Kapitza resistance and thermal conductivity of Mylar at superfluid helium temperature

G. Hattenberger, S. Carré, F.-P. Juster, B. Baudouy
CEA-Saclay, DSM/DAPNIA/SACM, 91191 Gif-sur-Yvette Cedex, France

Abstract

The Kapitza resistance and the thermal conductivity of type A Mylar sheets in the temperature range between 1.4 and 2.1 K have been determined. Four sheets with varying thickness from 37 µm to 255 µm, have been tested in steady-state condition. For a small temperature difference (10 to 30 mK) and heat flux density smaller than 30 Wm^{-2}, the total thermal resistance of the sheet is determined as a function of sheet thickness and bath temperature. The Kapitza resistance is given by R_K=(1.28±0.08) T^{-3} ×10^{-3} Km^{2}W^{-1}, and the thermal conductivity, κ = [(8.83±0.75)+(11.73±0.43)×T]× 10^{-3} Wm^{-1}K^{-1}.

Keywords: Mylar Polymer (A); He II (B); Thermal conductivity (C), Kapitza resistance (D)

Nomenclature

A	Total cross section (m^2)
ℓ	Thickness (m)
n	Exponent
Q	Heat flux (W)
R	Thermal resistance (Km^{2}W^{-1})
$\Delta T=T_i-T_b$	Total temperature difference (K)

Greek Letters

α	Kapitza coefficient (Wm^{-2}K^{-n})
κ	Average thermal conductivity (Wm^{-1}K^{-1})

Subscripts

κ	Conduction
K	Kapitza

1 Introduction

Mylar, polyethylene terephthalate polyester (PETP), is one of the most common thermoplastic polyesters used in industry. Mylar has good electrical and mechanical properties and can be thermally deformed at will into any shape. It absorbs very little water and has good gas barrier properties as well as chemical resistance. Therefore, it is used in many cryogenic applications such as cryogenic target or space components, low temperature heat exchangers and low-conductivity substrates for electrical leads. For all these applications, the knowledge of the thermal conductivity and the thermal resistance, dominated by the Kapitza resistance at the interface in superfluid helium, is crucial. In this work, we present Kapitza resistance and thermal conductivity of a commercial polyester film, type A Mylar, in the superfluid helium temperature range. We have determined simultaneously the thermal conductivity and the Kapitza resistance from 1.4 K to 2.1 K with a steady state heat transfer method that has been already used for Kapton foils [1]. The method consists in testing foils of different thicknesses in identical thermal condition which allows the separation of the conductive and the interface thermal resistance from the total thermal resistance.

2 Experimental set-up and error analysis

2.1 Experimental set-up and principle

The principle of the experiment is displayed in Figure 1 with the schematic temperature profile across the sample. Two sample sheets, in a "drum arrangement", create an inner bath that is considered isothermal in superfluid helium. The inner bath is instrumented with a heater and a temperature sensor (T_i). The outer bath, which corresponds to the cryostat bath, is temperature regulated (T_b). The experimental set-up consists of an instrumented cylindrical support where two 100-mm diameter sample sheets, clamped with two stainless steel flanges, are attached, one on each side, to prevent helium leak and to create the "drum arrangement". A detailed description of the experimental set-up is found in [1, 2]. Four different values of thickness of Mylar A foil (37 µm ~ 255 µm) have been tested. The geometrical dimensions of the sheets are detailed in Table 1. Before each measurement, the sample surfaces underwent a simple cleaning with alcohol.

The steady-state temperature of the inner bath is measured using an AC lock-in amplifier. The thermometer of the inner bath is connected in series with a large resistance (5 MΩ) and the input feeding current is verified at each bath temperature change. The temperature of the cryostat bath, T_b, is obtained using a four-wire measuring technique with a DC battery current source. T_b is regulated within 1 mK and held constant for the entire range of power dissipation, Q.

The temperature difference, $\Delta T = T_i - T_b$, reflects the overall thermal resistance perpendicular to the Mylar sheets. It includes the Kapitza resistance at the boundaries, the thermal resistance due to conduction of the sheet and heat leaks. For temperature differences much smaller than the temperature, $\Delta T \ll T_b$ and T_i, one can take $R = A.\Delta T/Q$ as the definition for thermal resistance. Then the Kapitza resistance on both side of the sample can be simplified to the first order [1] and the total resistance is

$$R = \frac{2}{\alpha n T_b^{\,n-1}}\left(1 - \frac{1}{2}\frac{\Delta T}{T_b} + O(\Delta T)^2\right) + \frac{\ell}{\kappa} \approx \frac{2}{n\alpha} T_b^{\,1-n} + \frac{\ell}{\kappa}. \tag{1}$$

The first term of the right hand side of Eq. (1) is the Kapitza resistance at the helium boundary whereas the second term is the resistance due to thermal conduction within the sheet. Note that the second term in parenthesis of Eq. (1), $\frac{1}{2}\frac{\Delta T}{T_b}$, is lower than 1% of the total resistance in our experiment and thus will be neglected hereafter.

