Uncertainty analysis of thermal conductivity measurements in materials for energy-efficient buildings

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Abstract. The accuracy of thermal conductivity measurements is even more requested for materials characterization in energy-efficient buildings field. ENEA-UTTMATF and CertiMaC research group, as national institute and private laboratory respectively, cooperate in development of new measurement and analysis methods applied to buildings materials and their performances. For what concerns this kind of measurements, an Heat Flow-meter Transducer (HFT) is used. In order to give to both customers and other research institutes involved in the same field (e.g. International Comparison or International Round Robin Tests) the most exhaustive evaluation of the tested material thermal conductivity, a complete uncertainty analysis is implemented on the HFT measures. This uncertainty analysis, developed accordingly to the international standards and with the contribution of INRiM Institute, is described in this paper.

Keywords: Energy efficiency; building materials; heat flow meter; calibration; regression analysis; uncertainty budget; thermal conductivity.

1 Introduction

In this article, a brief description of the Unitherm™ 2022 Heat Flow-meter Transducer (HFT) and an uncertainty analysis of its thermal conductivity measurements are reported (Refs. [1–3]). The analysis was performed taking into account the following three phases:

– calibration of the HFT by means of reference materials whose thermal properties are certified;
– construction of the HFT calibration curve by means of the Ordinary Least Squares method (OLS);
– use of the calibration curve to determine thermal conductivity of unknown materials under test.

The results, obtained by a collaboration among CertiMaC, ENEA-UTTMATF and INRiM, have to be considered as an important development to fully evaluate the uncertainty budget associated to thermal conductivity measurements performed by CertiMaC. This work has been developed in order to improve the metrological knowledge on thermal conductivity measurements for materials characterization in energy-efficient buildings field. In this application field such metrological characterisation is strongly requested by most recent European standards [4,5], even if actually it’s not still implemented as a typical data analysis routine.

2 Unitherm™ 2022 heat flow meter

Thermal conductivity in the Unitherm™ 2022 HFT (Figs. 1, 2) is measured by the guarded heat flow meter method (Refs. [1, 2]). This test method covers a steady-state technique for the determination of the resistance to thermal transmission (thermal resistance) of materials whose specimen thicknesses is less than 25 mm. A specimen and an HFT are sandwiched between two flat plates controlled at different temperatures to produce a heat flow through the test stack. The lower contact surface (with the sample) is part of a calibrated heat flux transducer. A reproducible load is applied to the test stack by a pneumatic cylinder, to ensure that there is a reproducible contact resistance between the specimen and plate surfaces. A guard surrounding the test stack is maintained at a uniform mean temperature of the two plates, in order to minimize lateral heat flow to and from the stack. Moreover, the guard is replaced by an insulating ring when the test mean temperature is under 20 °C, in cryogenic conditions. As heat flows from the upper surface through the sample to the lower surface, an axial temperature gradient
Fig. 1. (Color online) HFT laboratory at CertiMaC – ENEA, in Faenza. (1) Command and Control Panel in order to supervise the temperatures along the stack and the cylinder pressure. (2) Chiller with temperature automatic controller. (3) Stack section with HFT and Guard Heater. (4) Personal Computer with software and acquisition system. (5) Control and Command Panel for air and nitrogen system.

Fig. 2. (Color online) Test section schematic – temperature setting for 10 °C measurement.
is established in the stack and at steady state, the difference in temperature between the surfaces contacting the specimen is measured with temperature sensors embedded in the surfaces, together with the electrical output of the HFT (Fig. 2).

This output (voltage) is proportional to the heat flow through the specimen, the HFT and the interfaces between the specimen and the apparatus. The proportionality is obtained through prior calibration of the system with six specimens of known and certificated thermal resistance measured under the same conditions, so that contact resistance at the surfaces is made reproducible.

At thermal equilibrium, the Fourier heat flow equation applied to the test sample becomes equation (1):

\[ R_s = \frac{(T_u - T_m)}{Q} - R_{int} \]

where:
- \( R_s \) = thermal resistance of the test sample \((\text{m}^2 \text{K}/\text{W})\);
- \( T_u \) = upper plate surface temperature \((^\circ\text{C})\);
- \( T_m \) = lower plate surface temperature \((^\circ\text{C})\);
- \( Q \) = heat flux through the test sample \((\text{W/m}^2)\);
- \( R_{int} \) = total interface resistance between sample and surface plates \((\text{m}^2 \text{K}/\text{W})\).

