

C. A. NIETO DE CASTRO (1)

W. A. WAKEHAM (2)

J. C. G. CALADO (1)



THERMAL CONDUCTIVITY MEASUREMENTS OF N-HEPTANE ALONG THE SATURATION LINE BY A TRANSIENT HOT WIRE TECHNIQUE

The thermal conductivity of liquid n-heptane has been measured at temperatures around room temperature using a transient hot wire technique. The apparatus has been designed so as to minimize all possible spurious effects. The thermal conductivity of the liquid is obtained from the slope of the temperature increase of a 10 μ diameter platinum wire versus logarithm of time. Convection has been avoided by a careful choice of the duration of the experiment; small corrections due to the finite heat capacity of the platinum wire, the bounded medium, the temperature dependence of fluid properties, the finite diameter of the wire, were made. The end effects of the wire have been reduced to less than 0.01 % by a compensation device, employing a shorter wire as another arm of the Wheatstone bridge used for the measurement. An automatic bridge provides the times at which the resistance of the wire reaches six-predetermined values, using a comparator and a crystal controlled clock of 100 kHz with a resolution of $\pm 10 \mu$ sec and working in conjunction with a six-channel counter. The other two arms of the bridge consist of ultrastable metal-film resistors to avoid resistance drifts.

1 — INTRODUCTION

Accurate values of transport properties of liquids are required in order to obtain meaningful information on the intermolecular potential in the repulsive region [1]. The energy transfer between molecules during collision is strongly dependent on the directional forces between molecules and their internal degrees of freedom, and there is still a lot of work to be done on the effect of liquid structure on the transport properties, even for simple molecules (including the light hydrocarbons) before that transfer process is completely understood.

Unfortunately, the data available for the thermal conductivity of liquid hydrocarbons are scarce, and, moreover, there is considerable disparity between the results obtained by different workers and by different techniques. For instance, the available data for the thermal conductivity of saturated hydrocarbons at 30 °C, taken from 23 different sources [2] are plotted in fig. 1, showing a considerable scattering of the experimental points, although most of them seem to lie within a band whose width extend from about $\pm 6\%$ for nC_5 to $\pm 2\%$ for nC_{18} . It is thus clear that there is a need for reliable measurements of the thermal conductivity of liquids both for fundamental studies and also for the purposes of optimal technological design.

HAARMAN [3, 4] has now developed a refined theory for the transient temperature behaviour of a thin

(1) Centro de Química Estrutural das Universidades de Lisboa, Complexo Interdisciplinar, I.S.T., Lisboa-1, Portugal.

(2) Department of Chemical Engineering, Imperial College of Science and Technology, London SW7 2BY, England.

(2) Presented at CHEMPOR' 75 held in Lisbon, 7-12 September 1975 at the Calouste Gulbenkian Foundation Center.

Papers presented at this International Chemical Engineering Conference can be purchased directly from Revista Portuguesa de Química (Instituto Superior Técnico, Lisboa 1, Portugal) at the following prices per volume sent by surface mail, postage included (in Portuguese Escudos):

Whole set	500
Transport processes	200
Reaction engineering	150
Environmental engineering	150
Management studies	150

This paper was presented at the Transport processes section.

conducting wire, immersed in a fluid, as a result of a step change in the electrical energy dissipated within it. We have thus applied Haarman's theory to the design of an apparatus for the measurement of thermal conductivity of liquids [5], and some preliminary measurements of the thermal conductivity of n-heptane are reported here.

DE GROOT *et al.* [6] applied recently Haarman's theory to the design of an apparatus to measure the thermal conductivity of gases, and HEALY *et al.* [7] developed a complete and up-to-date theory for the transient hot wire which can, in part, be applied to our calculations.

