International Journal of Thermophysics, Vol. 19, No. 4, 1998

A Thermal Conductivity Experimental Method Based on the Peltier Effect[1]

D. González-Mendizabal,[2] P. Bortot,[2] and A. L. López de Ramos[2,3]

The objective of this work was to test a novel experimental technique to determine the thermal conductivity of low-thermal conductivity materials and tropical foods. The experimental method was based on the Peltier effect and its application to the thermoelectric heat pump. This device became practical recently with the development of semiconductor thermocouple materials. The module assembly used in this work had 127 thermocouples connected in series electrically and in parallel thermally. The heat transfer area of the module was 3.96x3.96 cm^2. The equipment was calibrated using standard materials of known thermal conductivity: Plexiglas and Bakelite. Then the κ values were easily computed from a steady-state energy balance equation.

KEY WORDS: food properties; Peltier effect; thermal conductivity; thermoelectric heat pump; tropical foods.

1. INTRODUCTION

Heating and cooling processes are frequently used in many food processing plants. In all of these heat transfer processes, it is necessary to predict the thermal behavior of the system under study, namely, the temperature distribution and the heat flux. These variables are a function of the nature of the solid and, consequently, a function of certain physical properties. Prior knowledge of thermal conductivity (κ) is necessary in the design of heat transfer equipment and cooling or freezing processes. There are several methods that allow the determination of κ. Most of these methods are based on the integral form of the Fourier law of heat conduction, when

[1] Paper presented at the Thirteenth Symposium on Thermophysical Properties, June 22–27, 1997, Boulder, Colorado, U.S.A.

[2] Grupo FTUSB, Departamento de Termodinámica y Fenómenos de Transferencia, Universidad Simón Bolívar, Apartado Postal 89000, Caracas 1080-A, Venezuela.

[3] To whom correspondence should be addressed.

0195-928X/98/0700-1229$15.00/0

they are applied to steady-state heat transfer processes. Fourier's law can be expressed by the following equation:

$$Q = \kappa A \frac{\Delta T}{\Delta x} \tag{1}$$

where Q is the heat transfer rate, A is the heat transfer area, κ is the thermal conductivity of the sample, and $\Delta T/\Delta x$ is the temperature gradient through the sample.

Equation (1) allows a direct experimental determination of the value of κ, under steady-state conditions. This equation also requires a measurement of the temperature difference between two points in the direction of the heat flux. In addition, it is required that the heat flux be unidirectional. Previous work [1–3] has reported thermal conductivity values for different solids (polymers, tropical fruits, and vegetables) and composite materials, under steady and transient conditions. The objective of this work was to test a novel experimental technique to determine the thermal conductivity of low-thermal conductivity materials and tropical foods. The experimental method is based on the Peltier effect and its application to the thermoelectric heat pump. This device is employed to heat or cool the sample under study, making it possible to calculate precisely the heat introduced to the system. Once the heat transferred and the temperature difference through the solid are known at steady-state conditions, the thermal conductivity (κ) can be calculated using Eq. (1).

1.1. The Thermoelectric Heat Pump

Thermoelectric heat pumps perform the same cooling functions as Freon-based vapor compression or absorption refrigerators. In all such units, thermal energy is extracted from a region, thereby reducing its temperature and, then rejected to a heat-sink region of higher temperature. Vapor-cycle devices have moving parts and require a working fluid, while thermoelectric elements are totally solid state. Four basic physical phenomena can be associated with the operation of thermoelectric devices [4]: the Seebeck effect, the Thomson effect, the Joule effect, and the Peltier effect. The Seebeck effect is the electromotive force generated when two sides of a thermoelectric module are maintained at different temperatures. The Thomson effect is a heating or cooling effect in a homogeneous conductor observed when an electrical current is passed in the direction of a temperature gradient. The Joule effect is the heating effect observed in a conductor as an electrical current is passed through the conductor. The Peltier effect is the heating or cooling effect observed when an electrical current is passed through two dissimilar junctions. Three of these effects, Peltier, Thomson, and Seebeck, are reversible phenomena.