The thermal resistance of the test sample is defined by equation (2):

\[ R_s = \frac{d}{\lambda} \]

where:
- \( d \) = samples thickness \((\text{m})\);
- \( \lambda \) = thermal conductivity \((\text{W/(m K)})\).

The interface thermal resistance \( R_{int} \) must be included in equation (1) because the HFT does not measure the actual temperature drop in the sample itself, but rather the temperature difference between the upper and lower surface plates in contact with the sample. The heat flux through the sample is measured with a transducer located just below the sample (HFT). The heat flux is determined by measuring the temperature difference across the reference calorimeter (see Eq. (3)):

\[ Q = N(T_m - T_L) \]

where:
- \( N \) = reference calorimeter heat transfer coefficient \((\text{W/(m}^2 \text{K)})\);
- \( T_m \) = lower plate surface temperature \((^\circ\text{C})\);
- \( T_L \) = bottom heater temperature \((^\circ\text{C})\);  

Combining equations (2) and (3) yields the following expression for the sample thermal resistance (Eqs. (4) and (5)):

\[ R_s = F[(T_u - T_m)/(T_m - T_L)] - R_{int} \]

or

\[ R_s = F(\Delta T_m/\Delta T_r) - R_{int} = FR_{RA} - R_{int} \]

where:
- \( F \) = proportionality constant \((\text{m}^2 \text{K}/\text{W})\);
- \( \Delta T_r \) = temperature difference across the sample \((^\circ\text{C})\);
- \( \Delta T_m \) = temperature difference across the reference calorimeter \((^\circ\text{C})\);
- \( T_{RA} = \Delta T_r/\Delta T_r \) \((^\circ\text{C}/^\circ\text{C})\).

Under ideal conditions, when there is no heat loss or gain along the outer surface of the test stack, the factor \( F \) is the inverse of the reference calorimeter heat transfer coefficient, \( N \). Such conditions are closely approximated in the Model 2022 because the guard heater surrounding the test stack is actively controlled. Its temperature, comparable to the sample mean temperature, is controlled by means of thermocouples in order to avoid circumferential heat flow distortions and to guarantee a mono-dimensional flux.

To determine \( F \) and \( R_{int} \) in equation (5), the Model 2022 must be calibrated first. Equation (5) shows that there is a linear relationship between \( R_s \) and \( T_{RA} \) which can be estimated by means of a linear regression obtained with OLS Method. After the temperature ratios \( T_{RA} \) are measured for several samples of known thermal resistance and the results are plotted on a graph, a straight line fitting the data points can be found (Fig. 3). The slope of the line is \( F \) and the \( y \)-axis intersection is \( R_{int} \).

These points represent the various calibration samples with certified thermal properties (by a producer by means of Technical Certificates) and thickness (see Eq. (2)): Vesvel 6.35 mm, Vesvel 3.125 mm Vesvel 9.525 mm, Pirex 12.7 mm, Pirex 6.35 mm, Stainless Steel 19.05 mm. This set is suitably chosen in order to sweep completely the thermal resistance range of the instrument, from 0.002 m²K/W to 0.02 m²K/W.

Finally, although \( R_{int} \) is accounted for in the analysis, it is important for obtaining high test accuracy that it is made as small as possible. This is achieved by using highly polished metal surfaces in contact with the sample, by clamping the sample with a reproducible force, and by applying heat transfer compound to the contacting surfaces.

The thermal conductivity determination of an unknown specimen shall only be conducted at a temperature within a range and under applied load conditions for which valid calibration data exist. Under the same conditions and after thermal equilibrium is attained, it is possible to measure \( T_{RA} \) by calculating the mean temperature values on the sample and the reference material in a fixed temporal range (Ref. [1]). Moreover, it will be possible to estimate thermal resistance on the basis of the calibration linear fit (Fig. 4). Finally, thermal conductivity is estimated from thermal resistance value by measuring the sample thickness.

### 3 Evaluation of the uncertainty budget associated to the heat flow meter

A procedure to evaluate the uncertainties associated to the measures obtained from HFT is described (Refs. [3, 6–10]).

