International Journal of Mechanics and Energy (IJME)
Vol. 2, Issue 1, 2014, ISSN: 2286-5845

Thermal characterization of fluids using the coaxial cylinders method

Ali Adili [*a], Mohamed Lachheb [b], Sassi Ben Nasrallah [b]

[*a] *Centre de Recherches et des Technologies de l'Energie de Borj-Cédria. Laboratoire des Procédés Thermiques. B.P. 95. Hammam-Lif 2050. Tunisie.*

[b] *Ecole Nationale d'Ingénieurs de Monastir. Laboratoire des Etudes des systèmes Thermiques et Energétiques (LESTE). Avenue Ibn El Jazzar, Route de Kairouan, 5019 Monastir, Tunisie.*

Abstract:

Thermal conductivity is an important thermophysical property; its value is required in all heat transfer calculations. This study deals with the elaboration of theoretical principles of measurement and with the realization of an apparatus based on the coaxial cylinders method allowing us to obtain, simply, the thermal conductivity of liquids. In this work, we have measured the variation of thermal conductivity versus temperature of some liquids like ethanol and ethylene glycol. Thermal conductivities of some other liquids are measured at 25°C. The obtained results have been compared with literature data and they present a good agreement with them.

Key words: Thermal conductivity, liquids, coaxial cylinders method.

1. Introduction

The knowledge of the thermal conductivity is particularly important for science and industry. The accurate measurement of this property is vital not only for practical engineering, but also for theoretical studies and analyses. Indeed, the importance of this parameter appears in all phenomena of heat transfers. For example, a weak knowledge of the thermal conductivity can modify significantly the cost and the performance of heat exchangers. Moreover, the thermal conductivity influences the estimation of thermal diffusivity, Nusselt number, Rayleigh number, etc. Several authors have reported the measurement of the thermal conductivity of liquids using different equipment based on steady-state or transient methods: the hot wire method [1, 2, 3], the hot disk method [4], the concentric (coaxial) cylinders [5, 6, 7], and the concentric sphere [8]. In steady-state methods, the partial derivation of the temperature versus time is zero, while for transient methods; the principal measurement is the temporal behaviour of the temperature field in the liquid. The majority of the mentioned methods, of the thermal conductivity measurement, is too complex, time consuming and needs expensive instrumentation. However, the coaxial cylinders method, which is used in this work, is known by its simplicity, cheapness, fastness and its good precision. These advantages would be of great benefit to the scientific and engineering communities. In this method, the fluid whose thermal conductivity is to be measured fills a small radial clearance, of thickness Δr, between a heated plug and water cooled jacket. The clearance is small enough to prevent natural convection in the fluid. In bibliography concerning the measure of the thermal conductivity of liquids, among authors who are interested in the coaxial cylinders method, we mention Naimi et al. [6]

*** Corresponding author:** Ali Adili
E-mail: ladiliali@yahoo.fr

who have used a cell of coaxial cylinders in steady state mode to measure the thermal conductivity of the diluted SMC (sodium carboxymethyl cellulose) solutions. Bellet et al. [9] have also described a cell of coaxial cylinders which makes it possible to measure simultaneously the thermal conductivity and the specific heat of fluids at ambient temperature. In addition, D. Frezzoti et al. [10] have used a steady state coaxial cylinders method to measure the thermal conductivity of cis-and trans-decahydronophtalene isomers. In the present work, the experimental apparatus of the coaxial cylinders method is used to measure the thermal conductivities of some liquids. The comparison between the obtained results and results reported in literature shows a good agreement.

2. Experimental setup

2.1. Experimental apparatus

The experimental apparatus is schematically shown in Fig. 1. It involves a cell of coaxial cylinders which is constructed of brass, a heat source, two thermocouples, a refrigerator bath circulator and a data acquisition system. The liquid to be characterized is introduced in the annular space between the two coaxial cylinders.