2—THE APPARATUS

2.1—MECHANICAL ASSEMBLY AND THERMOSTATS

An apparatus for the measurement of thermal conductivity of liquids using a transient hot wire

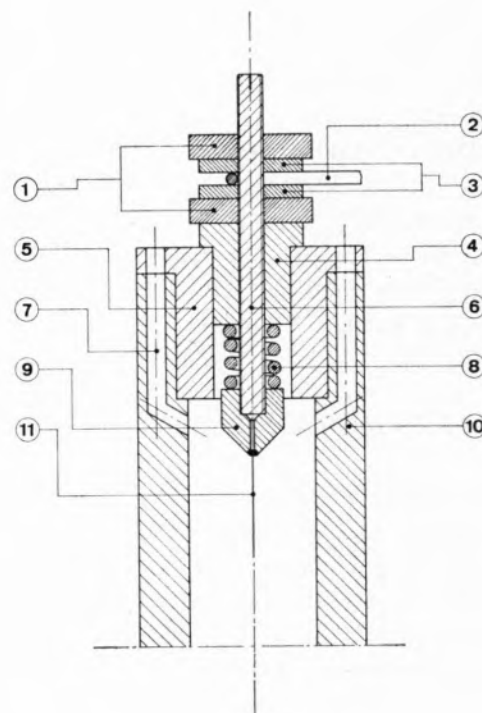


Fig. 2

Adjustment mechanism of the wire

1—Nut; 2—electric cable; 3—metallic ring; 4—teflon insulation; 5, 10—cell parts; 6—adjustment screw; 7—fluid inlet; 8—spring; 9—connection with the Wood metal drop; 11—platinum wire

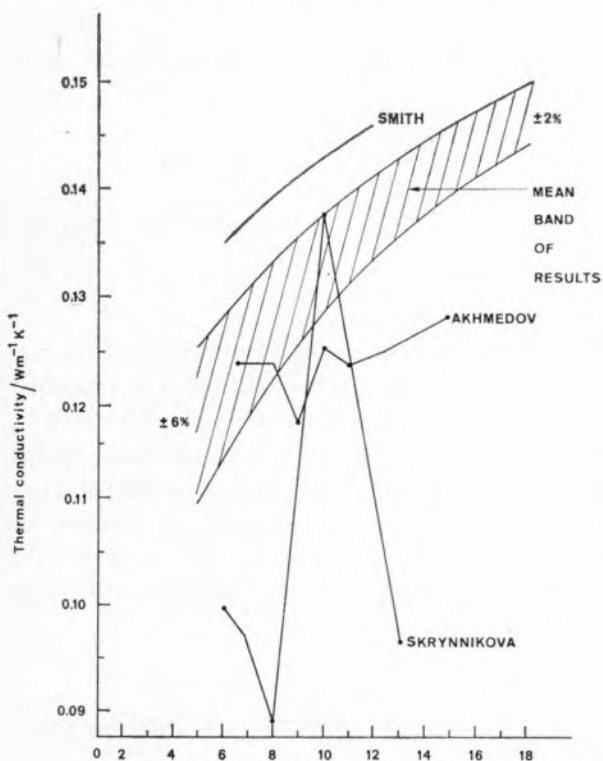


Fig. 1

Diagrammatic plot of the thermal conductivity of saturated hydrocarbons at 30°C as a function of the number of carbon atoms

method has been designed and built according to theory and features described elsewhere [5].

Two stainless steel cells, the measuring cell and the compensating one, are immersed in a pressure vessel within a temperature controlled bath. The 10μ platinum wire used (Goodfellow Metals Ltd.) is connected to the cell ends by means of an adjustment mechanism shown in fig. 2. Because of the delicacy of thin platinum wire, extreme care must be taken while assembling the fluid cell. Good electrical contact with the adjustment mechanism is achieved with a drop of Wood's metal (b.p. $\sim 70^\circ\text{C}$) near the spot where the platinum wire reaches part 11 on fig. 2. After assembling, the wire is annealed until it becomes incandescent in a dark room for several seconds. Subsequently the wire is stretched with the aid of the screws 6, placed horizontally, and its length measured with a cathetometer within ± 0.01 mm.

The pressure vessel is a standard stainless steel cylinder, fitted with two clamps to hold the cells.

