Viscosity of Selected Liquid *n*-Alkanes

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A critical assessment has been made of the available experimental viscosity data for liquid *n*-hexane, *n*-heptane, *n*-octane, *n*-decane, *n*-dodecane and *n*-tetradecane, with the aim of establishing standard reference values along the saturation line. Recommended viscosities are given at 298.15 K with an uncertainty conservatively estimated to be ±0.3%, except for *n*-hexane and *n*-heptane where it is 0.4%. Selected data which cover most of the normal liquid range are satisfactorily correlated using a modified form of Arrhenius equation. The estimated uncertainty in this correlation is ±0.5% for viscosities above 0.2 mPa s and ±1% for lower viscosities.

Key words: Arrhenius, critically-assessed data, *n*-decane, *n*-dodecane, *n*-heptane, *n*-hexane, *n*-octane, *n*-tetradecane, viscometer, viscosity.

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1. Introduction

Recent accurate experimental measurements (80DYM, 89KNA, 91ASS, 92OLI) by different techniques of the viscosity of certain *n*-alkanes have shown that even for common members of this series, the American Petroleum Institute Tables (71API) are in error by up to 3% at temperatures not far removed from room temperature. It is therefore appropriate at this time to carry out a critical assessment of all the available viscosity data for these *n*-alkanes, namely *n*-hexane, *n*-heptane, *n*-octane, *n*-decane, *n*-dodecane and *n*-tetradecane. The Subcommittee on Transport Properties of the International Union of Pure and Applied Chemistry initiated this project with the aim of producing a set of standard reference viscosity values for these compounds. Other *n*-alkanes are not considered here because such extensive investigations of their viscosities have not yet been made.

In this paper we report the results of this study. After a brief summary of the various experimental methods used in viscosity determination, individual data sets for each compound are then considered. The criteria used in the selection of data sets as a basis for the recommendations are described. The selected data were then fitted as a function of temperature using a modified Arrhenius equation, by a weighted least squares method. Tables are given of the parameters in the equation. Values at 25 °C are proposed as standard reference values to be used in viscometer calibration.

2. Experimental Techniques

The experimental methods used for the determination of liquid viscosity are outlined briefly below. The main purpose of this survey is to explain the meaning of the abbreviations used in Tables 1 to 6, which summarize the available data.

Low pressure experimental viscosity measurements are generally made along the saturation line or at atmospheric pressure. In practice, the distinction between the values obtained under these different conditions is small since an increase in pressure of 1 bar will result in a viscosity higher by about 0.1%. The most common experimental method uses some kind of capillary viscometer (CAP). Where a specific type of viscometer has been used, it has been identified as follows:

OST – The Ostwald viscometer provides a simple method for the measurement of relative viscosities. In its basic form, there are errors due to volume change at different temperatures, and to surface tension effects. As a result, several modifications have been made to overcome these problems in the basic instrument, particularly in having the reference marks above and below the bulb in tubing of identical bore. OSM indicates a general modified Ostwald viscometer;

CF – Cannon-Fenske viscometer (38CAN).

UBB – The Ubbelohde "suspended-level" viscometer has the capillary opening at its lower end into a cylindrical tube of much larger diameter, and the liquid then flows down the sides. There is no requirement to have exactly the same volume of liquid at each temperature.

CUB – refers to the commercial Cannon-Ubbelohde viscometer, and CUM to a modified form (76ISL).

HCAP – Horizontal capillary viscometers, as used in the extensive investigations of organic liquids by Thorpe and Rodger (94THO) with air pressure to force the liquid through the capillary. Bingham and White (BIN) ground the capillary in sockets rather than sealing it in position.

SCAP – Steel capillary viscometers, for measurements at temperatures well above the normal boiling-point.

SSL – Specially constructed suspended-level glass viscometers which were sealed to enable measurements to be made at temperatures above the normal boiling-point.

WAS – The Washburn and Williams viscometer (WAS) was designed to reduce surface tension effects, but had a large lower bulb and required a large volume of liquid.

Capillary viscometers can be used to provide primary data; the exact solution (73KES) to the flow problem is practically identical to the working formula used by most experimenters. However, care must be taken in the construction of the viscometers, and in the majority of measurements the instrument is used to obtain relative values. In this case, it is essential that accurate values are known for the viscosity coefficient of the calibration liquid. For this reason, water is frequently used for viscometer calibration, with the recommended viscosity of 1.002 mPa *s* at 20 °C and 0.1 MPa, based on the value 1.0019 ± 0.0003 mPa s obtained by Swindells, Coe and Godfrey (52SWI). Consideration of the results obtained by other absolute methods led Marvin (71MAR) to conclude that the uncertainty associated with this reference value was ±0.25%. Kestin, Sokolov and Wakeham (73KES) give the uncertainty as ±0.1%. Recent measurements (88BER) using an absolute oscillation viscometer give a value of 1.0006 mPa s ± 0.05% at 20 °C and 0.1 MPa. When measurements are to be made for hydrocarbons of relatively low kinematic viscosity, it is not sufficient just to use water in the region of room temperature for calibration, since the coefficient of the kinetic energy term will not generally then be determined with sufficient accuracy, and surface tension effects may become important (91GON).

In assessing the accuracy of reported experimental viscosities, it is therefore necessary to take into consideration the viscosity values used for the calibration liquids. For the common calibration liquids benzene, toluene and *n*-hexane, viscosities taken as reference values from different sources at 25 °C can differ by more than 1%. These factors must also be taken into account with the following relative methods:

GFB – Guided falling-body method in which the time of fall of a body of specified shape between two points is accurately measured.

RB – Rolling ball method where the time taken for

a ball to roll between two points down an inclined plane is measured. This is the basis of the Hoppler (HOP) viscometer.

In contrast, the oscillating cylinder viscometer (OC) has the great advantage in requiring no calibration. Measurements are made of the damping of a right circular cylinder oscillating in contact with the liquid, and absolute viscosities are calculated from the working equations. A rotating cylinder viscometer (RCY) in which angular deformation of a stator is measured as a result of viscous drag is another absolute instrument.

The torsionally-vibrating quartz crystal method (VIB) can also be applied on an absolute basis but because of difficulties in background damping it has been used for relative measurements of *n*-alkane viscosities (82KAS).

More recently (87RET), the correct working equation for a vibrating-wire viscometer (VW) has been derived, and used for the determination of the viscosity of *n*-heptane (91bASS) and other *n*-alkanes (91aASS, 92OLI). The precision is high, but the accuracy (0.5%) is limited by the accuracy in the viscosity of the calibration liquids since it is not practicable to use water in the present apparatus.

3. Experimental Data

The available experimental data for which it was possible to obtain copies for each of the *n*-alkanes considered are summarised in Tables 1–6. For each reference, the following information is given.

Year of publication as (19)XX followed by the first three letters of the first author's name. This helps to identify the research group. References in the year 18XX are denoted *XX.

Temperature range and number of points. In many instances, viscosity measurements are at a single temperature. This often, though not always, indicates that viscosity determination was not the prime objective of the research. Accuracy is then often lower than where a series of measurements has been made over an extended temperature range.

Figures given for the accuracy are the authors own estimates. NSP (not specified) indicates that no such estimate was given.

