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Johra, Hicham

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Hicham Johra

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by

Hicham Johra

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Contents

1. Foreword

The aim of this lecture note is to detail the methodology of the Guarded Hot Plate method for the measurement of thermal conductivity of medium-size test samples. Such measurements can be conducted with the Guarded Hot Plate apparatus EP500 (Lambda-Messtechnik GmbH Dresden [1]) at the Building Material Characterization Laboratory of Aalborg University - Department of Civil Engineering [2].

2. Introduction

The mathematical equation at the core of most of the heat transfer and thermodynamics models and simulation tools in sciences and engineering is the "Heat Equation":

$$\frac{\partial \theta}{\partial t} = \alpha \nabla^2 \theta \qquad (1)^*$$

Where,
θ: Temperature [K or °C]
t: Time [sec]
α: Thermal diffusivity [m^2/s]

**In here, the heat equation is in its simplest form and only accounts for heat transfer by conduction without internal volumetric heat source, advection or radiative heat transfer terms.*

The heat equation can also be written with the fundamental thermophysical characteristics of a material: the density, the specific heat capacity, and the thermal conductivity:

$$\rho \cdot C_p \frac{\partial \theta}{\partial t} = \lambda \nabla^2 \theta \qquad (2)$$

Where,
θ: Temperature [K or °C]
t: Time [sec]
λ: Thermal conductivity [W/m.K]
ρ: Density of the material [kg/m^3]
C_p: Specific heat capacity of the material [J/kg.K]

Solving this differential equation enables the calculation of the heat transfer and temperature spatial distribution as a function of time.

In steady-state conditions of heat transfer (no change of temperature over time at any given point), the heat equation can be simplified to the Fourier's law of heat conduction (first formulated by Joseph Fourier in 1822). The latter states that the rate of heat transfer through a material is proportional to the negative temperature gradient in the body through which the heat flows and proportional to the section area at right angles to that temperature gradient. In the case of a one-dimensional heat transfer through a planar element (which is the common assumption for most of the building elements), the Fourier's law of heat conduction can be written with the following equation:

$$\vec{q} = -\lambda \nabla \theta \qquad (3)$$

Where,
$\vec{q}$: Vector of local heat flux density [W/m^2]
λ: Thermal conductivity [W/m.K]
$\nabla \theta$: Temperature gradient [K/m]

This equation can be further simplified by considering the heat flux between 2 points (heat flux flowing from a hot point towards a cold point) separated by a given distance in a material:

$$q = \lambda \frac{\Delta\theta}{\Delta x} \qquad (4)$$

Where,
q: Heat flux density [W/m^2]
λ: Thermal conductivity [W/m.K]
$\Delta\theta$: Temperature difference between the 2 points in the material [K]
Δx: Distance between the 2 points in the material [m]

This simple equation is commonly used to estimate the (steady-state) heat transfer and heat losses through building elements. One can notice that the heat transfer through a planar element is proportional to the thermal conductivity of the material. The thermal conductivity is the ability of a material to transmit and propagate heat by conduction. Knowing this material characteristic is thus crucial to calculate the thermodynamics, heat transfer, heat losses temperature distribution inside a material, the thermal resistance (R-value) or the heat transfer coefficient (U-value) of building elements.

3. History of the Guarded Hot Plate Method

The developments in the fields of *Thermodynamics* and the study of the different heat transfer mechanisms during the 19th century fostered the development of experimental methodologies to measure and quantify the fundamental thermophysical properties of materials in order to perform accurate calculations, design, and modelling. One of the first simple and effective experimental method to measure the thermal conductivity of materials is the “Lee’s Disc Method”, presented in 1896 [3].

In 1910, the *American Society of Refrigerating Engineers* requested to the *National Bureau of Standards* (now NIST – USA) to provide usable data of insulation materials for design purposes. However, there was no available accurate method to measure the thermal conductivity of insulation materials at that time. To tackle that issue, Hobart Cutler Dickinson developed and built the first Guarded Hot Plate apparatus at the NIST in 1912. In the meantime, a Guarded Hot Plate apparatus had also been developed and used for thermal conductivity measurements in Germany since 1910 [4].

