Evaluating a line heat source method using a COMSOL® multiphysics axisymmetric 2D model

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Abstract. Research into global warming has increased significantly in the last twenty years due to the pressing nature of environmental concerns, and several transient techniques have been developed to reduce the time and cost of such research. In this work, a non-steady state probe (NSSP), the TP02 Hukseflux® probe with TPSYS02 control interface, was used to determine the thermal conductivity for insulation materials such as glass wool; the experimental processes were calibrated using glycerol as variation of temperature with logarithm of time is linear. The experimental tests were validated using COMSOL Multiphysics® software, and the effects of parameters that cannot be obtained experimentally, such as the component layers of the probe and the length/diameter ratio were also validated using this software. The reference temperature sensor (Pt1000), its position in the base, and how much was inserted into the materials during the experimental testing were thus evaluated. The thickness of the layers of probe material in the radial direction was also simulated in COMSOL to study its effect on the results. The results obtained experimentally were consistent with the results of simulation of COMSOL Multiphysics®.

Key words: COMSOL Multiphysics®, thermal conductivity, TP02 probe of Hukseflux®

Introduction

The building sector consumes more than 40% of the energy produced globally and generates about 25% of greenhouse gases. Most of this energy consumption comes from buildings built before the 1970s, which were not generally well insulated [1]. Since 1974, several regulations have been emplaced to reduce energy consumption and to make buildings more comfortable; several laws have also been introduced to limit emissions of CO$_2$.

There are many clean solutions that can now be implemented to reduce energy wastage, though thermal insulation is considered to be one of the most important methods to save positive energy in buildings. Several different standards have been introduced to encourage the general reduction of energy consumption and to develop new technologies to produce energy more cleanly. Insulation materials are thus frequently used to reduce consumption of energy in buildings; however, studies on the aging of such insulators are rare and no precise measurement method has yet been found to determine the thermal conductivity of insulators in the field.
Heat transfer refers to the thermal energy transmission from one region to another under the influence of a temperature difference. Thermal insulation reduces heat loss to the outside of a building during winter and also helps to control heat levels inside rooms in summer. Transient techniques take less time than steady state techniques to calculate the results of thermal conductivity; they also have better suitability for moist materials. A non-steady state probe (NSSP) in particular can be used to overcome changes in the structure of materials during transfers from site to laboratory. In this study, therefore, a TP02 Hukseflux® probe was used to measure thermal conductivity for insulation materials.

Hust and Smith [2] used a hot wire and probe technique in their study and concluded that these techniques can be used to measure thermal conductivity for various insulation materials (fibre glass insulation and paraffin wax). Pilkington et al. [3] further proved that the probe technique is suitable for materials with thermal conductivity more than 0.07 W.m-1.K-1 due to the S-shape and increasing variation of temperature with the logarithm of time.

The calibration process of the probe in this study was conducted using glycerol due to the lack of contact resistance for liquid materials. Variation of temperature with logarithm of time is linear and therefore equation (6) (stated in full in section 2) can be applied directly to calculate thermal conductivity [4],[5]. For insulation materials, the best straight line on the variation of temperature with logarithm of time curve was selected to obtain thermal conductivity closest to the references.

In this study, COMSOL Multiphysics® software with an axisymmetric 2D module was used to validate the experimental tests and to investigate on the position of reference sensor (Pt1000). This module was also used to check the thickness of the hot wire, the outer face of the TP02 Hukseflux® probe, and the best ratio of length to the diameter of the probe.

**Theory of the thermal probe**

The major priorities of transient techniques are use in situ and reducing the time for testing. Assumptions within theory around non-steady state probe (NSSP) methods include inserting the line heat source in an infinite and homogeneous medium. These assumptions are expressed by the general Fourier equation:

\[
\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{1}
\]

for boundary conditions

- at \( r = 0 \) and \( t \geq 0 \), \( \lim_{r \to 0} \left[ \frac{rdT}{dr} \right] = -\frac{Q}{2\pi \lambda} \) \tag{2}
- at \( r = \infty \) and \( t \geq 0 \), \( \lim_{r \to \infty} [\Delta T(r, t)] = 0 \) \tag{3}

The variation of temperature with time is described by the Carslaw and Jaeger solution [6] and the change of temperature can be approximated by equation (4).

\[
\Delta T = \frac{Q}{4\pi \lambda} \left[ \ln \left( \frac{t_2}{t_1} \right) \right] + B \tag{4}
\]

where

\[
B = \ln \left( \frac{4a}{r^2} \right) - \gamma + \frac{2\lambda}{rH} \tag{5}
\]

and

\( H \) = the air gap thermal conductance.