The purity of the chemical used is a most important factor, to which increasing attention needs to be paid, preferably by analysis by gas chromatography (CHR). Unfortunately, in by far the majority of instances, indicated by NSP (not specified), no attempt was made to determine the percentage purity of the sample. Reported measurements of other physical properties (boiling-point BP, melting-point MP, refractive index RI and density RHO) do give some indication of the purity, by reference to literature values for the pure compounds, although even this information is often omitted. However, the effect of impurities cannot be assessed without knowledge of the actual impurities present.

The type of viscometer is identified by reference to the key in the above section.

A note on the calibration liquids is given. To assess the error arising in relative measurements, it is necessary to consider the values used for the viscosities of these liquids.

In order to establish standard reference values for the viscosity of these liquid *n*-alkanes, the most reliable experimental data must be collected by making critical assessment of the measuring techniques employed and the precision obtained. To assist in this assessment, it is convenient to follow the procedure which was set out by Nieto de Castro *et al.* (86NIE) for the determination of standard reference values for liquid thermal conductivity, and to define two categories of experimental data:

(1) Primary data – these are the results of measurements carried out with an instrument of high precision for which a complete working equation and a detailed knowledge of all corrections are available.

(2) Secondary data – these are the results of measurements of inferior accuracy to primary data. This may arise from incomplete characterisation of the apparatus, or the use of materials which are not standard reference materials for calibration where this is necessary for the method employed.

As previously noted (86NIE), this subdivision is somewhat subjective, but the following factors have been taken into account in identifying primary data:

(i) The correct working equation must be used for the technique employed.

(ii) All principal variables must be measured to a high precision.

(iii) There must be a description of purification methods and a guarantee of purity.

(iv) The data reported must be unsmoothed data.

(v) The measurements reported should ideally be absolute measurements, or relative values based on calibration with water using the 293.15 K viscosity values of 1.0019 mPa s (52SWI) or 1.0006 mPa s (88BER). Relative values based on calibration with toluene can be included, where measurements with water are not possible, although there is larger uncertainty in the toluene viscosity (87GON)

(vi) Explicit quantitative estimates of the uncertainty of the reported values should be given.

(vii) In order to produce high-accuracy reference values, data with uncertainties greater than a certain limit should be excluded. With these *n*-alkanes, the limit has been set at 0.6%.

3.1. Primary Data

The viscosity measurements that have been taken as primary data sets are summarised in Table 7. They were obtained by Dymond and Young (80DYM, 81DYM), Knapstad, Skjolsvik and Øye (89KNA), Assael *et al.* (92ASS) and Oliveira and Wakeham (92OLI), using three entirely different methods – capillary flow, oscillating cylinder and vibrating wire.

Dymond and Young (80DYM, 81DYM) used specially made sealed suspended-level viscometers to measure the viscosity of degassed liquids under their own vapour pressure from 10 to 120 °C. All materials were fractionally distilled before use, and subsequent chromatographic analysis gave the purities shown in Table 7. A Townson and Mercer bridge-controlled thermostat bath maintained temperatures to 0.02 K and temperatures were measured using a precision mercury in glass thermometer, which had been calibrated by the National Physical Laboratory, London. Viscosity measurements were made in pairs of viscometers having different dimensions to obtain a realistic estimate of the uncertainty of the reported viscosities. The results are traceable to water calibration in a Master viscometer. The uncertainty ranges from ±0.5% up to ±1%, for *n*-hexane above 313 K.

Knapstad, Skjolsvik and Øye (89KNA) used an absolute oscillating cylinder viscometer to measure the viscosities for each of these *n*-alkanes from 20 °C up to 150 °C, or approximately 20 °C below the normal boiling point. Gas chromatographic analysis showed that only the *n*-hexane and *n*-dodecane needed to be purified by distillation. The hollow cup was thermostatted inside a triple-walled column connected to a water bath circulator (*n*-hexane) or a double-walled column connected to an oil bath circulator (other *n*-alkanes). A calibrated Ni-NiCr thermocouple was used for temperature measurement. Previous viscosity measurements on water (88BER) have demonstrated the high accuracy of this method. The estimated uncertainty is ±0.3% for viscosities above 0.5 mPa *s*, ±0.4% for viscosities between 0.5 and 0.4 mPa s, and ±0.5% below 0.3 mPa *s*.

Recent measurements made by a vibrating-wire technique (92ASS and 92OLI) have high precision, and an improved accuracy following careful viscometer calibration to overcome the problems of measuring the density and radius of the wire. Temperatures were determined from measurement of resistance of a platinum wire element – with calibration against an N.P.L. calibrated platinum resistance thermometer. These viscosity results have an estimated uncertainty of ±0.5%.

Viscosities reported with a stated accuracy of better than 0.5% in other references have been rejected on one or more of the following grounds: impure samples [49GIL] (as evidenced by incorrect values for physical properties such as density, freezing-point or boiling-point), use of incorrect values of viscosity for calibration liquids [55HAM, 89WAK], lack of information on calibration liquid viscosity [76OZ, 80ADE, 87CEL], use of incorrect working equations [51DOO has too high a kinetic energy contribution] or absence of some essential experimental details [31SHE, 60MAC, 82SRF].

4. Correlation Procedure and Results

In order to obtain the most satisfactory representation of the temperature dependence of the *n*-alkane viscosities, attention was paid to the need for the expression to fit the selected data within the estimated uncertainties over the whole temperature range with a minimum number of parameters. In view of the success of the Arrhenius equation in fitting viscosity coefficient data over a limited temperature range, the modified Arrhenius equation was adopted:

$$\ln \mu / \mu_{298.15} = A + B / T^* + C / T^{*2} + D / T^{*3} \quad (1)$$

where $T^* = T/298.15$ and $\mu_{298.15}$ is the viscosity coefficient at 298.15 K.

Values for $\mu_{298.15}$, A, B, C and D were determined from the selected data sets by a weighted least squares procedure, with weights inversely proportional to the estimated uncertainties (Table 7). Different sets of parameters gave fits which were equally satisfactory, and values were selected which showed a good correlation with carbon number of the *n*-alkanes. Values obtained for the parameters A, B, C and D in equation (1) are listed in Table 8, together with a note of the temperature range for which this equation can be applied. Figure 1 shows the remarkable regular variation of each of the coefficients with carbon number of the alkanes. A similar observation has previously been pointed out (89AMB) in connection with the temperature dependence of the vapour pressure of these compounds.

The values derived for the viscosities of these compounds at 298.15 K are given in Table 9. The accuracy of these recommended values is estimated to be ±0.3%, except for *n*-hexane and *n*-heptane where it is 0.4%. The vibrating-wire viscometer experiments of Assael *et al.* (92ASS) provide a test of the consistency of these recommendations. They used viscosities for toluene (87GON) paired with values for *n*-hexane, *n*-heptane, *n*-octane and *n*-decane (89KNA) for calibration purposes to obtain the radius, R, and density, ρ_s, for the oscillating tungsten wire. They found R to be consistent within ±0.1% and ρ_s within 0.04%. As errors in the radius and in the density propagate with a factor of 2 with respect to viscosity, and the selected viscosities were within ±0.1% of the present recommendations at 298.15 K, it is an indication that the estimated uncertainties which are given here are conservative.