In the following years, the NIST continued to improve and standardize the Hot Plate method until 1929 when Van Dusen built the final version of this type of first-generation Guarded Hot Plate apparatus. In 1945, the *American Society for Testing and Materials* (ASTM) adopted the Guarded Hot Plate method as a standard test method. In 1947, Robinson and Watson extended the temperature range of the guarded hot plate apparatus [4].

In 1964, H.E. Robinson (NIST) presented the design of the Line-Heat-Source Guarded Hot Plate apparatus. In contrast to the first-generation Guarded Hot Plate that uses uniformly distributed heating elements, a Line-Heat-Source Guarded Hot Plate utilizes circular line-heat sources at specific locations. By doing so, the temperature at the edge of the meter plate can be made equal to the mean temperature of its center, thereby facilitating thermal guarding to the surrounding, temperature regulation, and temperature measurements. The construction of the apparatus was thus easier, together with better accuracy and simpler mathematical analyses for calculating the mean surface temperature of the plate and determining the heat gains or losses at the edges of the tested sample. After several years of development, testing and improvement, the ASTM formally adopted the second-generation line-heat-source Guarded Hot Plate as a standard practice in 1996 [4].

Nowadays, The Guarded Hot Plate method is a widely used state-of-the-art steady-state measurement method for the determination of the thermal conductivity of insulation materials (ISO 8302:1991 [5] and BS EN 12667:2001 [6]).

4. Description of the Guarded Hot Plate Method

The Guarded Hot Plate method is a widely used state-of-the-art steady-state measurement method for the determination of the thermal conductivity of insulation materials (ISO 8302:1991 [5] and BS EN 12667:2001 [6]). It can also be used for other common building materials with higher thermal conductivity such as wood, plastic or concrete (see *Figure 1*).

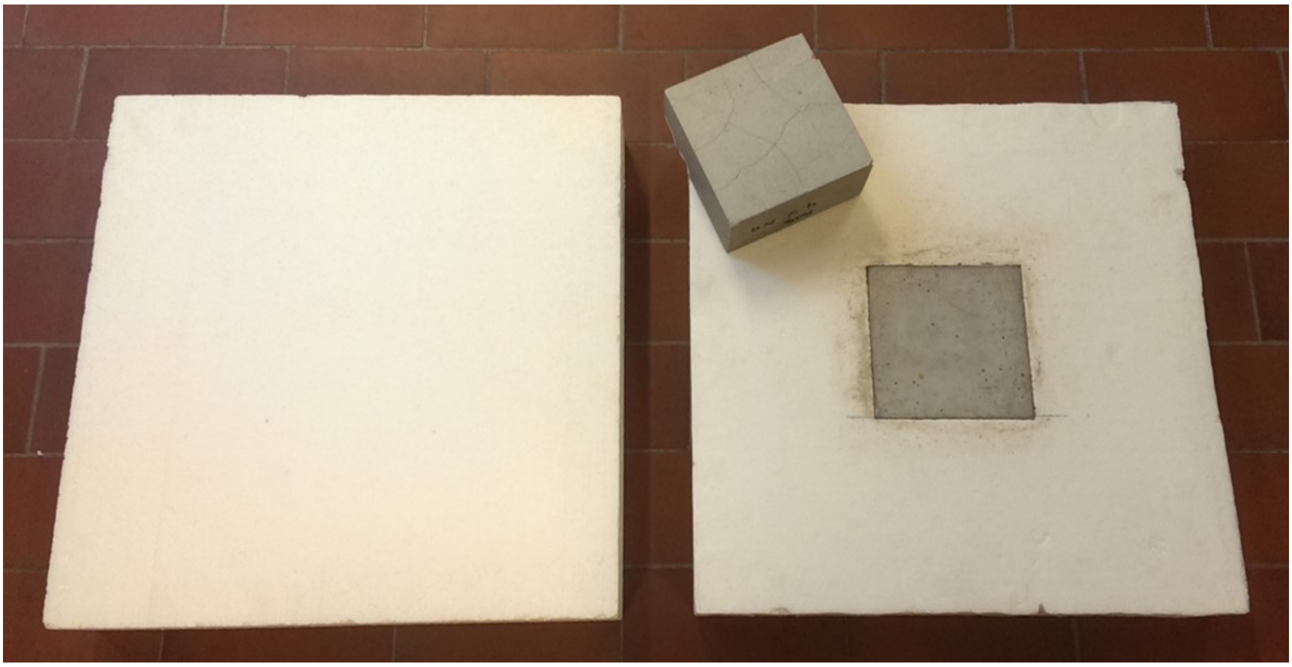

Figure 1: *A typical insulation material (EPS) test sample (50 x 50 x 10 cm) for a Guarded Hot Plate measurement (left); a concrete test sample (15 x 15 x 10 cm, surrounded by a guarding thermal insulation frame of 50 x 50 x 10 cm) for a Guarded Hot Plate measurement (right).*

