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# Thermal characterization of polyethylene glycol 600 in liquid and solid phase and across the phase transition

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## Abstract

The polyethylene glycol (PEG) is characterized by experimental means in both solid and liquid phase. Main thermal properties inherent to the phase transition are also provided. More specifically, we focus on PEG 600, whose average molar mass is  $600 \text{ g mol}^{-1}$  and melting temperature transition is around 283-298 K. The phase change does not occur at a given temperature but rather over a range of temperature, highlighting the complexity of the material. Several methodologies have been developed and calibrated in order to obtain, in both phases, the density and the thermal conductivity. A temperature dependence fit is proposed for the density in liquid phase. The relative density variation from the liquid to solid phase is significant as it can reach about 35 %, meaning a quite large volume shrinkage. Differential Scanning Calorimetry (DSC) has been used for measuring the heat capacity of solid and liquid phase and the effective heat capacity at the transition states. The latent heat of fusion and solidification converge to a value of around  $128 \text{ kJ kg}^{-1}$ . Undercooling effects are mitigated by performing DSC with slow temperature variation rates. Lastly, we have also observed several exothermic peaks during the solidification process that are related to structural reorganizations of the material.

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## 1. Introduction

2 Polyethylene glycol (PEG) is a polyether present in our daily life and its  
3 employment covers a wide range of industries, such as cosmetics, pharma-  
4 ceuticals, food manufacturing, inks. As an example, it is used as a thickener

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5 agent in cosmetic products (liquid soaps, moisturizers, shampoos, etc.) and  
6 paramedical products (hydro-alcoholic gels, intimate lubricants [1], etc.). It  
7 is also used as a solvent in printer inks or to manufacture paint balls, as a  
8 food additive and in certain polyester resins. Because it is a bio-compatible  
9 product [2], it is also widely used in medical treatments and vaccines [3], as  
10 recently for Covid-19 vaccine. In addition, the polyethylene glycol presents  
11 remarkable properties: from a chemical viewpoint it is stable, non corro-  
12 sive and non toxic. Another significant advantage lies in the large variety  
13 of temperatures at which the solid/liquid transition occurs. Depending on  
14 PEG's molecular weight, phase transition occurs for instance around 283-  
15 293 K for PEG 600, 321-323 K for PEG 1000 [4] and around 324 K for PEG  
16 1500 [5]. For these reasons, numerous studies have been devoted to propose  
17 Composite Phase Change Materials (CPCMs) based on polyethylene glycol  
18 [6, 7, 8, 9, 10, 11, 12]. Phase change materials (PCMs) are widely studied  
19 in the field of energy storage/release since a large amount of energy can be  
20 transferred during the phase change via latent heat. Energy is stored during  
21 endothermic transformations (e.g. solid to liquid) while it is released dur-  
22 ing exothermic transformations. The large latent heat of PEG makes it a  
23 very interesting and attractive PCM. Furthermore, it matches perfectly the  
24 criteria related to the choice of PCMs, such as being low-cost, non-toxic,  
25 non-flammable, non-corrosive and biodegradable (bio-compatible), i.e. eco-  
26 friendly. The uses of PEG in Composite PCMs can concern thermal reg-  
27 ulation in buildings [13] or pavements [8] as well as in photovoltaic panels  
28 [4, 12].

29 Despite the wide use of PEG, only few papers were devoted to characterize  
30 the thermal properties of polyethylene glycol alone. Recently, Kou et al. [14]  
31 have measured heat capacities of PEG for molar mass varying from 2000 to  
32 20 000 g mol<sup>-1</sup>. For smaller molar mass, as it is the case of PEG 600 (average  
33 molar mass of 600 g mol<sup>-1</sup>), available data correspond mainly to properties  
34 for the liquid phase only. For instance, density measurements are provided  
35 by several authors [15, 16, 17, 18], but they are given only for the liquid phase  
36 for few temperature values, not sufficient to obtain the thermal expansion  
37 coefficient. Some properties of PEG 600 are also given by Lane [19] who  
38 focuses on properties of several PCMs. For PEG 600, the author indicates  
39 the latent heat of melting and only one value for the melting temperature.  
40 Lane [19] also provides the thermal conductivity and the density in liquid  
41 phase for a couple of temperature values. Only a few other studies present  
42 the thermal conductivity of liquid phase, e.g. [17, 19]. Thus, properties of

43 PEG remain partially and scatteredly described in the literature. Moreover,  
44 this small number of measured properties is obtained only for the liquid  
45 phase. To our knowledge, the latent heat of solidification, the freezing point,  
46 the thermal conductivity, the density and the heat capacity for the solid  
47 phase are not available in the literature.

48 From a structural viewpoint, PEG's properties - in particular at the  
49 solid/liquid transition - depend not only on the molecular weight but also  
50 on the protocols involved in measuring them. Several types of aggregate  
51 structures, such as helical or spherical conformations have been observed  
52 within the freezing process [20, 21]. Understanding the correlation between  
53 structural modifications and imposed experimental conditions is crucial since  
54 the structural organization can have a significant impact on the macroscopic  
55 properties. Indeed, in the case of semi-crystalline polymers as it is for PEG,  
56 Bogdanov et al. [22] highlighted the influence of the cooling rate on the  
57 exothermic crystallization peak by means of isothermal Differential Scan-  
58 ning Calorimetry (DSC). Furthermore, a correlation between the heat flux  
59 measured by DSC and the degree of crystallinity of PEG is proposed by  
60 Pielichowski & Flejtuch [23].

61 As a first step in the understanding of the relationships between PEG's  
62 behaviour and conditions of use, we clarify and provide new macroscopic  
63 properties for PEG 600. The aim of our study is to characterize this polyether  
64 in both the solid and liquid phase. In the liquid phase, we provide original  
65 values of macroscopic properties and how they vary with temperature. In the  
66 solid phase, we aim to fill the data gap in the literature. We carefully detail  
67 the methodologies and protocols used to obtain the main thermal properties  
68 in each phase (density, effective heat capacity and thermal conductivity) and  
69 the latent heat of melting and solidification. In section 2, the different mea-  
70 surement techniques and protocols used are detailed. Results are provided  
71 in section 3 where they are also compared with the available literature. The  
72 paper ends with conclusions and perspectives.

## 73 **2. Methods and experimental devices**

### 74 *2.1. Material*

75 Polyethylene glycol (PEG) is a linear polyether made from ethylene gly-  
76 col monomers characterized by a molar mass generally smaller than 20 000  
77  $\text{g mol}^{-1}$ . In this study, we aim to characterize the polyethylene glycol with

78 molar mass of around  $600 \text{ g mol}^{-1}$ , named PEG 600 (Table 1). The sam-  
79 ples of PEG 600 that we used were purchased in synthesis grade from Merck  
80 (CAS 25322-68-3, labeled average molecular mass of  $570\text{-}630 \text{ g mol}^{-1}$ ) and  
81 were used as received, i.e. without further purification. Several batches have  
82 been used to verify reproducibility of results (batches numbers: S8111586  
83 136 and S8111586 121).

84 The temperature of the solid-liquid phase change is indicated by the sup-  
85 plier within the range of  $290.15\text{-}293.15 \text{ K}$ .

86 The initial degree of purity of the material is not stated in the product  
87 specifications provided by the manufacturer and has not been subsequently  
88 measured. However, [18] report an initial purity of  $\geq 99.8\%$  for PEG 600  
89 provided by the same manufacturer as our (same CAS number). No purifi-  
90 cation method was used in [18]. For this reason, and considering the good  
91 agreement we have obtained in thermophysical properties with available lit-  
92 erature (see next section 3), no further purification was performed on our  
93 PEG samples.

94 The water content ( $w$ ) in our samples is estimated by taking the weight  
95 of PEG samples before and after drying them at  $353.15 \text{ K}$  for 24 hours (see  
96 supplementary materials). We have found a water content of  $0.24 \%$ , with a  
97 combined expanded uncertainty  $U_c(w) = 0.02 \%$  with 0.95 level of confidence  
98 (coverage factor  $k=2$ ).

99 In Table 1 we also report the samples of water, glycerol and sapphire em-  
100 ployed during methods validation. We used ultra-pure water (Anton Paar)  
101 to verify density measurements obtained with the densimeter. We used glyc-  
102 erol for the validation of the transient hot needle method used to estimate  
103 thermal conductivity. For the validation of other analysis methods we used  
104 demineralized water. The latter is produced by a reverse osmosis unit from  
105 Ondeo (Purite Select A640/GP,  $1\text{-}10 \text{ M}\Omega \text{ cm}$ ). To ensure good water quality,  
106 filter cartridges are changed before the water resistance drops to  $1 \text{ M}\Omega \text{ cm}$ .  
107 We underline that the water resistance is given directly by the device when it  
108 is produced. Finally, a sapphire sample was used to validate the solid phase  
109 heat capacity measurements (see also Section 2.4 of this article and Section  
110 2.3 of the supplementary material). The sample corresponds to a cylinder of  
111  $5 \text{ mm}$  height,  $2.5 \text{ mm}$  diameter and  $97.0 \text{ mg}$  mass.