The entire assembly was degreased with Decon 90 solution and acetone.

The pressure vessel was immersed within a temperature controlled bath, consisting of a thermostat (LAUDA, type D40) controlled by a PTR temperature controller (LAUDA type R52 Electronic), and cryostat (HAAKE, type FK2) acting as the cold source. Tests have shown that the temperature stability is very good (around: ± 0.004 K at 288 K and ± 0.01 K at 313 K).

2.2 — THE ELECTRONICS

Our measurement technique is similar to that used by HAARMAN [3] and DE GROOT *et al.* [6] in their work for the gas phase. In an earlier communication [5] we have described the principle of the method and the design of the bridge. A high precision Wheatstone bridge with automatic timing and control equipment was built according to the specifications required by the proper design. The details of bridge operation are described elsewhere [17].

3 — EXPERIMENTAL

3.1 — PURIFICATION OF *n*-HEPTANE

Commercial BDH *n*-heptane, with a purity of no less than 99,5 % was treated with 4A molecular sieves to remove water, degassed in vacuum and then distilled under its own vapour pressure. Its refractive index at 25 °C was found to be 1.38488 (to be compared with the literature values 1.3851 [18] and 1.3852 [19] at the same temperature).

3.2 — CALIBRATION OF THE WIRE RESISTANCE

The measuring technique used in this work monitors the resistance of the wire as a function of time. In order to find the temperature increase of the wire during the measurements, it is necessary to calibrate the resistance of the platinum wire as a function of temperature. This requires firstly the measurement of the wire resistance with a precision

similar to that given by the automatic Wheatstone bridge, and secondly the knowledge of the wire temperature with sufficient accuracy for a reliable temperature resistance coefficient to be obtained. This is a very delicate procedure, well known to all who work in platinum resistance thermometry. We used a DANA 5900 digital multimeter and a four wire measurement with shielded two conductor cables, recommended for this kind of measurement. The precision of the measurement is of the order of 0.006 %, compared to the estimated accuracy of the automatic bridge of 0.05 %. The temperature was measured with a platinum resistance thermometer (TINSLEY TYPE 5187SA) which has an accuracy of ± 0.001 K, with the aid of an automatic bridge (Automatic Systems Laboratory A6) that measures $R_{pt}/(R_{st} + R_{pt})$, (R_{st} being a standard resistance of 100 Ω to one part in 10^6). For the calibration the vessel was filled with helium. As temperature differences between the thermometer and the wire were expected, a measurement of the wire resistance at 20 °C immersed in *n*-heptane was done, and no difference was found. Twenty-two data points were fitted to a quadratic polynomial between 8 °C and 41 °C and the result was

$$\frac{R_T}{R(273.16)} = 1 + 3.9985 \times 10^{-3} (T - 273.16) - 1.700 \times 10^{-6} (T - 273.16)^2 \quad (1)$$

with a variance of 0.04 Ω .

The percentage difference between experimental values (R_{exp}) and fitted values (R_{fit}) is presented in fig. 3 and a scatter of no more than 0.04 % is found. An analysis of the figure shows that a better calibration has been reached for temperatures above 24 °C where the residuals are smaller (of the order of 0.01 %). A better calibration for the temperatures below 24 °C will be tried in the near future.

3.3 — OTHER EXPERIMENTAL PROBLEMS

3.3.1 — TEMPERATURE STABILITY

After selecting the working temperature, we must wait for the temperature to stabilize inside the

