavior, samples were withdrawn from the bottom of the thermal conductivity cell before temperature gradients were applied to the system. These are also reported in a portion of Table II. It is apparent that satisfactory agreement between the composition of the system as determined in the volumetric equipment and that obtained from the thermal conductivity cell was realized.

The thermocouples employed in the investigation were calibrated independently by varying the temperature of the agitated-silicone bath within which the conductivity cell was immersed. The temperature of the bath itself was determined by means of a strain-free, platinum resistance thermometer (*21*). This instrument was compared recently with the indications of a similar instrument that was calibrated at the National Bureau of Standards. The temperature of the silicone bath, which corresponds to that of the transport path at zero flux, was known relative to the International Platinum Scale within 0.01° F. throughout the range of temperatures of these measurements. The temperatures of the inner and outer surfaces of the spherical shell were known within 0.003° F. relative to each other. This permitted the radial thermal gradient to be established within 0.2% throughout the entire range of pressures and temperatures.

The pressure was measured by means of a balance involving a piston-cylinder combination (*27, 35*). This balance was connected to the thermal conductivity cell through an oil-mercury filled, stainless steel, aneroid-type diaphragm (*36*). The pressure balance was calibrated periodically against the vapor pressure of carbon dioxide at the ice point (*14, 16, 17*). Experience with the equipment over several decades (*35*) indicates that the pressures within the conductivity cell were known within 0.2 p.s.i. or 0.1%, whichever is the larger measure of uncertainty.

EXPERIMENTAL RESULTS

The apparent thermal conductivity as a function of flux shown in Figure 1 is typical of the experimental results obtained for the gas phase at low pressure. The standard deviation of the experimental points from the intercept of the straight lines of uniform slope was found to be 0.00009 B.t.u./(hr.)(ft.)(° F.), as is indicated on the figure. Little difficulty from thermal diffusion was experienced in the gas phase except at the higher temperatures and pressures. For these conditions, periods of at least 15 hours were required to reach steady state at the higher fluxes. Figure 2 shows corresponding information for this mixture at a pressure of 3927 p.s.i.a. and a temperature of 220° F. Under these circumstances a period of at least 24 hours was required to approach steady state at each flux. As is indicated on the figure, the standard deviation of the intercept of the straight lines of uniform slope from the experimental points was 0.00064 B.t.u./(hr.)(ft.)(° F.), which is nearly seven times the standard deviation obtained at the lower pressures and temperatures.

The unusually large increase in the standard deviation appears to result from thermal diffusion and the associated delay in obtaining steady state particularly near the equator of the spherical conductivity cell. A small part of this results from a slight loss of the symmetrical location of the sphere within the spherical cavity as a result of deformation at higher pressures. It is not believed that uncertainties, as a result of lack of symmetry in the inner and outer spheres (*4*), introduced more than 0.3% additional uncertainty in the experimental results.

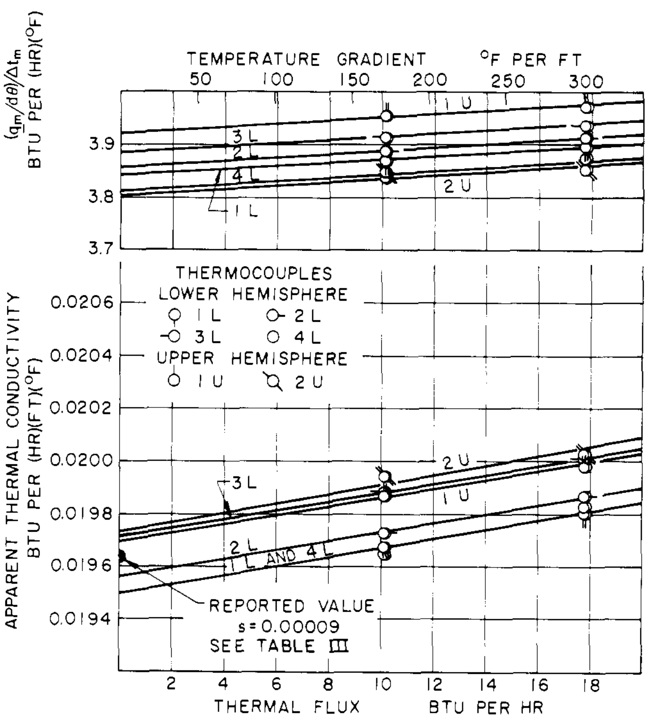

Figure 1. Effect of thermal flux upon apparent thermal conductivity at 280° F. and 95 p.s.i.a.

