International Journal of Thermal Sciences 117 (2017) 251–259

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

# Limit of validity of the log-linear model for determining thermal properties of light insulation materials with cylindrical hot probe

Laurent Marmoret [a,*], Hussein Humaish [a,b]

[a] Université de Picardie Jules Verne, LTI, IUT, Département Génie Civil, Avenue des Facultés, 80025 Amiens Cedex 01, France
[b] Foundation of Technical Institutes, Technical Institute, Department of Surveying, Al-Kut Iraq

A R T I C L E  I N F O

*Article history:*
Received 10 November 2015
Received in revised form
10 October 2016
Accepted 3 April 2017
Available online 8 April 2017

*Keywords:*
Thermal properties
Building insulation materials
Cylindrical probe
Glass wool
Optimization technique

A B S T R A C T

This work aims to contribute to the long term objective of developing in situ thermal characterization of building insulation material. Cylindrical hot probe can be considered the most adapted instrument but the heat flux is radial then unreliable results can be obtained if samples are not homogeneous or radially symmetric like common layered insulation materials. To avoid this difficulty, we have studied glass wool which has been performed by a "crimping" process in order to obtain a more isotropic structure. The main problem treated in this work concerns the identification procedure to determine thermal characteristics of insulation materials. The standard procedure to determine thermal conductivity requires linear thermogram representing temperature rise against the logarithm of the time. Sigmoid curve (not linear curve) has been obtained for insulation material. So we suggest to develop identification procedure applied from the whole thermogram and not only from the linear part. The interest of this procedure is also to determine simultaneously thermal conductivity and thermal capacity of the surrounding material. Analytical solution based on Jaeger model has been employed to resolve the time dependant problem of heat transfer. The mathematical approach of the model of Blackwell [22], Jaeger [23] and Devries [24] are very similar. However, none of these models described a proper way to calculate the thermal conductivity and thermal capacity simultaneously from thermogram. This work is referred to the work of van Haneghem [17] and Hutter [31] for granular materials which developed or applied revised model based on that of Jaeger. Inverse technique with optimization routines from Matlab has been used to minimize the difference between measured and estimated temperature thermograms.



## 1. Introduction

The European Commission's recent package of proposals on climate and energy presents set new aims for 2020 (compared to 1990, *so called EU's 20-20-20*): 20% less energy consumption, 20% of energy coming from Renewable Energy Source (RES), and reducing greenhouse gas (GHG) emission by 20%. The building and construction sector can be considered a key sector for sustainable development: 30–40% of all primary energy is used in buildings [1] and, in terms of $CO_2$ emissions, buildings in the developed world contribute approximately 50% (27% from dwellings). Sufficient insulation is considered the most efficient factor to reduce heating energy in new and existing buildings. To achieve the EU's 20-20-20, European member states have imposed more stringent requirements in building codes. It seems obvious that the lack of on-site measuring capacity is central to bridge the gap between theoretically predicted and real life performance of buildings. But, there is a need of developing thermal characterisation techniques and facilitating in situ traceability and calibration. The present work aims to make a contribution towards the development of a robust and reliable in situ thermal characterisation measurement instrument for building insulation materials.

Steady-state methods suffer from major drawbacks like the long time it takes to establish a steady-state temperature gradient across the sample and in addition to the fact that they need a large temperature gradient. Material properties for porous material can be altered during the test [2] due to water (for soil) or moisture (inside building materials) redistribution. Since the 1980s, many theoretical models of heat and moisture transfer in porous media have been proposed with improved modeling and more realistic considerations [3]. Transient technique use a heater embedded inside the characterized medium and a time interval of heating is defined.

* Corresponding author.
*E-mail address:* laurent.marmoret@u-picardie.fr (L. Marmoret).

http://dx.doi.org/10.1016/j.ijthermalsci.2017.04.002
1290-0729/

**Nomenclature**

| | |
|---|---|
| a | Thermal diffusivity ($m^{-2}.s^{-1}$) |
| $A_s$ | External surface ($m^2$) |
| $C_s$ | Specific capacity of the probe ($J.kg^{-1}.K^{-1}$) |
| $E_{sen}$ | Thermocouple sensitivity ($\mu V.K^{-1}$) |
| H | Air conductance ($W.K^{-1}.m^{-2}$) |
| $J_0$ | Bessel functions of the first kind of order 0 |
| $J_1$ | Bessel functions of the first kind of order 1 |
| $l_c$ | Characteristic length of the probe (m) |
| m | Mass (kg) |
| Q | Power supply ($W.m^{-1}$) |
| $R_c$ | Contact resistance ($m^2.k.W^{-1}$) |
| $R_s$ | Radius of the probe (mm) |
| $S_m$ | Heat capacity of the material ($J.m^{-1}.K^{-1}$) |
| $S_s$ | Heat capacity of the probe ($J.m^{-1}.K^{-1}$) |
| T | Basic temperature of $Pt_{1000}$ (K) |
| $T_m$ | Material temperature (K) |
| $T_s$ | Temperatures at the surface of the probe (K) |
| $U_{sen}$ | Voltage output (mV) |
| $Y_0$ | Bessel functions of the second kind of order 0 |
| $Y_1$ | Bessel functions of the second kind of order 1 |