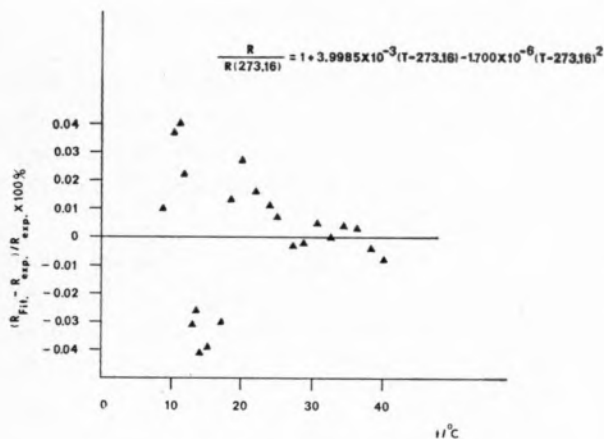


Fig. 3

Scattering of resistance fitted values as a function of temperature

vessel, ensuring that the temperature of the wire is the temperature measured with the platinum resistance thermometer. Experience shows that a waiting time of about 1 1/2 hour is enough to obtain a temperature stability of the order of $\pm 0.005^\circ\text{C}$.

3.3.2 — TIME LAPSE BETWEEN RUNS

In order to meet the initial condition of uniform fluid temperature, it is necessary to estimate the time needed for the wire to reach again the bath temperature after a run; in fact, if the temperature of fluid which surrounds the wire changes by more than 0.005 K, the behaviour of the hot wire is markedly altered, and the reproducibility of consecutive runs is lost. By trial and error we have arrived at a time lapse between runs of the order of 2 minutes; experience shows that longer intervals will change the temperature of the bath by more than 0.005 K, and shorter intervals are obviously insufficient to allow for the wire to cool down.

4 — DATA CALCULATIONS

4.1 — TEMPERATURE AND REFERENCE TEMPERATURE

The simplest temperature profile that describes the

temperature jump at the hot wire is the solution for the infinite line source of heat

$$\Delta T_o(a, t) = -\frac{q}{4\pi\lambda} E_i(-a^2/4Kt) \quad (2)$$

Assuming that the quantity $a^2/4Kt$ is sufficiently small, equation (2) can be put into the form

$$\begin{aligned} \Delta T_o(a, t) &= \frac{q}{4\pi\lambda} \left\{ \ln \frac{4Kt}{a^2C} + \frac{a^2}{4Kt} + \dots \right\} \\ &= \frac{q}{4\pi\lambda} \left\{ \ln \frac{4t^*}{C} + \frac{1}{4t^*} + \dots \right\} \end{aligned} \quad (3)$$

where $t^* = Kt/a^2$ is the reduced time.

Our instrument has been designed in such a way as to follow very closely the behaviour of a finite portion of an infinitely long and infinitely thin line source of constant heat flux q [5].

Recently HEALY and co-workers [7] refined the theory of the hot wire, firstly proposed by HAARMAN [3, 4]. Using a general perturbation technique, these authors arrived at several correcting terms which can be analysed separately or as a whole; these corrections are small ($< 1\%$) and since they were fully described elsewhere [4] they will only be briefly discussed here.

The thermal conductivity of the fluid at temperature T_r , λ_r , can be calculated from the slope of the temperature increase ΔT versus $\ln t$ diagram, according to the equation

$$\Delta T = \frac{q}{4\pi\lambda_r} \ln \left\{ \frac{4(\lambda_o/\rho_o C_p)t}{a^2C} \right\} \quad (4)$$

where λ_o and ρ_o are the thermal conductivity and density of the fluid at bath temperature T_b and

$$\Delta T = \Delta T_w(t) + \sum_i \delta T_i \quad (5)$$

$\Delta T_w(t)$ is obtained from the wire resistance and the δT_i 's are the temperature corrections.

The associated temperature T_r is obtained from the expression

$$T_r = T_b + \delta T_1^* \quad (6)$$

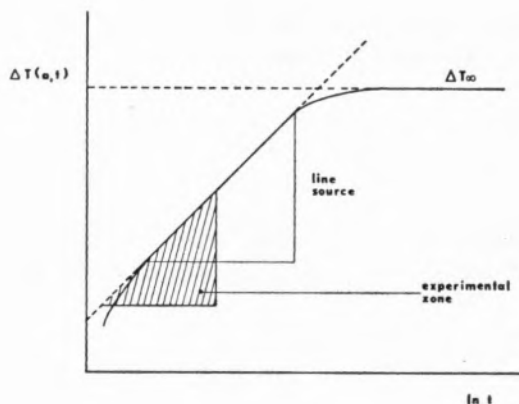


Fig. 4

Temperature increase of the wire as a function of logarithm of time

where the correction δT_1^* arises from the temperature dependence of fluid properties, ρC_p and λ .

