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Thermal conductivity of Torlon between 4.2 and 300 K

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Abstract

Torlon is an organic polymer (polyamide-imide) which exhibits room temperature good mechanical and thermal properties and high chemical resistance. The thermal conductivity of Torlon 4203 was measured in the range of temperature 4.2–300 K. These data complete existing measurement in the temperature range 0.1–5 K. The thermal conductivity shows a linear behavior between 30 K and 250 K and a plateau, typical of many amorphous materials, around 7 K.

Keywords: Thermal conductivity; Polymer

1. Introduction

We have measured the thermal conductivity of Torlon[1] 4203 PAI Polyamide-imide (Solvay Advance Polimers, L.L.C.) in the 4.2–300 K range. Torlon is an amorphous organic polymer which exhibits room temperature superior mechanical properties (low coefficient of linear thermal expansion, high creep resistance, excellent compressive strength, etc.) and a good chemical resistance. Torlon is capable of performing throughout a wide temperature range; in particular, it retains its high strength at low temperatures.

Difficulties to measure the physical characteristics at low temperature often limit our understanding of material behaviour used in the realization of cryogenic devices. Three parameters are extremely important to know for cryogenic applications: the thermal conductivity, which controls the thermal input; the specific heat, which controls the cool-down time; and the integrated thermal contraction whose magnitude controls, with a proper mechanical design, the mechanical stability of the apparatus.

However, in some cases, the choice of the material for low temperature applications starts from data of thermal conductivity; hence it would be useful to be able to compare data of thermal conductivity of various materials. In the case of polymers, which are frequently used in the realization of a cryogenic apparatus, many data are available for temperatures below 4 K [1,2]. Data of thermal conductivity between 4 K and room temperature are less common [1].

The thermal conductivity of Torlon 4203 in the temperature range 0.1–5 K and the thermal expansion relative to 4.2 K were measured by Ventura et al. [3]. The stimulus to extend the thermal conductivity data of Torlon 4203 to the 4.2–300 K temperature range is the fact that this material is the candidate for the spacers (see Fig. 1) of the thermal shields of the Wendelstein 7-X stellarator [4,5].

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Fig. 1. Torlon support for the thermal shield of the Wendelstein 7-X stellarator (Courtesy of MAN DWE, LINDE, and IPP).

2. Experimental set-up and measurements

The measurement of the thermal conductivity of Torlon has been carried out on a sample whose shape and dimensions are shown in Fig. 2. The part of the sample along which the gradient of temperature is produced has a cylindrical form of length $L = 5.75 \pm 0.03$ mm and radius $r = 4.00 \pm 0.01$ mm, giving a form factor $g = \frac{A}{L} = \frac{\pi r^2}{L} = 8.74 \pm 0.09$ mm at room temperature.

The thermal contacts at the end of the sample have been realized by means of two gold-plated copper screws (A_1, A_2) 4 mm in diameter. The threadings in the sample had a depth of 5 mm. Since the thermal contraction of Torlon is slightly greater than that of copper [3,6], the thermal contact between the screws and the threaded parts of the sample becomes better on cooling. On the other hand, to ensure the thermal contacts on the two flat surfaces of the sample, two gold-plated copper blocks (B_1, B_2), on which thermometers were mounted, were pressed by stainless steel springs (C) against the two ends of the sample.

Thermal conductivity was measured by a steady state technique. One end of the sample was fixed (see Fig. 3) onto a gold-plated copper platform PF whose temperature T_1 can be set by means of a heater H_1. A thermometer R_1 measured T_1. The copper block B_2 held a carbon thermometer R_2 and a NiCr heater H_2 was glued on the top of the screw A_2 (see Fig. 2). Electrical connections were made of ∅50 μm, ~35 cm long manganine wires. A cylindric gold-plated copper thermal shield enclosed the sample and an outer gold-plated copper thermal shield (S) enclosed the experiment (see Figs. 2 and 3). The cylindric copper shield had a length of 28 mm, an inner diameter of 12 mm and a thickness of 1.5 mm. A power P_e was supplied to H_2 in order to create a temperature gradient $\Delta T \sim 2\% \cdot T_1$ along the sample. The thermal conductivity at a temperature T was evaluated from:

$$\begin{cases} k(T) = \dfrac{P_e}{g \cdot \Delta T} \\ T = \dfrac{T_1 + T_2}{2}; \;\; \Delta T = T_2 - T_1 \end{cases} \qquad (1)$$

Three runs of measurements were carried out in a ^{4}He Dewar at a pressure of about 10^{-4} Pa:

(1) 8–25 K: thermal bath at 4.2 K and Dewar shield at 77 K;