Differences between values calculated using this correlating equation and the selected viscosity data are shown in Figs. 2–7. For *n*-hexane, the agreement with the selected viscosities is better than ±0.2% up to 325 K, but the deviations increase to ±1% from the capillary viscometer measurements at temperatures above the normal boiling-point. However, this is the estimated experimental uncertainty for *n*-hexane in this temperature range (80DYM). In the case of *n*-heptane, the oscillating cup measurements (89KNA) agree with the calculated values to better than 0.15%. The vibrating-wire results [92ASS] are lower by 0.43% at 303.15 K and higher by 0.26% at 323.15 K, but both lie within the estimated experimental uncertainty. The correlating equation fits the selected *n*-octane data to within 0.1% up to 313 K except for the capillary measurement at 298.19 K (80DYM) which is low by 0.38%, but within the quoted

experimental uncertainty. At higher temperatures, the agreement is better than ±0.25% up to 393 K, where the difference is 0.38%. The fit to the primary data for *n*-decane, *n*-dodecane and *n*-tetradecane is better than 0.2% over the whole temperature range. The data fit is especially pleasing for *n*-hexane, *n*-octane and *n*-decane since measurements here were made by three different techniques. The agreement between values given by the correlating equation and other experimental data for these *n*-alkanes is very variable, as shown in Figs. 8–13. Some data sets are in close agreement, but others are seen to be significantly in error and to have an incorrect temperature dependence. Also shown are the deviations of widely-used tabulated viscosities (71API, 79ESD) from the present correlated values. It is observed that, except at the lowest temperatures, the values given by the American Petroleum Institute are too high, and this difference increases to more than 3% at temperatures above 330 K for hexane and heptane, above 350 and 410 K for octane and decane and above 430K for dodecane and tetra-decane. On the other hand, viscosities given by the Engineering Sciences Data Unit (79ESD) are in much closer agreement with the present values. They are in general slightly higher at the lowest temperatures; the difference decreases as the temperature is raised. For *n*-hexane and *n*-dodecane, the ESDU values are lower at the upper end of the temperature range. However, these differences all lie within their given conservative uncertainty limits.

5. Conclusions

Recommended viscosity values are given at 298.15 K for *n*-hexane, *n*-heptane *n*-octane, *n*-decane, *n*-dodecane and *n*-tetradecane. The estimated uncertainty in these values is ±0.3%, except for *n*-hexane and *n*-heptane where it is ±0.4%. For temperatures in the range 283 K to around 400 K, the recommended values along the saturation line are represented by parameters in a modified Arrhenius equation. The estimated uncertainty is ±0.5%, increasing to ±1% where the viscosity is less than 0.2 mPa s. These recommendations are based upon a critical assessment of all available data up to the end of 1991, and are therefore considered to be more reliable than any of the correlations at present available in the literature.

TABLE 1. Experimental viscosity data for *n*-hexane

Reference	*T* range/K	No. points	Accuracy /%	Purity /%	Method	Viscometer	Calibration liquid
*94THO	273.9–336.9	24	NSP	NSP	BP	HCAP	–
11DRA	289.5–295.4	5	NSP	NSP	BP	OST	WATER
13BIN	298.2–338.2	4	NSP	NSP	BP	HCAP	–
28TIM	288.2–303.2	2	NSP	NSP	BP/RI/RHO	OSM	WATER
31SHE	298.2	1	0.5	NSP	BP/MP/RI/RHO	WAS	NSP
39KHA	353.2–463.2	12					
46GEI	273.2–313.2	3	0.5	NSP	RHO	CF	WATER/HYDROCARB.
49GIL	174.7–293.2	14	0.5	NSP	MP/RI	CF	WATER
61PAR	299.8–454.8	11	2.0	NSP	NSP	SCAP	HEXANE
62HOL	298.2	1	NSP	NSP	RHO	NSP	WATER
64BID	298.2	1	NSP	NSP	RI/RHO	OST	NSP
67HER	298.2	1	NSP	NSP	RI/RHO	CF	NBSOILS
69BRA	273.2–333.2	3	NSP	NSP	RHO	RB	ALKANES
71GHA	298.2	1	NSP	99.95	RHO	CUB	SUPPLIED
72EIC	266.7–318.4	7	0.3–1.2	99.95	FP/CHR	UBB	WATER
73NAU	268.2–298.2	4	NSP	NSP	NSP	HOP	NSP
74BUL	293.2–372.2	11	0.5–1.5	NSP	NSP	HCAP	TOLUENE
74MOO	293.2–313.2	4	NSP	99+	CHR	CF	NSP
77MED	353.2–463.2	12	NSP	NSP	NSP	RB	BENZENE
79ISD	298.2–373.2	4	0.5	99+	RHO	SSL	WATER/HYDROCARB.
80DYM	283.2–393.2	12	0.5	99+	RI/RHO	SSL	WATER/HYDROCARB.
81ASF	298.2	1	NSP	99+	RHO/CHR	CUB	CANNON STANDARDS
81TEJ	298.2–323.2	3	1.0	NSP	NSP	CF	NPL CALIBRATION
82KAS	298.2–333.2	4	2.0	99+	NSP	VIB	12ORGANIC LIQUIDS
82SRE	303.2	1	0.5	NSP	NSP	OST	NSP
84BAU	293.2,298.2	2	NSP	99+	RHO	UBB	WATER
85AWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86aAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86bAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86SIN	303.2–333.2	4	NSP	NSP	RI/RHO	OST	NSP
89KNA	288.6–326.6	7	0.3–0.6	99.4	CHR	OC	–
89SCH	298.2	1	NSP	HPLC	RI/RHO	CF	WATER
90CHE	298.2	1	0.2	97+	RHO	UBB	WATER
91aASS	298.2	1	0.5	NSP	RHO	VW	TOLUENE
91COO	293.2	1	NSP	99.9	CHR	CUB	CANNON STANDARDS
92OLI	303.2–323.2	3	0.5	99.99+	CHR	VW	TOLUENE

TABLE 2. Experimental viscosity data for *n*-heptane

Reference	*T* range/K	No. points	Accuracy /%	Purity /%	Method	Viscometer	Calibration liquid
*94THO	279.6–365.4	26	NSP	NSP	BP	HCAP	–
25LEW	298.2	1	NSP	NSP	RHO	WAS	WATER
28SMY	293.2	1	NSP	NSP	RI/RHO	HCAP	NSP
31SHE	298.2	1	0.5	NSP	BP/MP/RI/RHO	WAS	NSP
35TIM	288.2–303.2	2	NSP	NSP	BP/RI/RHO	OST	WATER
46GEI	273.2–313.2	3	0.5	NSP	RHO	CUB	WATER/HYDROCARB.
46FAW	293.2	1	NSP	NSP	BP/RI/RHO	NSP	NSP
49GIL	180.2–293.2	15	0.5	NSP	MP/RI	CF	WATER
51DOO	263.1–372.7	4	0.2–0.5	NSP	FP/RI/RHO	UBB	WATER
55HAM	298.2	1	0.4	NSP	BP/RI/RHO	OST	7 LIQUIDS
60MAC	311.0	1	0.5	NSP	NSP	NSP	NSP
64BID	298.2	1	NSP	NSP	RI/RHO	OST	NSP
67DAR	293.2	1	NSP	NSP	RHO	NSP	NSP
73NAU	268.2–298.2	4	NSP	NSP	NSP	HOP	NSP
74MOO	293.2–313.2	4	NSP	99+	CHR	CF	NSP
75BAL	290.7–361.2	3	1.0	NSP	BP/RI/RHO	CAP	NSP
75MUS	293.2–298.2	2	<1.0	NSP	RI/RHO/CHR	HOP	AQGLYCERIN
76OZ	288.6–307.7	5	0.3	99.9+	CHR	UBB	HYDROCARBONS
78DUS	298.2	1	NSP	NSP	NSP	NSP	NSP
82KAS	298.2–348.2	4	2.0	99+	NSP	VIB	12 ORGANIC LIQUIDS
82SRE	303.2	1	0.5	NSP	NSP	OST	NSP
85AWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86aAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
87CEL	293.2	1	0.3	99+	NSP	UBB	WATER/BENZENE
89KNA	292.0–346.5	9	0.3–0.6	99.8+	CHR	OC	–
89KOU	298.2	1	0.4	99+	CHR	OST	NSP
89SCH	298.2	1	NSP	HPLC	RI/RHO	CF	WATER
90CHE	298.2	1	0.2	97+	RHO	UBB	WATER
91bASS	298.2–323.2	4	0.5	99.5	RHO	VW	TOLUENE
91COO	293.2	1	NSP	99.5	CHR	CUB	CANNON STANDARDS
92ASS	303.2–323.2	2	0.5	99.5	RHO	VW	TOLUENE