In order to perform an accurate measurement of the thermal conductivity of a test sample, steady-state temperature boundary conditions are maintained on the top and the down surfaces of the latter to maintain a one-dimensional temperature gradient and heat flux between the hot surface plate and a cold surface plate (see *Figure 2*). The temperature of the hot plate, the temperature of the cold plate, the heat flux supplied to the sample and the thickness of the sample are continuously monitored (see *Figure 2*).

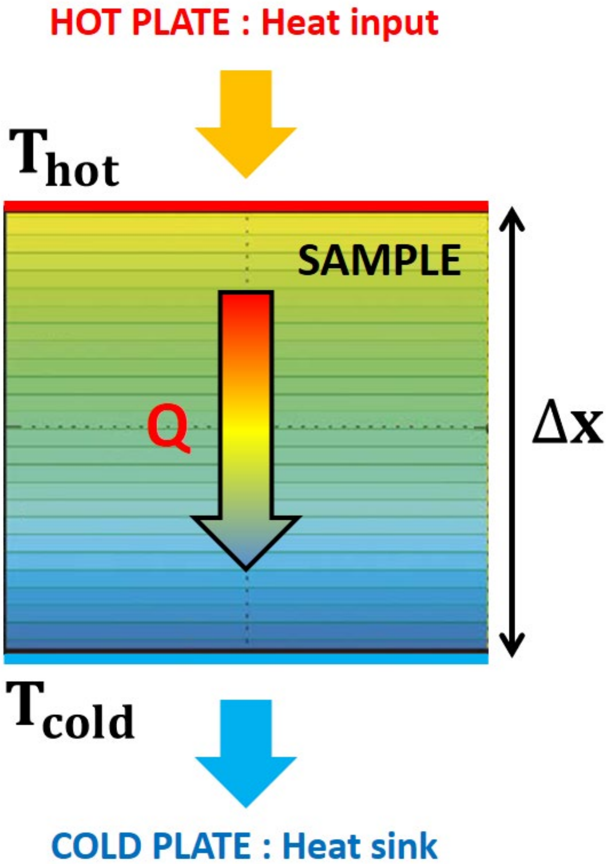

Figure 2: *Measurement of the steady-state one-dimensional heat flux (Q), temperature gradient (T_{hot} - T_{cold}) at the center of the test sample in the Guarded Hot Plate apparatus, together with the thickness of the sample (Δx).*

When steady-state one-dimensional heat flux and temperature gradient are achieved at the centre of the tested sample, it is very simple to determine the material thermal conductivity from the measurement of the heat flux going through the sample, the temperature difference between the hot and cold surface of the sample, the thickness of the sample and section area of the zone where the heat flux is monitored (see "Field of measurement" in *Figure 3*). In those conditions, the Fourier's law of heat conduction can be rearranged as follows to calculate the material thermal conductivity at a given temperature (average between hot and cold plate temperatures):

$$q = \lambda \frac{\Delta\theta}{\Delta x} \qquad (4)$$

$$\Leftrightarrow \frac{Q}{A} = \lambda \frac{\Delta\theta}{\Delta x}$$

$$\Leftrightarrow \lambda = Q \frac{\Delta x}{\Delta\theta \times A}$$

$$\Leftrightarrow \lambda = Q \frac{\Delta x}{(T_{hot} - T_{cold}) \times A} \qquad (5)$$

Where,

q: Heat flux density at the center of the test sample [W/m^2]

Q: Heat flux at the center of the test sample (field of measurement) [W]

λ: Thermal conductivity of the material test sample [W/m.K]

$\Delta\theta$: Temperature difference between the hot and cold surface of the test sample [K]