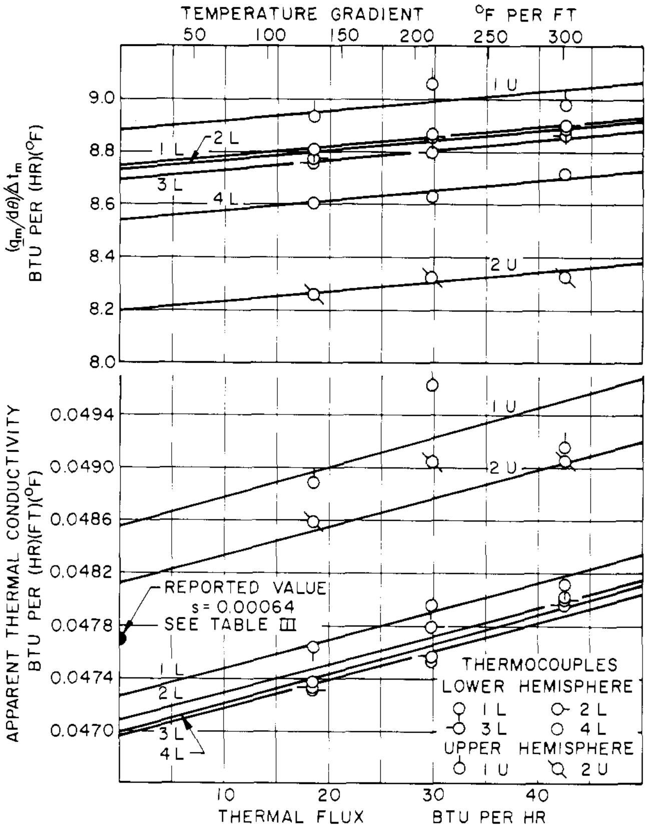

Figure 2. Effect of thermal flux upon apparent thermal conductivity at 220° F. and 3927 p.s.i.a.

The experimental investigations are summarized in Table III. The standard errors of estimate of the apparent thermal conductivity for all the experimental measurements are included. The average value of the aforementioned quantity has also been tabulated in order to make the standard

Table III. Experimental Conditions

Pressure, P.S.I.A.	No. of Flux Values	Maximum Flux, B.t.u./(Hr.)	No. of Points	Gradient[a], °F.$^{-1}$	Std. Error of Estimate[b], B.t.u./(Hr.)(°F.)	Thermal Conductivity[c], B.t.u./(Hr.)(Ft.)(°F.)	Std. Dev.[d], B.t.u./(Hr.)(Ft.)(°F.)
				40° F.			
16	4	15.37	24	0.00387	0.00314	0.01185	0.00005
1350	4	42.81	24	−0.00031	0.00706	0.05799	0.00097
1351[e]	2	28.46	12	...	...	0.05724	0.00067
2027	4	42.99	24	0.00688[f] −0.00157[g]	0.00587	0.05866	0.00080
3925	4	36.39	24	−0.00587	0.01189	0.06556	0.00112
4977	4	45.81	24	0.00067[f] −0.00230[g]	0.00663	0.06643	0.00207
				100° F.			
17	4	13.23	24	−0.00073	0.00241	0.01363	0.00006
70	4	11.89	24	0.01406	0.00316	0.01272	0.00008
1351	4	30.21	24	−0.00750	0.01168	0.05158	0.00045
2024	4	38.91	24	0.00248[f] 0.00041[g]	0.00275	0.05227	0.00034
3842	4	37.15	24	0.01017	0.00782	0.05474	0.00084
4935	4	35.38	24	0.00320	0.01308	0.05910	0.00130
				220° F.			
18	4	13.02	24	0.00078	0.00411	0.01645	0.00009
92	4	11.29	24	−0.00900	0.00369	0.01813	0.00010
373	4	13.15	24	−0.00081	0.00563	0.01929	0.00014
1530	4	27.29	24	0.01520	0.00840	0.04129	0.00080
2060[e]	3	60.10	18	0.01497	0.00701	0.03971	0.00050
2068[e]	4	17.21	24	−0.00157	0.00873	0.04239	0.00020
2151	4	26.72	24	0.00511	0.00798	0.04252	0.00010
2477[e]	24	61.46	144	...	...	0.04518	...
3927	3	42.61	18	0.00369	0.06095	0.04770	0.00064
				280° F.			
18	4	15.49	24	0.00006	0.00488	0.01684	0.00034
95	4	17.78	24	0.00324	0.00306	0.01964	0.00009
394	4	15.40	24	0.00305	0.00144	0.02131	0.00013
443[e]	4	15.55	24	0.00530	0.00459	0.02113	0.00008
				340° F.			
18	4	15.30	24	0.00057	0.00200	0.01854	0.00019
107	4	15.44	24	0.00145	0.00228	0.02222	0.00008

