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# Energy performance of five different building envelope structures using a modified Guarded Hot Box apparatus—Comparative analysis☆

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ABSTRACT

The most of thermal characteristics of buildings are currently calculated by simplified mathematical models of building envelope behaviour. The main parameter needed for these calculations is the thermal transmittance. The aim of this study is to evaluate thermal performance of several building envelopes suitable for thermal insulating purposes and to compare parameters of thermal performance given by national standards or the thermal performance declared by producers. The experimental measurements were conducted with dynamic conditions in the cold chamber of the Hot Box. Dynamic testing was running under weekly temperature cycle using programmable temperature controller in the cold chamber. Hot site temperature was kept steady according to controlled ambient temperature. Behaviour of each system was investigated under similar conditions with room temperature 22–23 °C in the hot chamber and with temperature fluctuation between +6 °C and −13 °C in the cold chamber. This study provides interesting results. Especially heat flow in case of laminated log wall (massive wood) of thickness 200 mm was measured as significantly lower than it would be calculated by currently known thermal conductivity of soft wood. The presented method of thermal transmittance measurements in dynamic conditions might bring increasing accuracy for building envelope energy loss calculations. The difference between result from one-week long test compared with 20 days long test of the same sample was found as 2,3%. Correlation coefficient between experimental values and calculated total energy loss in time was always found higher than 0,997 and accuracy seems to be increasing with length of the measurement.



## 1. Introduction

Increasing interest in energy efficiency during the past decade has delivered higher standards for thermal insulation of building envelopes. Buildings are responsible for 40% of the energy consumption in the European Union [1]. By 2020, EU countries should be able to ensure that new buildings meet zero-energy requirements [2]. Likewise, similar standards should be also enforced for the existing building stock. As a consequence, an increasing demand in thermal insulation is expected during the coming years, along with the need for improved production technologies [3]. This includes demands in insulation materials based on mineral wool, polystyrene foam sheathing insulation, or foamed polyurethanes products. Polystyrene is produced from ethylene, a natural gas component, and benzene, which is derived from petroleum. Polyurethanes are made from polymeric methylene diisocyanate (PMDI) and polyol, both derived from petroleum. However, these insulation materials constitute an environmental burden, which needs to be addressed with eco-friendly alternatives. Bio-based alternatives are currently available at restricted but accessible volumes, and they include straw, hemp, flax, wood fibres, reed grasses, and others [4]. Most of these materials have been used for centuries, but they were gradually replaced by artificial materials, due to many advantages over natural materials such as higher durability, better fire retardancy and water resistance.

Today, artificial insulations are preferred also due to existing market regulations, which are aiming at a strictly controlled production of building materials that are supervised by certification authorities. Decision-making processes for insulation materials are mainly driven by the demands expressed by architects, builders and of course safety requirements. In this respect, the European commission stated that construction product manufacturers shall

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**Nomenclature**

| | |
|---|---|
| A | area $m^2$ |
| c | specific heat capacity $Jkg^{-1}K^{-1}$ |
| d | thickness m |
| E | total energy leaked through the sample Wh |
| H | heat loss Wh |
| m | weight kg |
| RH | relative humidity% |
| R | thermal resistance $m^2KW^{-1}$ |
| T | temperature K,°C |
| t | time h |
| U | thermal transmittance $Wm^{-2}K^{-1}$ |
| $\Delta$ | difference - |
| $\lambda$ | thermal conductivity $Wm^{-1}K^{-1}$ |
| $\rho$ | density $kgm^{-3}$ |
| $\varphi$ | heat flow rate W |
| $\psi$ | linear thermal transmittance $Wm^{-1}K^{-1}$ |
| r | correlation coefficient - |

*Subscripts*

| | |
|---|---|
| a | air |
| e | external |
| i | internal |
| I | infiltration |
| s | surface |
| t | total |
| T | transmission |
| V | ventilation |

draw up a performance declaration for marketable construction products, which should comply with European Technical Assessment procedures. Such a declaration should be supplied with the product either in paper or electronically [5].

Thermal characteristics of buildings are currently mostly calculated by simplified mathematical models with respect to the building envelope behaviour. These models are widely based on the knowledge of thermal conductivity of individual materials. The main parameter needed for these calculations is the thermal conductivity $\lambda$ ($Wm^{-1}K^{-1}$). Many authors have elaborated the reliability of currently suggested calculation procedures, with published studies also offering software or algorithms to estimate heat losses, based on multi-parametric mathematical models. There can be doubt on the reliability of currently employed procedures and technical standards that are based on simplified models, estimating the thermal performance of building systems under changing climatic conditions. This is particularly evident when comparing different calculations for energy losses that are based on various mathematical models [6–14]. As for thermal conductivity, this parameter is determined by the energy flow under steady state boundary conditions. For low thermally conductive materials, the calculation for thermal conductivity and the subsequent heat loss is using a linear model. Materials with high thermal capacity show varying results with respect to changing exterior temperatures. In the case of temperature shifts there is always significant response time, and differences between steady-state based model and real heat flow. Studies [7–9,15] have focused on the dynamic modelling of thermal performance of building, considering the building mass. Authors are also introducing a dynamic model, by comparing it with semi-steady state or steady-state models and highlighting the differences. The calibration of dynamic models is difficult, especially when multi-layered constructions are considered.

Thermal conductivity itself is not the only parameter that influences thermal loss of building envelopes. The second most important attribute here is the thermal inertia of perimeter walls, and the remaining building mass. There are available studies that focus on thermal energy storage systems, of energy efficient buildings with cooling and heating demands, respectively [10,16–19]. Current international standards for evaluating the buildings energy performance are mostly based on parameters measured “in vitro”, i.e. during steady state working conditions, and on simplified calculations that estimate the energy demand by using monthly or seasonal average outdoor temperatures [7].