In order to simultaneously extract the thermal conductivity and the Kapitza resistance as functions of temperature, different thicknesses of the same material at different bath temperatures must be tested. The first step is to determine the total resistance of the sample, R, by measuring ΔT against Q, as presents Figure 2. For each bath temperature, the thermal resistance R is plotted as a function of the thickness and the data are fitted to Eq. (1) using a non-linear least square method. This method allows determining simultaneously the thermal conduction, κ, and the Kapitza resistance, $R_K = \frac{2}{n\alpha} T_b^{\,1-n}$, as it is shown in Figure 3.

2.2 *Error analysis*

Although the heat dissipated by the heater mainly goes through the Mylar sheets, heat losses through the capillary containing the instrumentation wiring and the stainless steel support need to be considered as systematic errors. We calculate these heat losses with a finite element analysis of the experimental set-up and published values of the thermal properties of stainless steel and liquid helium [1]. We present the results for the 254 μm thick sheet and at 1.9 K which is a typical case. The heat through the stainless steel support represents about 3% of the total heat flux over the entire range of Q (maximum value of 56 mW for this sample). The heat loss through the helium contained in the capillary reaches 6% of the total heat flux for a ΔT of 2.5 mK. To avoid such high heat loss as well as to satisfy the $\Delta T \ll T_b$ and T_i condition imposed by Eq. (1), we limit our analysis to the [10-30 mK] ΔT range where the loss is contained between 1.7% and 3.2% of the total heat flux. The analysis has been done for a maximum heat flux density of 27 W/m^2 (37 μm thick sheet at 2.1 K).

All electronic components are connected to the power network through an insulated transformer in order to minimize electrical disturbances. The lock-in amplifier provides an AC voltage of 5 V rms at 10 Hz across the thermometer and a 5 MΩ stable resistance is placed in series to obtain a 1μA (±0.2%) feeding current to the thermometer. The temperature measurement sensitivity is ±20 μK at 1.4 K and ±200 μK at 2.0 K. The ΔT error is at most ±0.2 mK in the range of our investigation. This error analysis includes the resistance error measurement and the propagation error through the calibration curve. Heat flux, is generated and monitored by a Keithley source meter with an uncertainty of at most 0.5%.

3 Results and discussion

3.1 *Thermal conductivity*

The result of the thermal conductivity (κ) is plotted in Figure 4. We found κ to be proportional to T, which is consistent with the evolution of semi crystalline polymer thermal conductivity at low temperatures [3, 4]. This is in contrast to the amorphous polymer thermal conductivity that is known to exhibit a quadratic dependency on temperature ($\kappa \propto T^2$). For our temperature range of investigation, we use a dependency evolution as,

$$\kappa=[(8.83\pm0.75)+(11.73\pm0.43)\times T]\times 10^{-3}\ \mathrm{Wm^{-1}K^{-1}}. \quad (2)$$

In Figure 4, the data reported by Hays *et al.* are also presented [5]. They present data on thermal conductivity parallel to the sheet obtained between 0.1 K to 2 K with a classical steady state method on unspecified Mylar. Our results present also a linear temperature dependency, but are three to four times higher than Hays' results. This difference might be explained by the difference in crystalline fraction and by the anisotropic transport properties of Mylar sheet. The fabrication of Mylar sheets creates structural anisotropy of this semi crystalline polymer and might be an important element to explain the difference in thermal transport between the directions normal and parallel to the sheets, and thus in thermal conductivity [6].

3.2 *Kapitza Resistance*

Figure 5 presents our experimental result and the best fit to the Kapitza resistance data described as,

$$R_K=[(1.79\pm0.46)\ T^{-(3.71\pm0.54)}]\times10^{-3}\ \mathrm{Km^2W^{-1}} \quad (3)$$