[a] Average value of $d[(q_m/d\theta)/\Delta t_m]/d(q_m/d\theta)$ for all thermocouple measurements, which corresponds to average slope of straight line shown in Figures 1 and 2. [b] Standard error of estimate of $[(q_m/d\theta)/\Delta t_m]_e$ from linear regression analysis of data from each of the several thermocouples:

$$\sigma = \left[\left\{ \sum_{1}^{N_p} \left[\left(\frac{q_m/d\theta}{\Delta t_m} \right)_e - \left(\frac{q_m/d\theta}{\Delta t_m} \right)_s \right]^2 \right\} / (N_p - 1) \right]^{1/2}$$

Extrapolated to zero time and zero flux. [d] Standard deviation from area-weighted average of indication of six thermocouples at zero time and zero flux:

$$s = \left[\sum_{1}^{N_p} (k'_{\text{av}} - k')^2 / N_p \right]^{1/2}$$

[e] Check measurement. [f] Average value of gradient of thermocouples in lower hemisphere. [g] Average value of gradient of thermocouples in upper hemisphere.

error of estimate more meaningful to the reader. The average value of the slope of the straight lines such as shown in Figures 1 and 2 has been included for each state. A markedly larger value of this gradient at the higher pressures, particularly at states involving liquids near the critical region, is evident from a review of Table III. As a matter of interest, there is shown in Figure 3, on a pressure-temperature diagram, the locus (*33, 34*) of the bubble point and dew point states of a mixture of methane and *n*-butane containing 0.394 mole fraction methane. This phase behavior presented in the figures was established much earlier (*33, 34*) and has been included only to indicate the location of the heterogeneous region and the unique states. The locations of the 27 states investigated in this study have been indicated to familiarize the reader with the position of the experimental states investigated relative to the border of the heterogenous region.

The effect of pressure upon the thermal conductivity of the mixture of methane and *n*-butane containing 0.394 mole fraction methane is shown in Figure 4. For the most part, each experimental point shown involves a total of some 24 experimental measurements, each based upon four different levels of flux. Experience indicated that approximately a week of continuous experimental effort was required to obtain the information depicted by each experimental point in Figure 4. Two check measurements were made at the higher pressure at a temperature of 220° F., and one check measurement was at the higher pressure at 40° F. Some difficulty was experienced in reaching steady state at the higher pressures even after 24 hours of operation of the equipment at a fixed radial temperature gradient.