TABLE 3. Experimental viscosity data for *n*-octane

Reference	*T* range/K	No. points	Accuracy /%	Purity /%	Method	Viscometer	Calibration liquid
*94THO	273.4–395.2	24	NSP	NSP	BP	HCAP	–
28TIM	288.2–303.2	2	NSP	NSP	BP/RI/RHO	OST	WATER
30MAD	273.2–393.2	13	NSP	NSP	NSP	NSP	NSP
31SHE	298.2	1	0.5	NSP	BP/MP/RI/RHO	WAS	NSP
41SCH	293.2–353.2	7	NSP	NSP	MP/RI/RHO	NSP	NSP
46GEI	273.2–313.2	3	0.5	NSP	RHO	CF	WATER/HYDROCARB.
49GIL	211.2–293.2	15	0.5	NSP	MP/RI	CF	WATER
51DOO	263.1–372.7	4	0.2–0.5	NSP	FP/RI/RHO	UBB	WATER
69BRA	273.2–333.2	3	NSP	NSP	RHO	RB	ALKANES
73NAU	268.2–298.2	4	NSP	NSP	NSP	HOP	NSP
74MOO	293.2–313.2	4	NSP	99+	CHR	CF	NSP
76ISL	313.0–363.5	6	2.6	NSP	RHO	CUM	STANDARDS SUPPLIED
78DUS	288.2	1	NSP	NSP	NSP	NSP	NSP
80DYM	283.2–393.2	8	0.5	99+	RI/RHO	SSL	WATER/HYDROCARB.
82KAS	298.2–348.2	4	2.0	99+	NSP	VIB	12 ORGANIC LIQUIDS
82SRE	303.2	1	0.5	NSP	NSP	OST	NSP
86aAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86bAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
87WAK	328.2–338.2	2	0.5	99+	CHR	OST	WATER/ALKANES
89KNA	283.1–369.9	5	0.3–0.6	99.5+	CHR	OC	–
90ASF	293.2,298.2	2	NSP	99.7	CHR	CUB	CANNON STANDARDS
90CHE	298.2	1	0.2	97+	RHO	UBB	WATER
91COO	293.2	1	NSP	99.7	CHR	CUB	CANNON STANDARDS
91VAV	308.2,313.2	2	NSP	99.7	CHR	CUB	CANNON STANDARDS
92OLI	303.15	1	0.5	99.9+	CHR	VW	TOLUENE

TABLE 4. Experimental viscosity data for *n*-decane

Reference	*T* range/K	No. points	Accuracy /%	Purity /%	Method	Viscometer	Calibration liquid
13BIN	298.2–338.2	4	NSP	NSP	NSP	HCAP	–
30BIN	273.3–373.2	16	NSP	NSP	RHO	BIN	WATER
31SHE	298.2	1	0.5	NSP	BP/MP/RI/RHO	WAS	NSP
49GIL	240.2–293.2	14	0.5	NSP	MP/RI	CF	WATER
50MUM	293.2–298.2	2	NSP	NSP	BP/RI/RHO	OST	WATER/SUGAR SOLN
62HOL	298.2	1	NSP	NSP	RHO	NSP	WATER
69CAR	277.6–477.6	5	NSP	99.5+	RI	RCY	–
73NAU	268.2–298.2	4	NSP	NSP	NSP	HOP	NSP
74MOO	293.2–313.2	4	NSP	99+	CHR	CF	NSP
78DUS	288.2	1	NSP	NSP	NSP	NSP	NSP
80ADE	241.9–323.1	16	0.5	99+	RHO	CUB	STANDARDS SUPPLIED
81DYM	283.2–393.2	8	0.5	98+	RI/RHO	SSL	WATER/HYDROCARB.
82KAS	298.2–348.2	4	2.0	99+	NSP	VIB	12ORGANIC LIQUIDS
85AWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86AUS	298.2	1	NSP	NSP	RI/RHO	CUM10	ORGANIC LIQUIDS
86aAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86bAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86DUC	293.2–373.2	5	NSP	PURUM	NSP	GFB	NSP
87CEL	293.2	1	0.3	99+	NSP	UBB	WATER/BENZENE
87WAK	318.2–338.2	3	0.5	99+	CHR	OST	WATER/ALKANES
89KNA	293.1–423.2	11	0.3–0.6	100	CHR	OC	–
90ASF	293.2,298.2	2	NSP	99.8	CHR	CUB	CANNON STANDARDS
90CHE	298.2	1	0.2	97+	RHO	UBB	WATER
91COO	293.2	1	NSP	99.8	CHR	CUB	CANNON STANDARDS
91VAV	308.2,313.2	2	NSP	99.7	CHR	CUB	CANNON STANDARDS
92OLI	303.15	1	0.5	99.0	CHR	VW	TOLUENE

TABLE 5. Experimental viscosity data for *n*-dodecane

Reference	*T* range/K	No. points	Accuracy /%	Purity /%	Method	Viscometer	Calibration liquid
30BIN	273.3–373.2	8	NSP	NSP	RHO	BIN	WATER
31SHE	298.2	1	0.5	NSP	BP/MP/RI/RHO	WAS	NSP
38EVA	278.2–363.2	7	NSP	NSP	BP/RI/RHO	OSM	WATER/MERCURY
49GIL	262.2–293.2	11	0.5	NSP	MP/RI	CF	WATER
64BID	298.2	1	NSP	NSP	RI/RHO	OST	NSP
67HOG	352.6–408.2	3	5.0	NSP	MP	RB	WATER
67HOG	310.9–372.1	3	NSP	NSP	NSP	CF	NSP
80DYM	283.2–393.2	12	0.5	99+	RI/RHO	SSL	WATER/HYDROCARB.
82KAS	298.2–348.2	4	2.0	99+	NSP	VIB	12 ORGANIC LIQUIDS
85AWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86AUC	298.2	1	NSP	NSP	RI/RHO	CUM	10 ORGANIC LIQUIDS
85AWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86aAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86bAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86DUC	293.2–373.2	5	NSP	PURUM	NSP	GFB	NSP
87CEL	293.2	1	0.3	99+	NSP	UBB	WATER/BENZENE
87WAK	318.2–338.2	3	0.5	99+	CHR	OST	WATER/ALKANES
89KNA	293.8–425.5	11	0.3–0.6	100	CHR	OC	–
90ASF	293.2,298.2	2	NSP	99.9	CHR	CUB	CANNON STANDARDS
90CHE	298.2	1	0.2	97+	RHO	UBB	WATER
91COO	293.2	1	NSP	99.9	CHR	CUB	CANNON STANDARDS
91VAV	308.2,313.2	2	NSP	99.9	CHR	CUB	CANNON STANDARDS