Internationally standardised method for measurement of thermal conductivity of a single material, or whole insulating systems, are critical. Here, the Hot Box method, following ISO 8990 [20], or the Hot Plate method, following ISO 8302 [21], need to be mentioned. There are other absolute and relative methods to determine thermal conductivity, as exemplified in [22]. Results published in [23] show inconsistent results for identical samples coming from seven materials and measured by a number of different methods. Here, higher thermal conductivity values as declared by the manufacturer were recorded for foam polyurethane, polystyrol and polystyrene. Different results are also seen when comparing the Hot Box method with the Heat Flux method. Polyurethane foam with a declared thermal conductivity of 0,0245 $Wm^{-1}K^{-1}$ was measured in this study [23] by the Hot Box method at 0,0379 $Wm^{-1}K^{-1}$, and by the Heat Flux meter at 0,0254 $Wm^{-1}K^{-1}$. The seen difference is as high as 50%. All synthetic materials were measured in this study [23] with worse results of thermal conductivity. Nevertheless, wood and plaster board were measured with lower thermal conductivity about 0,1 $Wm^{-1}K^{-1}$.

Taking in account real thermal loading of building envelops it can be assumed that the Hot Box method is more appropriate to simulate the actual behaviour of walls and roofs under existing climate conditions. These parts of the building envelope are constantly in direct contact with the outdoor atmosphere, and the indoor conditions on the other side, as it is the case in a Hot Box apparatus [20]. The hot plate method is based on a direct contact and heat transfer between heating plates and the specimen's surface, which corresponds better with ground contact or a floor insulation system [21].

Hot Box apparatus also provides good ability for full scale testing of whole building systems in the same matter as they are used in real conditions [24].

The research questions were established as follows:

Is it possible to use dynamic thermal conditions in Hot Box for accurate thermal transmittance (*U* value) measurement of wall sample?

Can measurement with dynamic conditions provide different results about wall sample thermal transmittance in comparison with test results using steady state conditions?

## 2. Methodology

### 2.1. Testing device

Thermal energy performance of the tested samples was determined in the Modified Guarded Hot Box. Guarded Hot Box method according to EN ISO 8990 [20] was used and modified. Several modifications were done to reduce thermal losses through its envelope. The box consisted of two chambers, the cold-chamber with the cooling system to maintain low (thus *cold*) temperature and a hot-chamber to keep high (thus *hot*) temperature. Both chambers were separated by the sample. Fig. 1 shows the difference between a Guarded Hot Box, as designed by the appropriate Standard [20], and the Modified Hot Box used in this study.

This setting is minimising the heat losses that potentially occur through the hot site walls $\varphi_3$ (Fig. 1b). This allows a use of the Hot Box constructed as a Calibrated Hot Box according to

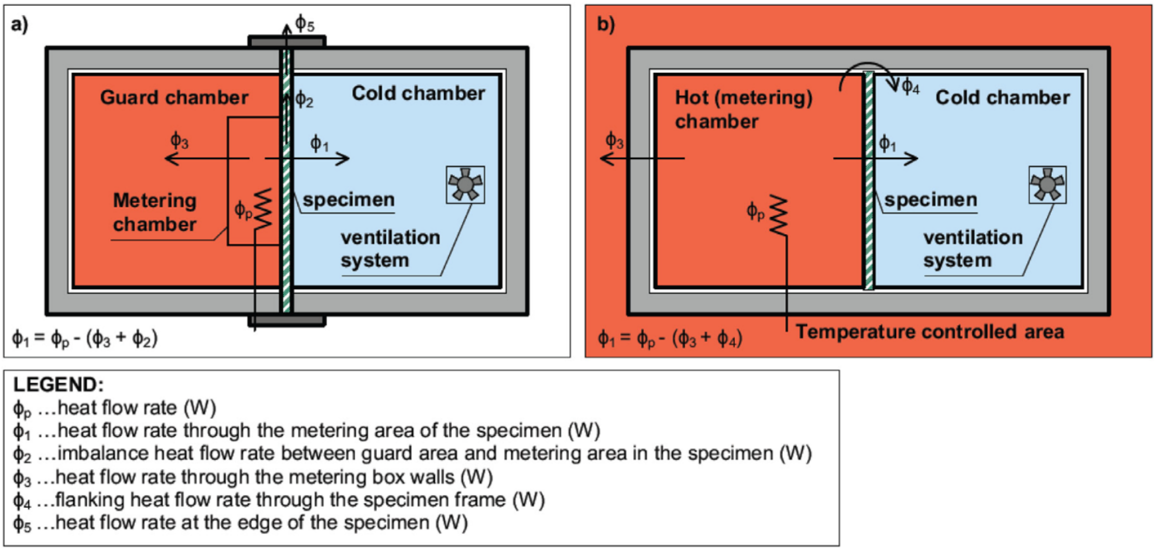


**Fig. 1.** (a) Guarded Hot Box (according to EN ISO 8990) and Modified Guarded Got Box used in this study (b).

**Table 1**
Description of temperature changes in the cold chamber of the Hot Box during the dynamic test.

| Day | Day 0 | Day 1 | Day 2 | Day 3 | Day 4 | Day 5 | Day 6 | Day 7 | Day 0 | Day 1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | 14:00 | 16:00 | 9:00 | 9:00 | 9:00 | 9:00 | 16:00 | 9:00 | 14:00 | Repeat |
| Temperature | +6 °C | −13 °C | +6 °C | −13 °C | +6 °C | −13 °C | −6 °C | −13 °C | +6 °C | Repeat |
| Hours | 26 | 17 | 24 | 24 | 24 | 31 | 17 | 29 | 26 | Repeat |

EN ISO 8990 [20] There is no need for calibration after minimising the system heat loss through hot chamber walls. The second most important advantage of this solution is minimising the three-dimensional conduction through the sample in flanging area of the metering chamber - $\varphi_2$ (Fig. 1a), as it is expectable in the case of the Guarded Hot Box method.

It was important to decide which temperature cycle for seven days cycle to choose. For this pilot study was used dynamic cycle shown in Table 1.

Each system was investigated under similar conditions with room temperature in the hot chamber. Ambient temperature 22–24 °C was kept steady by very powerful air conditioning with hysteresis 0,2 °C. The temperature in the cold chamber was changing between +6 °C and −13 °C. The current state of the art allows constructing of climate chambers to be accurately controlled and programmed with temperature progressions.