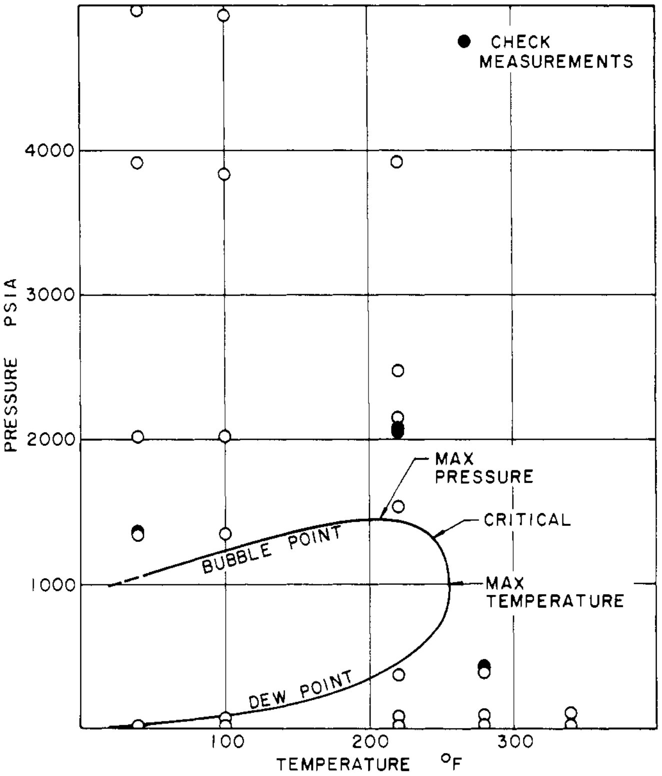

Figure 3. Pressure-temperature diagram and locus of bubble point and dew point

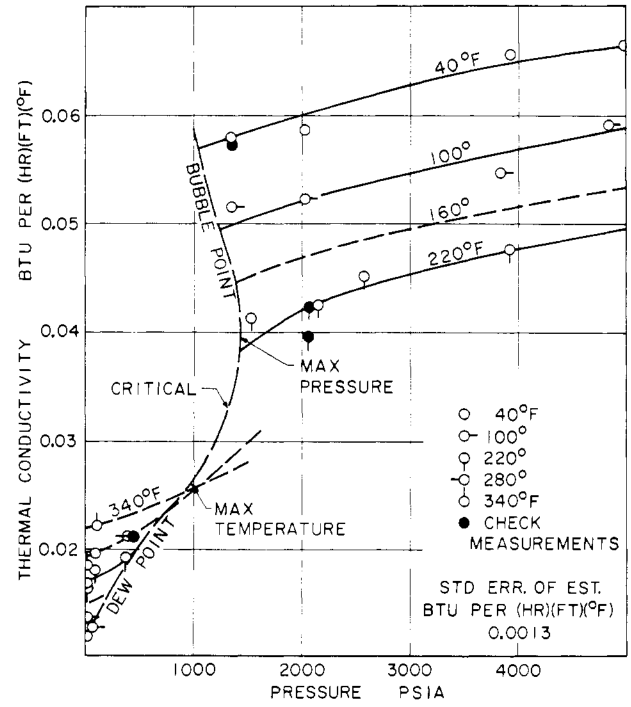

Figure 4. Effect of pressure upon thermal conductivity of a mixture of methane and *n*-butane

Each curve shown in Figure 4 at temperatures below the maximum heterogenous two-phase temperature for this mixture was extrapolated to the bubble point or dew point pressure as determined from volumetric and phase equilibrium study. From these a locus of bubble point and dew point states has been indicated. From the earlier volumetric and phase equilibrium investigations the critical point, the cricondentherm, and the point of maximum pressure have been indicated as a matter of interest. Greater uncertainties as the result of thermal diffusion were experienced at 280° and 340° F. It did not prove practical to obtain useful information at elevated pressures for these temperatures, which accounts for the absence of data above 220° F., except at the lower pressures.

From the data shown in Figure 4 the variations in the thermal conductivity with temperature were evaluated and are shown in graphical representation in Figure 5. Smooth values of the thermal conductivity of this mixture are reported in Table IV. The standard error of estimate of the experimental measurements from the smooth values shown in Figures 4 and 5 and recorded in Table IV was 0.0013 B.t.u./(hr)(ft.)(° F.).

In the opinion of the authors, these data at pressures above 500 p.s.i. involve an uncertainty of as much as 5% as the result of extensive thermal diffusion which was experienced in making such measurements. The behavior in the immediate vicinity of the critical state of this mixture was not studied because of increasing difficulties in obtaining steady state and large differences in composition found between the upper and lower hemispheres.