In accordance with the metrological features described in previous paragraphs, the uncertainty budget is performed on the basis of the following steps. These are

\[ R_s = \frac{(T_u - T_m)}{Q} - R_{int} \]

\[ R_s = \frac{d}{\lambda} \]

\[ Q = N(T_m - T_L) \]

\[ R_s = F[(T_u - T_m)/(T_m - T_L)] - R_{int} \]

or

\[ R_s = F(\Delta T_m/\Delta T_r) - R_{int} = FR_{RA} - R_{int} \]

where:
- \( F \) = proportionality constant \((\text{m}^2 \text{K}/\text{W})\); 
- \( \Delta T_r \) = temperature difference across the sample \((^\circ\text{C})\); 
- \( \Delta T_m \) = temperature difference across the reference calorimeter \((^\circ\text{C})\); 
- \( T_{RA} = \Delta T_r/\Delta T_r \) \((^\circ\text{C}/^\circ\text{C})\).
demonstratively applied to a set of calibration data obtained for a characterization of the HFT performed during July 2008 (at a mean temperature of the reference sample of about 10 °C):

(1) evaluation of the uncertainties associated to the six couples of values \((T_{RA}, R_s)\) related to the preliminary calibration of the HFT by means of the six reference materials;

(2) accordingly to the physical model at the basis of the HFT operation, adoption of a straight line as the model for fitting the calibration points: hence, estimation of both parameters \(F\) and \(R_{int}\) and evaluation of the associated uncertainties;

(3) uncertainty propagation to the thermal resistances of materials under test estimated by applying the calibration curve to the relevant \(T_{RA}\) measures;
3.1 Calibration: uncertainties associated to reference data

Six samples of reference materials are used to build a calibration straight line associated to the HFT, accordingly to equation (5). For each sample, the value of TRA is well-known and the expanded uncertainty associated to both thermal conductivity of the tested materials and the associated standard and expanded uncertainty.

The symbols in Table 1 have the following meanings:
- RA: symbol, value and note related to the adopted mathematical model
- Rs: symbol value notes
- TRA: confidence level P
- Rs: confidence level and the actual DOF
- ν: coverage factor

The expanded uncertainty U(TRA) of the calibration straight line associated to the HFT is calculated as

\[ U(TRA) = c \cdot \sigma \sqrt{\nu} \]

where
- \( c \) is the coverage factor
- \( \sigma \) is the standard uncertainty related to type A contributions
- \( \nu \) is the degrees of freedom

For what concerns the thickness state is attained. For what concerns the thickness, at the moment it is not possible to acquire a statistical sample of repeated measurements; a variability range of 0.2 \( \pm 0.05 \) is considered.

For what concerns temperatures, at the moment it is not possible to acquire a statistical sample of repeated measurements; a variability range of 0.2 \( \pm 0.05 \) is considered.

The expanded uncertainty U(Rs) of the calibration straight line associated to the HFT is calculated as

\[ U(Rs) = c \cdot \sigma \sqrt{\nu} \]

where
- \( c \) is the coverage factor
- \( \sigma \) is the standard uncertainty related to type B contributions
- \( \nu \) is the degrees of freedom

The expanded uncertainty U(Rs) of the calibration straight line associated to the HFT is calculated as

\[ U(Rs) = c \cdot \sigma \sqrt{\nu} \]

where
- \( c \) is the coverage factor
- \( \sigma \) is the standard uncertainty related to type B contributions
- \( \nu \) is the degrees of freedom

The expanded uncertainty U(Rs) of the calibration straight line associated to the HFT is calculated as

\[ U(Rs) = c \cdot \sigma \sqrt{\nu} \]

where
- \( c \) is the coverage factor
- \( \sigma \) is the standard uncertainty related to type B contributions
- \( \nu \) is the degrees of freedom

The expanded uncertainty U(Rs) of the calibration straight line associated to the HFT is calculated as

\[ U(Rs) = c \cdot \sigma \sqrt{\nu} \]

where
- \( c \) is the coverage factor
- \( \sigma \) is the standard uncertainty related to type B contributions
- \( \nu \) is the degrees of freedom

The expanded uncertainty U(Rs) of the calibration straight line associated to the HFT is calculated as

\[ U(Rs) = c \cdot \sigma \sqrt{\nu} \]

where
- \( c \) is the coverage factor
- \( \sigma \) is the standard uncertainty related to type B contributions
- \( \nu \) is the degrees of freedom
3.2 Statistical method used to estimate the calibration curve of the heat flow meter

The six couples of values \((T_{RA}, R_s)\), obtained during the calibration phase by means of the reference materials, have been plotted on a corresponding \(x-y\) graph. In order to determine a straight line fitting the data points, the slope \(F\) of the line and the \(y\)-axis intercept \(R_{int}\) have to be estimated (see Sect. 2). It is here necessary to make the following considerations:

- as described in the previous paragraph, the calibration points in the \(x-y\) graph are characterized by uncertainties on both the abscessa and ordinate, that are comparable in relative terms. The statistical method that should be formally used to fit this data set is known as the Total Least Square (TLS) method. Generally, HFT metrology commonly uses OLS method, so the adoption of TLS method in treating this type of calibration curve is something relatively “new”. Therefore, some further analysis and considerations will be taken into consideration before validating its adoption;

- in the following, OLS will be implemented to fit the calibration data accordingly to the linear model (Fourier’s Law). It should be considered that this method needs to be applied under the hypothesis that all the experimental points have no uncertainties on abscessa and equal uncertainties on ordinate; it is obvious that both these hypothesis are not appropriate to describe the experimental situation under test here. In spite of this fact, OLS method is applied in order to guarantee the continuity with the previous way of data elaboration. The novelty in this approach, in comparison with the usual approach implemented up to now, can be summarized in these two points:

  1. the goodness of the method was tested and proved at the desired confidence level, taking into consideration in a proper way the expanded uncertainties of the experimental points determined in Sect. 3.1, Table 2;

  2. the covariance of the estimated parameters (slope \(F\) and intercept \(R_{int}\), respectively) was calculated and considered in the subsequent uncertainty propagation on the values of thermal resistance of unknown materials.

The calculations were performed by applying the formulas reported in reference [3] and checked by comparison versus the statistical tool provided by Excel. The term \(s(F, R_{int})\) indicates the covariance between the statistical estimates. The goodness of the OLS method in fitting the experimental data was verified by building around the regression line the uncertainty bands at the confidence level of 95\%, and checking if they overlap the expanded uncertainties of the experimental values. The confidence bands were estimated by combining in a proper way the uncertainties of both slope and intercept, and taking into account the actual DOF (by which the appropriate coverage factor was calculated). The results can be seen in the graph reported in Figure 5. It can be concluded that there is a reasonable accordance between the OLS fit and the expanded uncertainties of the calibration data: that justifies the use of OLS method as the fitting standard method in this type of applications.

3.3 Measurement of thermal resistance of unknown materials

Now, using the calibration curve of the HFT, it will be possible to estimate the thermal resistance of unknown materials. The procedure can be divided in the following two steps (see Sect. 2):

  1. measurement of \(T_{RA}\), and evaluation of its associated combined uncertainty \(u(T_{RA})\) and DOF, for the material under test;

  2. use of the parameter \(F\) and \(R_{int}\) to estimate the thermal resistance \(R_s\) of the material under test; the associated combined uncertainty \(u(R_s)\) is calculated propagating the contributions due to all the involved variables \((T_{RA}, F, R_{int})\) with their standard uncertainties and covariances).

As an example, this procedure was applied to experimental measures of \(T_{RA}\) obtained during the thermal characterization of four different materials (Tab. 3). The obtained results, related to one of considered materials, are

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Table 2. Synthesis of the calibration data obtained in correspondence to the reference materials.

<table>
<thead>
<tr>
<th>sample</th>
<th>(d) [m]</th>
<th>(T_{RA}) [°C/°C]</th>
<th>(u(T_{RA})) [%]</th>
<th>(u(R_s)) [%]</th>
<th>(R_s) [m²K/W]</th>
<th>(u(R_s)) [%]</th>
<th>(U(R_s)) [m²K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS QREF-941</td>
<td>0.01905</td>
<td>0.255</td>
<td>0.004</td>
<td>1.7</td>
<td>0.01</td>
<td>0.0013</td>
<td>1.5E-06</td>
</tr>
<tr>
<td>PIREX QREF-952</td>
<td>0.00635</td>
<td>0.946</td>
<td>0.009</td>
<td>1.0</td>
<td>0.02</td>
<td>0.0059</td>
<td>3.4E-05</td>
</tr>
<tr>
<td>VESPEL QREF-963</td>
<td>0.00318</td>
<td>1.239</td>
<td>0.012</td>
<td>1.0</td>
<td>0.02</td>
<td>0.0084</td>
<td>1.3E-04</td>
</tr>
<tr>
<td>PIREX QREF-951</td>
<td>0.01270</td>
<td>1.901</td>
<td>0.021</td>
<td>1.1</td>
<td>0.04</td>
<td>0.0118</td>
<td>6.1E-05</td>
</tr>
<tr>
<td>VESPEL QREF-962</td>
<td>0.00635</td>
<td>2.445</td>
<td>0.029</td>
<td>1.2</td>
<td>0.06</td>
<td>0.0169</td>
<td>2.4E-04</td>
</tr>
<tr>
<td>VESPEL QREF-969</td>
<td>0.00953</td>
<td>3.640</td>
<td>0.056</td>
<td>1.5</td>
<td>0.11</td>
<td>0.0253</td>
<td>3.6E-04</td>
</tr>
</tbody>
</table>