112

Table 1: Samples table

Chemical Name	Source	Initial Mass Fraction Purity, $x_e$	Purification Method <sup>a</sup>
Polyethylene	Merck	-	none
Glycol 600	CAS 25322-68-3	-	none
Ultra-pure water	Anton Paar	-	none
Demineralized water	Tap water	-	reverse osmosis
Glycerol	Fisher Chemical CAS 56-81-5	0.99	none
Sapphire (solid cylinder)	Setaram	-	none

<sup>a</sup>further purification in addition to that of the supplier ('Source')

113 *2.2. Density*

114 *2.2.1. Liquid phase*

115 The density ( $\rho$ ) of PEG 600 in liquid phase is measured by using a den-  
 116 simeter DMA 5000M, Anton Paar. The densimeter provides a  $10^{-6}$  g cm $^{-3}$   
 117 accuracy in the temperature range of 273.15-333.15 K, while for larger tem-  
 118 peratures (up to a maximum of 373.15 K) the accuracy decreases to  $10^{-4}$   
 119 g cm $^{-3}$ . The precision on the temperature is 0.01 K. Calibration and valida-  
 120 tion of the device are given in the supplementary material. Density measure-  
 121 ments are carried out at constant pressure  $P$  (atmospheric pressure) and at  
 122 different temperature values within the range of 294.15-373.15 K where PEG  
 123 600 is liquid. Isothermal conditions are obtained by imposing temperature  
 124 steps with a 1 K increment in the range 294.15-323.15 K, followed by a 5 K  
 125 increment up to the temperature of 373.15 K. In the liquid phase, the time  
 126 to achieve the thermal stability is about 5 minutes per temperature step.

127 To ensure reproducible results, density is measured on three different  
 128 samples (volume of  $\sim 1$  mL) from two different batches. At a given temper-  
 129 ature, the maximal variation between measurements is found to be  $2 \times 10^{-5}$   
 130 g cm $^{-3}$ . The final value of density is taken as the mean of these measure-  
 131 ments. From the temperature dependence of the density, we evaluate the  
 132 thermal expansion coefficient  $\beta$  as follows

$$\beta = -\frac{1}{\rho_{ref}} \left( \frac{\partial \rho}{\partial T} \right)_P, \quad (1)$$

133 with  $\rho_{ref} = \rho(T_{ref})$  being a reference density defined at the temperature  $T_{ref}$ .  
 134 The thermal expansion coefficient indicates the first-order density variations

Table 2: Pressure measurements performed for the pycnometer calibration at 273.75 K - Steps (1) and (2).  $P_i$  is the initial pressure and  $P_f$  the final pressure <sup>a</sup>.

Step (1)			Step (2)		
$P_i$ (bar)	$P_f$ (bar)	$P_f/P_i$	$P_i$ (bar)	$P_f$ (bar)	$P_f/P_i$
3.654	1.685	46.1 %	3.655	2.002	54.7 %
3.660	1.696	46.3 %	3.650	2.002	54.8 %
3.665	1.706	46.5 %	3.603	1.976	54.8 %

<sup>a</sup>Standard uncertainties  $u$  are  $u(P) = 0.001$  bar and  $u(T) = 0.01$  K.

135 with temperature (Boussinesq approximation) at constant pressure [24] and,  
 136 for a given mass of a material, it also corresponds to the volume variation  
 137 with temperature.

### 138 2.2.2. Solid phase

139 The density of PEG 600 in solid phase is achieved using a lab-made  
 140 pycnometer. The device is placed in a thermostatic enclosure Binder<sup>TM</sup>  
 141 KBF 115 in order to control the temperature. The temperature set in the  
 142 binder is 273.75 K in order to ensure that our PEG sample will be fully  
 143 solid. The pycnometer consists in two different cavities of volume  $V$  and  $V'$   
 144 separated by a valve, as represented in Fig. 1. The measurement procedure  
 145 is to initially obtain the vacuum in both cavities, i.e.  $P' = P = 0$ , then close  
 146 the valve and impose a pressure  $P_i$  to the lower cavity. The valve is then  
 147 opened involving pressure variations until an equilibrium is reached within  
 148 the two cavities, leading to a final pressure  $P_f$ . The pressure is measured  
 149 using a Mano 2000 Leo 3 Keller with an accuracy of 1 mbar.

150 We first start by a calibration of the device, i.e. we determine the volumes  
 151  $V$  and  $V'$  of each cavity by repeating several times the above mentioned  
 152 procedure through Steps (1) and (2), as indicated in Fig. 1 b. Volumes  $V$   
 153 and  $V'$  are determined via the following equation

$$P_i V = P_f \times (V + V' - V_{ref}), \quad (2)$$

154 where  $V_{ref}$  corresponds to the volume of a cylinder of height 0.02 m and  
 155 radius 0.04 m. The procedure is repeated three times. Measurements are  
 156 summarized in Table 2. The precision of the method has been evaluated by  
 157 performing step (3) using a calibrated volume of solid. Details are provided  
 158 in the supplementary material.

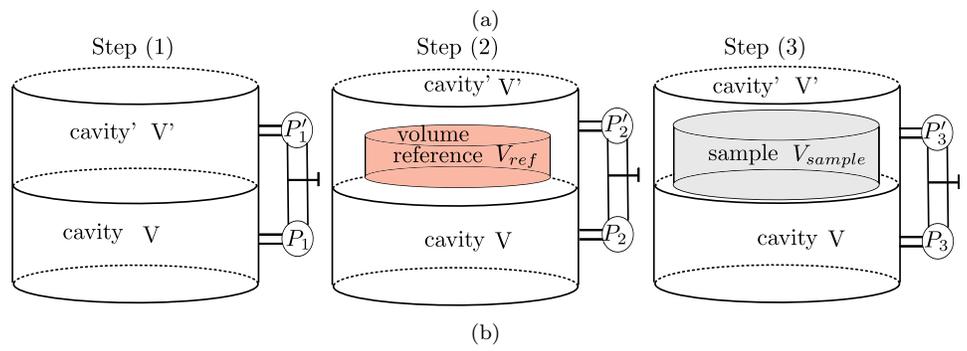


Figure 1: (a) Photo of the pycnometer. (b) Sketch of the set-up for calibration - Step (1) and Step (2) - and for measuring the density of solid PEG 600 - Step (3) -.

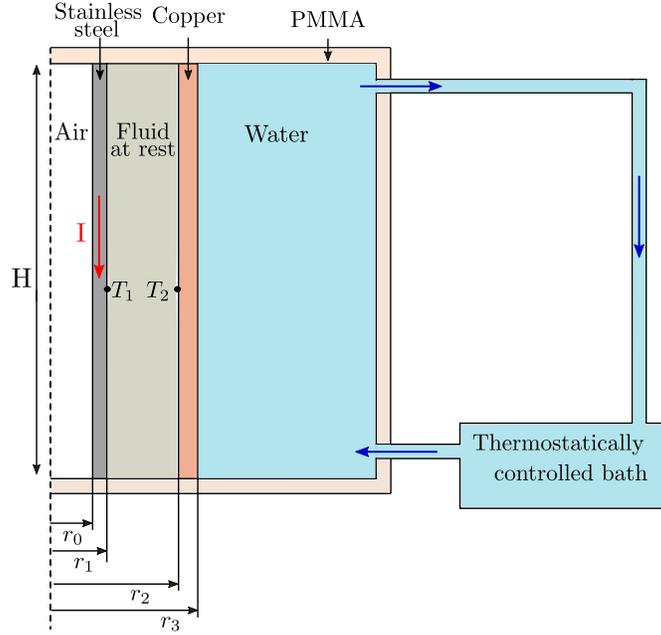


Figure 2: Sketch of the hot tube device used for thermal conductivity measurements.  $r_0 = 2.54$  mm,  $r_1 = 2.75$  mm,  $r_2 = 6.00$  mm

159 Finally, Step (3) is performed with a given mass of PEG (Fig. 1 b). The  
 160 volume of solid PEG is obtained using eq. (2) in which  $V_{ref}$  is replaced by  
 161 the unknown sample volume. The density of PEG in solid phase is deduced  
 162 from this measurement.

### 163 2.3. Thermal conductivity

#### 164 2.3.1. Liquid phase

The thermal conductivity of the liquid phase is measured via the stationary hot tube method [25, 26]. A sketch of the device developed in our laboratory is shown in Fig. 2. A validation of the device with demineralized water is provided in the supplementary material. The sample is introduced in liquid phase into the gap between two coaxial cylinders made of copper (the outer one) and stainless steel (the inner one). We ensure that the sample fills completely the space between the two cylinders, i.e. the space between  $r_1$  and  $r_2$  in Fig. 2. An electric current  $I$  is applied to the inner cylinder, producing heat flux by Joule effect. The outer part of the copper cylinder is maintained at a given temperature via a temperature controlled water flow. The temperatures  $T_1$  and  $T_2$  are measured using two type K thermocouples

locked on the wall of the cylinders, i.e. at the boundaries of the liquid layer (as indicated in Fig. 2). Moreover, in order to avoid any up-down wall effects, thermocouples are located at the mid-height of the device. The temperature difference is measured thanks to the voltage difference  $U$  between these two thermocouples:

$$\Delta T = T_1 - T_2 = U/k,$$

165 where  $k$  is a constant equal to  $k = (39.2 + 0.064 \times T_2 - 0.005 \times T_2^2) \times 10^{-6}$   
 166  $\text{V K}^{-1}$ . Thermocouples are connected to a cold junction block. Tension and  
 167 electrical current are measured with a Keysight U3401A and an ISO-TECH  
 168 IDM91E multimeter, respectively.