Solid-state heat pumps have been known since the discovery of the Peltier effect in 1834. When an electric current flows from one conducting material to another through a junction as shown in Fig. 1 [5], energy is brought by the charge carriers to the junction from material A at the left at a rate Q_A, and energy is carried from the junction to material B at the right at a rate Q_B. Because the energy level of the charge carriers will in general be different in the two materials, Q_A will be greater or less than Q_B. To maintain a constant junction temperature, heat must be transferred (Q_j) to or from the surroundings as shown. The energy level and thus the amount of energy transported, is a function of each material. The Peltier coefficient is defined as $\pi = Q/I$ (Q, heat flow; I, current density). The junction itself must have a finite electrical resistance so that current flow through it will result in the dissipation of the usual power I^2R (Joule effect, where R is the electrical resistance). This process, of course, is not reversible but is always a conversion from electrical energy to heat.

The application of this cooling effect remained minimal until the development of semiconductor materials. With the advent of semiconductor materials came the capability for a wide variety of practical thermoelectric refrigeration applications. Thermoelectric refrigeration is achieved when a direct current is passed through one or more pairs of n- and p-type semiconductor materials (Fig. 2). In the cooling mode [6], direct current passes from the n- to the p-type semiconductor material. The temperature T_C of

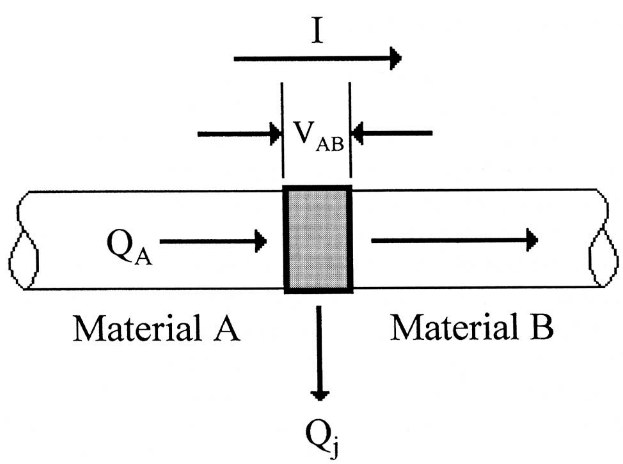


Fig. 1. Current through the junction of two materials (Peltier effect).

the interconnecting conductor decreases and heat is absorbed from the environment. The absorption of heat from the environment (cooling) occurs when electrons pass from a low energy level in the *p*-type material through the interconnecting conductor to a higher energy level in the *n*-type material. The absorbed heat is transferred through the semiconductor material by electron transport to the other end of the junction T_H and liberated as the electrons return to a lower energy level in the *p*-type material (Peltier effect).

When a temperature differential is established between the hot and the cold ends of the semiconductor materials, a voltage is generated (Seebeck effect). This voltage is called the Seebeck voltage, and it is directly proportional to the temperature differential ($\alpha \Delta T$). The constant of proportionality (α) is referred to as the Seebeck coefficient.

Ideally, the amount of heat absorbed at the cold end and the heat dissipated at the hot end are dependent on the product of the Peltier coefficient and the current through the semiconductor material. Practically the net amount of heat absorbed at the cold end due to the Peltier effect is reduced by two sources, conducted heat and Joule heat. Due to the differential between the cold and the hot ends of the semiconductor material, heat is conducted through the semiconductor material from the hot to the cold end. As the current is increased, the temperature differential, and thus the conducted heat, increases because the Peltier cooling effect increases. However, the other loss, Joule heat, is proportional to the square of the current and, therefore, eventually becomes the dominant factor. At any

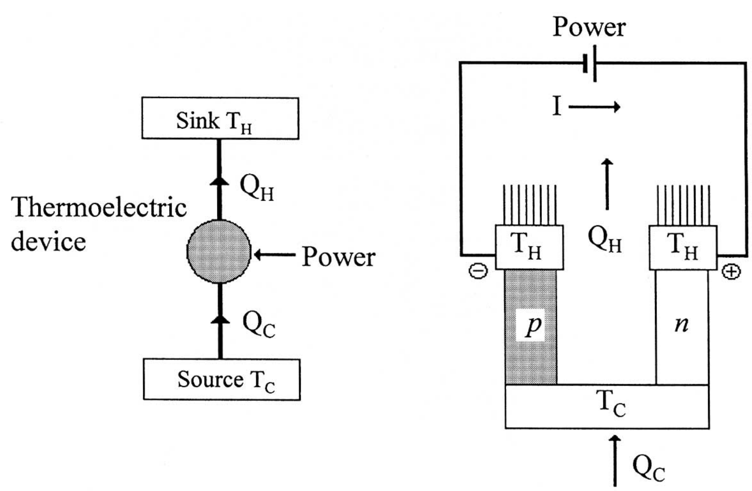
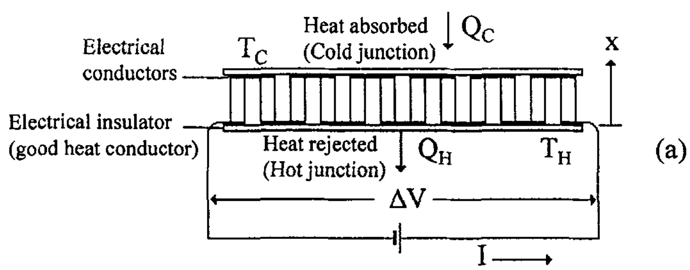