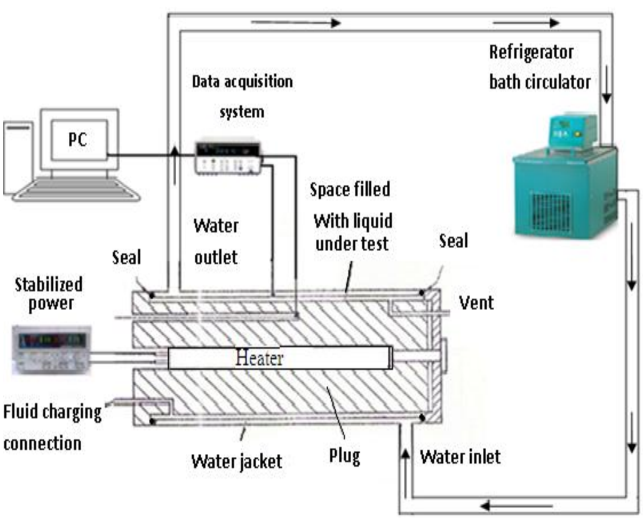


Fig. 1: Schematic experimental setup using the coaxial cylinders technique

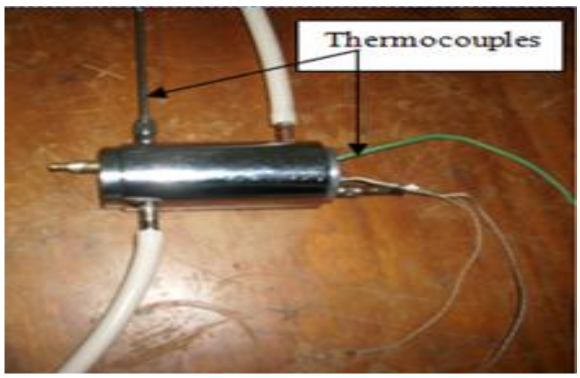
Real photos of the coaxial cylinders are shown in Fig. 2. Its geometrical characteristics are described bellow:

(i) Two coaxial cylinders are separated by 0.02 mm annular space.

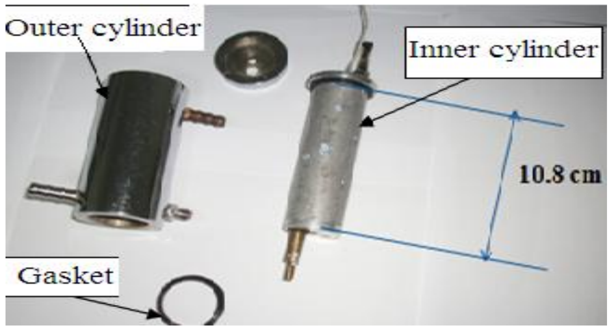
(ii) An inner cylinder contains a cylindrical heating element:

- The diameter of this inner cylinder is d_1=35.6mm
- The length of the annular space L =10.8 cm.

(iii) An outer cylinder is connected to the refrigerator bath circulator containing cooling water to keep the external temperature constant. The diameter of the outer cylinder is d_2=35.9mm.



(a)



(b)

Fig. 2: Photos of the cell of the coaxial cylinders: (a) Assembled, (b) Disassembled.

The experimental temperatures at the inner and the outer cylinders are measured by two K-Type thermocouples. These measured temperatures are read and recorded with a data acquisition unit (Agilent 34970 A) which allows transferring data to a computer via an RS-232 interface.