The box was placed in a laboratory with HVAC controlled temperature and humidity. The temperature on the hot side of the measuring box was always set to be the same as the ambient temperature, leading to elimination of overall system heat losses (refer to Fig. 1, heat flow $\phi_3$) and 3D heat dissipation through the sample (refer to Fig. 1, heat flow $\phi_2$). This environment thus replaces the separated Metering chamber (refer to Fig. 1a). The ambient temperature was kept the same as the set temperature in the hot chamber. This eliminates system heat losses through the chamber envelope and it can be assumed that the energy supplied to the hot chamber leaks only through the sample, including the flanking heat flow through the specimen frame, which is not calculated in this study. A gap between the panel and the box was filled with an additional mineral wool insulation and the whole panel/box wall perimeter was sealed with an air-tight tape, making thermal losses negligible.

The measuring device consists of two parts. The first part has external dimensions of 2 m × 0,65 m × 1,97 m representing the hot side. The second part is a cold side with external dimensions of 2 m × 0,65 m × 1,97 m and includes the test sample installation. The measurement area of the test sample is 1.7 × 1.7 m. Both parts of the box are equipped with wheels for easier handling and possible movement and the steel forging system serves to close the device. The supporting parts of the chamber (bottom, ceiling and side walls) are made of 50 × 50 mm wooden prisms filled with thermal insulation from 50 mm expanded polystyrene. To this layer, another one of 100 mm thick expanded polystyrene was added- to reduce heat losses through the peripheral wall of the chamber. The total thermal insulation thickness of the circumferential walls of the two chambers is 150 mm. Expanded polystyrene was used as a low emissivity material in Hot Box interior. Air velocity in the cold chamber was measured by digital anemometer and values of 0,3 – 0,7 $ms^{-1}$ were obtained. Fig. 4 shows the outline of the Modified Hot Box together with the position of the sample. At the beginning of the experiment, the hot chamber was opened and the sample was positioned in the box as a "septum" between hot and cold chamber.

There is an electric heater with a maximum power of 500 W in the hot chamber, which is regulated by a panel PID controller with an additional thermocouple in the hot chamber. A Rohde & Schwarz HMC 8015 Power Analyser measures the heat flow as an electric power going straight to the heater placed inside the hot chamber. Inside both chambers, the air temperature was measured using the Data Acquisition Base with humidity and temperature sensors. On each side of the measured sample, a set of temperature sensors was placed on the surface that measure surface temperatures according to EN ISO 8990. The location of the temperature sensors is shown in the Fig. 2.

Air temperatures and humidity were measured on the cold and hot side 200 mm from the sample surface. All the monitored parameters (air temperature, surface temperature and heat flow passing through the sample) were transferred to the computer.

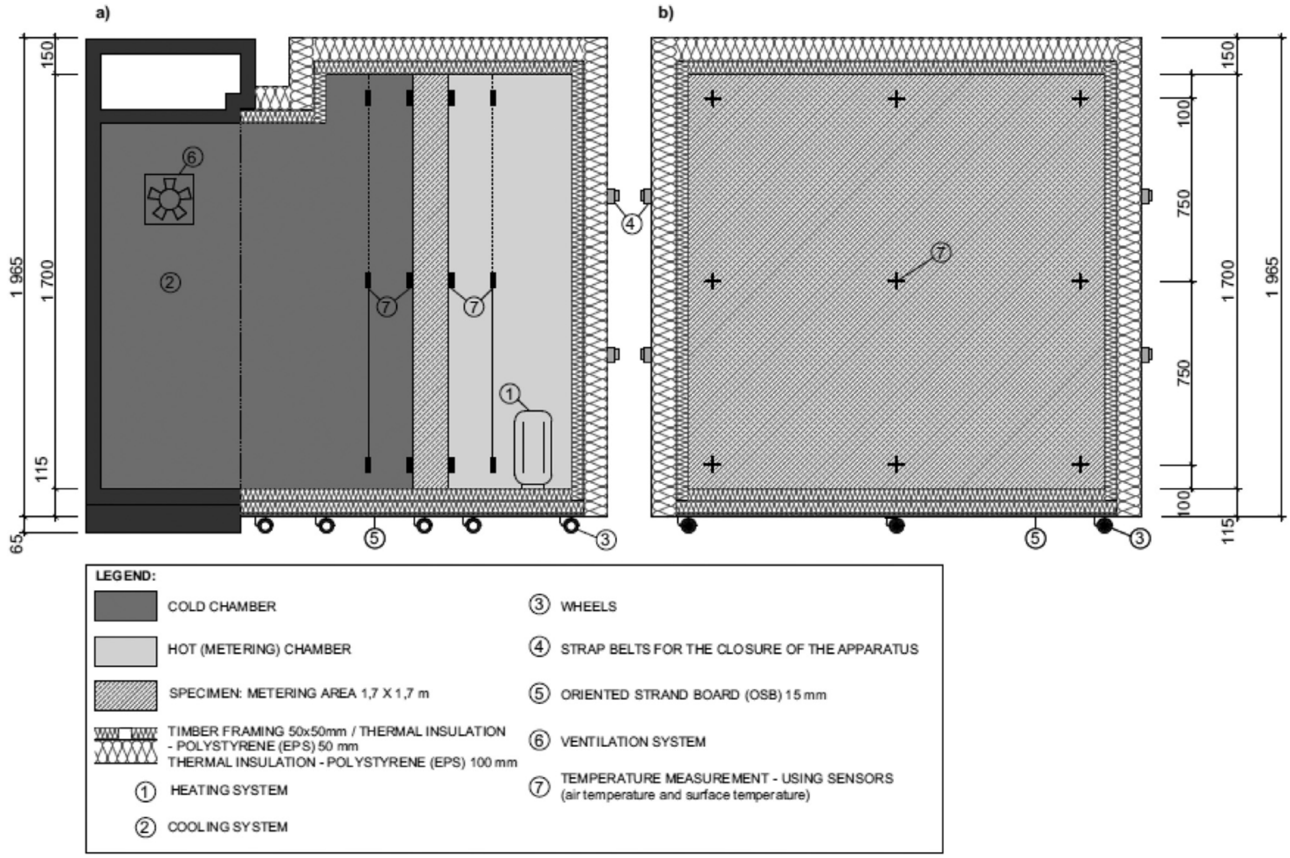


**Fig. 2.** Modified Guarded Hot Box design: (a) Hot Box vertical section; (b) frontal view from the hot/cold side.

### *2.2. Calculation procedure*

The total thermal transmittance $U_t$ ($Wm^{-2}K^{-1}$) of the experimental panel was calculated as the ratio of thermal energy $\phi_1$ (W) passing through sample area $A$ ($m^2$) perpendicular to the heat flow and $T_{ai} - T_{ae}$ was the difference in air temperatures between the hot and cold side of the sample (in K):

$$U_t = \frac{\phi_1}{A\ (T_{ai} - T_{ae})} \tag{1}$$

The total thermal resistance $R_t$ ($m^2KW^{-1}$) of the experimental panel was calculated as the inverted value of the total thermal transmittance.

