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Diagnosis of buildings' thermal performance - a quantitative method using thermography under non-steady state heat flow

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Abstract

This study describes a quantitative method using thermography to measure the thermal performance of complete building envelope elements that are subjected to non-steady state heat flow. The method presumes that thermal properties of external walls, like conductivity, could still be obtained by a linear regression over values of independent measurements. And therefore could be used during fluctuating indoor and outdoor thermal conditions. The method is divided into two parts. First, the convection heat transfer coefficient is measured by heat flux meters (HFM) and thermography. And then, the overall heat transfer coefficient of a complete building element is measured by thermography to include all non-uniformities.

In this study the thermal performance of a 140 mm thick laminated timber wall was measured. The wall was subjected to the outdoor weather conditions in Östersund, Sweden during January and February. The measurement values were found to have a large disparity as expected due to the rapid change in weather conditions. But still a linear regression with low confidence interval was obtained. The thermography results from a small uniform wall segment were validated with HFM measurements and 4% difference was found, which suggest that the two methods could be equally effective. Yet, thermography has the advantage of measuring surface temperature over large area of building element. The overall heat transfer coefficient of a large wall area was found to be 11% higher in comparison to the HFM measurements. This indicates that thermography could provide a more representative result as it captures areas of imperfections, point and linear thermal bridges.

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Keywords: heat transfer coefficient; convection; thermal transmittance; conductivity, infrared imaging

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1. Introduction

Buildings, in comparison to other commodity products, hold high costs for construction but also for service and maintenance. Design decisions made at an early stage may have large impact on the use of resources, production of waste, emissions and land use during the entire life of the building. Of all building elements, the most important is likely to be the building thermal envelope, which includes the external walls of the building. The design and thermal properties of building envelopes have direct effect on the use of construction materials, indoor thermal comfort and energy demand for space heating [1].

Still, the thermal performance of building envelops are rarely validated after construction. One reason for this is that current methods are either time consuming, costly or have low accuracy. Instead, new buildings are generally evaluated by indicators which are solely based on the architectural drawings together with assumptions regarding local weather conditions, occupant's behaviour and performance of heating systems, such as the specific final energy use. Such indicators seldom agree with monitored energy performance after the building is built. Danielski [2] examined more than hundred newly constructed buildings in 77 locations in Stockholm and showed that the final energy demand in average was 20% higher compared to their designed values. Danielski explained these variations by faulty assumptions and errors in building energy modelling. Occupant's behaviour may also be a cause for deviations [3].

Current methods used in building diagnostics, like moisture test and fan pressurization test, are qualitative. They are used to detect defects and imperfections in the building envelope but cannot fully evaluate thermal performance. Thermography is a method with increasing use in building diagnostics. Since the introduction of infrared cameras in 1929, infrared thermography is used to address an increasing range of applications [4]. Thermography is a non-destructive testing tool that can provide quick and accurate readings and therefore has large potential in defect detecting in building constructions [5-10]. The IEA has considered thermography for defect detecting in both annex 40 [11] and annex 46 [12]. And the Swedish standard SS-En 13187 specifies a qualitative method using thermography for detecting thermal irregularities in building envelopes.

However, quantitative methods to determine the thermal performance of building envelopes are still not fully developed. One method is the use of heat flux meters (HFM) for subsequent calculation of the heat transfer coefficient. This method is described in ISO 9869:1994. However, HFM provide point measurements, which can fail to detect imperfections, and do not accurately represent non-homogenous building elements.

BSRIA (13) claimed that thermography is not an accurate method to measure heat transfer coefficient in buildings with error in the order of ±25% due to unknown convection heat transfer and the non-steady state heat flow. Ohlsson, and Olofsson [14] used thermography for measuring the heat transfer coefficient of building elements during steady state conditions in controlled environment, in which heat flux is constant over time. Fokaides and Kalogirou [15] and Albatici and Tonelli [16] measured the heat transfer coefficient during quasi steady-state conditions, in which selective measurement periods with relative stable thermal conditions were selected. In all three studies 10% to 20% differences in measured values were recorded between the HFM and thermography measurements. The outdoor conditions in Sweden changes rapidly. Building's thermal envelops include thick insulation layers and may have large thermal capacity. Lehmann et al. [17] showed that solar irradiation, wind, IR-radiation of the environment have large effect on the heat flow through external walls. Therefore steady-state heat flow in building elements is difficult to achieve.

1.1. Aim

This study investigates a quantitative method to analyse the thermal performance of complete building envelope elements in a non-steady state condition. The method include two stages. First, the convective heat transfer coefficient is calculated based on thermographic imaging and HFS measurements. And then the overall heat transfer coefficient of a complete building element is calculated based on thermographic imaging. The measurements in both stages are performed simultaneously.