169 For a purely conductive regime in the liquid layer (fluid at rest), the  
 170 thermal conductivity can be deduced as follows [25]:

$$\lambda = \frac{\rho_{el} I^2 \ln(r_2/r_1)}{2\pi^2(r_1^2 - r_0^2)\Delta T} \quad (3)$$

171 with  $\rho_{el} = 7.3 \times 10^{-7}(1 + 1.36 \times 10^{-2}(T - T_{ref})) \Omega \text{m}$  being the electrical  
 172 resistivity of the stainless steel and  $T_{ref}$  a temperature reference equal to  
 173 293.15 K.

174 The dimensions of the device are determined under the condition that no  
 175 convection occurs for a wide range of fluids. According to [27], we ensure  
 176 that the following condition is satisfied:

$$\frac{Ra}{H^+} < 400 \quad (4)$$

177 where  $H^+ = H/\delta$ ,  $H$  is the height of the cylinders,  $\delta = r_2 - r_1$  is the thickness  
 178 of the liquid layer and  $Ra$  corresponds to the Rayleigh number given by

$$Ra = \frac{\rho g \beta \Delta T \delta^3}{\mu a}, \quad (5)$$

179 with  $\mu$  being the dynamic viscosity and  $a$  the thermal diffusivity of the  
 180 fluid.

181 This condition is verified a posteriori and in the case of our measurements  
 182 with PEG we estimate  $Ra/H^+ \approx 15 - 20 \ll 400$ .

183 Device validation performed with demineralized water leads to a maximal  
 184 difference in thermal conductivity of 2.5 % with values provided by Ramires  
 185 et al. [28], i.e. a variation of  $0.02 \text{ W m}^{-1} \text{ K}^{-1}$  (see supplementary material).

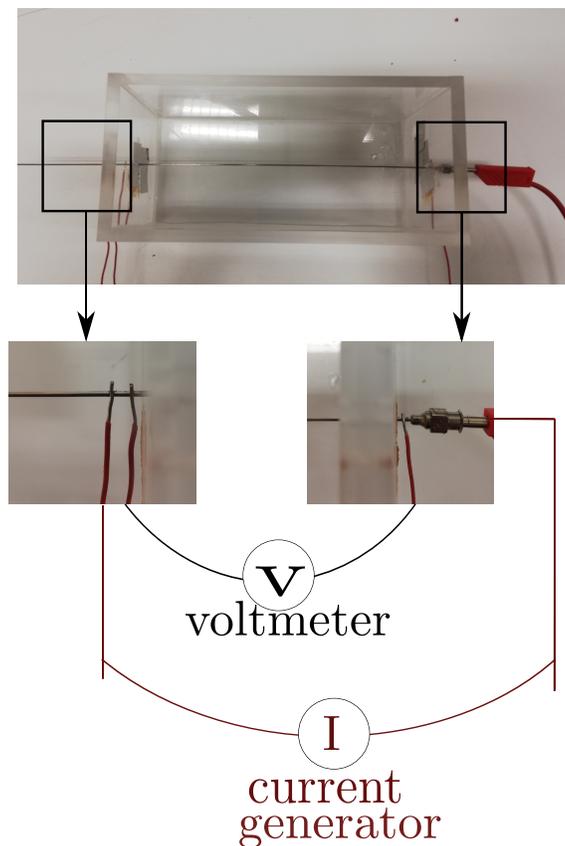


Figure 3: Photo of the heated needle device

186 Since the device is filled by the PCM in liquid phase, the volume of the sample  
 187 varies with the temperature with a maximal variation occurring during the  
 188 phase transition. As it is with most materials, PEG decreases in volume from  
 189 liquid to solid phase. This can lead to imperfect contacts at walls during the  
 190 solidification, as detailed in Appendix A. In this case, i.e. when thermal  
 191 contact resistances are present at walls, the device becomes unsuitable for  
 192 measuring thermal conductivity of materials in solid phase. For this reason,  
 193 we propose another technique to carry out measurements in the solid phase.  
 194 This technique is detailed in the following paragraph.

### 195 *2.3.2. Hot needle method*

196 We developed a specific device in order to measure the thermal con-  
 197 ductivity of materials in solid or liquid phase. The device consists in a

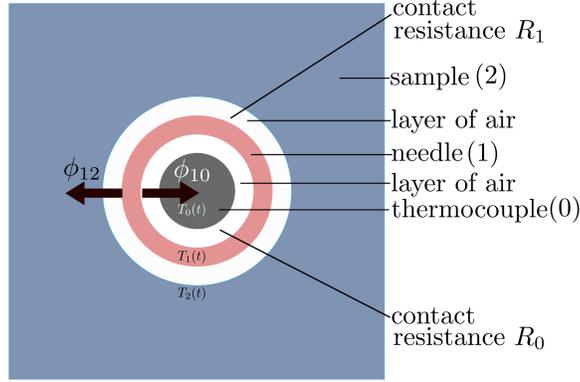


Figure 4: Schematic cross section of the hollow needle probe. The subscripts “0”, “1” and “2” refer to the thermocouple, the needle and the sample, respectively.

198  $200 \times 120 \times 120 \text{ mm}^3$  cavity made of PMMA that is filled with the sample.

199 A stainless steel hollow needle of length 300 mm is placed at the center  
 200 of the device (Fig. 3). Needle’s inner and outer radii are  $r_i = 0.80 \text{ mm}$  and  
 201  $r_e = 1.25 \text{ mm}$ , respectively. The needle is heated by Joule effect and the  
 202 corresponding heat flow rate per unit of length  $L$  is  $\phi = (UI)/L$ , with  $U$  the  
 203 electrical tension and  $I$  the electric intensity. Temperature is measured at the  
 204 central point inside the needle with a K-type sheath thermocouple of radius  
 205  $r_t = 0.5 \text{ mm}$ . Electrical tension and current are measured with a Tektronix  
 206 DMM and an ISO-TECH IDM91E multimeter, respectively. Temperatures  
 207 are recorded using a TC-08 Picolog device with a frequency of 10 Hz.

208 According to Fig. 4, in the following description we use the subscripts  
 209 “0”, “1” and “2” to refer to the thermocouple, the needle and the sample,  
 210 respectively.

211 The device is placed in a Binder<sup>TM</sup> KBF 115 thermostatic chamber in  
 212 order to maintain the system at a controlled temperature. The thermostatic  
 213 chamber also guarantee a constant initial temperature  $T(t = 0)$  in the whole  
 214 system, i.e.  $T_0(0) = T_1(0) = T_2(0)$ , being the initial temperature of the  
 215 thermocouple, the needle and the sample, respectively. We assume uniform  
 216 temperature field in the needle,  $T_1(t)$ , and in the thermocouple,  $T_0(t)$ , since  
 217 they are very thin. Moreover, since contacts at interface 1-2, i.e. needle-  
 218 sample, and at the interface 1-0, i.e. needle-thermocouple, are not perfect,  
 219 also the thermal contact resistances  $R_1$  and  $R_0$  (see Fig. 4) have to be taken  
 220 into account. Finally, due to the long length of the cavity, we consider an  
 221 unidirectional dependence of parameters at the center of the cavity.

222 As the needle is heated, the total heat flow rate  $\phi$  due to Joule effect can  
 223 be split in two components, i.e.  $\phi = \phi_{10} + \phi_{12}$  where  $\phi_{12}$  is the heat transferred  
 224 to the material and  $\phi_{10}$  the heat transferred to the thermocouple. Heating  
 225 the needle also induces transient variations in temperature within the whole  
 226 system. Thermal properties of PEG can be obtained by considering the  
 227 heat equation (conductive regime) in two domains assorted with boundary  
 228 conditions. For this purpose, we use the quadrupole formalism proposed by  
 229 Maillet *et al.* [29].

230 The first domain is bounded by the outer surface of the needle ( $r_1 = r_e (\approx$   
 231  $r_i)$ ) and a surface of the material sample ( $r_2 \rightarrow \infty$ ). Following the method  
 232 proposed by Maillet *et al.* [29], the thermal quadrupole formalism writes:

$$\begin{bmatrix} \theta_1 \\ \Phi_{12} \end{bmatrix} = [M1][M2] \begin{bmatrix} \theta_2 \\ \frac{\theta_2}{Z} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ C_1 p & 1 \end{bmatrix} \begin{bmatrix} 1 & R_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \theta_2 \\ \frac{\theta_2}{Z} \end{bmatrix} = \begin{bmatrix} 1 & R_1 \\ C_1 p & 1 + R_1 C_1 p \end{bmatrix} \begin{bmatrix} \theta_2 \\ \frac{\theta_2}{Z} \end{bmatrix} \quad (6)$$

with:

$\theta_1 = \mathcal{L}(T_1(t) - T_1(0))$  being the Laplace transform of the temperature varia-  
 tion in the needle, i.e.  $T_1(t) - T_1(0)$ ,

$\theta_2 = \mathcal{L}(T_2(t) - T_2(0))$  the Laplace transform of the temperature variation in  
 the sample at the interface needle-material, i.e.  $T_2(t) - T_2(0)$ ,

$\Phi_{12} = \mathcal{L}(\phi_{12})$  the Laplace transform of  $\phi_{12}$ ,

$M1$  the quadrupolar matrix representing the needle as a pure capacity  $C_1$ ,

$M2$  the quadrupolar matrix representing the contact resistance at the inter-  
 face 1-2,

$p$  the Laplace parameter ( $s^{-1}$ ),

$R_1$  the thermal contact resistance per unit of length at the interface 1-2  
 ( $\text{m K W}^{-1}$ ), and

$$C_1 = \pi(r_e^2 - r_i^2)\rho_1 c_1, \quad (7)$$

$$Z = \frac{K_0(qr_e)}{2\pi\lambda q r_e K_1(qr_e)}, \quad (8)$$

$$q = \sqrt{\frac{p}{a}} \quad (9)$$

233 where  $\rho_1$  is the density of the needle ( $\text{kg m}^{-3}$ ),  $c_1$  the specific heat of the  
 234 needle ( $\text{J K}^{-1} \text{kg}^{-1}$ ),  $a$  the thermal diffusivity of the sample ( $\text{m}^2 \text{s}^{-1}$ ), and  $\lambda$   
 235 the thermal conductivity of the sample ( $\text{W m}^{-1} \text{K}^{-1}$ ).