There is depicted in Figure 6 the thermal conductivity measured in this study as a function of specific weight, as established from earlier volumetric studies (*33*). It appears that the thermal conductivity, within the uncertainties associated with these measurements, is a single-

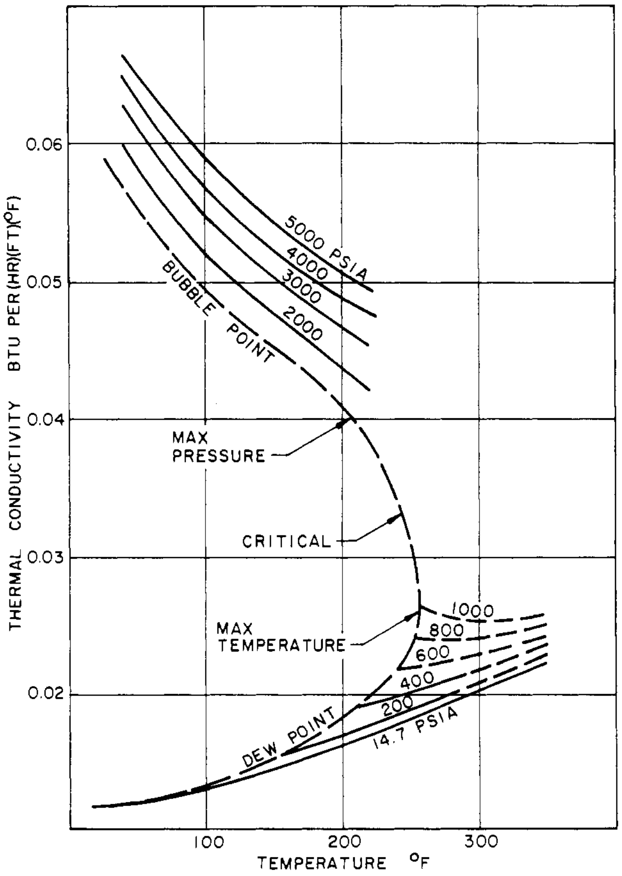

Figure 5. Influence of temperature upon thermal conductivity of a mixture of methane and *n*-butane

Table IV. Thermal Conductivity of a Mixture of Methane–*n*-Butane Containing 0.394 Mole Fraction Methane

Pressure, P.S.I.A.	Temperature, ° F. 40	100	160[a]	220	280	340
	(19)[b]	(90)	(216)	(465)		
Dew point	0.0119[c]	0.0133	0.0158	0.0200		
	(1050)	(1241)	(1387)	(1439)		
Bubble point	0.0570	0.0494	0.0445	0.0383		
Attenuation	0.0118[d]	0.0131	0.0149	0.0170	0.0194	0.0219
14.7	0.0118[c]	0.0131	0.0149	0.0171	0.0194	0.0220
100	...	...	0.0152	0.0173	0.0197	0.0222
200	...	...	0.0157	0.0178	0.0200	0.0225[d]
400	...	...	...	0.0193	0.0211	0.0232
600	...	...	...	...	0.0224[d]	0.0239
800	...	...	...	...	0.0239	0.0248
1000	...	...	...	...		
1500	0.0584	0.0504	0.0450	0.0387		
2000	0.0599	0.0521	0.0469	0.0420		
2500	0.0614	0.0535	0.0483	0.0439		
3000	0.0627	0.0547	0.0496	0.0452		
3500	0.0639	0.0557	0.0506	0.0465		
4000	0.0648	0.0568	0.0515	0.0476		
4500	0.0656	0.0578	0.0524	0.0486		
5000	0.0663	0.0589	0.0534	0.0494		
σ[e]	0.0008	0.0012	...	0.0014	0.0016	0.0035

[a] Values interpolated with respect to temperature. [b] Values in parentheses represent dew point or bubble point pressure expressed in p.s.i.a. [c] Thermal conductivity expressed in B.t.u./(hr)(ft.)(° F.). [d] Values extrapolated. [e] Standard error of estimate, σ, expressed in B.t.u./(hr)(ft.)(° F.):

$$\sigma = \left[\left\{\sum_{1}^{N_p} (k_e - k_s)^2\right\} / (N_p - 1)\right]^{1/2}$$