4.2 — CORRECTIONS

4.2.1 — FINITE VALUES OF THE PHYSICAL PROPERTIES OF THE WIRE

HEALY *et al.* [7] have derived an expression for the deviations of the measured temperature rise of the wire occurring as a result of its finite diameter, finite thermal conductivity and finite heat capacity.

$$\delta T_1 = a^2 \frac{(\rho C_p)_w - \rho C_p}{2\lambda t} \Delta T_w - \frac{q}{4\pi\lambda} \times \left[\frac{a^2}{4Kt} \left(2 - \frac{K}{K_w} \right) - \frac{q}{8\pi\lambda_w} \right] \quad (7)$$

The term $-q/4\pi\lambda_w$, which is very small, is independent of time and merely shifts the ΔT versus $\ln t$ diagram without changing the slope from which the thermal conductivity is calculated. The remaining terms are important at short times, but can be estimated with an error $\sim 5\%$. Thus, if we limit the application of such corrections to cases for which they are less than 1% of the measured temperature rise, we may expect that the resulting departures from the linearity indicated by equation (4) will be of the order of $\pm 0.05\%$.

4.2.2 — FINITE DIMENSIONS OF THE CELL

The existence of the cell wall causes the temperature rise in the fluid to be smaller than that for the ideal source solution. This fact is due to the heavy mass and high thermal conductivity of the cell walls (stainless steel).

FISCHER [9] obtained the solution for the effect of the cell wall at a finite radius b ; according to McLAUGHLIN [8], for $b^* = b/a \gg 1$, that solution can be approximated by

$$\Delta T(a, t) = \frac{q}{4\pi\lambda} \left\{ 2\ln b^* - 4 \times \sum_{n=1}^{\infty} \frac{\exp(-t^* g_n^2 / b^{*2})}{\frac{g_n^2}{b^{*2}} \left\{ \left(\frac{Y_1(g_n/b^*)}{Y_0(g_n)} \right)^2 - 1 \right\}} \right\} \quad (8)$$

where g_n are the roots of $J_0(g_n) = 0$.

This temperature profile was calculated using the first 50 zeros of the Bessel function J_0 but the results thus obtained do not agree with those of McLAUGHLIN [8]. Our calculations generated negative temperature corrections δT_2

$$\delta T_2 = \Delta T_0(a, t) - \Delta T(a, t) \quad (9)$$

decreasing in absolute value when $t^* \rightarrow \infty$. These results are meaningless because δT_2 must be positive as we explained above and increase with increasing time.

An alternative to equation (8) is that of FISCHER [9], valid for $b^* \gg 1$ and $4t^* \gg 1$

$$\Delta T(a, t) = \frac{q}{4\pi\lambda} \left\{ 2\ln b^* - 4 \times \sum_{n=1}^{\infty} \frac{\exp(-t^* g_n^2 / b^{*2})}{\left(\frac{2}{\pi Y_0(g_n)} \right)^2 - \frac{g_n^2}{b^{*2}}} \right\} \quad (8a)$$

which gives the expected values for δT_2 for $t^* > 200$; these are plotted in fig. 5 for three values of b^* . We can easily see that $\delta T_2 \rightarrow 0$ as $t^* \rightarrow 0$ and $\delta T_2 \rightarrow 0$ as b^* becomes larger. For $b^* = 1000$ this correction is negligible until $t^* = 40000$, about ten times the value used in our experiments. This confirms previous results obtained by us [5] using the qualitative method due to HAARMAN [3]. In Table II of reference [5] it is shown that for $t^* \sim 50000$, the relative error in assuming that the medium has infinite dimensions is of the order of 10^{-6} for $b^* = 1000$.