236 Similarly, we consider a second domain that is bounded by the thermocouple  
 237  $r_0 = 0 (\approx r_t)$  and the inner needle surface  $r_1 = r_i (\approx r_e)$ . The quadrupole  
 238 formalism leads to:

$$\begin{bmatrix} \theta_1 \\ \Phi_{10} \end{bmatrix} = [M3][M4] \begin{bmatrix} \theta_0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & R_0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ C_0 p & 1 \end{bmatrix} \begin{bmatrix} \theta_0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 + R_0 C_0 p & R_0 \\ C_0 p & 1 \end{bmatrix} \begin{bmatrix} \theta_0 \\ 0 \end{bmatrix} \quad (10)$$

239 with:

240  $\theta_0 = \mathcal{L}(T_0(t) - T_0(0))$  being the Laplace transform of the thermocouple's  
 241 temperature variation, i.e.  $T_0(t) - T_0(0)$ ,

242  $\Phi_{10} = \mathcal{L}(\phi_{10})$  the Laplace transform of the heat flow rate  $\phi_{10}$ ,

243  $M3$  the quadrupolar matrix representing the contact resistance at the inter-  
 244 face 0-1,

245  $M4$  the quadrupolar matrix representing the thermocouple as a pure capac-  
 246 ity  $C_0$ ,

247  $R_0$  the thermal contact resistance per unit length between the thermocouple  
 248 and the needle ( $\text{m K W}^{-1}$ ), and

249

$$C_0 = \pi r_t^2 \rho_0 c_0, \quad (11)$$

250 where  $\rho_0$  is the density of the thermocouple ( $\text{kg m}^{-3}$ ) and  $c_0$  the specific heat  
 251 of the thermocouple ( $\text{J K}^{-1} \text{kg}^{-1}$ ).

From Eq.(6) we deduce:

$$\theta_1 = \left(1 + \frac{R_1}{Z}\right) \theta_2, \quad (12)$$

$$\Phi_{12} = \left(C_1 p + \frac{1 + R_1 C_1 p}{Z}\right) \theta_2 = \left(C_1 p + \frac{1 + R_1 C_1 p}{Z}\right) \frac{\theta_1}{1 + \frac{R_1}{Z}}. \quad (13)$$

From Eq.(10) we deduce:

$$\theta_1 = (1 + R_0 C_0 p) \theta_0, \quad (14)$$

$$\Phi_{10} = C_0 p \theta_0 = \frac{C_0 p}{1 + R_0 C_0 p} \theta_1. \quad (15)$$

The Laplace transform of the total heat flow rate  $\phi$  writes:

$$\mathcal{L}(\phi) = \frac{\phi}{p} = \Phi_{12} + \Phi_{10} = \left(\frac{Z C_1 p + 1 + R_1 C_1 p}{Z + R_1} + \frac{C_0 p}{1 + R_0 C_0 p}\right) \theta_1, \quad (16)$$

and by substituting Eq.(14) into Eq.(16) we obtain

$$\theta_0 = \frac{\phi}{p} \frac{Z + R_1}{(Z + R_1)[(C_0 + C_1)p + R_0 C_0 C_1 p^2] + 1 + R_0 C_0 p}. \quad (17)$$

At long time ( $p \rightarrow 0$ ), the above equations simplify to:

$$\theta_0 = \frac{\phi}{p}(Z + R_1), \quad (18)$$

$$K_0(qr_e) = -\ln\left(\frac{qr_e}{2}\right) - \gamma, \quad (19)$$

$$K_1(qr_e) = \frac{1}{qr_e}, \quad (20)$$

$$\theta_0(p) = \frac{\phi}{p} \left[ -\frac{\ln\left(\frac{qr_e}{2}\right)}{2\pi\lambda} - \frac{\gamma}{2\pi\lambda} + R_1 \right] = \quad (21)$$

$$= \frac{\phi}{p} \left[ -\frac{\ln(p)}{4\pi\lambda} - \frac{\ln\left(\frac{r_e}{2\sqrt{a}}\right)}{2\pi\lambda} - \frac{\gamma}{2\pi\lambda} + R_1 \right]. \quad (22)$$

By performing the inverse Laplace transform, we obtain:

$$T_0(t) = \phi \left[ \frac{\ln(t)}{4\pi\lambda} + \frac{\gamma}{4\pi\lambda} - \frac{\ln\left(\frac{r_e}{2\sqrt{a}}\right)}{2\pi\lambda} - \frac{\gamma}{2\pi\lambda} + R_1 \right], \quad (23)$$

and finally

$$T_0(t) = \frac{\phi}{4\pi\lambda} \ln(t) + \phi \left( \frac{-\gamma}{4\pi\lambda} - \frac{\ln\left(\frac{r_e}{2\sqrt{a}}\right)}{2\pi\lambda} + R_1 \right). \quad (24)$$

252 Equation (24) highlights a logarithm dependence of  $T_0$  with time that  
 253 becomes the dominant term at long time. This equation is valid only if the  
 254 regime remains conductive and the medium is infinite. Hence, we can write:

$$T_0(t) = D_1 + D_2 \times \ln(t) \quad (25)$$

255 with  $D_1$  and  $D_2$  being two constants which depend on the material's thermal  
 256 conductivity  $\lambda$ . Temperature measurements allow us to identify these two  
 257 parameters by minimizing  $S = \sum_{t_d}^{t_f} (T_{\text{exp}}(t) - T_0(t))^2$  on a time interval  $[t_d, t_f]$ ,  
 258 where  $T_{\text{exp}}$  is the experimental temperature measured by the thermocouple  
 259 and  $T_0$  the temperature obtained from Eq. (25). The thermal conductivity  
 260 is finally obtained by evaluating the following equation:

$$\lambda = \frac{\phi}{4\pi D_2}. \quad (26)$$

261 At a given temperature, the experiments are repeated three times and the  
 262 final value of conductivity is taken as the mean of these experiments. The  
 263 maximum variation of  $\lambda$  obtained in this way is  $0.02 \text{ W m}^{-1} \text{ K}^{-1}$ .

#### 264 *2.4. Specific heat capacity and latent heat*

265 The specific heat capacity  $c_p$  as well as the latent heat of the material are  
 266 obtained using a Setaram  $\mu\text{dSc3}$  differential calorimeter.

267 The protocol consists in applying temperature variations to the sample  
 268 (sample mass about 200 - 300 mg) and in measuring simultaneously the  
 269 heat transfer over time. Here, temperature variations are generated either  
 270 through ramps of different rates of cooling/heating ( $1 \text{ K min}^{-1}$ ,  $0.5 \text{ K min}^{-1}$ ,  
 271  $0.2 \text{ K min}^{-1}$ ) or through temperature steps that lead to quasi-steady thermal  
 272 conditions. In the latter case, steps last long enough to recover the steady  
 273 state, that is, until there is no more heat flux between the sample and the  
 274 device. In our experiments, this corresponds to a minimum of 1 hour up  
 275 to 2 hours per temperature step. Increments between temperature steps are  
 276 set to 1 K when phase change occurs, i.e. between 283.15 K and 303.15 K,  
 277 to gain accuracy in evaluating the effective  $c_p(T)$ . Outside this temperature  
 278 range, the increment is 2 K. The increment between two successive steps is  
 279 obtained by applying a temperature ramp of  $0.2 \text{ K min}^{-1}$ .

280 Long steps or slow temperature variations have the advantage to avoid  
 281 or at least to minimize undercooling effects [26]. Reversibility of results  
 282 are tested performing the entire protocol both increasing and decreasing the  
 283 temperature. The effective heat capacity is deduced from the heat transferred  
 284 to the sample after each temperature variation. At the phase transition, the  
 285 effective  $c_p$  varies strongly due to the addition of latent heat to sensible  
 286 heat. The latent heat is therefore estimated by subtracting the sensible heat  
 287 obtained for the liquid or solid phase from the total heat measured at the  
 288 phase change.

289 A method validation for our experimental conditions and post-process is  
290 provided in the supplementary materials.

### 291 **3. Results**

#### 292 *3.1. Density*

##### 293 *3.1.1. Liquid phase*

294 Density measurements of PEG 600 are presented in Fig. 5 in the tem-  
295 perature range of [294.15, 373.15] K. Measurements have been performed by  
296 cooling the sample in order to avoid any issues related with the formation of  
297 bubbles (that occurs when the material is heated over a large temperature  
298 range) or with the presence of a mushy phase at the beginning of the analysis,  
299 i.e. around 294.15 K. This precaution enables to obtain reproducible density  
300 values under our experimental conditions.