After a short transient period, the temperature rise (\( \Delta T \)) depends only on heater power (\( Q \)) and medium thermal conductivity (\( \lambda \)). Thermal conductivity can thus be calculated from the slope (\( Q/4\pi \lambda \)) in equation (6).

\[
\lambda = \frac{Q}{4\pi} \left[ \ln(t_2/t_1) \right] / [T(t_2) - T(t_1)] \tag{6}
\]
This variation of temperature is function of the natural logarithm of time, and after a transient period the graph becomes linear in liquid materials such as glycerol, allowing the thermal conductivity to be calculated directly from equation (6). For non-linear variation or S-shapes, as seen in porous materials such as insulation, the best-fit straight line to the curve can thus be chosen to calculate an approximate thermal conductivity (figure 1). Hakansson et al [4] attributed the S-shaped curve to the thermal diffusivity of samples, while Pilkington and Grove [5] said the S-shape depended on the structure of the material. Batty et al. [7] showed that the cause of the S-shape was contact resistance between the probe and the material.

Figure 1. Variation of temperature against logarithm of time for glass wool and glycerol [8]

Non-steady-state probe: TP02 Hukseflux ®

The Non-Steady-State Probe (NSSP) used to measure thermal conductivity of each medium was a TP02 Hukseflux ®. This complies with ASTM D 5334-00, D 5930-97 and IEEE 442-1981 standards. The standard TP02 probe is suitable for soils, thermal backfill materials, powders, paints and various other materials, and it is designed to be used in-situ field experiments. The probe has a reference temperature sensor of pt1000, (1) located in the base, (6), and a hot joint (3) located in centre of the heating wire, (2). The cold joint is at the end of the needle. The TP02 Hukseflux® also has a 2 m copper cable connected to the TPSYS02 interface (5) (figure 2).
The differential temperature between $T_{\text{hot}}$ and $T_{\text{cold}}$ is obtained using equation (7).

$$\Delta T = \frac{U_{\text{sen}}}{E_{\text{sen}}}$$  \hspace{1cm} (7)

where $U_{\text{sen}}$ (µV.K$^{-1}$) is a voltage output and $E_{\text{sen}}$ (µV.K$^{-1}$) is calculated from the equation (8).

$$E_{\text{sen}} = 39.40 + 0.05 T - 0.0003T^2$$  \hspace{1cm} (8)

The TP02 Hukseflux® has a length of 150 mm and a diameter of 1.5 mm, giving $L/D=100$, being composed of three layers in the radial direction (Constantan, Glass pearl, and Stainless steel) from the inside to the outside.

In this study, the probe was used to examine an insulation material (glass wool) after calibration with glycerol (fluid material). The thermal conductivity of glycerol was investigated, and the results found to be close to the real value (0.29 W/mK) based on the behaviour of the variation of the temperature with the logarithm of time (linear).

**COMSOL Multiphysics® simulation**

COMSOL Multiphysics® software was used to validate the experimental tests and to study those parameters that could not be obtained experimentally. The axisymmetric 2D module was selected to represent the layers of the Hukseflux TP02. COMSOL Multiphysics is software that allows numerical simulation using the finite element method. The layers of the TP02 probe were thus modelled to study the effect of changing components of the probe on the experimental tests, and this phase of COMSOL simulation helped to highlight some problems that might occur during experimental work.

In this study, the COMSOL simulation provided data about the spread of heat inside the materials. Increases in temperature on the surface of the probe tend to increase the temperature along the contact resistance layer (air between the material and the probe) (figure 3). Moreover, this study illustrated the changes in the distribution of heat between the probe and the material over time, allowing better design space and geometries with regard to the thermal characteristics of the reference material based on effective calibration of the COMSOL simulation. Several different steps were required in the modelling process, including the geometry of materials, their properties, operational transfer, and the appropriate meshes (figure 4).
Validation of the experimental measurement

The contact resistance (air gap between probe and materials) was modelled as part of the COMSOL® simulation. Different contact resistances (air gap) were thus selected (0 mm, 1 mm, and 2 mm) to better study the effect of contact resistance. Low flow $Q=0.87 \text{ w/m}$ with time of 1,500s was chosen for the glass wool material. The results showed that variation of temperature with the logarithm of time validated experimental values with a contact resistance (air gap) of 1 mm (figure 5). The minor difference can be attributed to radiation effects inside the material (glass wool).
Components layers of the probe
The TP02 Hukseflux® has three layers in the radial direction, Constantan, Glass pearl, and Stainless steel. The internal layer is made from Constantan with thickness 0.065 mm, representing the hot wire that emits heat. This metal has a density of 9,810 kg.m\(^{-3}\), thermal conductivity of 19.5 W.m.K\(^{-1}\), and Specific heat of 390 J.kg.K\(^{-1}\). The effect of this layer was investigated to study the influence of the thickness on the measurement of thermal conductivity. Low flow Q=0.87 w/m with time 1,500s was selected, and an air thickness between the probe and materials (CR) equal to 1mm was chosen. The results showed that increasing the thickness of the Constantan tended to increase the S-shape curve for the variation of temperature with logarithm of time (figure 6), deviating from the results in the literature.