Referring back to the Fig. 1, the heat flow through the sample ($\phi_1$ in watts) was determined as the input power ($\phi_p$ in watts). $\phi_3$ and $\phi_4$ in watts were neglected. The inlet heat flow in the hot chamber was calculated from the power of the electric heater being powered and regulated by a PID panel controller with an additional temperature probe in the hot chamber. Electric power outgoing from PID controller was measured using the Rohde & Schwarz HMC 8015 power analyser.

There was a cooling system for maintaining low temperatures in the cold chamber. The metering area of the test sample was 1.7 × 1.7 m.

The thermal conductivity calculation of the wood was based on the following equation:

$$\lambda_{wood} = \frac{d_{wood}}{\underbrace{\left(\frac{(T_{si} - T_{se})\ A}{\phi_1}\right)}_{R}} \tag{2}$$

where $d$ (m) is the thickness of the wood, $T_{si} - T_{se}$ is the difference in surface temperatures between the hot and cold side of the sample (K), $A$ is the surface of the panel ($m^2$), $\phi_1$ is the heat flow in the sample (W).

### *2.3. Experiment design—panel response to dynamic thermal loading*

The panel was subjected to a dynamic thermal loading. The hot chamber temperature ($T_{ai}$) was continuously maintained at 24 °C. The temperature in the cold chamber ($T_{ae}$) fluctuated between +6 °C and −13 °C. The air temperature in the hot chamber $T_{ai}$ was continuously measured (every minute) as an indication of the structure's reaction to temperature changes. The total heat flow depending on time, as the total energy leaked through the panel $E_{searched}$ (Wh), was calculated using $U_{searched}$ for every minute according to the following equation:

$$E_{searched} = U_{searched} \cdot A \cdot (T_{ai} - T_{ae}) \cdot t \tag{3}$$

$$E_{declared} = U_{declared} \cdot A \cdot (T_{ai} - T_{ae}) \cdot t \tag{4}$$

where $U_{searched}$ is the thermal transmittance ($Wm^{-2}K^{-1}$) given by calculation using solver function, $A$ is the surface of the panel ($m^2$), $T_{ai} - T_{ae}$ is the difference in air temperatures between the hot and cold side of the sample (K), t is the time (h).

$E_{declared}$ is given by $U$ or $\lambda$ value known from producers or national standard.

$$Q = \sum_{j=1}^{n} (E_{searched,j} - E_{experimental,\ j})^2 \tag{5}$$

where $E_{experimental}$ is the total energy leaked through the sample (Wh). The solver function finds a variable $U_{searched}$ to minimize the

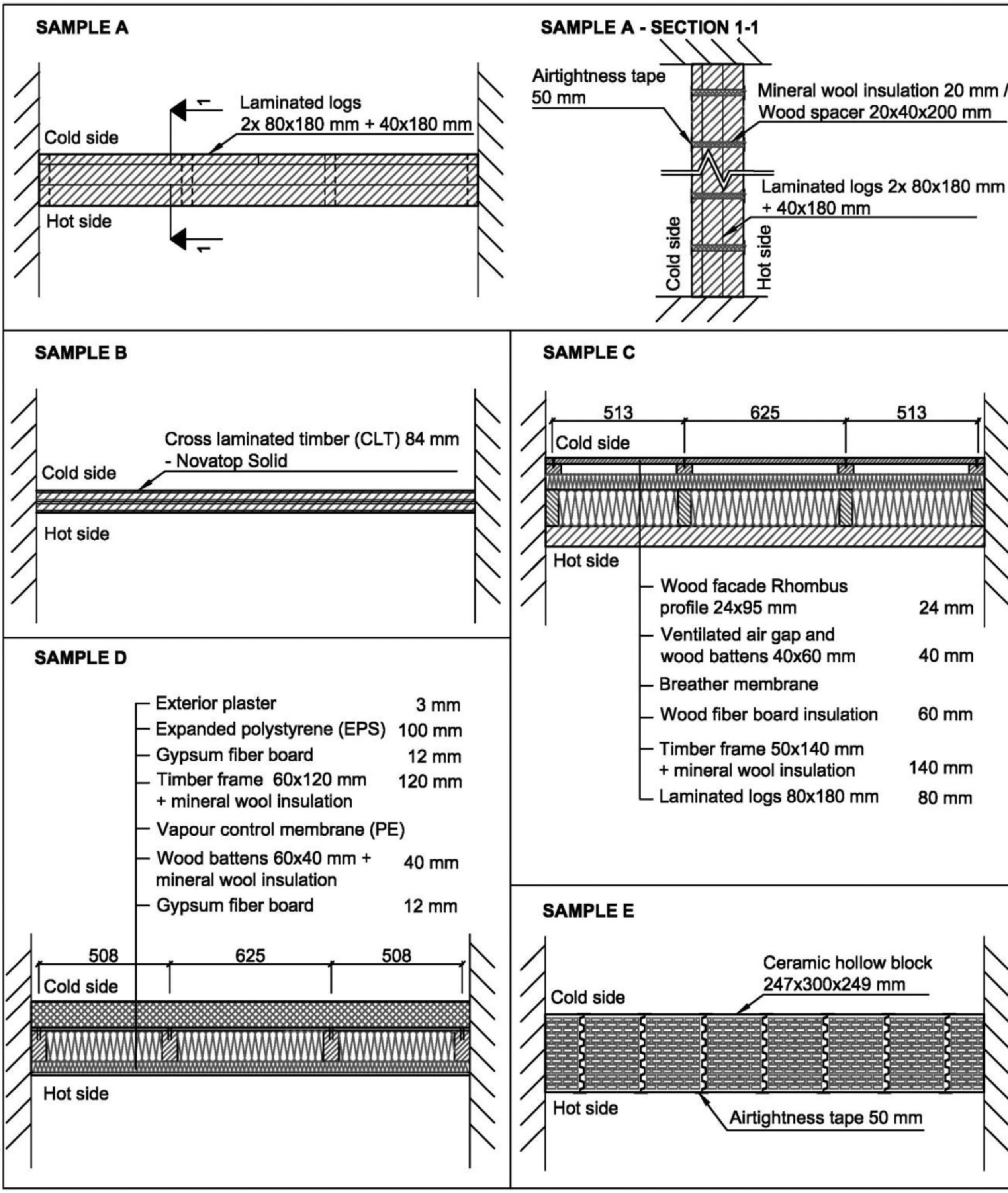


**Fig. 3.** Sample A – laminated log wall (thickness 200 mm), Sample B – CLT wall - Novatop Solid (thickness 84 mm), Sample C – laminated log wall with insulation (thickness 344 mm), Sample D – sandwich wall based on timber frame (thickness 287 mm), Sample E – ceramic hollow block wall (thickness 300 mm).