Δx: Thickness of the test sample [m]

A: Section area of the field of measurement at the center of the test sample [m^2]

T_{hot}: Temperature of the hot surface of the test sample [°C]

T_{cold}: Temperature of the cold surface of the test sample [°C]

As mentioned before, the use of a steady-state method like the Guarded Hot Plate requires that the test sample is in thermal equilibrium with its surroundings in order ensure steady-state one-dimensional heat flux and temperature gradient leading to accurate thermal conductivity measurements. The apparatus thus comprises a heating guarded "hot plate" and a cooling guarded "cold" plate sandwiching the test sample with a specified and controlled pressure. In order to avoid excessive heat exchange between the centre field of measurement of the sample and its lateral sides, and ensure a one-dimensional temperature gradient in the field of measurement (see *Figure 5*), the latter has to be insulated from the lateral sides by a thick layer of insulation material. This is already the case if the test sample itself is made of insulation material. But in the case of thermal conductivity measurement of a non-insulating material (such as wood, plastic or concrete), the test sample should be sized at the dimension of the field of measurement (see *Figure 4*) and surrounded by a frame made of insulation material (EPS, PUR, mineral wool) acting as a thermal guarding insulation (see *Figure 4*).

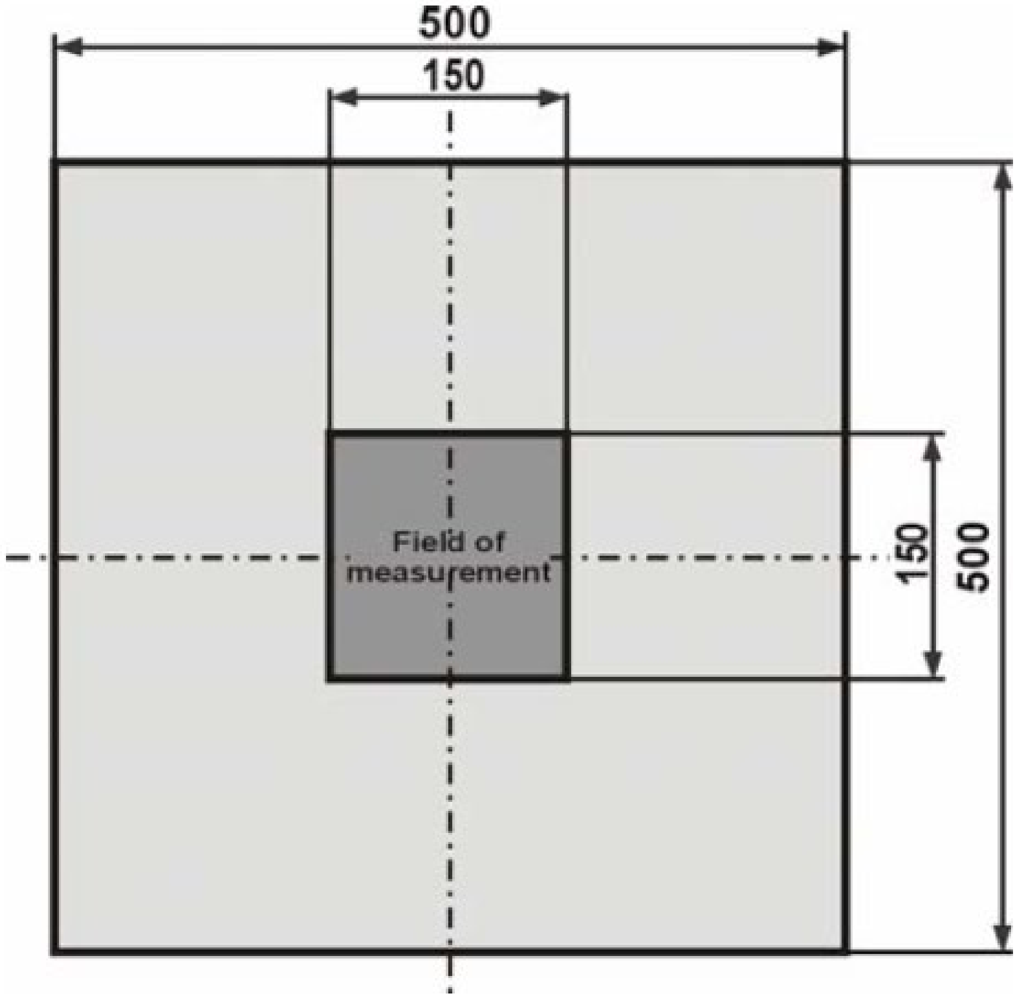

Figure 3: *Dimension and location of the field of measurement for the Guarded Hot Plate apparatus EP500 [1].*