![Figure 6. Variation of temperature with logarithm of time for different thicknesses of Constantan](image)

The outer face layer is Stainless steel with a thickness of 0.33 mm. This metal has a density of 7,900 kg.m\(^{-3}\), thermal conductivity of 16 W.m.K\(^{-1}\), and Specific heat of 500 J.kg.K\(^{-1}\). The effect of stainless steel was investigated to study the influence of thickness on variation of temperature with the logarithm of time. Low heat flow Q=0.87 w/m with time 1,500s was chosen to study the effect of the outer face. The results showed that the S-shape for variation of temperature with logarithm of time increased with the thickness of the outer face (stainless steel) due to high resistivity of this material \((6.9 \times 10^8 \text{ } \Omega \cdot \text{m})\) in spite of the advantages of lower thermal diffusivity \((\text{mm}^2\cdot\text{s}^{-1})\) (figure 7).
The results for thermal conductivity are illustrated in table 1, which shows that the thermal conductivity increased with outer face (stainless steel) thickness. To reduce variation of temperature with the logarithm of time, nickel [9] or copper can be used to access different physical characteristics [8].

**Table 1. Variation of thermal conductivity with thickness of outer face**

| Outer face thickness | 0.33 mm  | 0.66 mm  | 1.00 mm  |
|----------------------|----------|----------|----------|
| Thermal conductivity | 0.034 [W.(m.K)^{-1}] | 0.048 [W.(m.K)^{-1}] | 0.068 [W.(m.K)^{-1}] |

**Position of Pt 1000**

The Hukseflux® TP02 thermal Sensor has a reference temperature sensor of pt1000 at the base of the probe that acts as a cold junction. This reference measures the base temperature and must be corrected to obtained accuracy across the temperature range.

The position of the Pt1000 reference was investigated to achieve the best position in the base using COMSOL Multiphysics® simulation. Heat power of 0.05 W/m with test time of 1,500s was selected to obtain the variation of the temperature less than 1°C (figure 8) [10]. This value of heat power could not achieved with experimental tests (low heat power 0.87 w/m, medium heat power 2.64 w/m and high heat power 4.44 W/m).
The length of the base inserted into the material was also studied to check the effect of the base on the inserting needle of the probe. The results showed that there was no effect whether one centimetre or the full base was inserted into the sample of material (figure 9).

![Figure 8. Variation of temperature with position of Pt1000](image)

**Figure 8.** Variation of temperature with position of Pt1000

![Figure 9. Effect length of inserted base](image)

**Figure 9.** Effect length of inserted base
Length/diameter (L/D) ratio of the Hukseflux TP02 probe

The minimum ratio for length to diameter (L/D) must be 25, according to [11], in order to minimise heat losses in the axial direction of the probe. The Hukseflux TP02® probe has an L/D ratio of 100 (150 mm length and 1.5 mm diameter). Different ratios from L/D were, however, selected and modelled in COMSOL Multiphysics® to investigate the effects of these ratios on thermal conductivity. The results showed that increasing the ratio up to 100 tended to obtain values of thermal conductivity closer to the real value (figure 10).

![Figure 10. Variation of thermal conductivity with L/D ratio](image)

Conclusion

The TP02 Non-steady state probe by Hukseflux® was used to investigate the effect of different parameters on the value of the thermal conductivity for insulation materials. Calibration of the probe was done using glycerol due to its lack of contact resistance and porosity, and as the variation of temperature with the logarithm of time is linear in this material. When an S-curve appears, such as in insulation materials, the best line must be selected to calculate the thermal conductivity during the application of equation (6).

COMSOL Multiphysics® axisymmetric 2D module was used to validate the experimental test. The variation of temperature in the COMSOL simulation was considered and the experimental test was validated in spite of simple differences between two curves. The results showed that thermal conductivity is influenced by changing the outer face thickness of the probe, while the length of inserted base has no effect on the variation of temperature with logarithm of time and hence on the thermal conductivity.

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