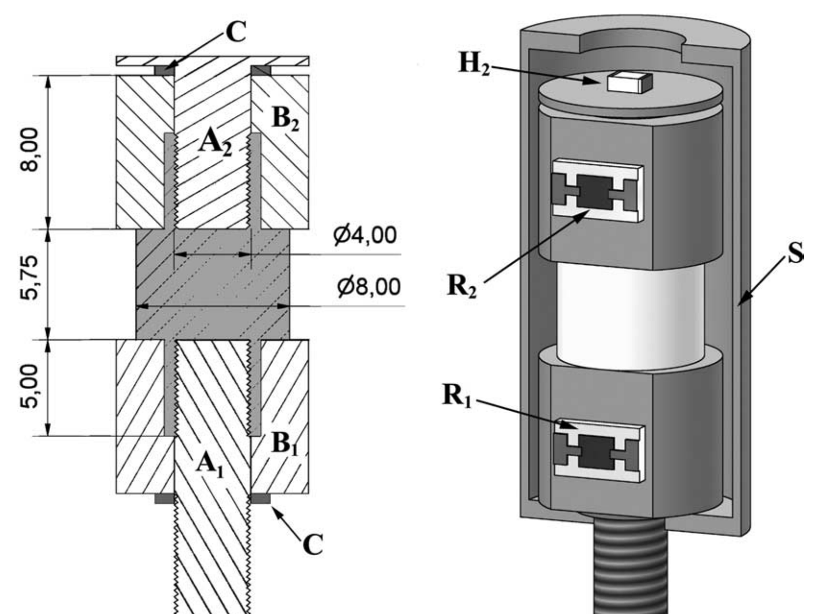

Fig. 2. Shape and size of the sample (mm) and view of the sample holders.

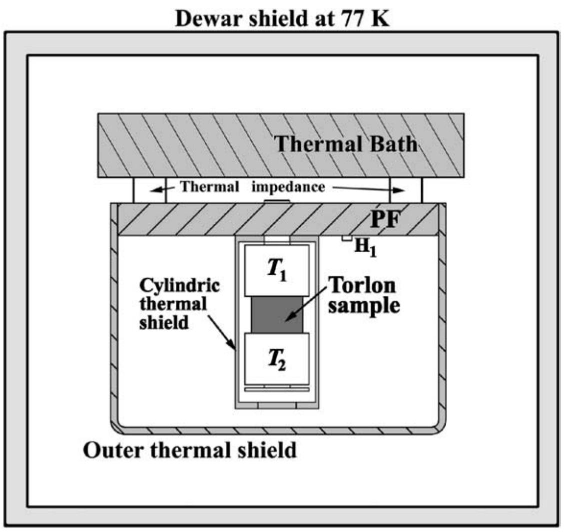

Fig. 3. Schematic of the experimental set-up.

(2) 30–80 K: same as (1), with a greater bath-platform thermal impedance to reduce helium consumption;
(3) 80–300 K: thermal bath and Dewar shield at 77 K, with a greater bath-platform thermal impedance.

Measured thermal conductivity of Torlon 4203 is shown in Figs. 4 and 5. The correction due to the thermal contraction (max $\Delta g/g = 0.4\%$) was neglected [3].

Data for Torlon, presented in Fig. 5 together with data of Ref. [3], are typical of amorphous polymers. In particular, they show:

(1) a T^2 dependence of k below 1 K, in agreement with the "tunneling model" [7,8];
(2) a plateau between 5 and 10 K, as predicted by the "soft potential model" [9];
(3) a steep rise of conductivity after the plateau;

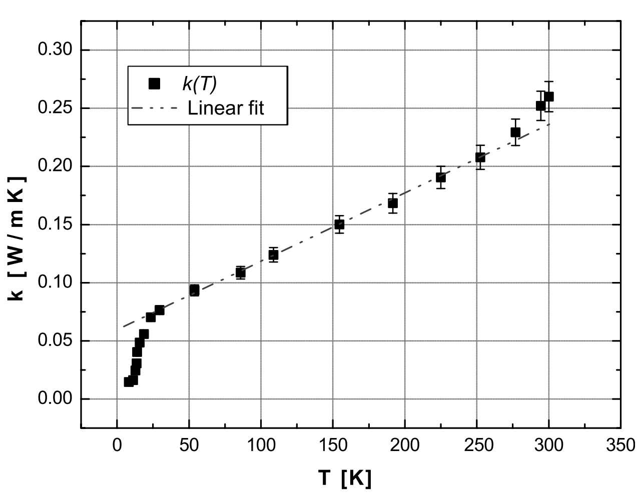

Fig. 4. Thermal conductivity of Torlon in the temperature range 4.2–300 K. The dashed line represents formula (2).

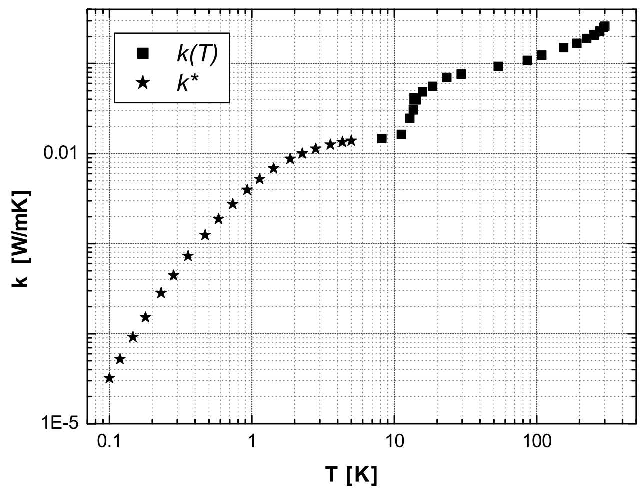

Fig. 5. Thermal conductivity of Torlon in the 0.1–300 K range. Note the good match of data of Ref. [3] (★) and present data (■) at the beginning of the plateau region.