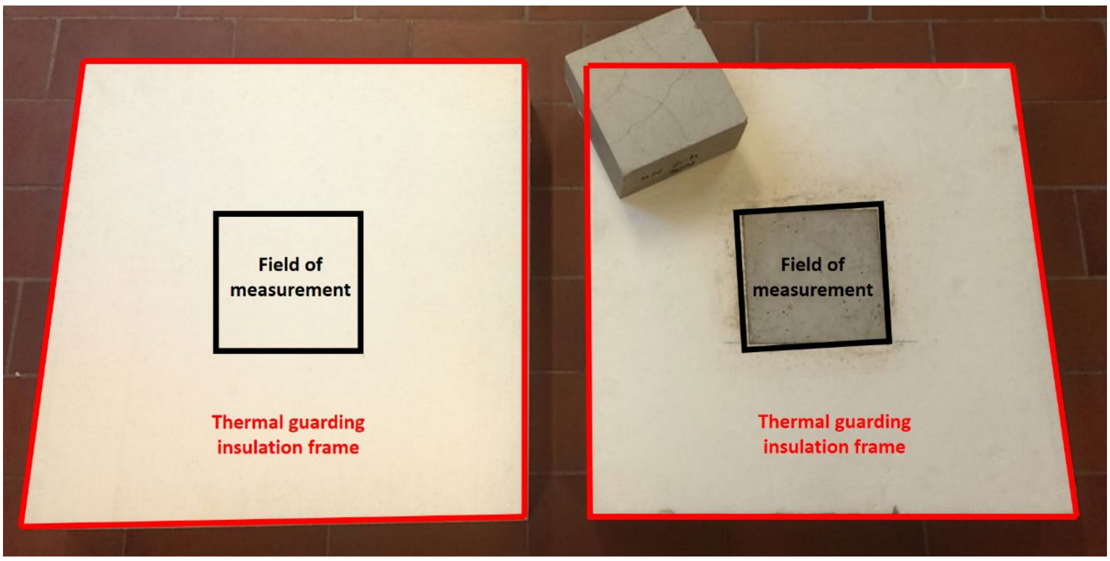

Figure 4: *Location of the field of measurement and thermal guarding insulation frame for an insulation material test sample (left); and a non-insulating material concrete sample (right).*

One can see in *Figure 5* the temperature field inside a (half) insulation material test sample. One can clearly observe that the centre of the sample (on the left of the figure) where the measurement is performed, presents a perfectly one-dimensional vertical temperature gradient. There is no horizontal temperature gradient between the centre of the sample and the surrounding room environment because of the insulation frame of the sample around the measuring zone (field of measurement) and thanks for a double active thermal guarding ring: an inner protection heating ring and an outer protection cooling ring. In addition, the double guarding heating/cooling ring configuration prevents any humidity migration from the surrounding room environment to the centre of the test sample through the interface between the test sample and the hot and cold plates of the apparatus. The humidity possibly condensates on the outer protection cooling ring but does not penetrate further.