OLS method used to fit a set of calibration data
(data set measured at the mean calibration temperature of 10 °C - July 2008)

![Graph](image)

**Fig. 5.** (Color online) Fit of the calibration data by OLS method and construction of the confidence bands.

**Table 3.** Synthesis of thermal resistances, and associated uncertainties, determined for different materials by using the regression parameters estimated by OLS.

<table>
<thead>
<tr>
<th>label CertiMaC</th>
<th>T_{RA}</th>
<th>u(T_{RA})</th>
<th>R_s</th>
<th>u(R_s)</th>
<th>U(T_{RA})</th>
<th>U(R_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 - B exp. point. 1</td>
<td>0.76</td>
<td>0.01</td>
<td>4.6E-03</td>
<td>3.1E-04</td>
<td>1.5E-02</td>
<td>8.5E-04</td>
</tr>
<tr>
<td>CLT0376 exp. point. 2</td>
<td>1.81</td>
<td>0.02</td>
<td>1.21E-02</td>
<td>2.6E-04</td>
<td>3.8E-02</td>
<td>6.2E-04</td>
</tr>
<tr>
<td>CMT0379 exp. point. 3</td>
<td>3.09</td>
<td>0.04</td>
<td>2.12E-02</td>
<td>4.6E-04</td>
<td>8.3E-02</td>
<td>1.0E-03</td>
</tr>
<tr>
<td>CMT0396 exp. point. 4</td>
<td>4.14</td>
<td>0.07</td>
<td>2.87E-02</td>
<td>7.2E-04</td>
<td>1.3E-01</td>
<td>1.6E-03</td>
</tr>
</tbody>
</table>

reported in Tables 4 and 5, respectively. The tables are based on the same uncertainty analysis described in Section 3.1. A synthesis of the obtained results is reported in Figure 6.

### 3.4 Measurement of thermal conductivity of unknown materials

The final step consists in the determination of the thermal conductivity of the tested materials, by applying equation (2) and the usual rules for the uncertainty propagation. As an example, the values of λ were calculated for the experimental data considered in Section 3.3. The example takes into consideration a measurement at 10 °C in dry state, that represents a reference condition for analysis on building materials (Fig. 2 - temperature setting) as requested from European standards [4, 5]. Moreover, the operative temperature span is related to the sample mean temperature in the instrument range from 0 °C to 300 °C. In this specific case, for analysis at 10 °C on building materials, T_u and T_m are controlled at about 20 °C and 0 °C respectively, in accordance with the instrument specification (Fig. 2).

### 3.5 Uncertainty analysis implemented on a customized LabVIEW executable

The whole uncertainty analysis was implemented in a proper executable by means of LabVIEW software. Some
OLS method used to estimate experimental values of thermal resistance

\[ T_{Ra} = \frac{\Delta T_s}{\Delta T_r} \text{ [°C/°C]} \]

Fig. 6. (Color online) Thermal resistances determined by applying OLS method.

Table 4. Measures of \( T_{RA} \) and \( R_s \), and associated combined uncertainties \( u(T_{RA}) \), \( u(R_s) \) and DOF, for materials under test.

<table>
<thead>
<tr>
<th>( T_{Ra} )</th>
<th>symbol value notes</th>
<th>( u^2(x_j) )</th>
<th>( \nu )</th>
<th>( u(R_s) )</th>
<th>( u(T_{Ra}) )</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{Ra} )</td>
<td>19.85</td>
<td>1.0E-01</td>
<td>50</td>
<td>3.3E-03</td>
<td>6.2E-02</td>
<td>1.2E-05</td>
</tr>
<tr>
<td>( T_{Ra} )</td>
<td>7.56</td>
<td>1.0E-01</td>
<td>50</td>
<td>3.3E-03</td>
<td>-1.1E-01</td>
<td>3.9E-09</td>
</tr>
<tr>
<td>( T_{Ra} )</td>
<td>-8.64</td>
<td>1.0E-01</td>
<td>50</td>
<td>3.3E-03</td>
<td>4.7E-02</td>
<td>7.2E-06</td>
</tr>
</tbody>
</table>

\[ u^2(T_{Ra}) = 5.99E-05 \]