TABLE 6. Experimental viscosity data for *n*-tetradecane

Reference	*T* range/K	No. points	Accuracy /%	Purity /%	Method	Viscometer	Calibration liquid
49GIL	277.7–293.2	10	0.5	NSP	MP/RI	CF	WATER
62HOL	298.1	1	NSP	NSP	RHO	NSP	WATER
67HER	298.2	1	NSP	NSP	RI/RHO	CF	NBS OILS
72RAS	302.7–523.5	7	1.5	NSP	NSP	CAP	NSP
85AWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86aAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86bAWW	298.2	1	NSP	99.5	CHR	UBB	NSP
86DUC	293.2–373.2	5	NSP	PURUM	NSP	GFB	NSP
87WAK	318.2–338.2	3	0.5	99+	CHR	OST	WATER/ALKANES
89KNA	292.9–424.0	10	0.3–0.6	99+	CHR	OC	–
90ASF	293.2,298.2	2	NSP	99.8	CHR	CUB	CANNON STANDARDS
90CHE	298.2	1	0.2	97+	RHO	UBB	WATER
91COO	293.2	1	NSP	99.8	CHR	CUB	CANNON STANDARDS
91VAV	308.2,313.2	2	NSP	99.8	CHR	CUB	CANNON STANDARDS

TABLE 7. Primary experimental data sources for viscosity

n-Alkane	Purity /%	Temperature/K control accuracy		No. of runs per Viscosity	Reproducibility /%	Assigned accuracy/%
Ref: 80DYM	Method: SSL					
n-Hexane	99.7[a]	0.02	0.05	minimum of	better	0.5
n-Octane	99.8[a]			3 per viscometer	than	
n-Dodecane	99.7[a]				0.3	
Ref: 81DYM	Method: SSL					
n-Decane	99.0[a]	0.02	0.05	3 per viscometer	<0.3	0.5
Ref: 89KNA	Method: OC					
n-Hexane	99.4	0.05	0.1 at	minimum of 4	0.09[b]	0.4–0.5[c]
n-Heptane	99.78	0.01	298 K		0.10[b]	0.4–0.5[c]
n-Octane	99.5+	0.01	to		0.12[b]	0.3–0.5[c]
n-Decane	100.0	0.01	0.2 at		0.09[b]	0.3–0.5[c]
n-Dodecane	100.0	0.01	398 K		0.09[b]	0.3–0.5[c]
Tetradecane	99+	0.01			0.10[b]	0.3–0.4[c]
Ref: 92ASS	Method: VW					
n-Heptane	99.5	0.005	0.01	20–40 cycles	0.1	0.5
Ref: 92OLI	Method: VW					
n-Hexane	99.99+	0.05	0.05	20–40 cycles	0.1	0.5
n-Octane	99.99+					
n-Decane	99.0					

[a]Personal communication (JHD).
[b]Standard deviation.
[c]In hindsight, the authors consider the assigned accuracy to be too conservative.

TABLE 8. Parameters in Eq. (1)

n-Alkane	*T* range / K	*A*	*B*	*C*	*D*	RMS/%
Hexane	283 – 393	−5.8734	11.0471	−7.3844	2.2107	0.20[a]
Heptane	292 – 346	−6.2654	12.0216	−8.4110	2.6546	0.17
Octane	283 – 393	−6.4960	12.6817	−9.4044	3.2187	0.19
Decane	283 – 423	−7.1561	14.2582	−11.3963	4.2942	0.12
Dodecane	283 – 425	−7.8074	16.0114	−13.8627	5.6586	0.12
Tetradecane	293 – 424	−8.5427	17.6373	−15.7492	6.6550	0.10

RMS Root-mean-square percentage deviation;
[a]for data up to 355 K.

TABLE 9. Recommended viscosities at 25 °C

n-Alkane	Viscosity / mPa s	Estimated Uncertainty/%
Hexane	0.2949	0.4
Heptane	0.3890	0.4
Octane	0.5092	0.3
Decane	0.8498	0.3
Dodecane	1.3585	0.3
Tetradecane	2.078	0.3

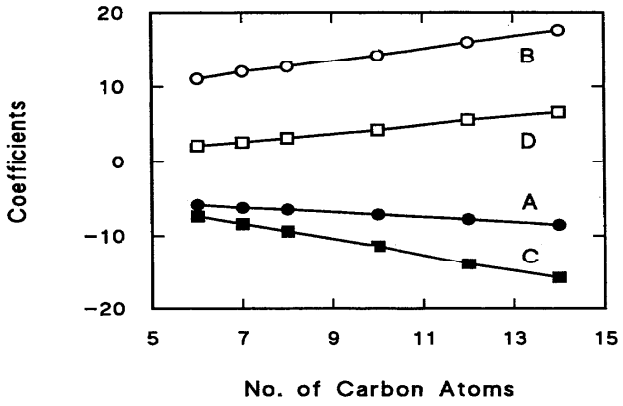


FIG. 1. Parameters in Eq. (1).

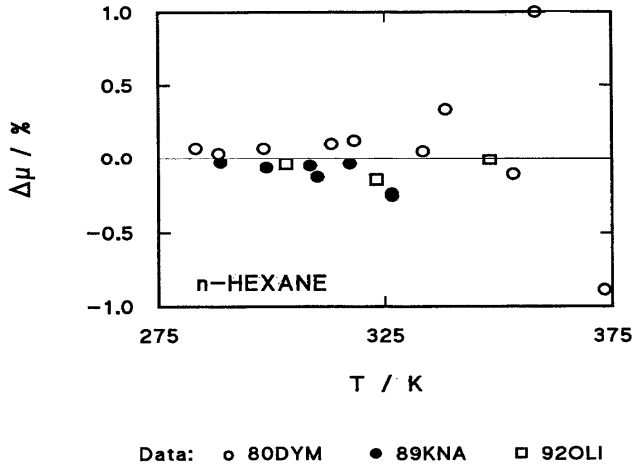


FIG. 2. The deviations of the primary data for the viscosity of *n*-hexane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.

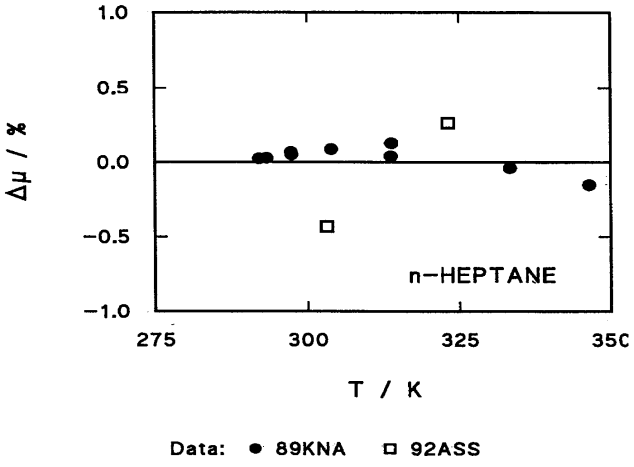


FIG. 3. The deviations of the primary data for the viscosity of *n*-heptane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.