Fig. 2. Thermoelectric heat pump.

given current, thermal equilibrium is established at the cold end when the Peltier effect at the cold end is equal to the sum of the conducted heat plus one-half of the Joule heat. The other half of the Joule heat goes to the hot end. The net heat dissipated at the hot end is the sum of the net heat absorbed at the cold end plus the applied electric power.

More than one pair of semiconductors are usually assembled together to form a thermoelectric module. A single-stage module, as shown in Fig. 3a, consists of several thermocouples connected thermally in parallel and electrically in series to increase the operating voltage of the module. These thermocouples are interconnected with good electric conductors such as copper. The conductors must be electrically isolated from the device being cooled; otherwise the module will be electrically short-circuited to the surface being cooled. However, the electrical isolation material must also be a thermally conductive material to minimize the temperature difference between the conductor and the device being cooled. The module shown in Fig. 3b has a ceramic plate on the top and bottom surfaces of the module. Alumina ceramics typically provide the electrical isolation and thermal conductance that satisfies this requirement.

In the operation of thermoelectric modules, it is reasonable to assume that the heat flows only in the x direction; this means that there is no heat flow except through the junctions [4]. Moreover, all the heat may be



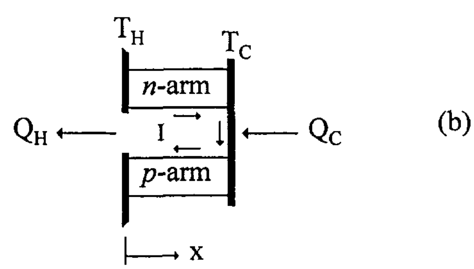


Fig. 3. (a) Single-stage thermoelectric module. (b) Thermoelectric couple.

considered to flow through the plates which sandwich the thermoelectric couples. To find a formula for Q_C or Q_H, it is necessary to look at one of these thermoelectric couples. As shown in Fig. 3b the direction of the current is opposite for n- versus p-material. Most of the properties of these two materials differ from each other, in fact. If one makes use of these differences, it is possible to derive the equation of the heat flow for a couple using the equation of heat flow through a bar. Under steady-state conditions, the differential equation for energy flow through a unit volume is written as

$$TI\frac{\partial\alpha}{\partial x}+\tau I\frac{\partial T}{\partial x}-\rho I^2-\frac{\partial}{\partial x}\left(\kappa\frac{\partial T}{\partial x}\right)=0 \tag{2}$$

where T is the temperature, x is the coordinate, I is the current density, κ is the thermal conductivity of the material, α is the Seebeck coefficient, τ is the Thomson coefficient, and ρ is the electrical resistivity.

To solve Eq. (2), a numerical method would be applied knowing the transport properties as a function of temperature. Therefore, it is rather necessary and convenient to assume averaged transport properties. Equation (2) will be applied for the n- and p-arms, but with different properties and opposite directions of current. Thus, adding Peltier terms, one can have the equation of heat flow at the junction of two dissimilar conductors [4].

$$\text{Heat flow at } T_C: \quad q_C=\alpha T_C I+\tfrac{1}{2}\bar{\tau}I\,\Delta T-\tfrac{1}{2}I^2\bar{R}-\bar{\kappa}\,\Delta T \tag{3}$$

$$\text{Heat flow at } T_H: \quad q_H=\alpha T_H I-\tfrac{1}{2}\bar{\tau}I\,\Delta T+\tfrac{1}{2}I^2\bar{R}-\bar{\kappa}\,\Delta T \tag{4}$$

where $\Delta T=T_H-T_C$, and α is the net Seebeck coefficient of a couple at the temperature of the junction. $\bar{R}$, $\bar{\kappa}$, and $\bar{\tau}$ are the average properties of a couple in the temperature range of $T_C<T<T_H$.