\( u(T_{Ra}) \) and actual DOF

confidence level \( P \)

covering factor \( k = (P, \text{DOF}) \)

expanded uncertainty \( U(T_{Ra}) \)

\[ RS = -7.13E-04 \]

Heat Flow Meter during working - evaluation of \( R_s \), \( u(R_s) \) and DOF

<table>
<thead>
<tr>
<th>( R_s )</th>
<th>symbol value notes</th>
<th>( u^2(x_j) )</th>
<th>( \nu )</th>
<th>( u(R_s) )</th>
<th>( u(R_s) )</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_s )</td>
<td>7.09E-03</td>
<td>2.0E-04</td>
<td>4.2E-04</td>
<td>0.0E+00</td>
<td>2.0E+02</td>
<td>1.0E+00</td>
</tr>
<tr>
<td>( R_s )</td>
<td>-7.13E-04</td>
<td>4.2E-04</td>
<td>1.8E-07</td>
<td>0.0E+00</td>
<td>1.76E-07</td>
<td>1.0E-00</td>
</tr>
<tr>
<td>( R_s )</td>
<td>-7.13E-04</td>
<td>4.2E-04</td>
<td>1.8E-07</td>
<td>0.0E+00</td>
<td>1.76E-07</td>
<td>1.0E-00</td>
</tr>
</tbody>
</table>

\( u(R_s) \) and actual DOF

confidence level \( P \)

covering factor \( k = (P, \text{DOF}) \)

expanded uncertainty \( U(R_s) \)

\[ pt1 \]

Heat Flow Meter during working - evaluation of \( T_{Ra} \), \( u(T_{Ra}) \) and DOF

<table>
<thead>
<tr>
<th>( T_{Ra} )</th>
<th>symbol value notes</th>
<th>( u^2(x_j) )</th>
<th>( \nu )</th>
<th>( u(T_{Ra}) )</th>
<th>( u(T_{Ra}) )</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{Ra} )</td>
<td>0.00E+00</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>7.1E-03</td>
<td>0.00E+00</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>( T_{Ra} )</td>
<td>0.00E+00</td>
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<td>7.1E-03</td>
<td>0.00E+00</td>
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<tr>
<td>( T_{Ra} )</td>
<td>0.00E+00</td>
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<td>7.1E-03</td>
<td>0.00E+00</td>
<td>0.0E+00</td>
</tr>
</tbody>
</table>

\( u(T_{Ra}) \) and actual DOF

confidence level \( P \)

covering factor \( k = (P, \text{DOF}) \)

expanded uncertainty \( U(T_{Ra}) \)
Fig. 7. (Color online) Software Snapshot – Sheet 1: calibration part.

Fig. 8. (Color online) Software Snapshot – Sheet 2: measured values.

snapshots of the software execution are reported in Figures 7–9.

4 Discussion

A complete metrological characterisation of thermal conductivity measurements requests a deep analysis of the various uncertainty experimental contributes in order to give an even more accurate technical support to all building materials manufacturers involved in energy efficiency and thermal insulation field. For these reasons a statistical method has been implemented to obtain a proper characterisation of building materials in terms of their thermal conductivity uncertainty. Moreover, this uncertainty analysis has confirmed that OLS method can be considered as reasonably appropriate to fit the calibration data for HFT measurements of thermal conductivity. Finally, this analysis has allowed to accurately evaluate the uncertainties associated to the main physical quantities involved in this experimental process.
Fig. 9. (Color online) Software Snapshot – Sheet 2: estimated conductivity.

Table 5. Final results of $\lambda$ with their associated combined uncertainties and DOF.

<table>
<thead>
<tr>
<th>pt</th>
<th>P1 - B</th>
<th>xj</th>
<th>$\lambda$</th>
<th>$u_c(\lambda)$</th>
<th>$u_\alpha(\lambda)$</th>
<th>$k$</th>
<th>$U(\lambda)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.376</td>
<td>0.6454 ± 0.0140</td>
<td>2.2</td>
<td>0.95</td>
<td>2.447</td>
<td>0.07</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Heat Flow Meter during working - evaluation of $\lambda$, $u(\lambda)$ and DOF.
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References

5. EN 12667:2002, Thermal performance of building materials and products, Determination of thermal resistance by means of guarded hot plate and heat flow meter methods, Products of high and medium thermal resistance
7. Statistica e probabilità per ingegneri, edited by G. Vicario, R. Levi (Società Editrice Esculapio s.r.l. Bologna, Italy, 2001)