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Thermal conductivity probe length to radius ratio problem when measuring building insulation materials

Brian Pilkington [a,*], Stephen Grove [b,1]

[a] School of Architecture, Design and Environment, Plymouth University, Drake Circus, Plymouth PL4 8AA, United Kingdom
[b] School of Marine Science and Engineering, Plymouth University, Drake Circus, Plymouth PL4 8AA, United Kingdom

HIGHLIGHTS

- ▶ Identifies various sources of potential error in thermal probe measurements.
- ▶ Assesses length to radius ratios in building insulation thermal probe measurements.
- ▶ Reports volumetric heat capacity for various insulation materials.
- ▶ Provides finite element analyses of thermal probe axial losses.

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ABSTRACT

Thermal conductivity probes are assessed in relation to measuring the effective thermal conductivity of building insulations as samples or in situ. Thermal conductivity and volumetric heat capacity results are given for a range of building insulations, including open and closed cell materials. It was found that the thermal probe technique had potential to be a valuable tool in helping measure, manage and reduce the energy demand of buildings but that traditional solutions for probe length to radius ratios need revision before reliable results can be consistently achieved.

1. Introduction

Energy efficiency in buildings is greatly reliant on the reducing heat transfer through building envelopes. In calculating the heating and cooling loads and the energy efficiency of buildings, it is common to use the steady state U value, units $\mathrm{W\,m^{-2}\,K^{-1}}$, for the heat transfer coefficient. In pursuance of reduced CO_2 emissions and lower running costs, it is a requirement of building codes in many countries, especially in temperate climates, to achieve target U values in new and refurbished domestic and commercial buildings. An example is the Standard Assessment Procedure (SAP) currently used in the UK [1]. U values are calculated, in the main, from the thickness and effective thermal conductivity of component materials making up a building envelope, plus standardised air resistances of cavities, and surface resistances to air of building elements [2].

Thermal conductivity values used in U value calculations are often those supplied by manufacturers and derived from guarded hot plate (GHP) measurements undertaken in controlled, laboratory conditions. GHP measurements require materials to be in a steady state, and so usually require materials to be dried prior to measurement [3–5]. Thermal conductivity probes use a transient measurement, a well known technique [6,7] where the rate of temperature rise of a line source of known power, placed within a material sample, can quickly and easily give the thermal conductivity of that material from the gradient of temperature rise plotted over the natural logarithm of elapsed time ($\Delta T/\ln t$), where that gradient is linear after a short time. Pilkington et al. [8] has shown that, as the measurements employ low temperature rises over short periods of time, moisture migration has negligible effects on results. Many common building materials are porous and hygroscopic in nature and Pilkington et al. [9] have shown that in situ thermal

* Corresponding author. Tel.: +44 1752 586129.
E-mail addresses: brian.pilkington@plymouth.ac.uk (B. Pilkington), S.Grove@plymouth.ac.uk (S. Grove).
URL: http://www.plymouth.ac.uk/staff/bpilkington (B. Pilkington).
1 Tel.: +44 1752 586124.

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conductivity values can be significantly greater than those of dry material GHP values. While various sources give estimated thermal conductivities for a range of materials at varying moisture content, e.g. [10,11], a rigorous, robust, fast and simple measurement device could be a more reliable indicator of actual values in situ, and would allow values for a wider range of materials, whether dry or containing moisture, to be found.

Recent work at the University of Plymouth [12] has shown that thermal probe measurements can be reliable for materials with thermal conductivities above about 0.2 W m^{-1} K^{-1}. However, the materials of more interest regarding building energy efficiency are insulations with typical thermal conductivities in the range 0.025–0.08 W m^{-1} K^{-1}. When measuring these lower thermal conductivity materials with commercially available thermal probes, it has been found that, although the results have excellent levels of repeatability, they rise over time during the measurement. Touloukian's standard work [13], documenting the thermal conductivities of non-metallic solids at various temperatures, indicates that the thermal conductivities of the subject materials should not be expected to alter significantly with the small temperature changes used with thermal probes, which are usually below 20 K.

Where $\Delta T/\ln t$ is non-linear, it is possible to identify a segment of the curve to give a linear asymptote that gives a result matching measurements by alternative means (e.g. GHP) or values from the literature. However, a reliable method of identifying the appropriate segment and finding reliable values where thermal properties of sample materials are unknown has not yet been found. This may explain why a potentially convenient technique has not come into common use, despite it being advocated by many researchers for over 80 years, for example [14,15].