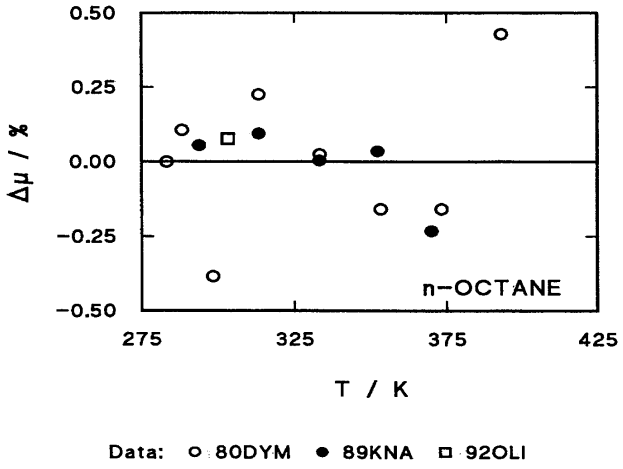


FIG. 4. The deviations of the primary data for the viscosity of *n*-octane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.

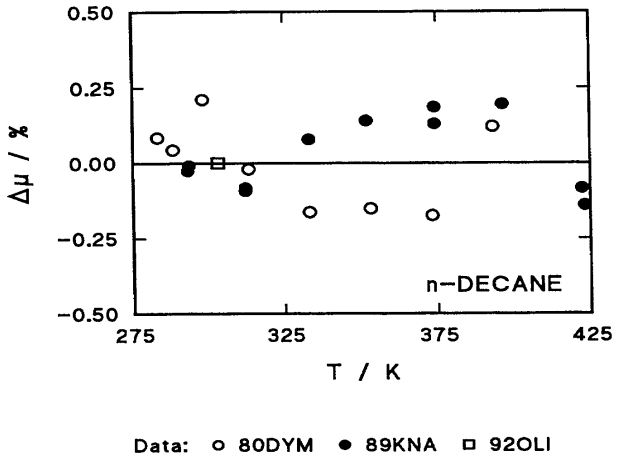


FIG. 5. The deviations of the primary data for the viscosity of n-decane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.

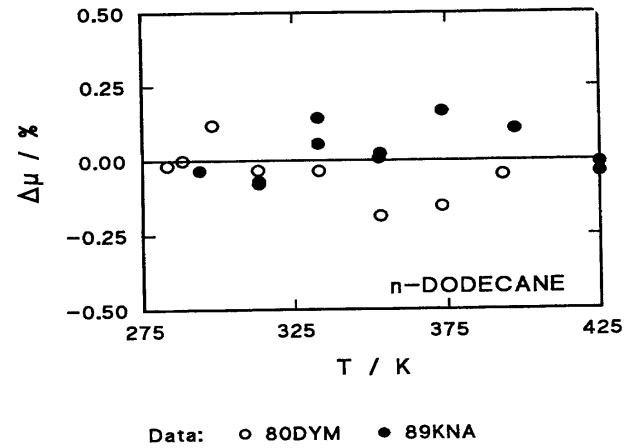


FIG. 6. The deviations of the primary data for the viscosity of n-dodecane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.

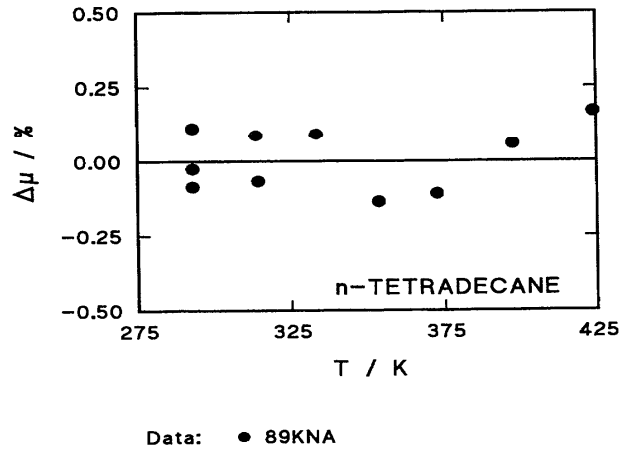


FIG. 7. The deviations of the primary data for the viscosity of n-tetradecane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.

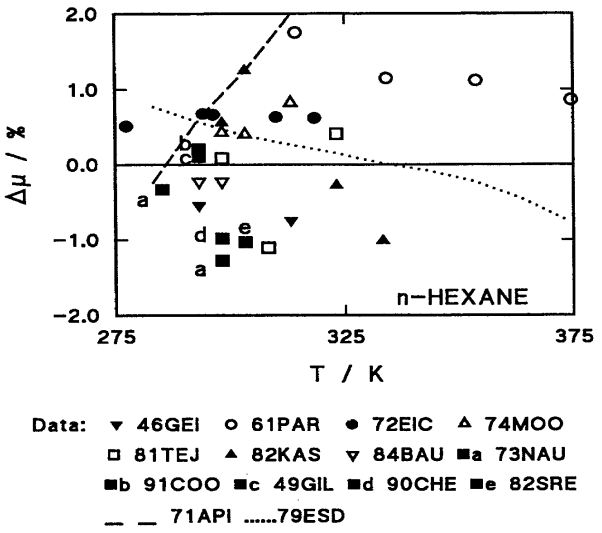


FIG. 8. The deviations of the secondary data for the viscosity of n-hexane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.

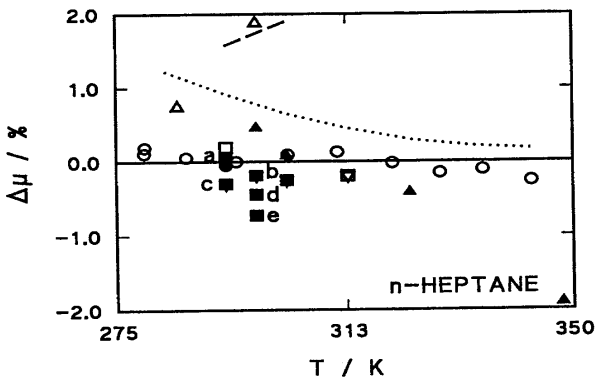
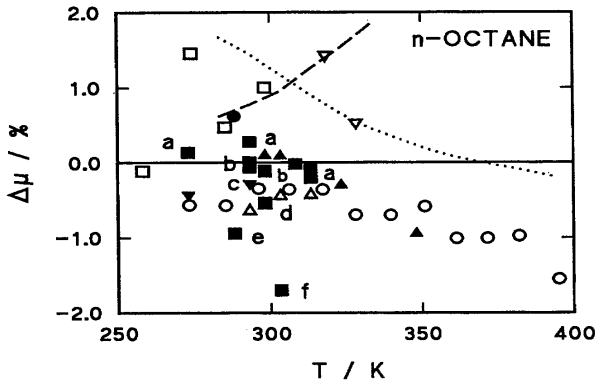
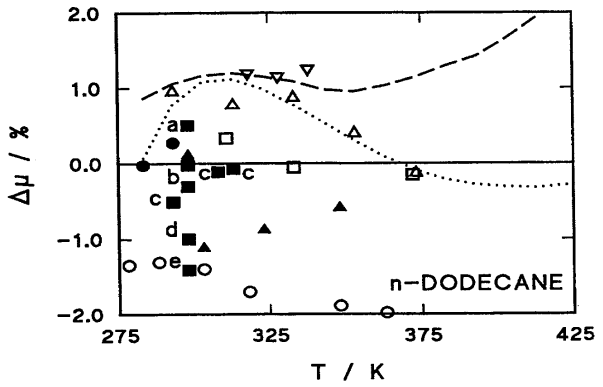


FIG. 9. The deviations of the secondary data for the viscosity of n-heptane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.