For a module that contains n couples connected electrically in series and thermally in parallel:

$$Q_C=nq_C=\alpha_m T_C I-\tfrac{1}{2}I^2R_m-\kappa_m\,\Delta T \tag{5}$$

$$Q_H=nq_H=\alpha_m T_H I+\tfrac{1}{2}I^2R_m-\kappa_m\,\Delta T \tag{6}$$

where $\Delta T=T_H-T_C$, and α_m, R_m, and κ_m are the mean values of the transport properties of the module in the temperature range of $T_C<T<T_H$.

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in Fig. 4. The thermoelectric device is a Peltier module MELCOR [7], Model CP1.4-127-045L; the low-current ceramic-insulated thermoelectric contains 127 thermocouples, each element 1.143 mm in length and 1.4 mm square in cross section. The thermoelectric material is a quaternary alloy of bismuth, tellurium, selenium, and antimony, with small amounts of suitable dopents, processed to produce an oriented polycrystalline ingot with superior anisotropic thermoelectric properties. Metallized ceramic square plates, with sides of 3.96 cm, afford maximum electrical insulation and thermal conduction. The operating temperature range is -150 to $+80°C$. The mean values of the transport properties for this module are reported as a function of T [8].

Before the experiments, the thermoelectric module surfaces were cleaned and degreased. Then, a thin continuous film (approximately 0.025 mm thick) of thermal grease was applied to the surfaces of the thermoelectric device to minimize contact resistance. The module was moved back and forward exerting a uniform downward pressure until noting efflux of thermal compound around the edges of the module. The cold surface of the module was located over the finned heat exchanger. In order to promote heat transfer, a fan was placed beneath the finned heat exchanger.

The sample was sliced and placed on top of the ceramic plate. To guarantee one-dimensional heat flow, the sample was isolated by surrounding it with a block of very low conductive material. Three very thin

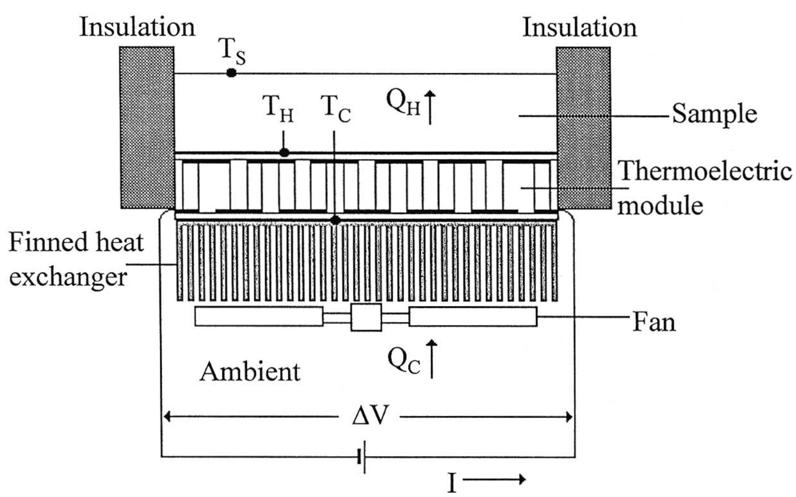


Fig. 4. Experimental arrangement.

thermocouples (J type) were placed on both sides of the sample and on the cold surface of the thermoelectric module to measure T_H, T_C, and T_S (sample external surface temperature). The temperature and intensity of current (supplied during the experiment) were recorded with a data acquisition system.

3. RESULTS AND DISCUSSION

To test the performance of the proposed method, two samples (Plexiglas and Bakelite) with known thermal properties were selected as test materials. Their thermal conductivity values are reported in Table I. For the Plexiglas, the thermal conductivity value calculated in this work is within the ranges reported in the literature. In the case of the Bakelite, the experimental value of κ was slightly higher when it was compared with literature values, since the test temperature was also higher. These results support the assumptions leading to the proposed mathematical model and the experimental methodology used.

The values of thermal conductivity and water content (wc) for the tropical foods selected in this work—carrot (*Daucus carota*), yucca (*Manihot dulcis*), and sugar beet (*Beta vulgaris*)—are summarized in Table I. The heating process takes about 7 min. This test time is considerably less than that required for the guarded hot-plate method [12], since the size of the sample is considerably smaller and the heat transfer process (Peltier effect) is more efficient than with the traditional wired hot plate. When a small sample is required for any thermal method, it is easier to achieve a uniform thickness and temperature. Using cascaded thermoelectric modules (or a device with more thermocouples), it is possible to reduce the cooling or heating time of the thermal conductivity measurement to a few seconds. This processing time would be similar to those used in the food industry.