sum of squares of difference between $E_{experimental}$ and $E_{searched}$ calculated as $Q$.

Heat flow (W) was recorded from the experimental data for every 1 min, at the same time it was calculated from the following relationship:

$$Heat\ flow_{searched} = U_{searched} \cdot A(T_{ai} - T_{ae}) \tag{6}$$

Correlation coefficient was calculated by MS excel in Data analysis by tool Correlation.

The alternative approach used also in [25] brings the opportunity to measure total energy (Wh) leaked through the sample and to find appropriate U value using dynamic conditions. Heat capacity, thermal response to real weather conditions and water/vapour content influence can be incorporated in this test

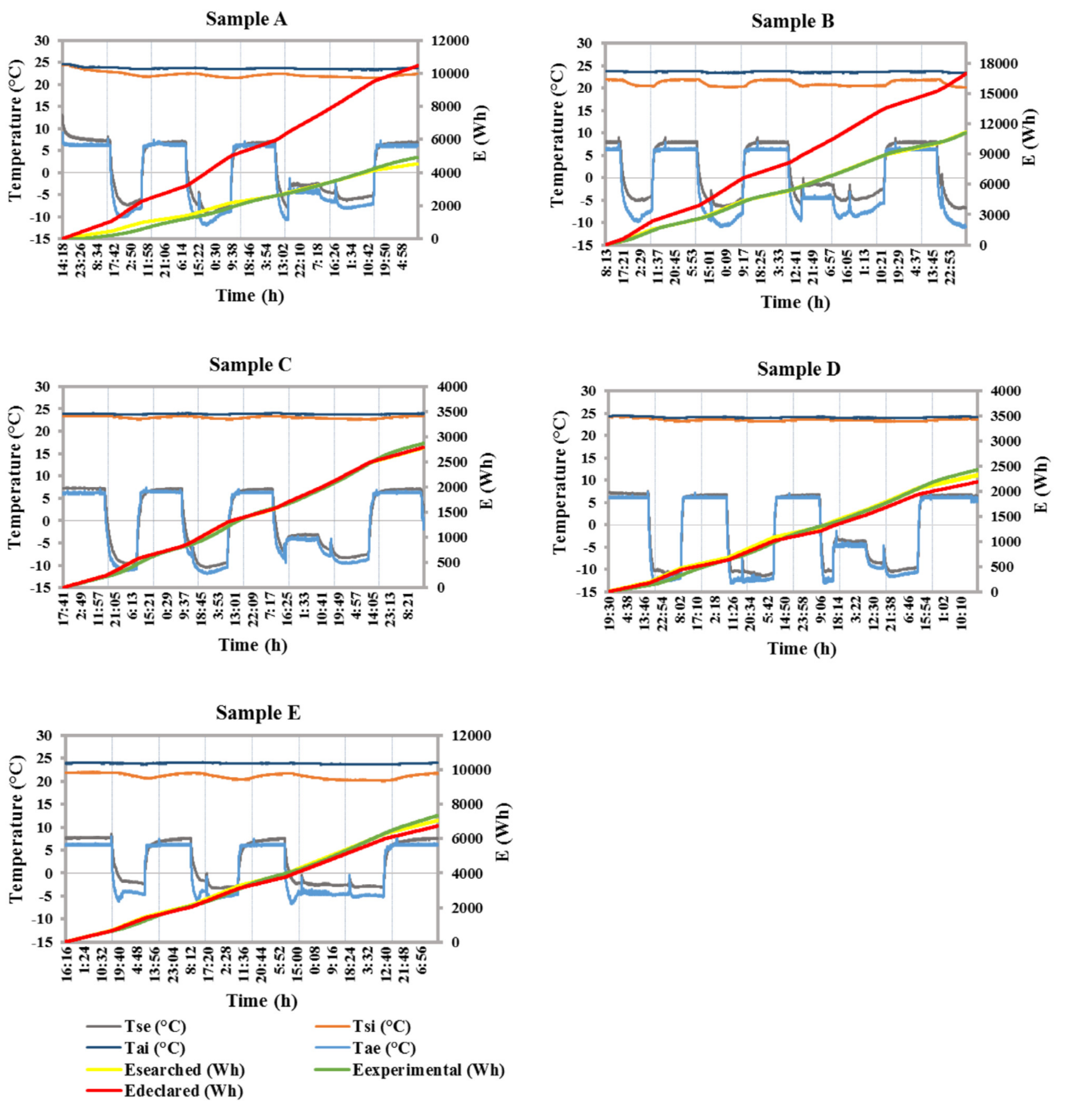


**Fig. 4.** Total energy leaked through the sample using searched *U*-value under dynamic conditions; $T_{ae}$ = air temperature in the cold chamber, $T_{ai}$ - air temperature in the hot chamber, $T_{se}$ - surface temperature of the sample in the cold chamber, $T_{si}$ - surface temperature of the sample in the hot chamber, $E_{experimental}$ - total energy leaked through the sample (Wh), $E_{searched}$ - calculated total energy consumption using *U*-value given by Solver and $E_{declared}$ - calculated total energy consumption using declared U value.

method compared to the currently used steady state conditions. More accurate calculation of total annual heat loss due to transmission can be provided using long term real climate temperatures collected for example with 1-minute resolution.