The observed non-linear temperature dependency ($R_K \propto T^{-3.71}$) is consistent with experimental results on Kapitza resistance temperature dependence. Here, the Kapitza coefficient, α, as defined in Eq. (1), is given as α=236.5±88.5 $Wm^{-2}K^{-4.71}$. We propose to fit the data with the cubic temperature dependence given by acoustic mismatch theory [7]. This simplifies the fit to one independent parameter fit and reduces therefore the error of the fitting parameter. The Kapitza resistance is given by the following equation,

$$R_K=(1.28\pm0.08)\, T^{-3} \times 10^{-3}\ Km^2W^{-1} \quad (4)$$

This is also depicted in Figure 5 as a dotted line. From this expression, one can deduce the Kapitza coefficient as α=391.3±25.5 $Wm^{-2}K^{-4}$. To the best of our knowledge, there is only one experiment on Kapitza resistance on unspecified type of Mylar at low temperatures by Nacher *et al.* [8]. They have determined the Kapitza resistance in the temperature range of 30–150 mK on 8 and 12 µm thick Mylar sheets. Our R_K values are an order of magnitude higher than Nacher's result, which follows a power law $R_K=1.2\, T^{-3}\times10^{-4}\ Km^2W^{-1}$ in the range of their investigation. It should be noted that there is not an acceptable explanation why their value is an order of magnitude lower than the value of Kapitza resistance between liquid helium and solids, except by a possible thermal leak. The fact that our thermal conductivity value is in the same order of magnitude as other results, that our Kapitza resistance is typical for solid-He II interface [9] and that it is in close agreement with the theoretical model make us confident in our results.

4 Conclusion

The simultaneous determination of thermal conductivity and Kapitza resistance in superfluid helium gives reasonable results with acceptable accuracy for Mylar foils. The thermal conductivity of Mylar sheets reported here is comparable to those found in the literature. For small ΔT, the Kapitza resistance is determined within 10% of the theoretical cubic temperature dependency and is in the order of Kapitza resistance of solid-He II interface found in the literature.

References

[1] Baudouy B. Kapitza resistance and thermal conductivity of Kapton in superfluid helium. Cryogenics 2003; 43: 667-672.

[2] Baudouy B, François MX, Juster F-P, and Meuris C. He II heat transfer through superconducting cables electrical insulation. Cryogenics 2000; 40: 127-136.

[3] Finlayson DM and Mason PJ. The thermal properties of semicrystalline polymer at very low temperature. J. Phys. C: Solid States Phys. 1985; 18: 1777-1789.

[4] Finlayson DM and Mason PJ. Structure scattering and thermal conductivity of a semicrystalline polymer. J. Phys. C: Solid States Phys. 1985; 18: 1791-1802.

[5] Hays KM, Rutledge JE, and Sellers GJ. Low thermal conductivity superconducting metallized Mylar leads. Review of Scientific Instruments 1984; 55: 1660-1662.

[6] Dupont-Teijin-(Luxembourg). *Personal communication on Mylar properties*, September 2004.

[7] Khalatnikov IM. An introduction to theory of superfluidity. New York Amsterdam: Benjamin Publishing inc., 1965.

[8] Nacher PJ, Schleger P, Shinkoda I, and Hardy WN. Heat exchange in liquid helium through thin plastic foils. Cryogenics 1992; 32: 353-361.

[9] Van Sciver SW. Helium cryogenics: Plenum press, 1986.

Table 1. Geometrical Dimensions of the Mylar foils

ℓ, Thickness (μm)	A, Cross section (mm^2)
37±1	8891 ± 57
98±1	8560 ± 22
172±1	8625 ± 65
254±2	8860 ± 11

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Figure 1. Principle of the experimental measurement. ΔT=T_i-T_b is the total temperature difference across the sample. T_1 and T_2 are the inner and outer surface temperatures of the Mylar sheets due to the Kapitza resistance.

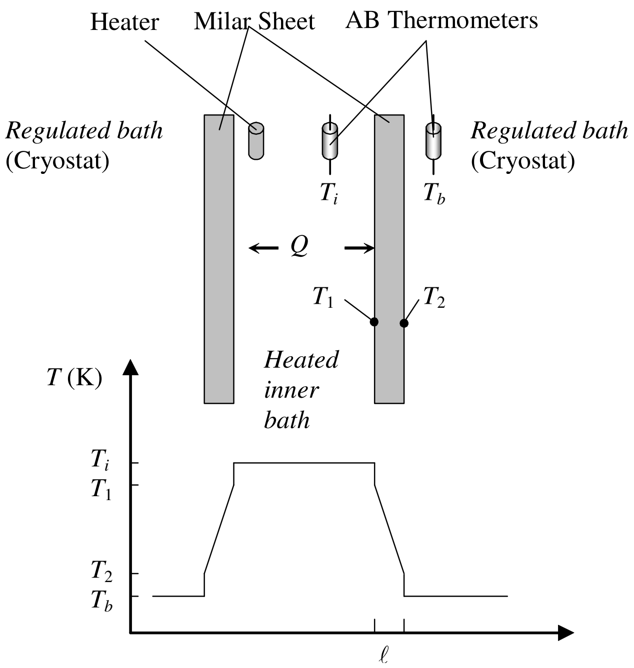
Figure 2. Temperature difference as a function of heat input for the 172 µm thick sheet at different bath temperature. The overall thermal resistance, *R*, is given by the slop of the solid lines results of the linear fit over the [10-30 mK] ΔT range.