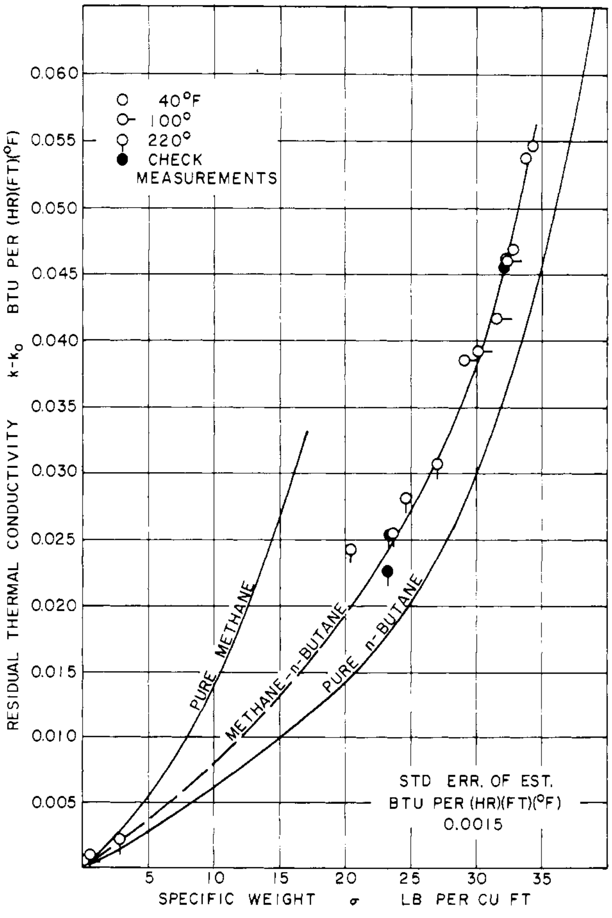

Figure 6. Residual conductivity of pure methane and pure *n*-butane and a mixture of methane and *n*-butane containing 0.394 mole fraction methane

valued function of the specific weight. It was predicted by Abas-Zade (*1*) that the residual thermal conductivity would be a single-valued function of specific weight for a pure substance. Michels and Sengers (*22, 37–39*) calculated the thermal conductivity excess for a large number of pure substances. They submitted evidence that the single-valued relationship of the residual thermal conductivity to specific weight is not valid in the critical region for pure substances but indicated it should apply for mixtures. This point of view is confirmed by the recent work of Bailey and Kellner (*2*) upon the thermal conductivity of argon near the critical point. Needham and Ziebland (*23*) recently confirmed the existence of an anomalous "enhancement" of the thermal conductivity of ammonia in the critical region. Guildner found a similar anomaly for carbon dioxide near the critical state. These matters are discussed in some detail by Reid and Sherwood (*29*). Insufficient experimental data were available from this study of methane and *n*-butane to offer any worthwhile indications as to whether or not the single-valued relationship expected by Abas-Zade for pure substances is valid in the critical region for hydrocarbon mixtures containing methane. The standard error of estimate of the experimental points shown in Figure 6 from the smooth curve drawn through the data was 0.0015 B.t.u./(hr.)(ft.)(° F.), which is several times as large as the standard error of estimate for methane (*5*) and *n*-butane (*7*). As a matter of interest, the corresponding curves for pure methane (*5*) and pure *n*-butane (*7*) have been included for comparison.

The data of Figure 4, extrapolated to attenuation and recorded in Table IV, are shown as a function of temperature in Figure 7. Values of the thermal conductivity of methane (*5*) and *n*-butane (*7*) at attenuation are included on the same diagram.