### 2.4. Experimental walls (samples)

This study was performed using the device described above. Five different wall samples were constructed at Faculty of Forestry and Wood Sciences, Czech University of Life Sciences of Prague (refer to Fig. 3). Four wall structures are the representatives of the most used building systems based on wood. The five wall samples are: (A) laminated log wall; (B) cross laminated timber (CLT) wall – Novatop Solid; (C) laminated log wall with insulation; (D) timber frame sandwich wall; (E) ceramic hollow block wall. Typical plans and one section of the five samples with the corresponding dimensions are shown in Fig. 3. All wall samples were tested in vertical position. All samples were conditioned at 24 °C temperature and the relative humidity of 50% for at least two weeks prior to testing. Dried wood with maximum moister content 12% was used for preparation of all samples.

*U*-value was calculated for all wall samples using EN ISO 6946 [26].

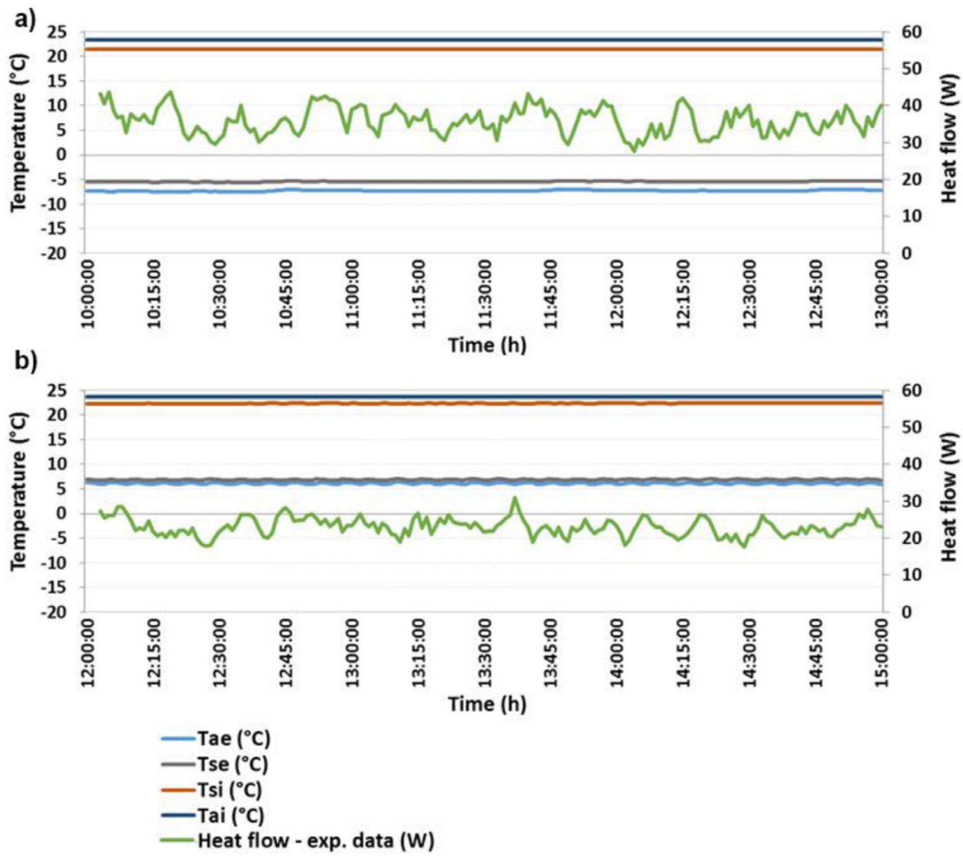


**Fig. 5.** Heat flow and temperature measurements from the sample A (laminated log wall) using the steady-state method: (**a**) set temperature in the cold chamber −7 °C, (**b**) set temperature in the cold chamber +6 °C. $T_{ae}$ - air temperature in the cold chamber, $T_{ai}$ - air temperature in the hot chamber, $T_{se}$ - surface temperature of sample in the cold chamber, and $T_{si}$ - surface temperature of sample in the hot chamber.

## 3. Results and discussion

Samples A–E were tested under very similar conditions in hot-box constructed in January 2017 at Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Czech Republic. Data aquisition system was developed at Faculty of Electrical Engineering, Czech Technical University in Prague. Measurements were conducted between May 2017 and July 2018. Special care was taken to do all preparation works in the very same manner.

Measured total energy leaked through the sample was compared with calculated total energy consumption by Eq. (4).

Many interesting reactions and responses of tested samples are noticeable from presented study. The mostly interesting result is given by visualisation of total energy flow through the sample shown in Fig. 4. Measurements of total energy leaked through tested sample from the start of the test compared with calculated values from boundary conditions (°C) and searched or declared *U*-Value according to Eq. (3) or (4) provide very similar curves. Responses to temperature shifts didn't influence total energy consumption too much and the function of total energy loss is nearly linear unlike real time heat flow. This behaviour offers easy method how to measure *U*-value of the sample under dynamic conditions. Aimed *U*-value was found using excel function Solver with conditions of minimising the difference between the model and measured value of total energy loss ($E_{experimental}$ and $E_{searched}$). For this searching was used least squares method and function Solver.

Results obtained with 200 mm timber wall show very different U value and λ value of wood in comparison to calculation according to common standards. For example ČSN 73 0540-3 [27] provides design λ value perpendicular to the fibres of softwood 0,18 $Wm^{-1}K^{-1}$. Results of the sample A with $U_{searched} = 0{,}339\ Wm^{-2}K^{-1}$ correspond to $\lambda_{wood} = 0{,}072\ Wm^{-1}K^{-1}$. Table 2 provides a review of different sources of $\lambda_{wood}$ values. There are significant differences in national standards and scientific studies.

Similar surprising results shown in Table 3 were also obtained in case of the sample B. The 84 mm solid wood panel was resisting as a panel with $\lambda_{wood} = 0{,}078\ Wm^{-1}K^{-1}$. In these calculations is included the thermal resistances of the surface $R_{si} = 0{,}13\ m^2KW^{-1}$ and $R_{se} = 0{,}04\ m^2KW^{-1}$ were used in these calculations.