301 Our experimental values are summarized in Fig. 5 together with values  
302 currently present in literature [18, 15, 16]. We observe a very good agreement  
303 between our results and literature (see also Table 3 where deviations are  
304 shown). Our results are found within a maximum difference of 1% from  
305 those reported in the above cited studies. Our results can be fitted by a  
306 linear model (continuous line in Fig. 5) as follows:

$$\rho(T) = p_1 \times T + p_2 \quad (\text{g cm}^{-3}), \quad (27)$$

307 with  $p_1 = -0.00081643 \text{ g cm}^{-3} \text{ K}^{-1}$ ,  $p_2 = 1.3652 \text{ g cm}^{-3}$  and  $T$  the tempera-  
308 ture in K. The intervals of the coefficients with 95% confidence bounds are  
309  $p_1 = [-0.0008182, -0.0008147]$  and  $p_2 = [1.365, 1.366]$ .

310 Furthermore, the thermal expansion coefficient  $\beta$  can be evaluated ac-  
311 cording to Eq. (1). For instance, at  $P = 1.007 \text{ bar}$  and  $T_{ref} = 298.15 \text{ K}$ , we  
312 obtain  $\rho_{ref} = 1.121961 \text{ g cm}^{-3}$  and  $\beta = 7.28 \times 10^{-4} \text{ K}^{-1}$ , with an estimated  
313 standard uncertainty of  $u(\beta) = 0.02 \times 10^{-4} \text{ K}^{-1}$ .

##### 314 *3.1.2. Solid phase*

315 The density of PEG 600 in solid phase is obtained using the pycnometer  
316 described in section 2.2.2. A material sample of about 150 g is placed in the  
317 upper cavity of the pycnometer. The latter is left inside the thermostatic  
318 chamber for 24 hours at temperature of 273.75 K. This is done before per-  
319 forming any measurement in order to ensure the complete solidification of the  
320 sample. Density measurements are afterward carried out at the same tem-  
321 perature of 273.75 K by keeping the pycnometer with the solid sample inside

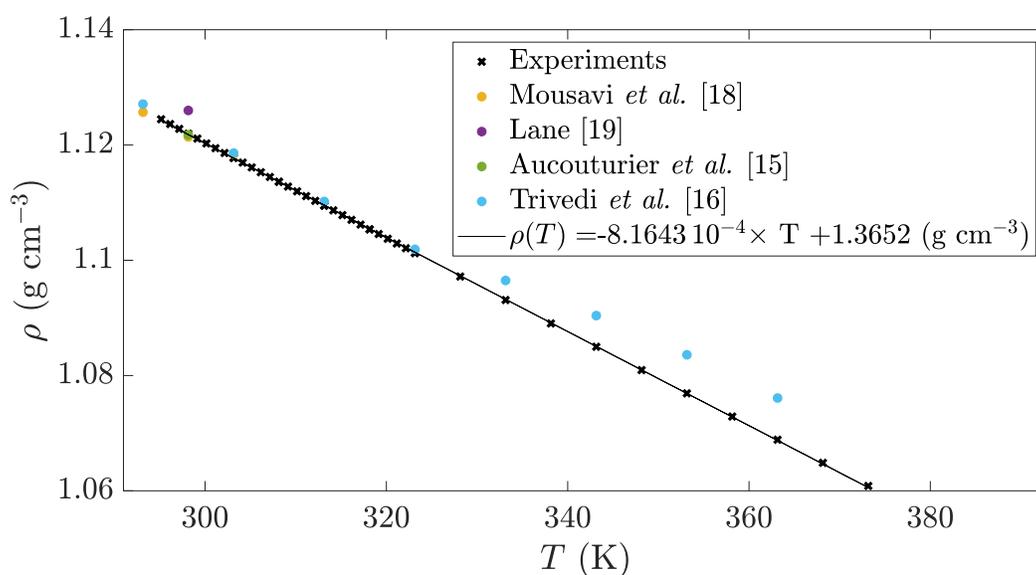


Figure 5: Density  $\rho$  of PEG 600 as a function of temperature  $T$  at the pressure  $P=1.007$  bar. Data are provided in supporting files. Standard uncertainties  $u$  are  $u(P)=0.018$  bar and  $u(T) = 0.01$  K. The combined expanded uncertainty  $U_c$  is  $U_c(\rho)=2\times 10^{-3}$  g cm $^{-3}$ , with 0.95 level of confidence ( $k=2$ ) and considering a contribution due to purity ( $x_e$ ) of  $u(x_e) = 0.002/\sqrt{3} = 0.0012$  after [18], who reported an initial purity of 99.8 % for samples of PEG 600 provided by the same manufacturer as ours.

Table 3: Comparison between some of our density measurements ( $\rho$ ) of PEG 600 with values given in literature ( $\rho_{\text{lit}}$ ) at different temperatures  $T$  and pressure  $P=1.007$  bar<sup>a</sup>.

$T$ (K)	$\rho$ ( $\times$ ) ( $\text{g cm}^{-3}$ )	$\rho_{\text{lit}}$ ( $\circ$ ) ( $\text{g cm}^{-3}$ )	Reference	Deviation (%)
298.15	1.121961	1.126	[19]	0.36
		1.1214	[18]	0.05
		1.12177	[15]	0.02
303.15	1.117783	1.1184	[18]	0.06
		1.1186	[16]	0.07
313.15	1.109468	1.1102	[16]	0.07
323.15	1.101273	1.1019	[16]	0.06
333.15	1.093104	1.0965	[16]	0.31
343.15	1.084992	1.0904	[16]	0.50
353.15	1.076914	1.0836	[16]	0.62
363.15	1.068864	1.0761	[16]	0.67

Standard uncertainties  $u$  are  $u(P)=0.018$  bar and  $u(T) = 0.01$  K. The combined expanded uncertainty  $U_c$  is  $U_c(\rho)=2\times 10^{-3}$   $\text{g cm}^{-3}$ , with 0.95 level of confidence ( $k=2$ ) and considering a contribution due to purity ( $x_e$ ) of  $u(x_e) = 0.002/\sqrt{3} = 0.0012$  after [18], who reported an initial purity of 99.8 % for samples of PEG 600 provided by the same manufacturer as ours.

Table 4: Pressure measurements performed for one sample of PEG 600 at 273.75 K. <sup>a</sup>

First set			Second set		
$P_i$ (bar)	$P_f$ (bar)	$P_f/P_i$	$P_i$ (bar)	$P_f$ (bar)	$P_f/P_i$
3.317	1.816	54.7 %	3.555	1.943	54.6 %
3.266	1.788	54.7 %	3.365	1.851	54.7 %
3.415	1.869	54.7 %	3.296	1.807	55.0 %
3.548	1.938	54.6 %	3.399	1.861	54.8 %

<sup>a</sup>Standard uncertainties  $u$  are  $u(P) = 0.001$  bar and  $u(T) = 0.01$  K.

322 the thermostatic chamber for the entire duration of the experiment. Two  
 323 sets of pressure measurements are performed, in each of which the measure-  
 324 ment is repeated 4 times (see Table 4). After the first set of measurement,  
 325 the sample is removed from the device and melted. The protocol is then  
 326 performed again for the second set.

327 For the range of PEG volume involved in our experiments, the error of  
 328 measurements is found smaller than 5%. This value is obtained using a  
 329 stainless steel sample with a known volume of  $3.92 \times 10^{-5}$  m<sup>3</sup>. The volume  
 330 measured with the pycnometer led to  $V_{sample} = 3.82 \times 10^{-5}$  m<sup>3</sup>, i.e. within  
 331 2.6 % difference with the real value.

332 The density of PEG 600 in solid phase and at 273.75 K is evaluated to  
 333  $\rho = 1510$  kg m<sup>-3</sup> with a standard uncertainty  $u(\rho) = 23$  kg m<sup>-3</sup>. This value  
 334 results to be quite different from the one obtained for the liquid phase. This  
 335 is not surprising as it is correlated to the large variation in volume occurring  
 336 during solidification.

### 337 3.2. Thermal conductivity

#### 338 3.2.1. Liquid phase - Steady hot tube method

339 As above mentioned in section 2.3.1, the steady hot tube method is rel-  
 340 evant only in the liquid phase as it requires good thermal contacts between  
 341 sample and tubes surfaces. Since the device is filled with PEG 600 in liquid  
 342 phase, the largest decrease in volume that leads to thermal resistances at  
 343 interfaces is observed at the liquid-to-solid transition. At temperature below  
 344 293.15 K results are indeed no longer reproducible. For higher temperatures,  
 345 however, surface contact resistances can be assumed to be negligible. Mea-  
 346 surements are performed at steady state. Results obtained with this device  
 347 are presented in Fig. 6 ('+' symbols) as a function of the mean temperature

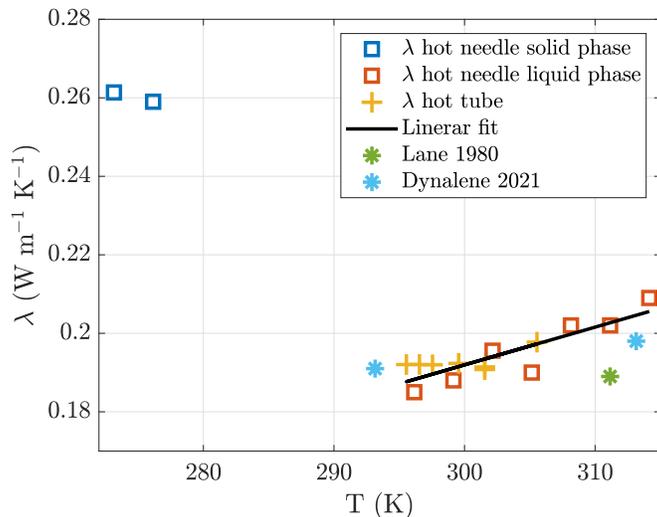


Figure 6: Thermal conductivity results for liquid phase and solid phases at the pressure  $P=1.007$  bar. The temperature  $T$  refers (i) to the mean temperature between thermocouples  $T = \bar{T} = (T_1 + T_2)/2$  in the case of the hot tube method and (ii) to the temperature in the thermostatic enclosure in the case of the hot needle method. Data are provided in supporting files. Standard uncertainties  $u$  are  $u(P) = 0.018$  bar and  $u(T) = 0.1$  K. The combined expanded uncertainty  $U_c$  is  $U_c(\lambda) = 0.04$  W m<sup>-1</sup> K<sup>-1</sup> with 0.95 level of confidence ( $k \approx 2$ ), for both hot tube method and hot needle method.

