Selected Problems of Heat Transfer Measuring by Hotbox Apparatus in Climate Chambers

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Abstract. Hotbox measurements are used for obtaining U-values of homogenous or non-homogenous samples in climate chambers for some time. With constant increase of the thermal resistance and lowering the thermal loss arise the problem of these measurements. This is caused by the limited minimal wattage of the hotbox. This paper deals with the measurement in climate chamber, which purpose was to made calibration of the chamber and various measurements equipment. The calibration was made with usage of sample with high thermal resistance, extruded polystyrene. Described problems are chamber and hotbox limitation, sensors accuracy and high thermal resistance of the sample.

1. Introduction
Measurement of heat flow using a calibrated and guarded hot box is a widely used method. It is regulated by standards in several developed countries around the world [1,2]. These standards were invented on the experience of measuring construction samples with small thermal resistance. With constant increase of this thermal resistance, problems with this kind of measurements arise. For this purpose were developed large size climatic chambers with innovative design. Researchers around the world are focused on developing new kinds of hotboxes, which are also capable to produce cold [3,4,5,6,7]. As it is described in this paper, it is necessary to measure small heat flow rates through tested sample.

2. Calibration panels and instrumentation
Two wall panels were used for calibration test with dimensions: width 2.4 m, high 2.6 m, thickness 0.12 m and 0.18 m. Each panel was made from 8 blocks of extruded polystyrene (XPS), with declared heat transfer coefficient 0.035 W / (m.K). Another thermodynamic properties are listed in Tab. 1. With higher temperature difference between chambers (Fig. 1), panel with thickness of 180 mm polystyrene requires about 100 hours to stabilize the temperature inside. The blocks are joined together using a special polyurethane foam for bonding polystyrene (see Fig. 2). For more airtightness of the panel, the joints were finally sealed by silicone. The airtightness and water-tightness of the calibration panel is usually provided by a board (made from plywood, glass or plexi-glass), that is applied from both sides of the thermal insulation. Extruded polystyrene is a non-absorbent material, so this layer was omitted from the calibration panel.
| Conductivity (W/m.K) | Water vapor diffusion resistance factor (-) | Long term water vapour absorption (%) |
|----------------------|------------------------------------------|--------------------------------------|
| 0.035                | 50                                       | 3                                    |

**Figure 1.** Course of temperatures in 180 mm calibration panel for difference 60 K

### 2.1. Thermal bridges

Some small thermal bridges on the calibration panel may arise where individual blocks of XPS are joined. By calculating the linear thermal bridging factor, it can be estimated, that this thermal bridge will increase the total heat loss by 1.5 %.

**Figure 2.** Calibration panel made from 8 XPS blocks with 120 mm thickness
2.2. Sensors
For the measurement of the calibration panel were used 6+6 digital temperature and relative humidity sensors, 4 PT100 film resistor sensors for surface temperature measurement, 4 PT100 wire-wound sensor approx. 0.5 mm thick with temperature-resistant foil and 4 heat flux plates as presented in Fig. 3. The accuracy of air temperature sensors is ±0.7 K in range from -40 to 80°C. Heat flux sensors have 5% accuracy.

Figure 3. Temperature and heat flux sensors a) outdoor chamber, b) indoor chamber

2.3. Climate chambers
Climate chambers have a 2.0 m wide and 2.0 m high interior space. The chamber envelope is made of sheet metal filled with polyurethane foam up to 200 mm thick. The inner surface of the chambers is made of stainless steel. It is only because it has a low emission and the radiant heat flow is then smaller. Inside surface temperatures can vary around doors and otherwise they are similar everywhere. Direct sunlight can pass into the hall and heat the outer surface of the climatic chamber. Therefore, the outer surface of envelope is white. Outdoor chamber allows simulate temperature up to -40.0 °C and still have good temperature homogeneity inside. The convection heat transfer on the sample can be varied by simulating the flow around the sample with variable velocity from 0.5 m/s to 3.0 m/s.