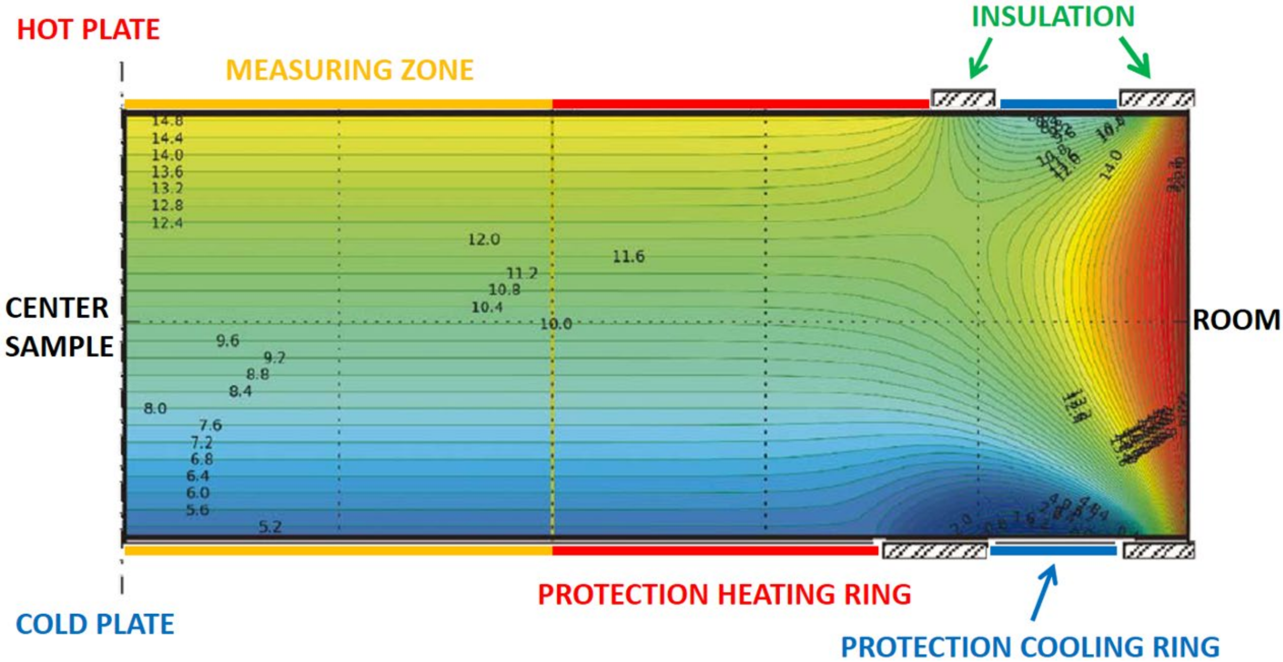

Figure 5: *Temperature field inside the test sample (insulation material) during a steady-state Guarded Hot Plate measurement (view from the side in the middle of the test sample).*

5. Guarded Hot Plate method for Thermal Conductivity Measurement with the EP500 Apparatus

The Guarded Hot Plate apparatus used for thermal conductivity measurement at the Building Material Characterization Laboratory of Aalborg University - Department of Civil Engineering [2] is an EP500 from Lambda-Messtechnik GmbH Dresden [1] (see *Figure 6*). This state-of-the-art instrument is a single-specimen thermal conductivity meter which complies with the related standards (ISO 8302:1991 [5] and BS EN 12667:2001 [6]).

Figure 6: *The Guarded Hot Plate apparatus EP500 from Lambda-Messtechnik GmbH Dresden [1].*

It is commonly used for testing insulation material with low thermal conductivity, but it can also be used for non-insulating materials such as plastics, polymers, wood, concrete, natural stones, ground, glass, and ceramics. It is designed to measure a cubical **50 x 50 cm** test sample of insulation materials or **15 x 15 cm** test sample of non-insulating materials (surrounding by a thermal guarding insulation frame of 50 x 50 cm) with a thickness ranging from 1 cm to 12 cm. The instrument can measure material thermal conductivities ranging from **0.005 W/m.K** to **2 W/m.K** at temperatures ranging from **10 °C** to **40 °C** (average temperature between the upper hot plate and the lower cold plate). The apparatus maintains a temperature difference between the hot and the cold plate ranging from **5 K** to **15 K**. The apparatus holds the test sample in place and ensure a good thermal contact between the test sample and the plates by exerting on the sample a vertical pressure ranging from **0.05 kN/m²** to **2.5 kN/m²** (5000 Pa to 25000 Pa).

During the measurement operation of the Guarded Hot Plate apparatus, the thermal conductivity of the material is continuously calculated by continuously measuring the temperature difference between the hot and cold plates, the thickness of the sample, and the heat flux going through the field of measurement. The measurement stops when the thermal conductivity measurement has been stable within a specified range for a specified period of time. Those 2 criteria are defined by the operator. The stability criteria correspond to an upper and a lower limits (as plus/minus a specified percentage of the current measurement value) in which the measurement should be comprised in over a specified amount of time (see *Figure 7*). Once the stability criteria are met (for example, the thermal conductivity measurement has been within the limit of ±0.3 % of variation over the past 300 minutes), the measurement is stopped and the thermal conductivity measurement at a given temperature is recorded.