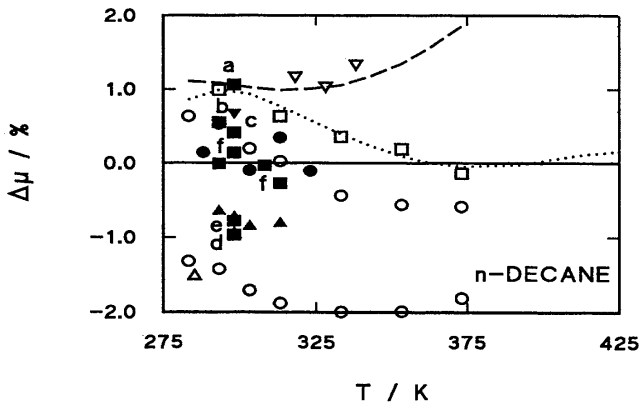
Data: ○ 94THO ● 28TIM ▼ 49GIL □ 73NAU
△ 74MOO ▲ 82KAS ▽ 87WAK ■a 46GEI
■c 31SHE ■d 90CHE ■e 78DUS ■f 82SRE
■b 90ASF, 91COO, 91VAV
_ _ 71API 79ESD

FIG. 10. The deviations of the secondary data for the viscosity of *n*-octane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.



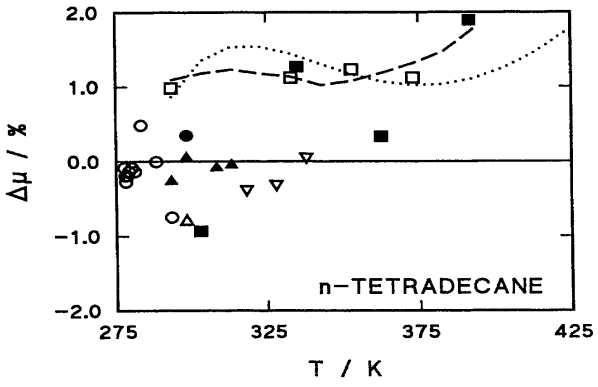
Data: ○ 38EVA ● 49GIL □ 67HOG ▲ 82KAS
△ 86DUC ▽ 87WAK ■a 86AUC ■b 31SHE
■c 90ASF,91COO,91VAV ■d 90CHE ■e 64BID
_ _ 71API 79ESD

FIG. 12. The deviations of the secondary data for the viscosity of *n*-dodecane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.



Data: ○ 31BIN ▼ 50MUM △ 73NAU ▲ 74MOO
● 80ADE □ 86DUC ▽ 87WAK ■a 86AUC
■b 87CEL ■c 31SHE ■d 78DUS ■e 90CHE
■f 90ASF, 91COO, 91VAV
_ _ 71API 79ESD

FIG. 11. The deviations of the secondary data for the viscosity of *n*-decane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.



Data: ○ 49GIL ● 67HER ■ 72RAS □ 86DUC
▽ 87WAK △ 90CHE ▲ 90ASF, 91COO, 91VAV
_ _ 71API 79ESD

FIG. 13. The deviations of the secondary data for the viscosity of *n*-tetradecane from the correlation of Eq. (1). $\Delta\mu = 100 \times (\mu_{expt} - \mu_{calc})/\mu_{calc}$.

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7. References

*94THO T. E. Thorpe and J. W. Rodger, Phil. Trans. Roy. Soc. (London) **A185**, 397 (1894).

11DRA P. Drapier, Bull. Classe Sci. Acad. Roy. Belg. **621** (1911).

13BAT A. J. Batschinski, Z. Physik. Chem. **84**, 643 (1913).

13BIN E. C. Bingham, G. F. White, A. Thomas and J. L. Cadwell, Zeit. f. Physik. Chem. **83**, 641 (1913).

25LEW J. R. Lewis, J. Am. Chem. Soc., **47**, 626 (1925).

28TIM J. Timmermans and F. Martin, J. Chim. Phys. **25**, 411 (1928).

28SMY C. P. Smyth and W. N. Stoops, J. Am. Chem. Soc., **50**, 1883 (1928).

29EDG G. Edgar and C. Calingaert, J. Amer. Chem. Soc. **51**, 1540 (1929).

30BIN E. C. Bingham and H. J. Fornwalt, J. Rheology **1**, 372 (1930).

30MAD E. W. Madge, J. Phys. Chem. **34**, 1599 (1930).

31SHE A. F. Shepard, A. L. Henne and T. Midgley, Jr., J. Am. Chem. Soc., **53**, 1948 (1931).

35TIM J. Timmermans and Mme. Hennaut-Roland, J. Chim. Phys. **32**, 501 (1935).

38CAN M. R. Cannon and M. R. Fenske, Ind. Eng. Chem., Anal. Edn. **10**, 297, (1938).

38EVA E. B. Evans, J. Inst. Pet. Tech. **24** (1938).

39KHA Kh. M. Khalilov, Zh. Eskp. Teor. Fiz. (USSR) **9**, 335 (1939).

41SCH A. W. Schmidt, V. Schoeller and K. Eberlein, Ber. Chemische. Gesell. **74B**, 1313 (1941).

46FAW F. S. Fawcett, Ind. Eng. Chem. **38** 338 (1946) and J. Am. Chem. Soc. **68**, 1420 (1946).

46GEI J. M. Geist and M. R. Cannon, Ind. Eng. Chem., Anal. Edn. **18**, 611 (1946).

49GIL E. B. Giller and H. G. Drickamer, Ind. Eng. Chem. **41**, 2067 (1949).

50MUM S. A. Mumford and J. W. C. Phillips, J. Chem. Soc., **75** (1950).

51DOO A. K. Doolittle and R. H. Peterson, J. Am. Chem. Soc. **73**, 2145 (1951).

52SWI J. F. Swindells, J. R. Coe and T. B. Godfrey, J. Res. Nat. Bur. Stand. **48**, 1 (1952).

55HAM B. R. Hammond and R. H. Stokes, Trans. Faraday Soc. **51**, 1641 (1955).

60MCA R. A. McAllister, A. I. Ch. E. Jl. **6**, 427 (1960).

61PAR P. E. Parisot and E. F. Johnson, J. Chem. Eng. Data **6**, 263 (1961).

62HOL J. T. Holmes, D. R. Olander and C. R. Wilke, A. I. Ch. E. J. **8**, 646 (1962).

64BID D. L. Bidlack and D. K. Anderson, J. Phys. Chem. **68**, 3790 (1964).

67DAR R. Darmois and J. Darmois, Chim. Anal. (Paris) **49**, 158 (1967).

67HER E. L. Heric and J. G. Brewer, J. Chem. Eng. Data **12**, 574 (1967).

67HOG D. L. Hogenboom, W. Webb and J. A. Dixon, J. Chem. Phys. **46**, 2586 (1967).