2.2. Basis of the coaxial cylinders method

In this study, a cell of coaxial cylinders has been used to measure the thermal conductivity of some liquids. A thin layer of the liquid to be characterized is located in the annular gap between the two coaxial cylinders. This liquid is homogeneous, in mechanical equilibrium and with uniform thermal conductivity. A heating element placed on the axis of the inner cylinder is connected to a constant stabilized power supply, which serves to give out a constant heat flux induced by Joule effect which is transferred through the liquid sample toward the outside cylinder. In this cylinder, which is connected to a refrigerator bath circulator, circulates cold water whose temperature is maintained lower than the temperature of the heating element. Therefore the liquid to be characterized is the siege of a temperature gradient. The clearance between the two cylinders is small enough to prevent natural convection in the liquid whose thermal conductivity is to be determined. When equilibrium is attained, the temperatures of the inner cylinder (T_1) and the outer cylinder (T_2) are constant, the thermal conductivity of the liquid to be characterized is determined using the Fourier's law for a cylindrical geometry.

3. Determination of the thermal conductivity

The determination of the thermal conductivity of the liquid under test is based on the solution of the energy conservation equation in one dimensional (radial) heat transfer. In the steady state, conduction inside the cell is described by the Fourier's equation in cylindrical coordinates, with boundary conditions corresponding to heat transfer between two concentric cylindrical surfaces kept at constant temperatures, as given by Eq. (1):

$$Q_c = -\lambda_f S \frac{\partial T}{\partial r} \quad (1)$$

$T(r = r_1) = T_1$

$T(r = r_2) = T_2$

Where:- $S = 2\pi . r . L$

- Q_c is the heat generation of the heating element
- r_1 is the radius of the inner cylinder
- r_2 is the radius of the outer cylinder
- L is the length of the annular space

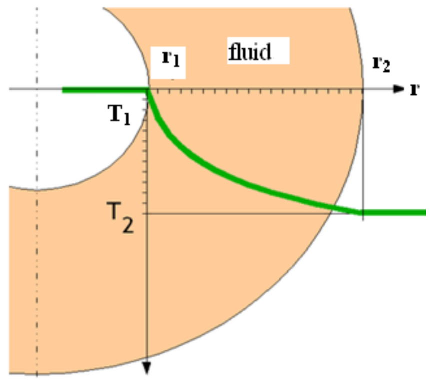


Fig. 3: Temperature evolution in the sample

Hence, the thermal conductivity can be determined by measuring the heat flux into the surface and the temperature difference between the two surfaces of the inner and the outer cylinders.

$$\frac{dr}{r} = -\frac{2\pi\lambda_f L}{Q_c} dT \quad (2)$$

Equation (2) was integrated:

$$\int_{r_1}^{r} \frac{dr}{r} = -\frac{2\pi\lambda_f L}{Q_c} \int_{T_1}^{T} dT \quad (3)$$

Therefore, the variation of temperature in the liquid sample is given by Eq. (4):

$$T = T_1 - \frac{Q_c}{2\pi L \lambda_f} \ln(\frac{r}{r_1}) \quad (4)$$

On the totality of the thickness of the liquid sample, the temperature difference is given by:

$$T_1 - T_2 = \frac{Q_c}{2\pi\lambda_f L} \ln(\frac{r_2}{r_1}) \quad (5)$$

Then, Eq. (6) permits us to calculate the thermal conductivity of the sample:

$$\lambda_f = \frac{\ln(\frac{r_2}{r_1})}{2\pi L} \frac{Q_c}{\Delta T} \quad (6)$$

Where: $Q_c = U.I = 57 Watt$

4. Results and discussions

Case of distilled water:

A sample of distilled water is filled in the radial space between the two coaxial cylinders using a searing. The temperature on the both sides of the liquid is monitored using a heating element on one side and a refrigerator bath circulator on the other side. The temperatures evolution on the both sides of the liquid were measured and plotted in Fig. 4. We remark that the temperature evolution is characterized by two phases. The first one is a transitory phase that lasts 14 min in which temperatures increases were observed in the inner and the outer cylinders. The second one is a steady state phase in which the temperatures evolution of the inner and the outer cylinder are maintained constant. This phase is used to measure the thermal conductivity of distilled water using Eq. (6).