Different *U*-values are also visible from shorter period records which can be separately used as steady state measurements. Fig. 5 shows two 3 h long periods with steady conditions on both sides of the Hot Box. Fig. 5a is recording measurement of the sample A with boundary conditions 7 °C on cold side and +24 °C on hot side with result $U_{wall} = 0{,}405\ Wm^{-2}\ K^{-1}$. Fig. 5b records the measurement with boundary conditions +6 °C and + 24 °C and with result $U_{wall} = 0{,}455\ Wm^{-2}\ K^{-1}$. The difference between these two results is 12%. The difference between $U_{searched} = 0{,}339\ W.m^{-2}.K^{-1}$ taken from dynamic measurement and $U_{wall} = 0{,}455\ Wm^{-2}\ K^{-1}$ taken from steady conditions is 34%.

Samples C-E results provide very similar values of calculated $E_{declared}$ (Wh) and $U_{declared}$ ($Wm^{-2}K^{-1}$) compared with experimental data. Measurement of the system based on industrial thermal insulation (sample C) provides results very similar to declared and expected values. Although there are significantly long responses of samples D and E, the measured total heat flow (Wh) is relatively close to calculated values (Fig. 3).

Studies [35,36] were using dynamic conditions resolving in creation of mathematical model based on temperature wave and response of the system (with measured heat flux), also in the study

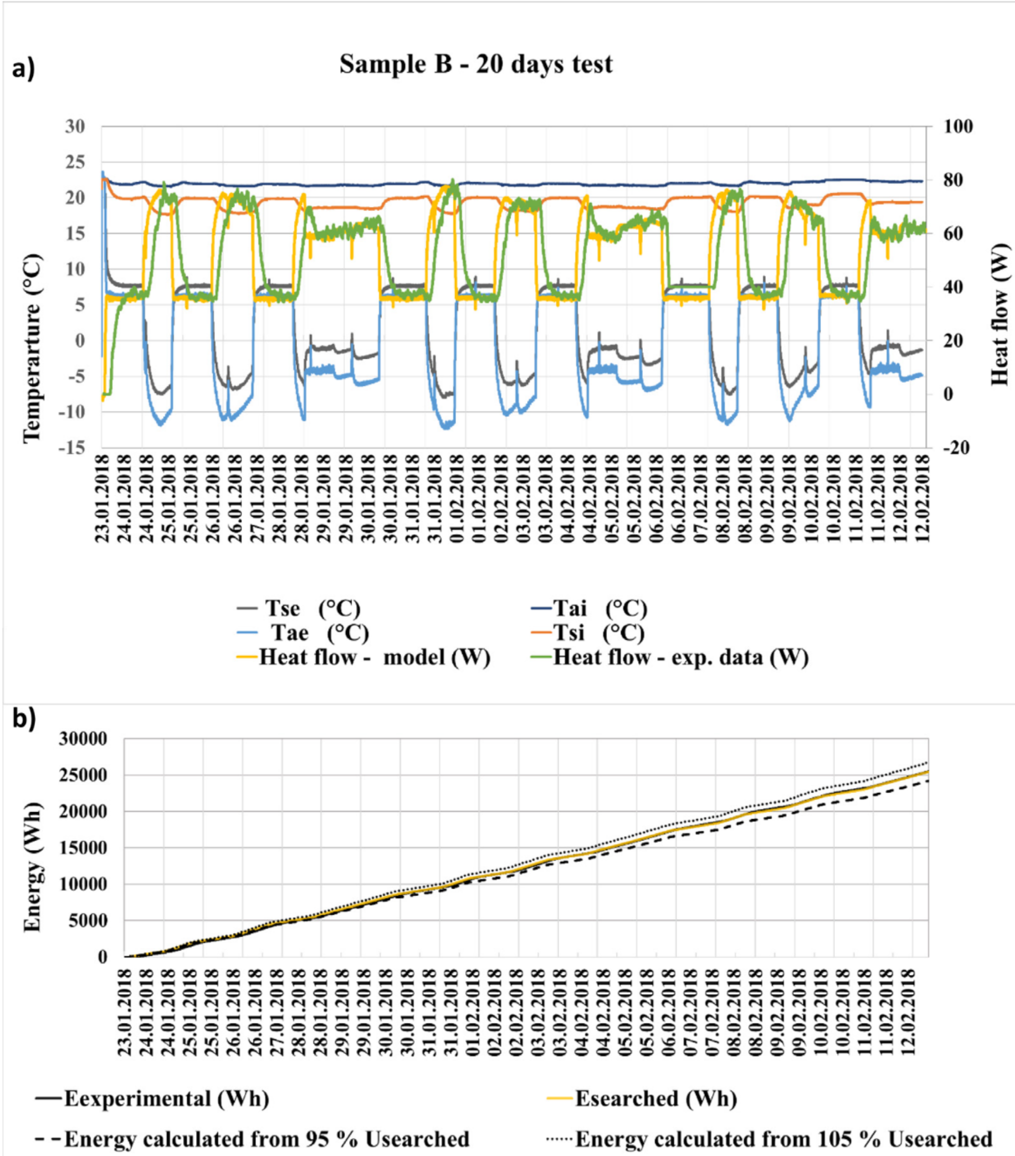


**Fig. 6.** Results from 20 days long test of the sample B under dynamic boundary conditions in the cold chamber. (a) Provides comparison of temperatures and heat flow measurements in (W) calculated according to the Eq. (6) from *Heat flow*$_{searched}$ and *Heat flow*$_{experimental}$ from wattmeter. (b) shows very high correlation ($r = 0{,}99996$) between $E_{experimental}$ and $E_{searched}$ and boundaries of $U_{searched}$. 5% variation.

