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Uncertainty in the thermal conductivity of insulation materials

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ABSTRACT

Increasing attention is being paid to the application of uncertainty and sensitivity analysis methods to model validation and thermal systems simulation. The idea is to let users to apply uncertainty bands to their model input data. These bands are then propagated through the model to determine the uncertainty bands of the simulation results. One of the main difficulties the practitioner finds when trying to apply these techniques is the lack of information on the uncertainty that affects to typical input variables. This paper is a contribution to fill this gap. It quantifies the uncertainty that can be expected in the thermal conductivity of insulation materials in the lack of specific experimental measurements. Results are presented for specific materials and for groups of materials, in order to consider situations in which the material under consideration is not well defined. The proposed conductivities are derived from a large set of measurements that was compiled in a previous European project headed by the BRE Scottish Laboratory. To illustrate how the uncertainty bands can be used in practice, an example is discussed on the validation of the mathematical model of a solar thermal collector.

1. Introduction

Thermal conductivity is the primary property of an insulation material. The most accurate way to determine its value for a specific sample is to measure it accordingly to a standard method. The guarded hot plate and the heat flow meter hot plate [1–4] are steady-state methods that can provide excellent results, with uncertainties as low as 3% [5] for measurements in the dry state. In engineering practice, however, these methods are seldom applied because they require resources and specialized personnel, as well as a sample available to measure. Instead of measurements, standard tabulated conductivities derived from measurements are extensively used in everyday calculations. Well-known sources of data are the European and ISO standards [6,7], the ASHRAE Handbook of Fundamentals [8] and the CIBSE Guide-A [9]. Because thermal conductivity depends on numerous factors, these references usually provide “design” or “extreme” values, which are high but statistically possible conductivities for each material.

Design values are well suited for the accepted engineering practices, in which uncertainties are handled through worst-case scenarios. These scenarios are built by assuming that all significant inputs will attain their most unfavourable values simultaneously. However, such type of hypotheses on input data are not adequate to solve problems like model validation [10,11] or building simulation under uncertainty [12–14]. For instance, in an experimental validation exercise we are interested in explaining the differences between the results of a model and some measurements. Differences arise from simplifications in the model and from the uncertainty in the value of the input factors. To determine the level of discrepancy attributable to the model itself, the analyst requires realistic estimations of the uncertainties that affect the significant inputs. The problem is that such information is hard to find because stochastic simulation methods have seldom been applied to building simulation, and consequently the sources of input data do not normally report on how the value of the factors spreads around the averages.

This paper estimates the uncertainty that can be expected in the thermal conductivity of insulation materials in the lack of specific experimental measurements. Results are presented for different levels of specification, in order to consider the common situation in which the definition of the material is imprecise (e.g. at early stages of a project). This means that the uncertainty in the conductivity of a sample of known material and density (e.g., EPS of 30 kg/m^3) should be less than the uncertainty in the conductivity of a sample just described by the kind of material (EPS), or by the family of insulation materials it belongs to (organic foams). As our knowledge evolves, uncertainties must decrease.

To quantify the intrinsic uncertainty in the thermal conductivity of a material, a large number of experimental measurements is required. A well-known and extensive compilation of thermophysical properties of building materials was prepared by Clarke et al. in

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Nomenclature

a	constant in the average conductivity fitting function (W/m K)
b	linear coefficient in the average conductivity fitting function (W m^2/kg K)
c	inverse coefficient in the average conductivity fitting function (W kg/m^4 K)
d	constant in the standard deviation fitting function (W/m K)
df	degrees of freedom
e	linear coefficient in the standard deviation fitting function (W m^2/kg K)
f	inverse coefficient in the standard deviation fitting function (W kg/m^4 K)
f_a	ageing conversion coefficient
f_i	ith row of the design matrix X
f_T	temperature conversion coefficient (1/K)
f_m	moisture conversion coefficient, mass by mass (kg/kg) or volume by volume (m^3/m^3)
n	number of measurements
$N[\mu, \sigma]$	normal distribution with average μ and standard deviation σ
R	sum of the squares of the residuals
R_i	residual at ith point
$t_{\alpha/2,df}$	$\alpha/2$-quantile of the t-distribution with df degrees of freedom
T	temperature (°C)
T_{amb}	ambient temperature (°C)
t_{insul}	thickness of the insulation layer (m)
$\bar{T}_{\text{insul}}$	average temperature of the insulation layer (°C)
T_{mp}	mean temperature of the plate (°C)
T_{ref}	temperature at reference conditions (°C)
W	weighting matrix
w	moisture content, mass by mass (kg/kg) or volume by volume (m^3/m^3)
w_{ref}	moisture content at reference conditions, mass by mass (kg/kg) or volume by volume (m^3/m^3)
x	spatial coordinate (m)
X	design matrix
z	thickness of the prediction interval