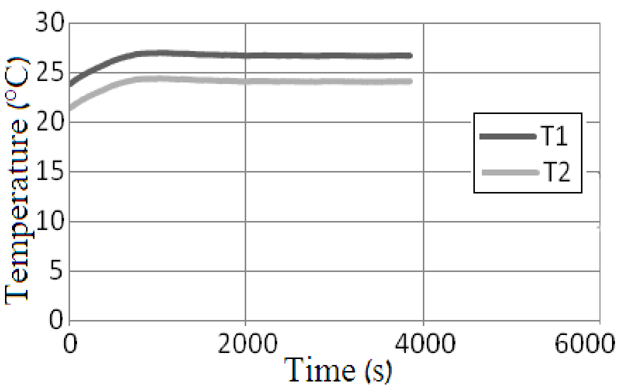


Fig. 4: Temperature evolution on both sides of the liquid

The temperature difference between the two cylinders is maintained at 3°C. The obtained value of the thermal conductivity of distilled water is equal to λ_{exp} = 0.57 W.m^{-1}.K^{-1} which is in good agreement with the reported value in the literature **[**11, 12**]** (λ_{lit}=0.607 W.m^{-1}.K^{-1}). Thermal conductivities of the other liquids were measured at 25°C. Results are presented in Table.1.

Table 1: Measured thermal conductivities

Liquids	λ (W m^{-1}.K^{-1}) Experimental data	λ (W m^{-1}.K^{-1}) Literature data
Ethanol	0.167	0.169 [11, 12]
Methanol	0.200	0.199 [11, 12]
Glycerol	0.291	0.292 [11, 12]
Acetone	0.220	0.180 [11, 12]
Ethylene glycol	0.330	0.256 [12, 13]

Table 1 shows that the measured thermal conductivities are in good agreement with literature data. In this study, we have also measured the variation of the thermal conductivity versus temperature of some liquids like ethanol and ethylene glycol. The average temperature of the fluid can be calculated using the mean average approximation ($T = \frac{T_1 + T_2}{2}$).

Measurements results are given in Fig. 5. and Fig. 6.

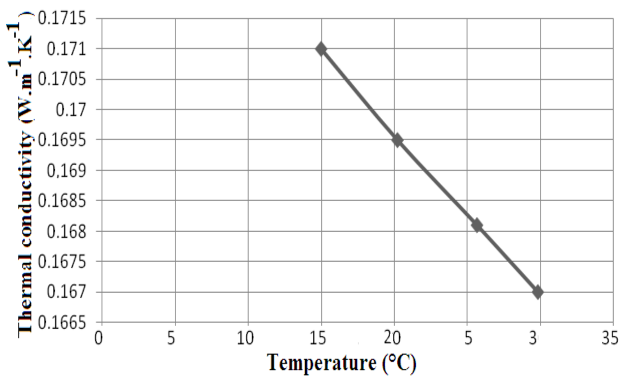


Fig. 5: Thermal conductivity of ethanol vs temperature

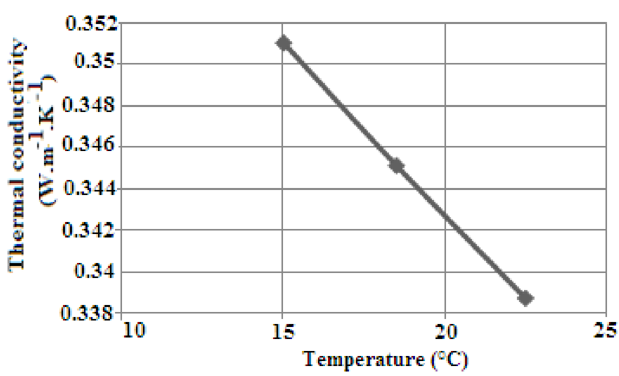


Fig. 6: Thermal conductivity of ethylene glycol vs temperature

According to Figs 5 and 6, we conclude that the thermal conductivity of most liquids decreases with temperature. The measured thermal conductivities are correlated by a linear equation [10]:

$$\lambda = \lambda_0[1+\alpha(T-T_0)] \tag{7}$$

where λ_0 is the thermal conductivity at an initial temperature T_0, which is equal to 15°C in this work, and α is a constant which can be determined experimentally.