2. Methodology

In this study a non-invasive approach, using thermography, is tested to measure the overall heat transfer coefficient of complete building envelope element, based on the interfacial thermal resistance from the thermal boundary layer between the envelope interior surface and the indoor ambient air. The method will be applied on external wall of existing building and will be validated by HFM. This methodology is based on the theory of heat transfer, which provide expressions for the calculation of conduction heat transfer (Q_{Cond}), convection heat transfer (Q_{Conv}) and radiation heat transfer (Q_{Rad}) under steady-state heat flux. These expressions are described in eq.1 to eq.3 with ε as the emissivity, σ is the Stefan-Boltzmann constant and T as temperature. Eq. 4 describes heat flow balance during steady-state on a wall element. T_{Hot} and T_{Cold} describe the indoor and outdoor wall surface temperature in Eq.1; the indoor wall surface and indoor ambient air temperatures in Eq.2; and the indoor wall surface and radiated temperature on the wall surface in eq.3. h_{Cond} and h_{Conv} are the conduction and convection heat transfer coefficients, respectively.

$$Q_{Cond} = h_{Cond} \cdot (T_{Hot} - T_{Cold}) \quad (1)$$

$$Q_{Conv} = h_{conv} \cdot (T_{Hot} - T_{Cold}) \quad (2)$$

$$Q_{Rad} = \varepsilon \cdot \sigma \cdot (T_{Hot}^4 - T_{Cold}^4) \quad (3)$$

$$Q_{Cond} = Q_{Conv} + Q_{Rad} \quad (4)$$

This study do not analyses transient changes of heat flux over time. That is, each measured value is considered as an independent measurement and the history prior to the measurement (e.g., changes in temperature, wind velocity, humidity, etc.) and between two subsequent thermography measurements are not considered, even if it could have large influence on each individual measured value. Instead we utilize the average values, obtained by linear regression of a large number of measurements [17]. Therefore each of the measured values may deviate from the expected value due to two reasons: (i) the internal error in the measurement tool that cannot be avoided; and (ii) the non-steady state thermal conditions, in which the equation of heat transfer (eq. 1 to eq.4) do not work. The hypothesis of this study is that it could still be possible to obtain good values of thermal properties of building elements by applying statistics on a larger number of independently measured values.

2.1. Test object

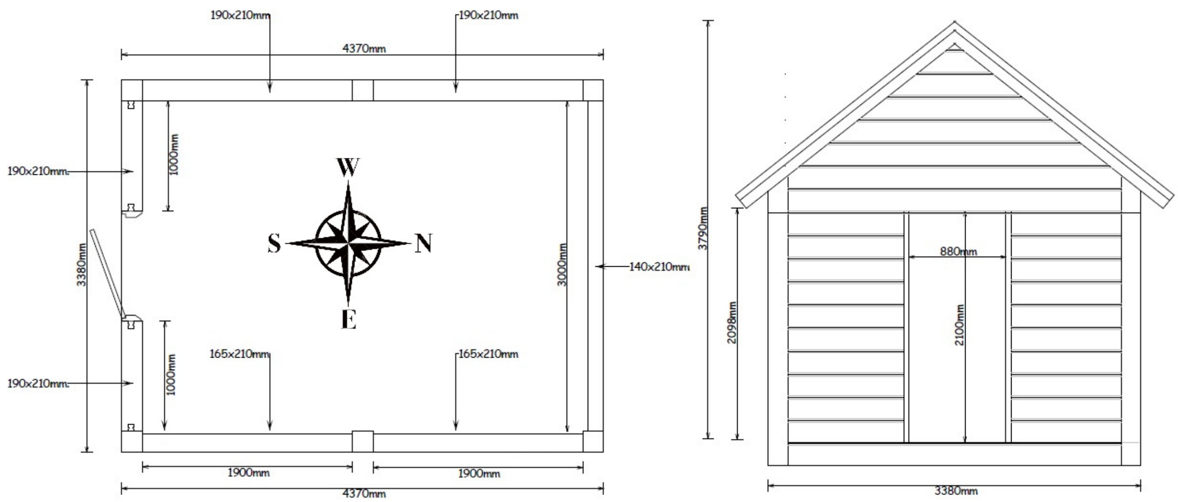

Fig. 1. Scematic drawing of the wooden cabin. The test object is the North facing external wall (wall without door).