Greek letters

$\hat{\beta}$	parameter vector
Λ	observation vector
λ	thermal conductivity (W/m K)
$\lambda_{10,\text{dry}}$	thermal conductivity at 10 °C, dry and aged material (W/m K)
$\bar{\lambda}_{10,\text{dry}}$	average thermal conductivity at 10 °C, dry and aged material (W/m K)
λ_{cond}	conductive portion of the thermal conductivity (W/m K)
λ_i	thermal conductivity ith data point (W/m K)
λ_{rad}	radiative portion of the thermal conductivity (W/m K)
ρ	density (kg/m^3)
ρ_i	density ith data point (kg/m^3)
$\sigma_{10,\text{dry}}$	standard deviation of thermal conductivity at 10 °C, dry and aged material (W/m K)
$\sigma_{\text{pred},i}$	standard deviation of model predictions at ith point (W/m K)
ω_i	weight at ith point
∇	gradient operator

1991 [15], based on data from 14 international sources. This work was the basis for the first published study on the uncertainty in the thermophysical properties of building materials, Ref. [16]. However, the authors of Ref. [15] identified two issues that limit the applicability of their data for characterizing the uncertainty in conductivity. First, the sources of much of the data are not identified, and little information is available on the underlying experimental conditions or procedure, and on properties such as density and internal structure. Second, much of the agreement that does exist between different sources may be attributable to historical 'borrowing' one from the other. These two points limit the accuracy and may lead to optimistic assessments of the inherent uncertainties.

The present paper improves and extends the results presented in Ref. [16] using an extensive and quality controlled set of conductivity measurements, which was compiled in the context of an European Project headed by the Building Research Establishment (BRE) Scottish Laboratory in 1999 [17]. In this project, seven European national laboratories provided hundreds of measurements of conductivity of different materials and manufacturers, tested under controlled and known conditions. The resulting dataset was used to prepare a new generation of international standards dealing with thermal properties of materials, for example EN 12524 [6] and ISO 10456 [7]. In the present paper, the same dataset is used to extract average values and uncertainties by material and by groups of materials.

The contents of the paper are as follows. Section 2 provides a concise overview of the main factors the thermal conductivity depends on, and establishes the framework and the basic assumptions of the paper. Section 3 describes the methodology applied on the raw data to quantify the average conductivities and the uncertainties. Section 4 presents the main results: mathematical expressions for the conductivity of specific materials and reliable ranges for the conductivity of groups of materials and incompletely defined materials. Section 5 presents an application example that illustrates how the results of Section 4 can be used to validate a model of flat-plate solar collector. Finally, Section 6 presents the conclusions of the paper and proposes topics for future research.

2. Thermal conductivity

Most mass-type thermal insulation materials are highly porous, and consist of a solid matrix full of small voids that comprise 90% or more of the total volume [8]. These voids contain air or some other harmless gas such as CO_2. The apparent thermal conductivity of the material is the macroscopic result of the various energy flow paths that are found in its complex porous structure: conduction through the solid matrix, conduction in the voids and radiation interchanging in a participating media. The contribution of natural convection has been shown to be negligible under normal operating conditions [18].

At the microscopic level, the apparent thermal conductivity depends on numerous factors such as cell size, diameter and arrangement of fibres or particles, transparency to thermal radiation, type and pressure of the gas, bonding materials, etc. A specific combination of these factors produces the minimum apparent thermal conductivity [8]. At the macroscopic level, the apparent thermal conductivity largely depends on four factors, namely density, moisture content, temperature, and age. The effect of pressure (i.e., compression of the insulation) will not be considered in this paper. Therefore:

$$\lambda = g(\rho, w, T, \text{age}). \tag{1}$$

Accordingly to the standard ISO 10456 [7], the effects of moisture, temperature and age are independent, and Eq. (1) can be written