5. Conclusions

In the present study, the thermal conductivity of some liquids was measured in atmospheric pressure by the coaxial cylinders method. Results are presented for six liquids: distilled water, ethanol, glycerol, methanol, acetone and ethylene glycol and they are found to be in good agreement with values reported in the literature. The variation of thermal conductivities versus temperature of ethanol and ethylene glycol are also determined in this work.

Finally we recall that for both industrial and scientific applications, it is important to measure the thermal conductivity coefficient using a simple technical device such as the coaxial cylinders.

References:

[1] L. P. Filippov, liquid thermal conductivity research at Mascow University, International Journal of Heat and Mass Transfer, Volume 11 (1968) 331-345.

[2] Xiaogang Jin, Jiangtao Wu, Zhigang Liu, Jiang Pan, The thermal conductivity of dimethyl carbonate in the liquid phase, Fluid Phase Equilibria, Volume 220 (2004) 37-40.

[3] Eiji Yamasue, Masahiro Susa, Hiroyuki Fukuyama, Kazuhiro Nagata, Thermal conductivities of silicon and germanium in solid and liquid states measured by non-stationary hot wire method with silica coated probe, Journal of Crystal Growth, Volume 234 (2002) 121-131.

[4] H. Nagai, F. Rossignol, Y. Nakata, T. Tsurue, M. Suzuki, T. Okutani, Thermal conductivity measurement of liquid materials by a hot-disk method in short-duration microgravity environments Journal of Materials Science and Engineering, Volume 276, Issues 1–2 (2000) 117- 123.

[5] J. J. C. Picot, G. I. Goobie and G. S. Mawhinney, Shear Induced anisotropy in thermal conductivity of polyethene melt, Polymer Engineering Science, Volume 22 (1982) 154-157.

[6] M. Naimi, R. Devienne et M. Lebouché, Mesure de la conductivité thermique des fluides complexes à l'aide d'une cellule à cylindres coaxiaux, Compte-rendu 11ème colloque rhéoloqie et transformation des matières agro-alimentaires. 23 I. Nancy, France, (1987).

[7] B. Benigo, P. Ricardo, S. Francisco, B. Eduardo, C. Carlos, Thermal conductivity measurement of liquids by means of a microcalorimeter, Journal of Thermal Analysis and Calorimetry, Volume 104, Number 2 (2011) 805-812.

[8] W. N. Vanderkooi, D.L. Hildenbrand and D.R. Stull, Concentric sphere apparatus, Journal of Chemical Engineering, Data (1967) 12-377.

[9] D. Bellet, M. Sengelin and C. Thirriot, Determination of thermophysical properties of non-Newtoniens liquids using a coaxial cylindrical cell, international Journal of Heat and Mass Transfer, Volume 18 (1975) 1177-1187.

[10] D. Frezzotti, G. Goffredi, E. Bencini, Thermal conductivity measurements of cis-and trans-decahydronaphtalene isomers using a steady-state coaxial cylinders method, J. Thermochimica Acta 265, (1995) 119-128.

[11] F. Maarten, V. Gelder, A Thermistor Based Method for Measurement of Thermal Conductivity and Thermal Diffusivity of Moist Food Materials at High Temperatures, Thesis of the Faculty of Virginia Polytechnic Institute and State University, (1998).

[12] C. Reid, J. H. Prausnitz, T. K. Sherwood, The properties of gases and liquids, Kingsport Press, 3rd ed. (1977).

[13] M. Lewis, Thermal cycling design alternatives for the polymerase chain reaction, Thesis of the University of Maryland, College Park, Department of Mechanical Engineering, (2005).