The test object is the North facing external wall of a one-room wooden cabin with 15 m^2 floor area, as illustrated in Fig. 1. The wall is constructed with 140 mm glued laminated timbers. A technique developed by *Glulam* [18]. Measurements were conducted over a period of two and a half weeks. During the measurement period, the test object was heated by an electric heater connected to a thermostat, resulting with indoor temperature that fluctuated between 20°C and 24°C, which assume to present living conditions. The wall was exposed to the local outdoor weather conditions in the city of Östersund in Sweden with outdoor temperature fluctuations between -19°C and 7°C. The overall temperature differences between the indoor and the outdoor environment fluctuated between 15°C and 43°C, as illustrated in Fig. 2. Other outdoor parameters as wind velocity, humidity and snowfall were fluctuating as well, and the heat flow through the wall was assumed to obtain steady-state condition only sparsely and during short periods, if at all. The surface temperature factor [19] was above 0.75 during the entire measurement period, which indicates that condensation on the interior surface of the wall did not occurred.

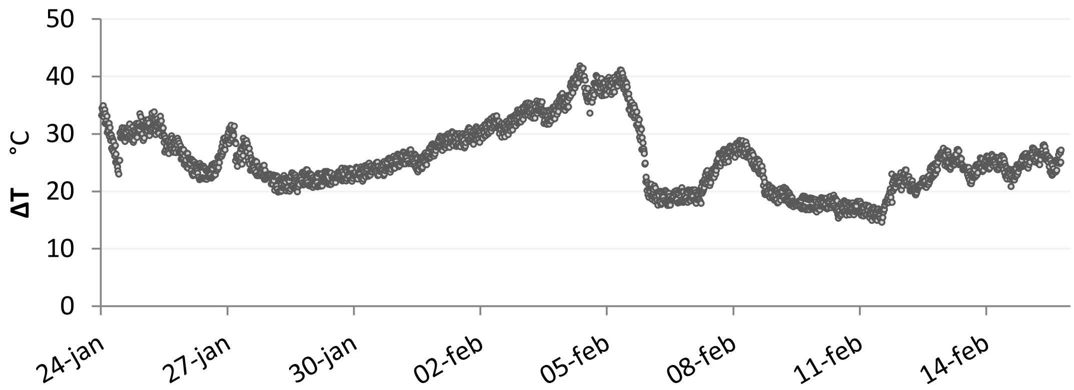

Fig. 2. Temperature difference between the indoor and outdoor ambient air over time.

2.2. Test equipment

The measurement equipment includes: High performance infrared camera of type Flir T440 with 76.8K pixels and ±2% accurate temperature measurement. Three HFMs of type HFP01 Hukseflux, with a nominal sensitivity of 50 $\mu V/Wm^2$, a working temperature range between -30°C to +70°C, and an expected typical accuracy of ±5%. The HFMs were connected to data logger of type LI-19 from Leiderdorp Instruments. Three types of humidity and temperature loggers were used: (i) RHTemp1000 MadgeTech for outdoor ambient air measurements with working temperature between -40°C and 80°C, temperature resolution of 0.1°C and temperature calibrated accuracy of ±0.5; (ii) MicroRHTemp MadgeTech for indoor ambient air measurements with working temperature between 0°C and 60°C, temperature resolution of 0.1°C and temperature calibrated accuracy of ±0.5; and (iii) ELOG9004 for wall surface measurements with temperature resolution of 0.5°C and temperature calibrated accuracy of ±0.5.

2.3. Experiment settings

Fig. 3 illustrates the experiment configuration. Three HFMs were attached to the indoor side of the wall with Dow 340 heat sink compound to reduce air cavities between the HFMs and the wall. The measurement location on the wall was chosen to have uniform surface temperatures. Three ELOG9004 were installed on the inner side of the wall and two on the outer side to measure its surface temperature. RHTemp1000 registered the outdoor temperature ($T_{Outdoor}$) and five MicroRHTemp registered the indoor temperatures (T_{Indoor}). All meters, temperature and heat flux, were configured to collect measurements with 15 minutes interval. The IR camera was located 2 m from the wall at an angle of 15° to avoid its own reflection on the wall. Thermal images of the interior surface of a small wall segment and ($T_{Small\ wall}$) a large wall element of 1 m X 0.6 m ($T_{Large\ wall}$) were taken at a rate of up to three images per day. Thermographic images and HFS measurements were taken only on the interior wall surface. Only ambient air and wall surface temperatures where taken outdoor, as well as indoor. That is also illustrated in fig.3.