348 between the two thermocouples, i.e.  $\bar{T} = T = (T_1 + T_2)/2$ . For comparison,  
 349 additional values of thermal conductivity given by Lane [19] and values from  
 350 a data sheet provided by Dynalene [30] are also displayed in Fig. 6. In our  
 351 experiments the temperature variation  $\Delta T = T_2 - T_1$  does not exceed 3 K  
 352 through the annular region of the device, i.e. between  $r_1$  and  $r_2$ . In the range  
 353 of the tested temperatures, we observe a slight temperature dependence of  
 354  $\lambda$ . These measurements are complemented by those obtained by using the  
 355 hot needle method.

### 356 3.2.2. Solid and liquid phases - Hot needle method

357 The measurements are carried out with the needle probe described pre-  
 358 viously in Section 2.3.2. The estimation of the thermal conductivity  $\lambda$  is  
 359 obtained assuming: (i) conductive regime in the vicinity of the needle, (ii)  
 360 an infinite medium and (iii)  $T_0(t) \propto \ln(t)$  at long time. The time interval  
 361  $[t_i, t_f]$ , in which the latter condition is satisfied, is determined empirically  
 362 when the difference between experiments and the model is close to zero (see  
 363 the discussion below about residuals).

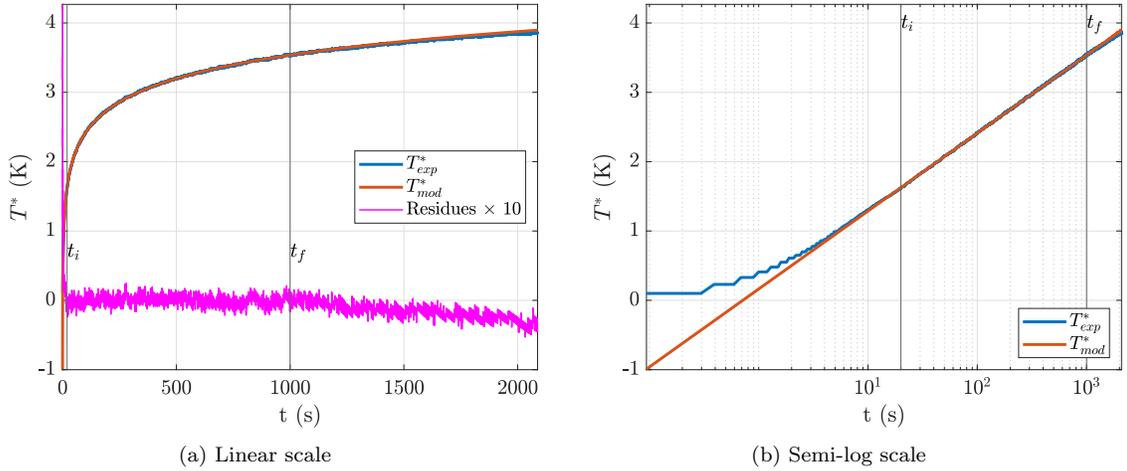


Figure 7: Time evolution of experimental ( $T_{\text{exp}}^*$ , in blue) and simulated ( $T_{\text{mod}}^*$ , in red) temperature difference  $T^*$  between the hot needle and the thermostatic enclosure set at 276.15 K and  $P=1.007$  bar. The red curve is obtained with the simplified model from Eq. (25). Magenta curve in (a) displays the residues  $S$  between  $T_{\text{exp}}$  and  $T_{\text{mod}}$  multiplied by 10 times. Data are provided in supporting materials. Standard uncertainties  $u$  are  $u(P)=0.018$  bar,  $u(T^*)=0.02$  K and  $u(t)=0.001$  s.

364 Thermal conductivity values in the solid phase are obtained placing the  
 365 device in the temperature controlled binder. An example of temperature  
 366 measurement ( $T^* = T_0(t) - T_0(0)$ ) is plotted in Fig. 7 as a function of  
 367 time. In the same figure we also display temperature values estimated by the  
 368 model given by Eq. (25). Residuals multiplied by 10 times are also plotted in  
 369 order to highlight the differences between measurements and the model. For  
 370 each set of experiments, we determine the time interval  $[t_i, t_f]$  along which  
 371 residuals are perfectly flat and centered on zero, i.e. the time interval in  
 372 which our model is consistent. This interval is bounded by vertical lines in  
 373 Figs. 7 and 8. In the case presented in Fig. 7, the estimation time interval is  
 374  $[20, 1000]$  s. The divergence of the residuals after 1000 s indicates the limit of  
 375 validity of the infinite medium assumption. Following Eq. (25), we evaluate  
 376  $D_2$  within the estimation interval as the slope of the temperature variation  
 377 with time in semi-log scale (Fig. 7b).

378 The model also applies to the liquid phase only if convection does not  
 379 occur. For this reason, we have also performed some measurements above  
 380 293.15 K. We show them in Fig. 8, where experimental and simulated tem-  
 381 perature variations are displayed as a function of time. The same conditions

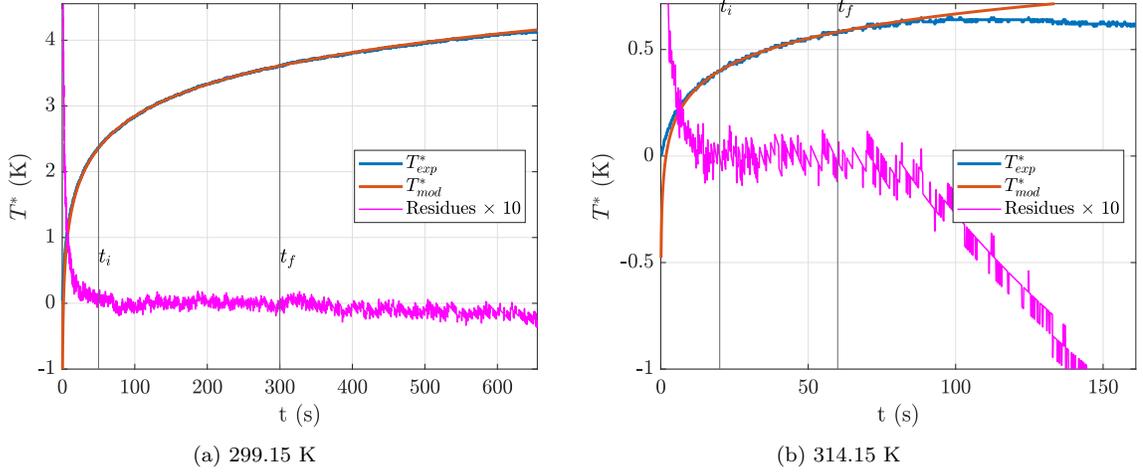


Figure 8: Time evolution of experimental ( $T_{\text{exp}}^*$ , in blue) and simulated ( $T_{\text{mod}}^*$ , in red) temperature difference  $T^*$  between the hot needle and the thermostatic enclosure set at  $P=1.007$  bar and 299.15 K (a) and 314.15 K (b). The red curve is obtained with the simplified model from Eq. (25). Magenta curves display the residues between  $T_{\text{exp}}^*$  and  $T_{\text{mod}}^*$  multiplied by 10 times. Data are provided in supporting materials. Standard uncertainties  $u$  are  $u(P)=0.018$  bar,  $u(T^*)=0.02$  K and  $u(t)=0.001$  s.

382 described above are assumed and residuals are again plotted multiplied by  
 383 10 times. Figure 8 corresponds to two different temperatures imposed in the  
 384 chamber, i.e. 299.15 K and 314.15 K. The estimation interval was adjusted  
 385 to  $[50, 300]$  s for the measurement at 299.15 K and to  $[20, 60]$  s for the  
 386 measurement at 314.15 K. The residuals are found flat and centered on zero  
 387 over these intervals. In the case of 314.15 K, the divergence of the residuals  
 388 after 60 s is explained by the occurrence of convection around the needle.  
 389 The higher the temperature is, the earlier this phenomenon appears. For  
 390 instance, convection is not observed before 300 s for the case at 299.15 K.