Fig. 5 can be used for a careful choice of cell dimensions which eliminate this correction, because δT_2 is only a function of t^* and b^* , and for the transient regime $\Delta T_0(a, t) < \Delta T_\infty$ which gives $4t^*/C < b^{*2}$.

4.2.3 — OTHER CORRECTIONS

MCLAUGHLIN *et al.* [8] have shown that the viscous dissipation in liquids during the measurement will not exceed 0.01 % of the conduction heating. Using their results, a careful choice of the measurement time can be made in such a way as to prevent the onset of free convection.

The finite length of the wire implies that the temperature profile cannot be uniform along the entire length of the wire. To overcome this difficulty we have used, as shown in a previous report [5], a compensating wire as the other arm of the automatic bridge, and found that $R_L/R_S \sim 1.0001 I_L/I_S$.

The last problem concern radiation. The simultaneous conduction and radiation in a participating medium has not yet been solved for coaxial cylinders in a transient regime. Recently MANI [11] attempted to solve the problem but his results have not yet become available. Meanwhile we are developing an approximate model which will allow us to correct the experimental results for radiative heat transfer in absorbing liquids. However, the results presented in this paper have not been corrected for radiation.

4.2.4 — VALUE OF δT_1^*

As explained above, the temperature at which the thermal conductivity of the fluid is measured (the

so-called associated temperature T_r) is not the bath temperature, but must be corrected for the temperature dependence of fluid properties, namely ρC_p and λ . This problem has been solved for gases by HEALY *et al.* [7], and for liquids MCLAUGHLIN and PITTMAN [8] have developed a correction which is only applicable for a small increase of the wire temperature.

We have applied the results of HEALY *et al.* which assume that the fluid properties ρC_p and λ have a linear dependence on temperature, an assumption which for liquids is valid for even wider temperature ranges. The solution of the heat transfer equation under those boundary conditions gives a correction δT_1^* to the reference temperature of the fluid, the so called bath temperature T_b

$$T_r = T_b + \delta T_1^* = T_b + \frac{1}{2} \{ \Delta T(t_1) + \Delta T(t_2) \}$$

$$\rho_r = \rho(T_r, p_s) ; \lambda_r = \lambda_r(T_r) \text{ at } p_s \quad (10)$$

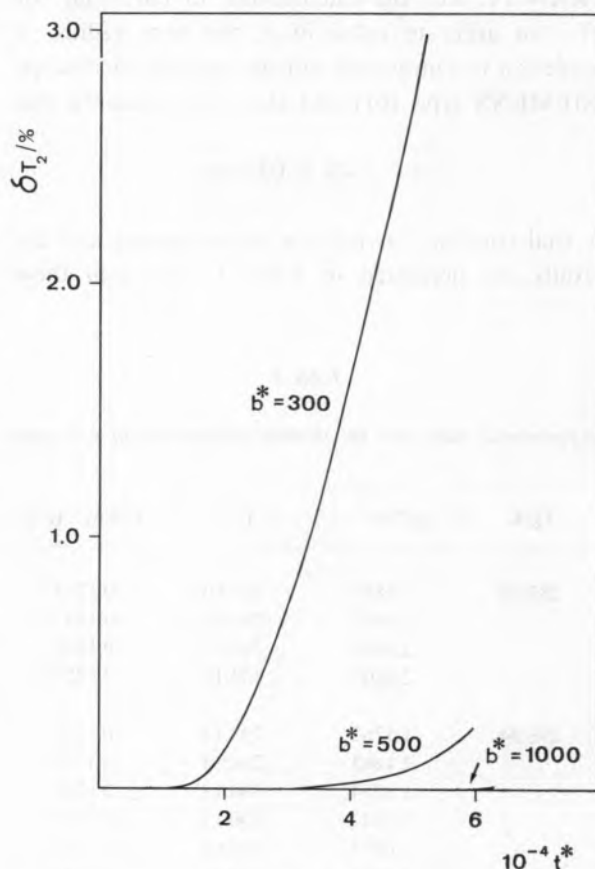


Fig. 5

Bounded medium correction for different values of b^* and t^*

Here t_1 and t_2 refer to the upper and lower limits of the time range within which ΔT is found to be a linear function of $\ln t$ to within 0.1 %. Typical values are $\Delta T(t_2) = 10\text{K}$, $\Delta T(t_1) = 5\text{K}$. The average slope of the ΔT vs $\ln t$ line in this range is then related to the thermal conductivity of the fluid at temperature T_r .