69BRA D. W. Brazier and G. R. Freeman, Canad. J. Chem. **47**, 893 (1969).

69CAR L. T. Carmichael, V. M. Berry and B. H. Sage, J. Chem. Eng. Data **14**, 27 (1969).

71API American Petroleum Institute Research Report 44, Selected Values of Properties of Hydrocarbons and Related Compounds, F. D. Rossini *et al.*, Carnegie Press, Pittsburgh (1971).

71GHA R. K. Ghai and F. A. L. Dullien, Can. J. Chem. Eng. **49**, 260 (1971).

71MAR R. S. Marvin, J. Res. Nat. Bur. Stand. **75A**, 535 (1971).

72EIC L. D. Eicher and B. J. Zwolinski, J. Phys. Chem. **76**, 3295 (1972).

72EICa L. D. Eicher and B. J. Zwolinski, Science **177**, 369 (1972).

72HIL J. H. Hildebrand and R. H. Lamoreaux, Proc. Nat. Acad. Sci. U. S. A **69**, 3428 (1972).

72RAS Yu. L. Rastorguev and A. S. Keramidi, Izv. Vyssh. Ucheb. Zared. Neft. Gaz. **15**, 61 (1972).

73KES J. Kestin, M. Sokolov and W. A. Wakeham, Appl. Sci. Res. **27**, 241 (1973).

73NAU M. Kh. Nauruzov, V. G. Ben'kovskii and T. M. Bogoslovskaya, Tr. Inst. Khim. Nefti. Prir. Solei Akad. Nauk Kaz. SSR **6**, 137 (1973).

74BUL N. V. Bulanov and V. P. Skripov, Teplofiz. Vys. Temp. **12**, 1184 (1974).

74MOO J. W. Moore and R. M. Wellek, J. Chem. Eng. Data **19**, 136 (1974).

75BAL Yu. A. Baladov, Ya. M. Naziev and S. O. Guseinov, Izv. Vyssh. Ucheb. Zared. Neft. Gaz. **18**, 67 (1975).

75MUS M. J. Mussche and L. A. Verhoeye, J. Chem. Eng. Data **20**, 46 (1975).

76ISL N. Islam and B. Waris, Ind. J. Chem. **14A**, 30 (1976).

76OZ H. Oz and T. Gaumann, Helv. Chim. Acta **59**, 1935 (1976).

77MED M. S. Medani and M. A. Hasan, Can. J. Chem. Eng. **55**, 203 (1977).

78DUS O. Dusart, C. Piekarski and S. Piekarski, J. Chim. Phys. **75**, 919 (1978).

79ESD Viscosity of Liquid Aliphatic Hydrocarbons: Alkanes, Item 79027, Engineering Sciences Data Unit, London (1979).

79ISD J. D. Isdale, J. H. Dymond and T. A. Brawn, High Temp. High Press. **11**, 571 (1979).

80ADE M. Adel-Hadadi, A. V. Lesikar and C. T. Moynihan, Report 1980, Gov. Rep. Ann. In. (US) **80**, 5628 (1980).

80DYM J. H. Dymond and K. J. Young, Int. J. Thermophys. **1**, 331 (1980).

81ASF A. -F. A. Asfour and F. A. L. Dullien, J. Chem. Eng. Data **26**, 312 (1981).

81DYM J. H. Dymond and K. J. Young, Int. J. Thermophys. **2**, 237 (1981).

81TEJ A. S. Teja and P. Rice, Chem. Eng. Sci. **36**, 7 (1981).

82KAS H. Kashiwagi and T. Makita, Int. J. Thermophys. **3**, 289 (1982).

82SRE M. Sreenivasulu and P. R. Naidu, Acta Cienc. India (Ser) Chem. **8**, 16 (1982).

84BAU H. Bauer and G. Meerlender, Rheol. Acta **23**, 514 (1984).

85AWW A. M. Awwad and E. I. Allos, Fluid Phase Equilib. **22**, 353 (1985)

86AUC A. Aucejo, E. Part, P. Medina and M. Sancho-Tello, J. Chem. Eng. Data **31**, 143 (1986).

86aAWW A. M. Awwad and M. A. Salman, Fluid Phase Equilib. **25**, 195 (1986)

86bAWW A. M. Awwad, S. F. Al-Azzawi and M. A. Salman, Fluid Phase Equilib. **31**, 171 (1986)

86DUC D. Ducoulombier, H. Zhou, C. Boned, J. Peyrelasse, H. Saint-Guirons and P. Xans, J. Phys. Chem. **90**, 1692 (1986).

86SIN R. P. Singh, C. P. Sinha and B. N. Singh, J. Chem. Eng. Data **31**, 107 (1986).

87CEL B. Celda, R. Gavara, R. Tejero and J. E. Figueruelo, J. Chem. Eng. Data **32**, 31 (1987).

87GON F. A. Goncalves, K. Hamano, J. V. Sengers and J. Kestin, Int. J. Thermophys. **8**, 641 (1987).

87RET T. Retsina, S. M. Richardson and W. A. Wakeham, Appl. Sci. Res. **43**, 325, (1987).

87WAK D. L. Wakefield and K. N. Marsh, Int. J. Thermophys. **8**, 649 (1987).

88BER D. A. Berstad, B. Knapstad, M. Lamvik, P. A. Skjolsvik, K. Torklep and H. A. Øye, Physica **A151**, 246 (1988).

89AMB D. Ambrose and J. Walton, Pure Appl. Chem. **61**, 1395 (1989).

89KNA B. Knapstad, P. A. Skjolsvik and H. A. Øye, J. Chem. Eng. Data **34**, 37 (1989).

89KOU S. Kouris and C. Panayiotou, J. Chem. Eng. Data **34**, 200 (1989).

89SCH J. T. Schrodt and R. M. Akel, J. Chem. Eng. Data **34**, 8 (1989).

90ASF A. -F. A. Asfour, M. H. Siddique and T. D. Vavanellos, J. Chem. Eng. Data **35**, 199 (1990).

90bASF A. -F. A. Asfour, M. H. Siddique and T. D. Vavanellos, J. Chem. Eng. Data **35**, 192 (1990).

90CHE J. L. E. Chevalier, P. J. Petrino and Y. H. Gaston-Bonhomme, J. Chem. Eng. Data **35**,206 (1990)

90CIB I. Cibulka (personal communication)

91aASS M. J. Assael, M. Papadaki, M. Dix, S. M. Richardson and W. A. Wakeham, Int. J. Thermophys. **12**, 231 (1991).

91bASS M. J. Assael and M. Papadaki, Int. J. Thermophys. **12**, 801 (1991).

91COO E. F. Cooper and A. -F. A. Asfour, J. Chem. Eng. Data **36**, 285 (1991).

91GON F. A. Goncalves, J. Kestin and J. V. Sengers, Int. J. Thermophys., **12**, 1013 (1991).

91VAV T. D. Vavanellos, A. -F. A. Asfour and M. H. Siddique, J. Chem. Eng. Data **36**, 281 (1991).

92ASS M. J. Assael, C. B. M. P. Oliveira, M. Papadaki, and W. A. Wakeham, Int. J. Thermophys. **13**, 593 (1992).

92OLI C. B. M. P. Oliveira and W. A. Wakeham, Int. J. Thermophys., **13**, 773 (1992)