391 Figure 6 summarizes all the thermal conductivity measurements as a function of  
 392 temperature carried out for PEG 600. In liquid phase, values obtained  
 393 via the needle method (square symbols) are consistent with those obtained  
 394 using the hot tube method. As temperature increases, the thermal conductivity  
 395 in the liquid phase shows a slight increase. This follows a linear variation  
 396 in the form of  $\lambda(T) = 9.61 \times 10^{-4} T - 9.66 \times 10^{-2}$ , with  $\lambda$  in  $\text{W m}^{-1} \text{K}^{-1}$  and  
 397 temperature  $T$  in K. The intervals of the coefficients with 95% confidence  
 398 bounds are  $p_1 = [0.0006076, 0.001316]$  and  $p_2 = [-0.2037, 0.01055]$ .

399 Our results are very close to those provided by Dynalene (see the data

400 sheet in [30]), i.e.  $\lambda = 0.191 \text{ W m}^{-1} \text{ K}^{-1}$  at 293.15 K and  $\lambda = 0.198$   
 401  $\text{W m}^{-1} \text{ K}^{-1}$  at 313.15 K. A good agreement is also found with values pub-  
 402 lished by Lane [19], who obtained  $\lambda = 0.189 \text{ W m}^{-1} \text{ K}^{-1}$  at 311.00 K and  
 403  $\lambda = 0.187 \text{ W m}^{-1} \text{ K}^{-1}$  at 340.15 K.

404 In solid phase, the value of conductivity measured at 273.15 K and 276.15  
 405 K does not vary much, leading for this temperature interval to  $\lambda_s \approx 0.260$   
 406  $\text{W m}^{-1} \text{ K}^{-1}$ , with a standard uncertainty of  $u(\lambda)=0.02 \text{ W m}^{-1} \text{ K}^{-1}$ . This  
 407 value is close to the one proposed by Kou et al [14] for PEG 1000, i.e.  
 408  $0.29 \pm 0.05 \text{ W m}^{-1} \text{ K}^{-1}$ . In our experiments, for an enclosure temperature  
 409 of 279.15 K, the temperature near the needle is around 283.00 K and the  
 410 material starts to melt. This makes it difficult to obtain values of  $\lambda$  of PEG  
 411 600 in solid phase above 276.15 K. The gap between 276.15 K and 293.15 K  
 412 in terms of thermal conductivity (Fig. 6) is explained by the occurrence of  
 413 the phase transition.

414 To summarize, our measurements provide values of thermal conductivity  
 415 in both liquid and solid phases. An effective value of  $\lambda$  in solid phase can  
 416 be measured in the temperature range [276.15, 293.15] K. However, we think  
 417 that a careful investigation of the material structure at the phase transition  
 418 would be more relevant. This aspect is beyond the scope of this article but  
 419 it will be investigated in the near future.

### 420 3.3. Specific heat capacity and latent heat

421 Raw data obtained by differential scanning calorimetry are presented in  
 422 Fig. 9. The figure displays the amount of heat flux (in blue) transferred  
 423 between the PCM sample and the calorimeter, for the case of imposed tem-  
 424 perature steps (in red). Each increment of temperature leads to a peak in  
 425 terms of heat exchanged. The latter goes back to zero as soon as the thermal  
 426 equilibrium is reached. Given this experimental protocol, the effective heat  
 427 capacity  $c_p$  is deduced by integrating the heat flux over the duration of a step  
 428 (including the increment) and dividing the result by the mass of the sample  
 429  $m$  and the temperature increment.

430 On the other hand, when the protocol involves temperature ramps, i.e.  
 431 continuous temperature variations with time, we directly determine the ef-  
 432 fective  $c_p$  from the measured heat flux  $\phi$  according to

$$\phi = mc_p \frac{dT}{dt}, \quad (28)$$

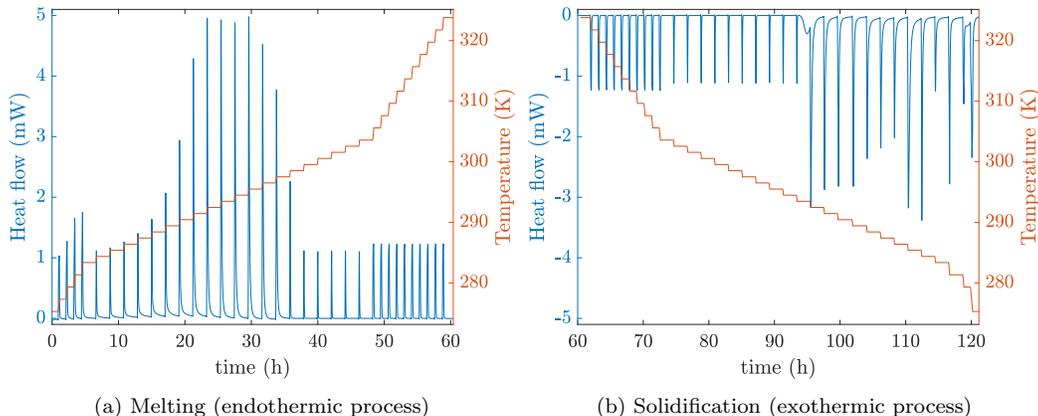


Figure 9: Heat flow rate measured from DSC (in blue) and imposed temperature steps (in red) as a function of time and at the pressure  $P=1.007$  bar. (a) Melting of PEG 600 for increasing temperature steps (endothermic process). (b) Solidification of PEG 600 for decreasing temperature steps (exothermic process). Data are provided in supporting files. Standard uncertainties  $u$  are  $u(P)=0.018$  bar,  $u(\text{Heat flow})=0.01$  mW and  $u(T)=0.01$  K.

433 where the temperature variation rate  $\frac{dT}{dt}$  is constant and imposed by the  
 434 ramp. We deduce then:

$$c_p = \frac{\phi}{m} \left( \frac{dT}{dt} \right)^{-1}. \quad (29)$$

435 The resulting values of effective  $c_p$  are shown in Fig. 10 as a function  
 436 of temperature. Similar trends are observed for all tested protocols. When  
 437 the material is liquid, i.e. for large temperature values (above 298.15 K) and  
 438 at pressure  $P=1.007 \pm 0.018$  bar, we obtain a quasi constant heat capacity,  
 439 i.e.  $c_p = 2.13 \text{ kJ kg}^{-1} \text{ K}^{-1}$ , corresponding to  $1278 \text{ J K}^{-1} \text{ mol}^{-1}$ . The standard  
 440 uncertainty for  $c_p$  is  $0.06 \text{ kJ kg}^{-1} \text{ K}^{-1}$ . This value of heat capacity is recovered  
 441 in the liquid phase for both cooling and heating experiments. However, as  
 442 shown in Fig. 10, we do not obtain a constant value of  $c_p$  around 280 K,  
 443 i.e. a temperature close to but below the solidification/melting peaks. The  
 444 values are provided in the supplementary material. Similar tendencies are  
 445 observed in [14].

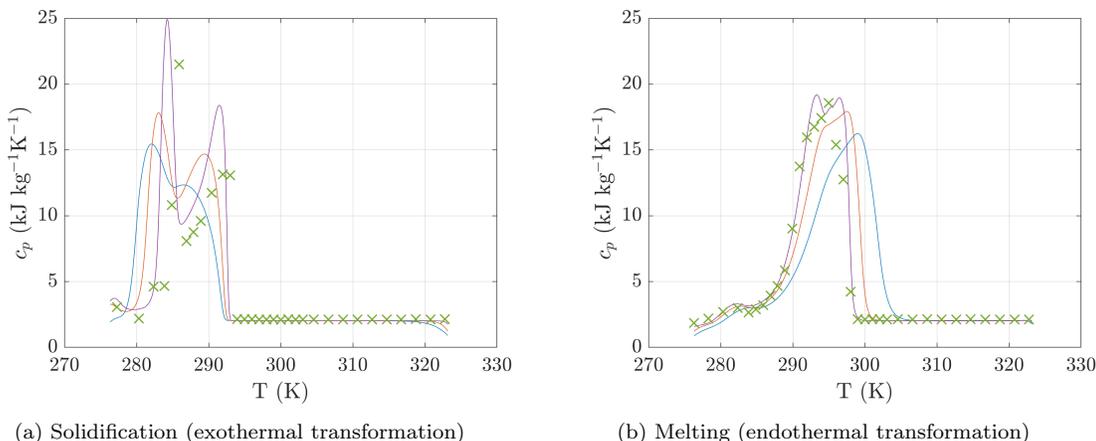
446 In the temperature range where the phase transition occurs (i.e. solidifi-  
 447 cation in Fig. 10a and melting in Fig. 10b), variations in the evaluated  $c_p$   
 448 are due to the competition between the kinetics of the phase change process

449 and the rate of temperature variations. This competition leads to a tempera-  
450 ture hysteresis during solidification that corresponds to undercooling effects.  
451 This latter phenomena decreases for slow temperature variations. In the case  
452 of imposed temperature steps, the melting of PEG 600 is observed between  
453 283.4 K and 298.5 K, while its solidification occurs between 294.5 K and  
454 281.3 K. Further differences between melting and freezing processes can be  
455 highlighted. Indeed, two distinct local maxima are observed during solidifi-  
456 cation as the temperature decreases (Fig. 10a). These extrema are always  
457 obtained for similar temperature values when the adopted cooling protocol  
458 lasts long enough. Here, extrema correspond to exothermal transformations  
459 correlated to structural modifications that occur during the crystallization  
460 [20, 21].