The experimental range used in our measurements ($t < 1\text{s}$) is compared in fig. 4 with the transient line source and the stationary temperature profile ΔT_∞ , for the temperature jumps involved in our experiments, showing that the corrections are important only in the earlier part of the measurement.

5 — RESULTS

ΔT_w , δT_i and δT^*_i were computed using a IBM 360 computer; the programs were written in FORTRAN IV. For the calculations, in particular for δT_i , an accurate value of a , the wire radius, is needed; a was measured with an electron microscope (SIEMENS type 101) and the value obtained was

$$a = 5.49 \pm 0.08 \mu\text{m}$$

A trial run was carried out for n-heptane and the results are presented in Table I. Although these

Table I

Experimental values for the thermal conductivity of n-heptane

T_b/K	q/Wm^{-1}	T_r/K	$\lambda/\text{Wm}^{-1}\text{K}^{-1}$
287.99	1.1874	293.60	0.1253
	1.8425	295.65	0.1242
	2.6303	298.15	0.1233
	2.6307	300.15	0.1227
293.04	1.1762	298.15	0.1235
	1.1493	298.15	0.1236
	1.8254	300.15	0.1229
	1.7842	300.15	0.1227
	2.6073	303.65	0.1217
	2.5471	303.65	0.1219
	2.5476	303.65	0.1220

Table II

Comparison of the available data for the thermal conductivity of n-heptane

$T = 293.25 \text{ K}$	$T = 303.15 \text{ K}$	Source
0.1244	0.1214	PITTMAN [13]
0.135	—	VILIM [14]
—	0.126	TSEDEBERG [15]
0.124	0.121	JOBST [20]
0.127	0.124	MISSENARD [16]
0.1254	0.1219	Present work

are preliminary results, a comparison with the values obtained by other authors shows a reasonable agreement — Table II. There are reasons to believe that Pittman's are the most reliable available data for n-heptane; our values agree with his to 0.5 %, which is within the claimed experimental accuracy.

LIST OF SYMBOLS

Mathematical

- $E_i(-x)$ — exponential integral
- C = 1,781072
- π = 3.14159
- J_0 — Bessel function of first kind, order zero
- Y_0, Y_1 — Bessel function of second kind, orders zero and one
- g_n — n^{th} zero of J_0

Fluid and wire properties

- a — wire radius
- b — cell radius
- $b^* = b/a$
- C_p — specific heat at constant pressure
- K — thermal diffusivity
- l — wire length
- P_s — saturation pressure
- q — heat input per unit time and length
- R_T — wire resistance at temperature T
- t — time
- $t^* = Kt/a^2$ — reduced time
- $\Delta T_0(a, t)$ — ideal wire temperature profile
- $\Delta T(a, t)$ — real wire temperature profile
- $\Delta T_w(t)$ — temperature profile obtained from bridge properties

T_r	— temperature associated to the measured λ
T_b	— bath temperature
T_∞	— steady state temperature
δT_i	— wire temperature corrections
δT_1^*	— bath temperature correction
w	— subscript referring to the wire properties
λ, λ_r	— thermal conductivity of the liquid
ρ	— density of the liquid