2.4. Hotbox
The hotbox is placed in the indoor chamber. It has a 1.3 m wide and 1.5 m high interior space. It is considerable smaller than the calibration panel. This ensures that the heat flow through the calibration panel to the hotbox is not affected by the edges of the calibration panel (see Fig.4). The inner surface is painted black. The convection heat transfer on the sample can be varied by simulating the flow around the sample with variable velocity level. There is a black plate separator wall in the hotbox. Hotbox is equipped also with temperature sensors, one in upper and other in lower position to obtain thermal gradient. The air velocity is measured in the centre. The separating wall can be moved deeper into the hotbox, up to 300 mm from the edge. Influence of the joint between the hotbox and the sample is insulated by the foam tape. Thermal insulation is narrow there and existence of thermal bridge is possible (Fig. 4). Small thermal bridges can also be over cable crossings. This made difference only, when the temperature of the hotbox and the indoor chamber is different.
3. Methods

A method of performing a calibration measurement for a climate chamber with a hotbox is described in standard STN EN ISO 8990. Test conditions in climate chambers were chosen to measure two temperature differences: 55.0 K and 70.0 K. The hotbox works in temperature range from 20 to 40 °C. The limitation on outdoor side is also in working range of temperature sensors, that is -40 °C. Although it would be appropriate to use the most common temperatures in building environment (10°C-20°C), a large temperature difference is required for accuracy in measuring structures with high thermal resistance. There is some lowest possible heating power in the hotbox also, for which we need a large temperature difference (28W for 1stage, 32W for 2stage, 36W for 3stage, 41 W for 4stage and so on). The average temperature in calibrated panel during the tests is then slightly lower than typical (around 0.0 °C). The conductivity of XPS should be lower than declared conductivity from data sheet, but because of the very high level of relative air humidity in outdoor chamber the conductivity may be again higher [7]. By using the terminology offered by the standard STN EN 1946-4 following formula of heat balance in climatic chambers with a hotbox can be written:

$$\phi_{hb} = \phi_1 + \phi_2 + \phi_3 + \phi_4 + \phi_5$$  \hspace{1cm} (1)

where is:

- $\phi_{hb}$ power supply to the hotbox measured with wattmeter
- $\phi_1$ heat flow rate through the metering area of the calibration panel
- $\phi_2$ heat flow rate between hotbox area and indoor chamber through the calibration panel
- $\phi_3$ heat flow rate through the hotbox walls
- $\phi_4$ flanking heat flow rate through the calibration panel
- $\phi_5$ heat flow rate through the edge of calibration panel

The heat flow rate through the metering area of the calibration panel $\phi_1$ is obtained by simple calculation of the thermal resistance and the heat transfer coefficients. The heat flow rate between hotbox area and indoor chamber through the calibration panel $\phi_2$ was obtained by differential method calculation (see Fig. 4) and it is 0.5 W/K together. When we use quarded hotbox, the flanking heat flow rate through the calibration panel $\phi_4$ is inoperative.

3.1. Heat flow rate through the hotbox walls

This heat flow depends on the temperature difference between the air in the hotbox and the indoor chamber. If this difference is negligibly small, the heat flow rate is approximately equal to zero. However, if there is a temperature difference, it is necessary to determine the heat flow through the hotbox wall area and the additional heat loss through the thermal bridges in the hotbox wall area. There
is a heat flow 1.5 W/K for the 6.43 m² hotbox wall area. Some additional heat loss is from a linear thermal bridge on the perimeter of the hotbox and from point thermal bridges because of the screws and cable passes. The additional heat flow from the linear bridge was obtained by two dimensional differential method calculation and is 0.5 W/K. Some point heat bridges were difficult to calculate, they had to be estimated (approximately 1.9 W/K). There is an infrared thermograph image of point thermal bridges on the hotbox wall on Fig. 5. The total heat flow rate thought the hotbox walls was 3.9 W/K.

Figure 5. Infrared camera image of hotbox wall with captured thermal bridges

3.2. The homogeneity of the thermal environment measurement

The results of thermal homogeneity of measured air temperature in outdoor chamber 100 mm near the calibration panel are given by graph in Fig. 6. The measured air temperature decreases with increasing height above the floor as it is closer to the air intake. The mean deviation from the average is 0.3 K and the highest difference is 0.7 K. The average air temperature is 1.5 K below the outdoor chamber nominal set temperature -35.0 °C.

Figure 6. Course of air temperatures near panel in outdoor chamber
Homogeneity of the wall sample surface temperatures in outdoor chamber are shown in Fig. 7. The temperatures decreases with increasing height above the floor level also. The mean deviation from the average is 0.1 K and the highest difference is 0.2 K. The average surface temperature is 1.2 K below the average air temperature -36.5 °C. The air flow velocity near the panel was continuously 3.0 m/s.