461 Reciprocally, at least one extremum value in terms of  $c_p$  is also obtained  
462 for the melting process (Fig. 10b). When the heating process is long enough  
463 ( $0.2 \text{ K min}^{-1}$ ), two local peaks are observed but their amplitudes are smaller  
464 than in the case of the solidification process. These multiple peaks are ob-  
465 served also in other studies where they are attributed to microstructural  
466 variations, i.e. crystals with different thickness due to variations in folds  
467 number in the polymer chain [31] or due to the evolution of the lamellar  
468 microstructure during the phase change [32].

469 A comparison of the effective  $c_p$  obtained for PEG 600 with PEGs with  
470 higher molar masses [14] is proposed in Fig. 11. All results are obtained  
471 during the melting process and by heating samples with a rate of  $1 \text{ K min}^{-1}$   
472 for PEG 600 and a rate of  $10 \text{ K min}^{-1}$  [14] for PEG with large molar masses  
473 (from 1000 to 20000). Our data for PEG 600 follow similar tendencies to  
474 those observed by [14] as the average molar mass of PEG increases, i.e. both  
475 melting temperature and  $c_p$  increase.

476 Finally, the latent heat is evaluated by integrating only the part due to the  
477 phase transition in the effective heat capacity. For the solidification process,  
478 the integration leads to a latent heat of  $128.0 \text{ kJ kg}^{-1}$ , while for the melting  
479 to  $128.7 \text{ kJ kg}^{-1}$ . In both cases, we estimate a standard uncertainty for the  
480 latent heat of  $2 \text{ kJ kg}^{-1}$ . These values are in very good agreement with the  
481 one proposed by Lane [19], i.e.  $127.2 \text{ kJ kg}^{-1}$ . According to Pielichowski  
482 & Flejtuch [33], the latent heat of melting of a 100% crystalline polymer is  
483  $196.8 \text{ kJ kg}^{-1}$ . Compared with this latter value, PEG 600 should correspond  
484 to a degree of crystallinity of 65%. Indeed, low molecular weight polymers  
485 are known to have higher segmental mobility, thus reducing the formation of  
486 the crystalline phase (geometric alignment), as observed for PEG at different



(a) Solidification (exothermal transformation)

(b) Melting (endothermal transformation)

Figure 10: Effective  $c_p(T)$  evaluated at constant pressure  $P=1.007$  bar and during (a) the solidification process and (b) the melting process, for temperature variations of  $1 \text{ K min}^{-1}$  (blue lines),  $0.5 \text{ K min}^{-1}$  (red lines),  $0.2 \text{ K min}^{-1}$  (purple lines) and temperature steps (green crosses). Data are provided in supporting materials. Standard uncertainties  $u$  are  $u(P)=0.018$  bar,  $u(\text{Heat flow})=0.01$  mW,  $u(T)=0.01$  K,  $u(m)=0.01$  mg and  $u(c_p)=0.06 \text{ kJ kg}^{-1} \text{ K}^{-1}$ .

487 molecular weight [14, 33].

#### 488 4. Conclusion

489 In this study we report the thermal properties of polyethylene glycol 600  
 490 (PEG 600). The density in liquid phase has been measured in the tempera-  
 491 ture range [298.15, 373.15] K. Given the small temperature increments used,  
 492 we have been able to provide a fit for the temperature-dependent density of  
 493 liquid PEG 600. The latter allows to determine the coefficient of thermal vol-  
 494 ume expansion with a good accuracy. The density of PEG 600 in solid phase  
 495 has been measured by using a pycnometer and it results in  $\rho = 1510 \text{ kg m}^{-3}$   
 496 with a standard uncertainty  $u(\rho) = 23 \text{ kg m}^{-3}$  at 273.75 K. The variation  
 497 of density between the two phases highlights a quite large volume shrinkage  
 498 of the material during solidification. This can have a drastic consequence on  
 499 thermal contacts at interfaces and hence a strong impact in the usability of  
 500 this PCM in thermal energy storage systems.

501 The thermal conductivity  $\lambda$  has been investigated with two different meth-  
 502 ods. Results for the liquid phase show a slight linear increase of  $\lambda$  with in-  
 503 creasing temperature. For the solid phase, and within the investigated tem-

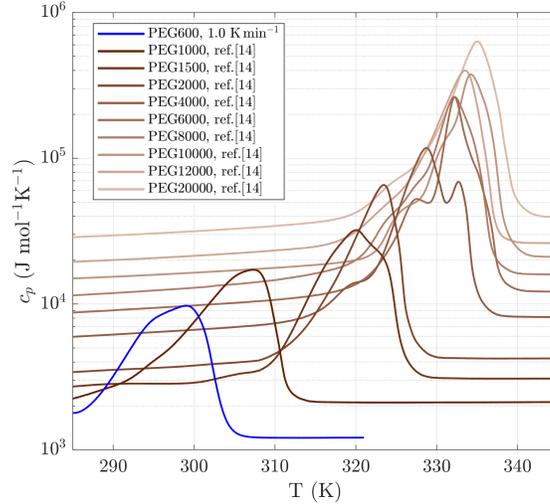


Figure 11: Comparison between the effective  $c_p(T)$  for PEG 600 (blue line) and data of [14] for PEG with large molar masses (brown lines). In both cases, the curves are obtained from DSC measurements during the melting process. For a better comparison, heat capacity is plotted in  $\text{J mol}^{-1} \text{K}^{-1}$ . For PEG 600 we display the same curve shown in Fig. 10b for a heating rate of  $1.0 \text{ K min}^{-1}$ . Uncertainties are those reported in Fig. 10b.

504 perature range, we find  $\lambda \approx 0.260 \text{ W m}^{-1} \text{K}^{-1}$  with a standard uncertainty  
 505 of  $u(\lambda)=0.02 \text{ W m}^{-1} \text{K}^{-1}$ .

506 Effective heat capacity and heat transfer have been described and quan-  
 507 tified by DSC measurements. Far from the phase transition, we obtain a  
 508 constant specific heat capacity for both solid and liquid phase. Whether  
 509 the sample is slowly cooled or heated, the phase transition starts at  $283.4 \text{ K}$   
 510 and at  $294.5 \text{ K}$  for the melting and solidification process, respectively. Under-  
 511 cooling effects are responsible for the hysteresis in phase change temperature,  
 512 however they decrease when the cooling rate is decreased. DSC experiments  
 513 enable us to obtain a latent heat of about  $128.0 \text{ kJ kg}^{-1}$ , which is close to the  
 514 value proposed by Lane [19]. Furthermore, during the solidification process  
 515 we observe several exothermic heat flow peaks that highlight consecutive re-  
 516 organizations of aggregates and/or crystals in the internal structure of PEG  
 517 600. This latter aspect is beyond the scope of this study. However, since  
 518 explanations on PEG crystallization are still controversial in literature, a  
 519 proper investigation at small scales of this process will be a fundamental  
 520 part of our future work.

521 **Appendix A. Estimation of the error due to steady-state contact**  
 522 **resistances**

523 During solidification, the density of the sample increases and  $\rho_l < \rho_s$ , with  
 524  $\rho_l$  being the density of the liquid phase and  $\rho_s$  the one of the solid phase.  
 525 This results in a decrease in volume with temperature. In the hot tube device  
 526 used to measure the thermal conductivity, this leads to an air/vacuum layer  
 527 of thickness  $\epsilon$  between the sample and the inner heating tube of radius  $r_1$   
 528 (Fig. 2).

529 One can write:

$$\rho_l \pi (r_2^2 - r_1^2) = \rho_s \pi [r_2^2 - (r_1 + \epsilon)^2], \quad (\text{A.1})$$

leading to

$$\epsilon = \left[ r_2^2 - \frac{\rho_l}{\rho_s} (r_2^2 - r_1^2) \right]^{0.5} - r_1.$$

530 The thermal resistance between the two tubes is:

$$R = \frac{1}{2\pi\lambda} \ln \left( \frac{r_2}{r_2 - r_1 - \epsilon} \right) + \frac{1}{2\pi\lambda_{air}} \ln \left( \frac{r_1 + \epsilon}{r_1} \right) = \frac{1}{2\pi\lambda_m} \ln \left( \frac{r_2}{r_1} \right). \quad (\text{A.2})$$

531 In this way,  $\lambda_m$  is the measured value of the thermal conductivity while  
 532  $\lambda$  is the real thermal conductivity of the solid sample. We deduce:

$$\lambda_m = \ln \left( \frac{r_2}{r_1} \right) \left[ \frac{1}{\lambda} \ln \left( \frac{r_2}{r_2 - r_1 - \epsilon} \right) + \frac{1}{\lambda_{air}} \ln \left( \frac{r_1 + \epsilon}{r_1} \right) \right]^{-1}. \quad (\text{A.3})$$

533 The radii values are  $r_1 = 2.75$  mm;  $r_2 = 6$  mm. With an estimated  
 534 value for the thermal conductivity in solid phase of  $\lambda = 0.26$  W m<sup>-1</sup> K<sup>-1</sup>, we  
 535 can calculate the value  $\lambda_m$  that we would have measured with the hot tube  
 536 method. For  $\rho_l/\rho_s = 0.75$ , the calculation leads to  $\lambda_m = 0.19$  W m<sup>-1</sup> K<sup>-1</sup>, i.e.  
 537 around 30% less than the actual value. For this reason, the steady-state hot  
 538 tube device used in this study to measure  $\lambda$  of liquid PEG 600 is unsuitable  
 539 to retrieve  $\lambda$  of the solid phase. For measurements of thermal conductivity  
 540 of solid PCMs is therefore preferable to use a transient measurement device  
 541 where contact resistances have no influence on estimating the conductivity.

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