**Table 2**
Thermal conductivity values of softwood perpendicular to the fibres by different sources.

| Method | Thickness | Thermal conductivity λ(W m$^{-1}$ K$^{-1}$) | | Reference |
|---|---|---|---|---|
| Declared by standard | x | Characteristic value 0,15 | Design value 0,18 | ČSN 73 0540-3 [27]<br>STN 73 0540-3 [28] |
| Declared by standard | x | Design value 0,13 | | ISO 10 456 [29] |
| Guarded Hot Box (EN ISO 8990) | 300 (diameter) | $U = 0{,}44$, $R = 2{,}11 \geq \lambda = 0{,}14$* | | Řihák and Školník [30] |
| Hot Box (EN ISO 8990) | 260 (diameter) | $U = 0{,}6$, $R = 1{,}66 \geq \lambda = 0{,}15$* | | Jochim [31] |
| Hot Strip | 130 | 0,1–0,3** | | Raji et al. [32] |
| Guarded Hot Plate (EN 12 664) | 48,6 | NARROW-RING WOOD: RADIAL | 0,079 ($t = 10$ °C); 0,08 ($t = 25$ a 40 °C) | Vololonirina et al. [33] |
| | 48,5 | NARROW-RING WOOD: TANGENTIAL | 0,082 ($t = 10$ °C); 0,084 ($t = 25$ a 40 °C) | |
| | 49,5 | WIDE-RING WOOD: RADIAL | 0,080 ($t = 10$ °C); 0,081 ($t = 25$ a 40 °C) | |
| | 49,7 | WIDE-RING WOOD: TANGENTIAL | 0,093 ($t = 10$ °C); 0,095 ($t = 25$ a 40 °C) | |
| Hot Wire (EN ISO 8894–1) | 50 | 0,13 | | Pralat (2016) [34] |

Relative humidity ≈13% or dried.
Volumetric weight in dry condition 400–500 kg m$^{-3}$.
* Thermal conductivity is derived from the thermal resistance.
** For different wood densities in the range of 364–415 kg m$^{-3}$.

**Table 3**
Comparison of declared and measured (experimental) thermal transmittance values.

| Wall sample | Thermal transmittance $U_t$ (W m$^{-2}$ K$^{-1}$) | | | Difference |
|---|---|---|---|---|
| | Declared value by producer or calculated by standard | | Measured value | |
| (A) Laminated Log Wall | 0,781* | EN ISO 6946 | 0,339 | −56,59% |
| (B) CLT Wall - Novatop Solid | 1,225** | Declared by the producer | 0,807 | −34,12% |
| (C) Laminated Log Wall with Insulation | 0,205 | EN ISO 6946 | 0,204 | −0,49% |
| (D) Sandwich Wall based on Timber Frame | 0,148 | Declared by the producer | 0,162 | +9,46 |
| (E) Ceramic Hollow Block | 0,531 | Declared by the producer | 0,560 | +5,46 |

* $\lambda_{wood}$ was used 0,18 W m$^{-1}$ K$^{-1}$ according to ČSN 73 0540-3.
** $\lambda_{wood}$ was declared 0,13 W m$^{-1}$ K$^{-1}$ by the producer.

**Table 4**
Correlation coefficient between $E_{searched}$ and $E_{experimental}$ (Wh)and *Heat flow*$_{searched}$ and *Heat flow*$_{experimental}$ (W).

| | Sample A | Sample B | Sample C | Sample D | Sample E | Sample B 20 days |
|---|---|---|---|---|---|---|
| $E_{searched}$ and $E_{experimental}$ correlation coefficientr | 0,9975 | 0,9998 | 0,9989 | 0,9986 | 0,9991 | 1,0000 |
| *Heat flow*$_{searched}$ and *Heat flow*$_{experimental}$ correlation coefficientr | 0,2637 | 0,5908 | 0,3771 | 0,2653 | 0,3564 | 0,6036 |

[37] has been solved the problem with simulation of real energy performance of whole buildings in continuously changing weather conditions. Authors in studies [12,38] confirm different real energy consumption compared with calculations according to EN standards.

There are many parameters which we can measure or estimate to supply mathematical models which can simulate and calculate annual building energy consumption. Influence of thermal inertia, moisture content, phase change materials or fibre direction were determined in studies [8,39].

Results of this study show interesting way, how to use relatively simple testing method for full scale energy performance of wall, ceiling or roof system in dynamic conditions in Hot Box. Temperature and humidity curves can be set according to expected real conditions and the length of the measurement can be as long as it is needed. Better and more accurate results can be expected for materials based on wood and other natural polymers which can provide good service for sustainable building industry. The need of current material base substitution in very near future is described in the study [40].

One can doubt about the accuracy of the presented method proofed just by one measurement of each sample. There has been conducted prolonged test with the sample B. Fig. 6 presents results form 20 days long measurement. It can be observed very high correlation between measured total energy leaked through the sample ($E_{experimental}$) and calculated total energy consumption using *U*-value given by Solver ($E_{searched}$). Correlation coefficient between these two curves reached the value 1,0000 (0,99996). The same sample *U*-value found as $U_{searched}$ was used as the variable in this calculation as well. The value of the total energy loss is the mostly searched value in building envelope energy performance.

It can be deducted that with the length of the measurement is decreasing the main part of presented method uncertainties.

There were calculated correlation coefficients for each test. Table 4 shows correlation coefficients between $E_{experimental}$ and $E_{searched}$ (Wh) and *Heat flow*$_{searched}$ and *Heat flow*$_{experimental}$ (W). Results seems to be surprising especially in case of energy loss model where as only one variable is *U*-value of the sample. Contrary, the correlation between measured heat flow and calculated heat flow seems to be relatively low. Even so, the only one variable is again *U*-value of the sample.

The main value of this study relates to proving of the pilot method and discovered opportunities in further research focused on massive wood-based building envelopes energy performance. Absolute values of thermal transmittance of massive wood mentioned in this study are based just on one measurement of one wall sample. However, all results were obtained by the very similar measurements, citation of all mentioned absolute values must be considered as pilot values. Further measurements with larger number of samples will be conducted for more convinced and general conclusions.

## 4. Conclusions

Presented study proofs reliability of the comparative testing method for full scale wall samples energy performance evaluation using dynamic boundary conditions. Measurements of described Wood massive wall samples A and B energy performance indicate differences comparing results under dynamic conditions and under steady state conditions. Further research of this phenomenon will be conducted.

The total energy consumption seems to be the most important and comparable parameter for thermal transmission determination using dynamic boundary conditions in Hot Box method. Correlation between calculated energy loss (Wh) and measured energy loss (Wh) was always higher than $r = 0{,}997$. Combination of hot side steady state conditions and dynamic conditions on cold side seems to be promising method for accurate energy performance determination. This method can simulate real thermal conditions and incorporate imperfections given by non-homogenous materials with higher heat capacity and hygroscopicity.

Further research should be conducted to discover the influence of the air humidity and wall moister content on real energy performance under real dynamic boundary conditions. The difference between Hot Plate and Hot Box method can be expected especially for massive wood and similar natural materials. The influence of timber wall thickness should be determined in further research.

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## Conflict of interest

The authors declare no conflict of interest.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.04.036.

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