REFERENCES

- [1] RICE, S. A., BOON, J. P., DAVIS, H. T., in «Simple Dense Fluids», ed. H. L. Frisch, Z. W. Salzburg, Acad. Press, 1968.
- [2] POWELL, R. W., GROOT, H., *Int. J. Heat. Mass Transfer*, **15**, 360 (1972).
- [3] HAARMAN, J. W., Ph. D. Thesis, Delft, 1969.
- [4] HAARMAN, J. W., *Physica*, **52**, 605 (1971).
- [5] CASTRO, C. A. Nieto de, WAKEHAM, W. A., CALADO, J. C. G., Proceedings of the 1st National Congress on Pure and Applied Mechanics, Lisbon, 1974.
- [6] DE GROOT, J. J., KESTIN, J., SOOKIAZIN, H., *Physica*, **75**, 454 (1974).
- [7] HEALY, J. J., DE GROOT, J. J., KESTIN, J., to be published.
- [8] McLAUGHLIN, E., PITTMAN, J. F. T., *Phil. Trans. Royal Soc. (London)*, **A270**, 557 (1971).
- [9] FISCHER, J., *Ann. Phys., Lpz.*, **34**, 669 (1939).
- [10] JAEGER, J. C., *Aust. J. Phys.*, **9**, 167 (1956).
- [11] MANI, N., Ph. D. Thesis, University of Calgary, Canada, 1971.
- [12] PITTMAN, J. F. T., Ph. D. Thesis, Imperial College, London, 1968.
- [13] KANDIYOTI, R., McLAUGHLIN, E., PITTMAN, J. F. T., *Faraday Trans. 1*, **68**, 860 (1972).
- [14] VILIM, O., *Colln. Czech. Chem. Commun.*, **25**, 993 (1960).
- [15] TSEDEBERG, N. V., in «Thermal Conductivity of Gases and Liquids», ed. MIT Press, 1965.
- [16] MISSENAARD, F. A., *Rev. Gén. Thermique*, **IV**, 409 (1965).
- [17] NIETO DE CASTRO, C. A., CALADO, J. C. G., WAKEHAM, W. A., DIX, M., (submitted to *J. Phys. E*).
- [18] BROWN, I., EWALD, A. H., *Aust. J. Sci. Res.*, **A**, **4**, 198 (1951).
- [19] KYLE, B. G., REED, T. M., *J. Chem. Soc.*, **80**, 6170 (1958).
- [20] JOBST, W., *Int. J. Heat. Mass Transfer.*, **7**, 725 (1964).

ACKNOWLEDGEMENTS

We wish to thank Professor J. Kestin, of Brown University, for sending us the manuscript of his paper on «The Theory of the Transient Hot-Wire Method for Measuring Thermal Conductivity» before publication, and Dr. David Ferreira of Laboratório de Biologia Celular of Instituto Gulbenkian de Ciência, for electron microscope facilities.

We are also indebted to the staff of our workshop who helped us to build the apparatus.

We gratefully acknowledge a research grant from the Instituto Nacional de Investigação Científica (TLQ III).

RESUMO

Apresenta-se a medida da condutibilidade térmica do n-heptano à temperatura ambiente, utilizando a técnica do fio aquecido em regime transiente. O equipamento de medida foi projectado de forma a minimizar todos os efeitos secundários para que a condutibilidade térmica do líquido se possa obter do declive do acréscimo de temperatura num fio de platina de 10 μm de diâmetro em função do tempo. Escolha criteriosa da escala de medida permitiu uma eliminação de convecção livre; fizeram-se pequenas correcções devidas às propriedades físicas finitas do fio, à limitação do meio e à dependência de temperatura das propriedades do líquido. Os efeitos terminais do fio foram reduzidos a menos de 0,01 % com a utilização dum sistema de compensação, constituído por um fio curto de platina, colocado num dos braços adjacentes da Ponte de Wheatstone utilizada. Esta ponte regista os instantes em que a resistência do fio atinge 6 valores prefixados, utilizando um comparador electrónico e um relógio de 100 kHz com uma resolução de ± 10 μs segundos acoplados a um contador de seis canais. Os outros braços da ponte são formados por resistências de filme metálico, ultra-estáveis, para evitar variações de resistência.