Figure 3. Overall thermal resistance, *R*, of Mylar as a function of thickness at 1.5 K.

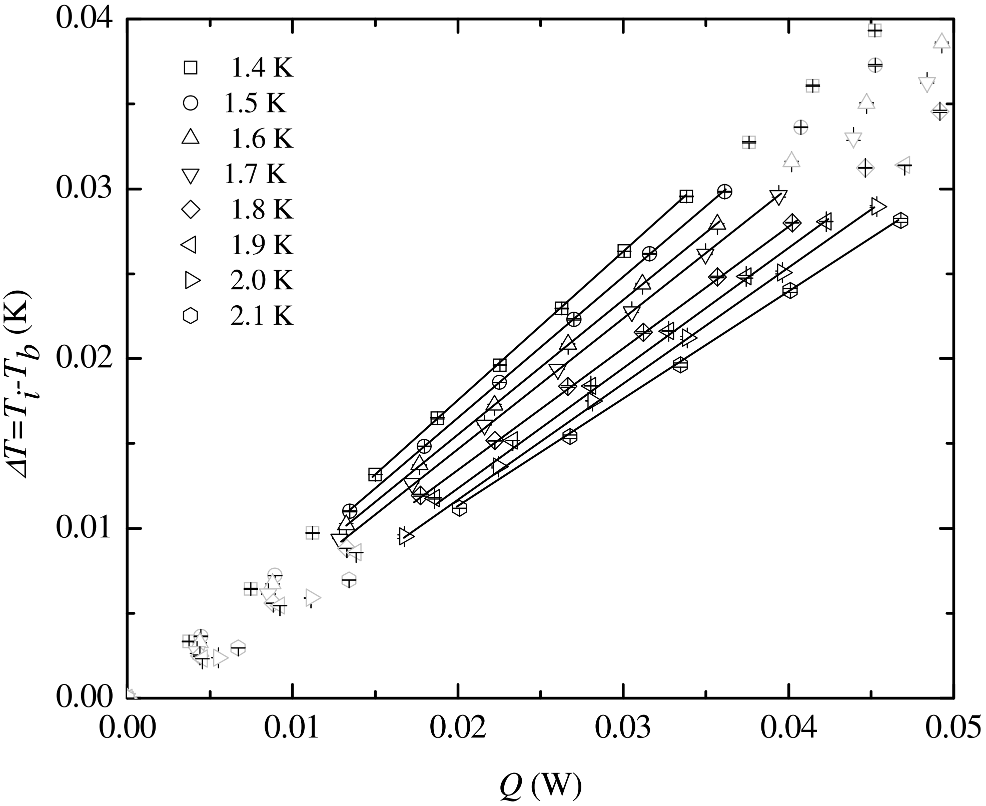
Figure 4. Thermal conductivity as a function of temperature