Fig. 1 shows a comparison of typical curves of $\Delta T/\ln t$ for polyisocyanurate foam (PIR) and polytetrafluoroethylene (PTFE) using a 70 mm × 1.2 mm thermal probe with temperature rise recorded at 1 Hz. Fig. 2 shows the thermal conductivity results for each, based on regression analyses of consecutive 100 s segments of $\Delta T/\ln t$ at 1 Hz, as described in [8], using the standard solution, Eq. (1), from [16,17]:

$$\lambda = \frac{Q'}{4\pi(\Delta T/\ln(t))} \tag{1}$$

The thermal conductivity of PIR is given by manufacturers in a range between 0.018 W m^{-1} K^{-1} and 0.025 W m^{-1} K^{-1}, and is partially dependent on the decreasing proportion of blowing agent to air within the pores of the cellular structure over time, following manufacture. The thermal conductivity of PTFE is given as 0.25 W m^{-1} K^{-1} [18].

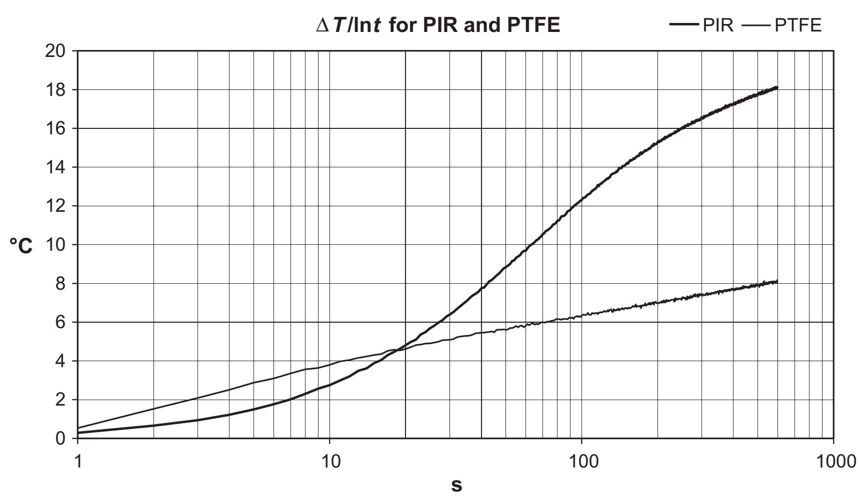

Fig. 1. Typical $\Delta T/\ln t$ curves for PIR and PTFE.

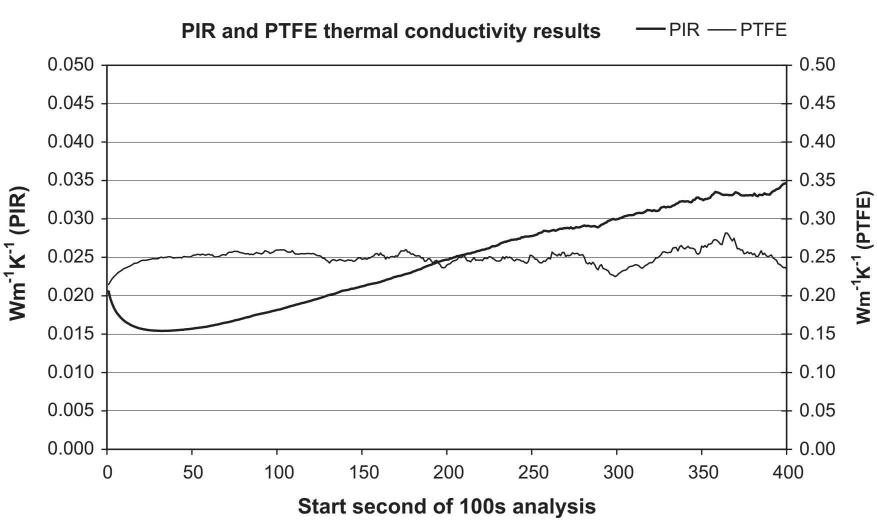

Fig. 2. Thermal conductivity results for PIR and PTFE using consecutive 100 s segments of $\Delta T/\ln t$.