Following the methods that have recently been applied to the prediction of the thermal conductivity of mixtures of nitrogen-*n*-heptane and nitrogen-*n*-octane (*6*) and the prediction of the transport properties of paraffin hydrocarbons (*10, 11*), the thermal conductivity of the methane-*n*-butane system at several temperatures has been predicted as a function of composition on the basis of the Lennard-Jones 6-12 potential (*13*, Equation 8.2-36). In addition, the predicted values of the thermal conductivity of the mixture investigated following the procedures of Lindsay and Bromley (*20*) have been included. These data, shown in Figure 8, indicate reasonable agreement with the experimentally measured thermal conductivities extrapolated to attenuation. Reid and Sherwood (*29*) recommended that the technique suggested by Lindsay and Bromley (*20*),

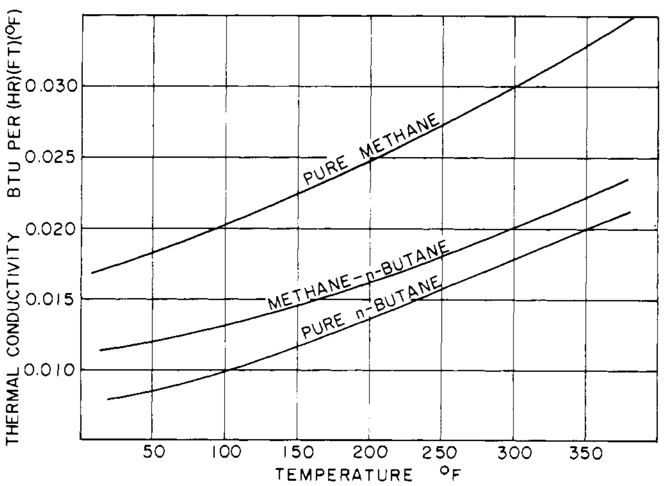

Figure 7. Thermal conductivity of pure methane and pure *n*-butane and a mixture of methane and *n*-butane at attenuation

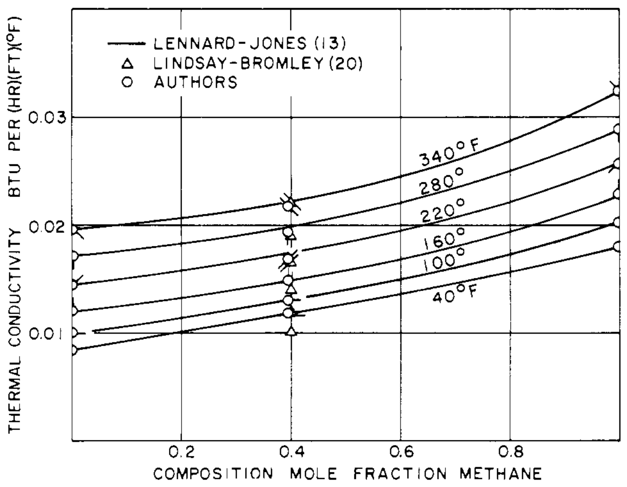

Figure 8. Effect of composition upon the thermal conductivity of methane–*n*-butane system at attenuation

as well as several other related methods, can be employed effectively in predicting the thermal conductivity of nonpolar mixtures at attenuation.

ACKNOWLEDGMENT

H. H. Reamer contributed to the supervision of the experimental measurements and Judith Bennett to the resolution of the experimental data.

NOMENCLATURE

d = differential operator
k = thermal conductivity, B.t.u./(hr.)(ft.)(° F.)
k_o = thermal conductivity at attenuation, B.t.u./(hr.)(ft.)(° F.)
k' = thermal conductivity uncorrected for effect of pressure on instrument, B.t.u./(hr.)(ft.)(° F.)
N_p = number of points
$q_m/d\theta$ = measured rate of energy addition, B.t.u./hr.
s = standard deviation defined in Tables II and III
s' = average deviation defined in Table I
x = mole fraction
Δt_m = measured temperature difference, ° F.
θ = time, hr.
σ = specific weight, lb./cu. ft.
σ = standard error of estimate defined in Tables III and IV
Σ = summation operator

Subscripts

av = average
e = experimental
r = reference
s = smooth
o = attenuation

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RECEIVED for review March 4, 1968. Accepted May 31, 1968. Experimental work carried out with the financial support of the National Science Foundation under Grant GP-2357.