Figure 5. Kapitza resistance as a function of temperature

Cryogenics, Hattenberger G., Figure 1



Cryogenics, Hattenberger G., Figure 2



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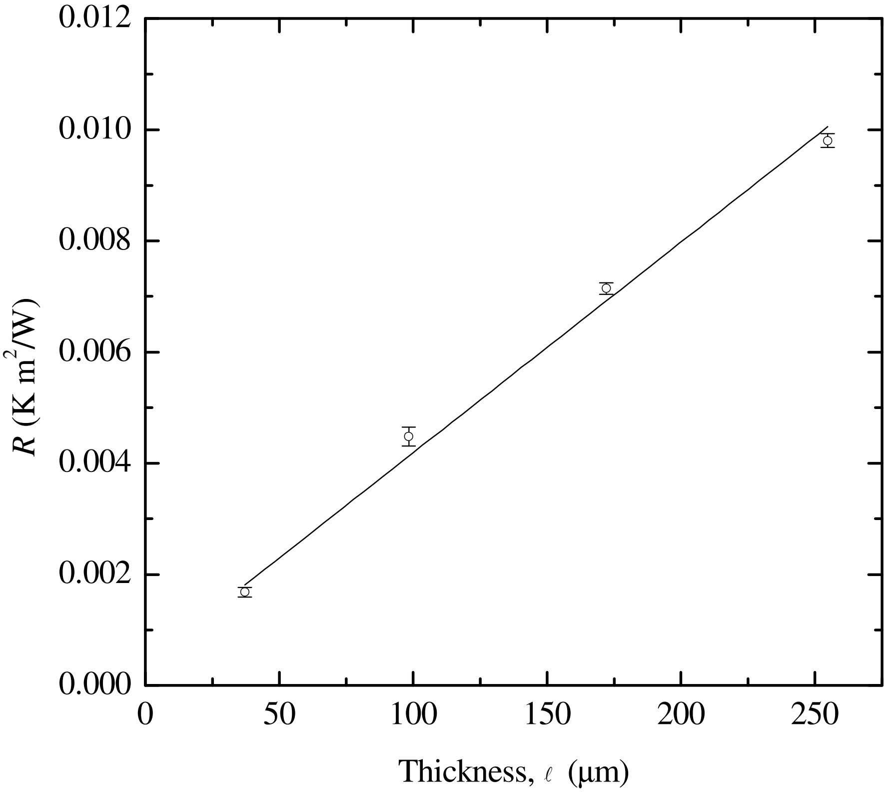
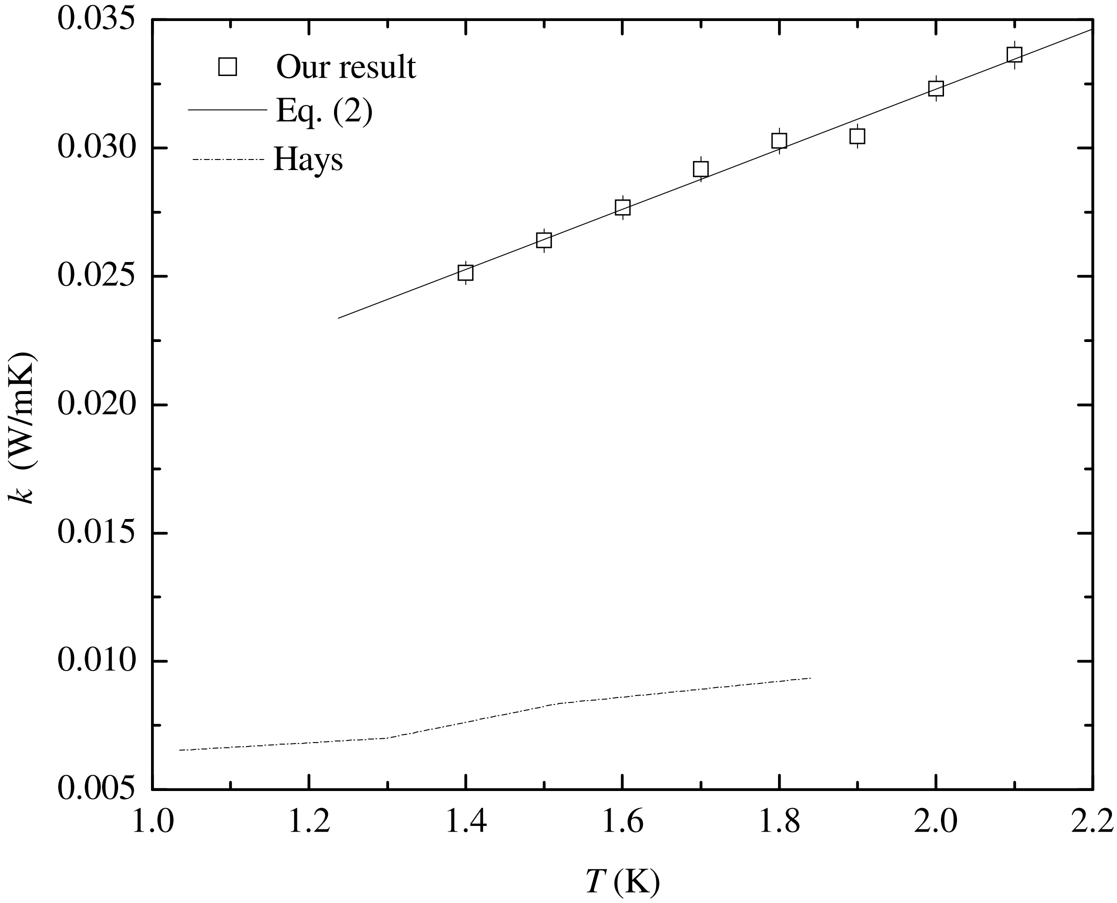


Cryogenics, Hattenberger G., Figure 4



Cryogenics, Hattenberger G., Figure 5