*Greek symbols*

| | |
|---|---|
| λ | Thermal conductivity ($W.m^{-1}.K)^{-1}$ |
| ρ | Density ($kg.m^{-3}$) |
| γ | Euler's constant (=0.5772157 …) |

*Dimensionless parameters*

| | |
|---|---|
| $B_i$ | Biot number (−) |
| $F_0$ | Fourier number (−) |
| Ω | Inertia contrast (−) |

Such techniques are generally considered rapid, potentially low cost, needed low flow and having a minimal effect on moisture content. So they are therefore better qualified for in situ measurement by giving a more realistic representation of thermal properties of placed materials using different forms of contact, such as the transient hot strip, hot plane and hot disk. Needle-shaped cylindrical test bodies as hot wires or cylindrical thermal probes (or, briefly, called probes thereafter) can be considered the most adapted method for in situ measurement. Recent work [4] has shown that thermal probe measurements can be reliable for materials with thermal conductivities above about 0.2 $Wm^{-1}$ $K^{-1}$. However, the materials of more significance regarding building energy efficiency are insulations with typical thermal conductivities in the range 0.02–0.08 $Wm^{-1}$ $K^{-1}$. 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. The results obtained with the hot wire techniques were 13–15% higher than with guarded hot plate technique for bulk densities below 25 kg.m-3 (or porosities > 99%).

Batty et al. [5] considered that this may be due to the layered structure of the material giving rise to increased thermal conduction in the planes parallel to the fibre layers. The steady state technique usually assumes that heat flows predominantly across these planes whereas the hot wire loses heat radially. To minimize the effect of layered structure, glass wool produced by industrial crimping process has been studied in this work.

Fibrous insulants have different structures in the heat flow and isothermal planes. This leads to differences of effective conductivity with direction of heat flow through the material. The thermal conductivity of an inhomogeneous material depends upon the region within the specimen where the temperature indications are being observed. Insulant thickness in wall structures are generally such that boundary effects occur towards the end of the inherently longer testing periods required for these inhomogeneous materials. They conclude that determining accurately the effective thermal conductivities of fibrous insulants of high porosity is difficult with the probe technique. Van der Held [6] observed that materials of high porosity and thus easily penetrated by thermal radiation appeared to possess higher thermal conductivities when measured by transient methods than those by steady state methods. When high probe power is used in insulating materials then high temperature gradients occur at the probe surface so increasing this radiation effect. Low flow (less than 1 Watt) has been sent on tested glass wool in order to minimize radiation effect. For such material, less than a tenth of the effective thermal conductivity is due to the radiation mode [7].

The objective of this work is to check the applicability of existing model (Jaeger model) on the whole experimental thermogram to determine simultaneously thermal conductivity, thermal diffusivity and contact resistance of insulation materials. Firstly, standard method exploiting the thermogram (linear temperature evolution versus the logarithm of the time) is employed to estimate thermal conductivity of a "crimped" glass wool. Secondly, analytical solution with the time dependent problem of heat transfer of the whole thermogram is used. Optimization technique by minimization the residue between measured and calculated temperatures is applied to estimate simultaneously contact resistance, thermal conductivity and thermal diffusivity.

## 2. Material

Glass wool studied consists of entangled fibers and glued produced by an industrial process developed by Isover Saint Gobain (Fig. 1). Bulk density of this glass wool is 68 kg $m^{-3}$ so it can classified in the heavy insulation category. This glass wool is also characterized by an important porosity closed to 97% [8].

Common glass wools have very good thermal performance but low compressive strength and tear which limits their applications. An operation known as "crimping" has been performed to improve the mechanical performance of this glass wool. It consists on uniaxial compression, in line along the bedding plane, to impose a rotation of the anisotropy axis and modify the dense layers to obtain a more isotropic texture.

In terms of thermal properties, the effective thermal conductivity has been determined both experimentally and by calculation from series and parallel model. Measurements have been obtained from guarded hot plate (normative steady-state method) and hot disk (transient method) techniques. Hot disk technique has also been used to determine the effective thermal conductivities in the three directions inside the material (Fig. 1). This procedure has established the quasi-isotropic character of the thermal conductivity of the crimped glass wool and the finely divided structure [9]. Theoretical models of heat transfer have estimated thermal conductivity by considering open-pore architecture material with a combination of series and parallel structures composed of pores and fibers. This model has been applied to estimate the total heat transfer and the contribution of the radiation, convection and