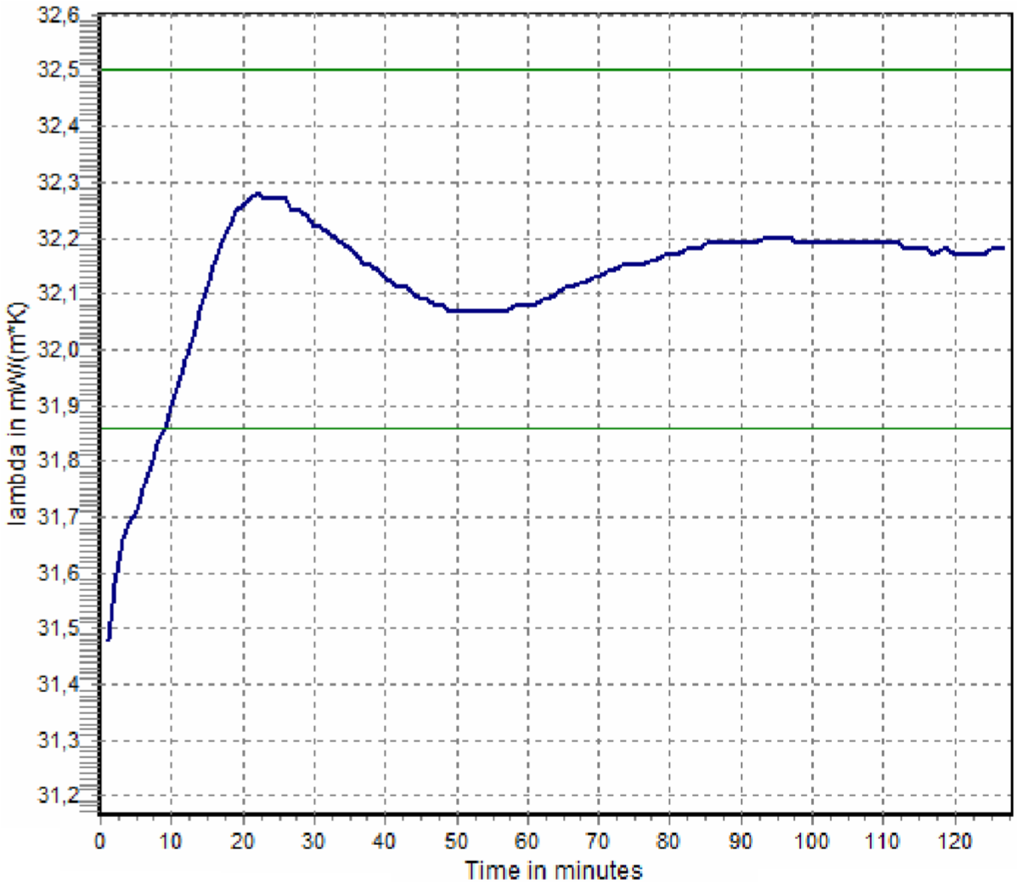

Figure 7: *On-going measurement of the thermal conductivity of a test sample by the Guarded Hot Plate apparatus EP500: the green lines are the limits of stability defined by the operator to stop the measurement; the blue line is the measurement of the thermal conductivity as a function of the elapsed time from the start of the experiment.*

The time needed to acquire 1 measurement of thermal conductivity at 1 specific temperature is at least a couple of hours, and usually more, depending on the diffusivity of the sample, its thickness and the stability criteria chosen by the operator.

The uncertainty performance of the Guarded Hot Plate apparatus EP500 complies with the requirements of the the related standards (ISO 8302:1991 [5] and BS EN 12667:2001 [6]). The measurement reproductibility error is always below 1 % and mostly below 0.5 %. The repeatability of subsequent measurements on a sample maintained within the apparatus without changes in testing conditions is typically better than ±0.5 %. For measurements made on the same reference sample removed and then mounted again after large time intervals, the repeatability of measurements is normally better than ± 1%.

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