**Figure 7.** Course of surface temperatures on calibration panel in outdoor chamber

The results of thermal homogeneity of measured air temperature in hotbox environment 250 mm near the calibration panel are given in Fig. 8. The measured air temperature increases with the height above the floor level. The mean deviation from the average is 0.3 K and the highest difference is 1.0 K. The average air temperature is 0.5 K over the indoor chamber nominal set temperature 35.0 °C. In addition, the mean air temperature measured in the indoor chamber was 0.4 K lower than the nominal 35 °C. There is 0.9 K difference between the hotbox and the indoor mean air temperature together. That caused heat flow through the hotbox walls, which was during this test approximately 3.5 W ($\phi_3$). The thermal homogeneity of air temperature in hotbox is improved when a higher degree of air flow rate in the hotbox is set.

**Figure 8.** Course of air temperatures on six positions in hotbox
Surface temperature courses on the wall sample in hotbox courses are shown in Fig. 9. The temperatures increase with increasing height above the floor level also. The mean deviation from the average is 0.2 K and the highest difference is 0.8 K. The average surface temperature is 2.0 K below the average air temperature 35.5 °C.

![Figure 9. Surface temperature courses on calibration panel in hotbox](image)

4. Results and discussions

Based on the findings described above, the equation 1 can be modified as follows:

\[
\phi_{hb} = \phi_1 + 4.0 \text{ W} \quad (2)
\]

This means that there will always be a difference between the power value measured in the hotbox and the heat loss through the sample around 4.0W.

This result was also supported by a Table 2 created from the results of repeated sample measurements with different heat resistance and at different temperature differences between the chambers. The internal and external surface resistance values were calculated from the surface temperatures and from the known air flow rate.

| Temperature difference - real | Thermal resistance | U.A.Δθ (from Eqv. 2) | Hotbox power | Diff. |
|-----------------------------|-------------------|----------------------|--------------|------|
| K                           | m2.K/W            | W                   | W            | W %  |
| 56,9                        | 3,428             | 30,8                 | 34,8         | 35,2 | 1,3 |
| 72,0                        | 3,428             | 38,9                 | 42,9         | 43,0 | 0,2 |
| 72,0                        | 5,143             | 26,4                 | 30,4         | 30,6 | 0,7 |
| 83,0                        | 5,143             | 30,4                 | 34,4         | 34,6 | 0,6 |

Note: Rsi = 0,12 m2.K/W  Rse = 0,06 m2.K/W  Average: 0,7 %

The real temperature difference between the outdoor chamber and the indoor chamber environment was several degrees greater than that selected with the chambers control software. That was because the
temperature near the sample was different from the chamber’s sensor. The highest possible temperature difference was 83 K. With such a high temperature difference, we can perform a calibration on a sample having a thermal resistance of about 5.0 \( m^2 K/W \). This means that this device can accurately measure the conductivity of a building structure that has this or slightly higher thermal resistance. Some structures with a thermal resistance about 10.0 \( m^2 K/W \) cannot be measured with this hotbox apparatus.

In order to measure structures with very high thermal resistance, it will be necessary to adjust the apparatus of the hotbox in different ways, such as described in [3]. However, the question is whether the hotbox is large enough. There has to be space to enlarge it, in this case there is some reserve for this possibility.

It has been shown in a simplified way that the accuracy of the thermal conductivity measurement in this hotbox is about 0.7%. Furthermore, it will be necessary to evaluate the measurement statistically. It will also be necessary to evaluate the effect of chambers ambient temperature on the repeatability of the results.

5. Conclusions

Although the thermal conductivity measurement using a hotbox is governed by the standard, it is not easy to make it. There may be some specific problems. Biggest problem in this case was temperature difference between hotbox and indoor chamber. This difference should be as low as possible. Also the edge of the sample must be dealt with in a detail if a large thermal resistance has to be measured. Finally, it is high heat capacity of the sample, which prolongs the settling time and a total testing time.

To calibrate the hotbox in climatic chambers, it is necessary to use many high quality air and surface temperature sensors because there may be significant temperature differences on the sample (even more than 1.0K).

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