(4) an almost linear $k(T)$ between 30 K and room temperature.

A similar behaviour has been found for the thermal conductivity of other polymers, e.g. polymetilmethacrylate (PMMA) [10].

As regards our data, in the 30–250 K range, the thermal conductivity of Torlon can be represented by

$$\begin{cases} k(T) = b + a \cdot T \\ a = (0.58 \pm 0.03) \times 10^{-3} \quad [\mathrm{W/m\,K^2}] \\ b = (0.60 \pm 0.03) \times 10^{-1} \quad [\mathrm{W/m\,K}] \end{cases} \tag{2}$$

Data at the lowest temperatures of Fig. 4 match well data at $T < 5$ K [3].

3. Discussion of the experimental method

Several assumptions in the preceeding paragraph deserve a more detailed explanation.

3.1. Thermometer accuracy

Two carbon thermometers R_1 and R_2 were used in this experiment at the ends of the sample.

The two thermometers (thermistors from the same batch) were "copied" from a secondary calibrated thermometer (courtesy of Air Liquide) in one thermal run between 4.2 and 300 K. We checked the accuracy (1%) of the secondary thermometer at:

- 4.22 K: He boiling temperature corrected for pressure dependance;
- 9.21 K: transition of Nb of a NBS-SMR 767 A fixed point device;

- 77.35 K: N_2 boiling temperature corrected for pressure dependance;
- 273.16 K: triple point of a water cell.

The resolution of the thermometers was 10 m K at 4.2 K and 0.05 K at room temperature.

The error in copying the secondary thermometer is of the order of 0.1%, hence the uncertainty on T is about 1%.

3.2. Comparison among the power passing through the sample and the spurious power leaks

Table 1 shows a comparison among:

- the electrical power P_e delivered to the warmer end of the sample;
- the power P_M shunted by the eight manganine wires;
- the power P_R radiated by the sample toward the cylindric shield.

In Table 1, P_R was calculated considering the thermal exchange for radiation between two cylindrical coaxial surfaces with the following hypotheses:

(1) neglecting the contribution from the gold plated supports B_1 and B_2;
(2) assuming emissivity $\varepsilon_T = 0.5$ for Torlon and an emissivity $\varepsilon_s = 0.03$ [11] for cylindric gold-plated copper shield;
(3) considering the sample at its mean temperature $T = \frac{T_2+T_1}{2}$;
(4) assuming a ratio between the surfaces $\frac{A_T}{A_s} = 0.5$, with A_T lateral surface of the sample and A_s surface of the cylindric gold-plated copper shield that the sample "sees".

From Table 1, at 300 K, the estimated P_R becomes about $\sim$1.1% of P_e.

3.3. Thermal contacts to the sample

The thermal resistance between the ends of the sample and the copper blocks must be negligible compared with the thermal resistance of the sample. This assumption must be verified especially for short samples at low temperature where the contact resistance is higher. For this reason we have carried out a second measurement of the thermal conductivity of Torlon in the 4.2–25 K range. The second sample had a different length (L = 24.51 mm) and the same section A. This additional measurement, gave the same value of k within 2%.

Moreover we see from Fig. 5 that data of thermal conductivity at 4.2 K well join data at lower temperatures (within 3%) obtained on a sample of much smaller form factor and with a different method (integrated thermal conductivity method) and a different apparatus [3]. Finally, at room temperature, we find k = 0.26 W/m K, which is the value supplied by the producer of Torlon.

3.4. Error budget

From equation (1) we obtain:

$$\frac{\Delta k}{k} = \frac{\Delta P_e}{P_e} + \frac{\Delta g}{g} + \frac{\Delta(\Delta T)}{\Delta T} \tag{3}$$

There are three main contributions to the maximum relative error in k:

(1) the power supplied to the sample: from Table 1 we can estimate that the relative error of P_e is of the order of $\sim$1%;
(2) the measurement of the form factor g. The error in the measurements of L and A has been estimated as 0.5% and 0.5%, respectively;
(3) the uncertainty on the temperature gap ΔT due to the sensitivity of the thermometers in temperature range 4.2–300 K. A conservative value of $\frac{\Delta(\Delta T)}{\Delta T}$ is $\sim$2%.

Taking into account the uncertainty on T, that is about 1%, we conclude that the maximum (at 300 K) relative error in k over the 4.2–300 K is 5%.

Table 1
Comparison among: the electrical power P_e delivered to the warmer end of the sample, the power P_M shunted by the eight manganine wires and the power P_R radiated by the sample toward the cylindric shield

T [K]	P_e [W]	P_M [W]	P_R [W]
10	3.5×10^{-5}	5.7×10^{-9}	1.8×10^{-10}
80	1.5×10^{-3}	3.0×10^{-7}	7.5×10^{-7}
300	1.4×10^{-2}	1.9×10^{-6}	1.5×10^{-4}

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