The values of thermal conductivity obtained in this work for sugar beet, yucca, and carrot were very similar to those reported in the literature

Table I. Water Content (wc) and Thermal Conductivity (κ) of Samples Studied in this Work

Sample	Thickness (mm)	wc (%)	κ from this work ($W \cdot m^{-1} \cdot K^{-1}$)	κ from literature ($W \cdot m^{-1} \cdot K^{-1}$)
Plexiglas	5.4	—	0.26 @ 350 K	0.20–0.26 @ 300–400 K [8,9]
Bakelite	6.5	—	1.5 @ 330 K	1.4 @ 300 K [10]
Carrot	6.5	66	0.7 @ 320 K	0.6 @ 80–90% wc [2,11]
Yucca	8.2	61	0.61 @ 320 K	0.63–0.66 @ 57–70% wc [2]
Sugar beet	9.95–10	87	0.77–0.88 @ 320 K	0.63 @ 55–65% wc [2,11]

[2, 11]. In general, the thermal conductivity varies in the range from 0.6 to $0.88\ W \cdot m^{-1} \cdot K^{-1}$. The deviations between experimental results and reported values in the literature can be attributed to the variations in the water content and the intrinsic chemical and physical differences due to the nature of the roots. For this reason, it is necessary to measure thermal properties for the specific kind of food, due mainly to the enormous variety of them.

4. CONCLUSIONS

The proposed method to determine solid thermal conductivity based on the Peltier effect (thermoelectric module) shows satisfactory results for all the standard samples used. This indicates that thermoelectric refrigeration is a highly reliable and practical method of cooling or heating small-volume samples at a low cost and with a high efficiency.

The total test time required is similar to the cooling and heating time used by the food industry in many of its wide variety of processes. The proposed experimental method is an excellent way to determine the thermal conductivity easily, accurately and at low cost.

ACKNOWLEDGMENTS

The authors want to thank the Decanato de Investigaciones y Desarrollo and Sección de Fenómenos de Transporte del Laboratorio A, Universidad Simón Bolivar, for their financial support. Special thanks go to Gabriela Morillo and Luis Castro, who helped with the previous experimental measurements.

REFERENCES

1. J. A. Pimentel, D. Fayés, A. López de Ramos, and D. González-Mendizabal, *Chem. Eng. Commun.* **103**:131 (1991).
2. A. López de Ramos, E. Palmisano, A. Dombey, J. A. Pimentel, D. Fayés, and D. González-Mendizabal, *Rev. Esp. Cienc. Tecnol. Aliment.* **33**:271 (1993).
3. A. Pimentel, T. Holoma, F. Camero, D. Fayés, D. González-Mendizabal, A. López de Ramos, and J. A. Pimentel, *Evaluación de un Método no Estacionario para la Determinación de Difusividades Térmicas en Medios Compuestos de Geometria Cilíndrica*, Memorias del V Congreso Latinoamericano de Transferencia de Calor y Materia: LATCYM'94 (1994), Vol. II, IID-20.1.
4. Cambridge Thermionic Corporation (CAMBION), Catalog: *Thermoelectric Handbook* (1978), p. 3.
5. B. D. Wood, *Applications of Thermodynamics* (Waveland Press, New York, 1982), p. 400.
6. R. Marlow, in *Handbook of Applied Thermal Design*, E. C. Guyer and D. L. Brownell, eds. (McGraw-Hill, New York, 1989), pp. 9–25.

7. *MELCOR Solid State Cooling with Thermoelectrics: Catalog of Frigichip*, Miniature Ceramic Modules Series FC (Melcor Corp., NJ, 1990).
8. *MELCOR Frigichip Thermoelectric Cooling Devices: Thermoelectric Engineering Handbook* (Melcor Corp., NJ, 1995).
9. P. Slade and L. Jenkins, *Thermal Characterization Techniques* (Marcel Dekker, New York, 1970), p. 254.
10. F. P. Incropera and D. P. De Witt, *Fundamentals of Heat and Mass Transfer* (Wiley, New York, 1990).
11. V. Sweat, *J. Food. Sci.* **39**:1080 (1974).
12. American National Standards Institute, *Standard Method of Test for Thermal Conductivity of Material by Means of the Guarded Hot Plate*, C177-63, Annual Book of ASTM Standards (ASTM, Philadelphia, 1970).