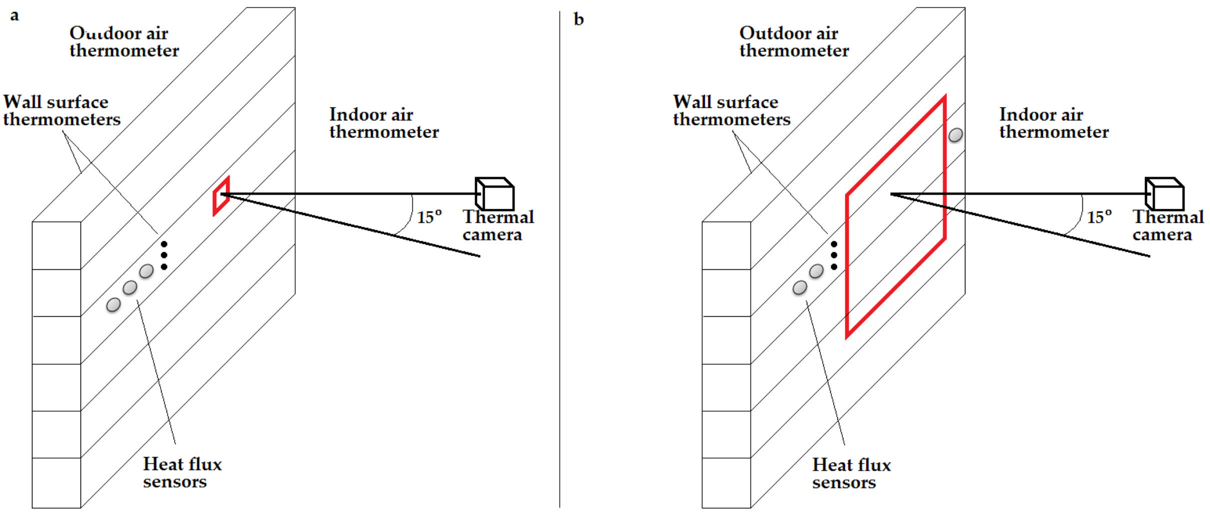

Fig. 3. Configuration for measuring the (a) small wall segment (b) large wall element. The thermal imaging were made from the inside.

The experiment was divided in two parts: (i) first the convection heat transfer coefficient (h_{conv}) was calculated by a linear regression of the convection heat flow (Q_{Conv}) against the temperature difference between T_{Indoor} and $T_{Small\ wall}$. Q_{Conv} was calculated according to eq.5 using HFS to measure the conduction heat flow (Q_{Cond}) and IR-camera to measure the reflection temperature ($T_{Reflection}$) and $T_{Small\ wall}$; (ii) second, the overall heat transfer coefficient (U) of the large wall element (0.6 m^2) was calculated by a linear regression of the conduction heat flow from a large wall element ($Q_{Cond,\ Large\ wall}$) against the difference between the indoor and outdoor temperatures. $Q_{Cond,\ Large\ wall}$ was calculated according to eq.6 using IR-camera and temperature sensors.

To validate the results, the conduction heat transfer coefficient was calculated using IR-camera on small wall segment and compared with simultaneous measurements done by HFS on similar wall size with similar temperature uniformity. The conduction heat transfer coefficient of the small wall segment was calculated by a linear regression of the conduction heat flow ($Q_{Cond,\ Small\ wall}$) against the difference between the indoor and the outdoor wall surface temperatures. $Q_{Cond,\ Small\ wall}$ was calculated according to eq.7 using IR-camera and temperature sensors.

$$Q_{Conv} = Q_{Cond} - \varepsilon \cdot \sigma \cdot (T^4_{Reflection} - T^4_{Small\ wall}) \quad (5)$$

$$Q_{Cond,\ Large\ wall} = h_{conv} \cdot (T_{Indoor} - T_{Large\ wall}) + \epsilon \cdot \sigma \cdot (T^4_{Reflection} - T^4_{Large\ wall}) \quad (6)$$

$$Q_{Cond,\ Small\ wall} = h_{conv} \cdot (T_{Indoor} - T_{Small\ wall}) + \epsilon \cdot \sigma \cdot (T^4_{Small\ wall} - T^4_{Reflection}) \quad (7)$$

Eq.5 to eq.7 were developed from eq.1 to eq.4. The reflection temperature ($T_{Reflection}$) was measured by IR-camera using a reflective surface near the surface of interest (crinkled aluminum foil). Q_{Cond} is the heat flux through the wall measured by the HFM. The emissivity of the wooden wall (ε) was measured by using similar wood segment covered partly by black tape with known emissivity. An IR image was taken while the wood segment was exposed to the outdoor colder temperature after maintaining it in room temperature. The temperature reading of the wood and the black tape was matched by adjusting the emissivity value of the wood until reaching the correct value, which was found to be 0.9. All the measurements were done simultaneously.

3. Results

3.1. Thermography

Fig. 4 illustrate one of the thermography measurements of the small wall segment and the large wall element. The HFMs, as well as the reflective surface, were located to the left and right sides of the thermography image, to avoid interfere with the measured wall area. The large wall element was found to have lower temperature uniformity (3.5°C) in comparison to the small wall segment (0.5°C), as listed in Table 1. The reason is the existence of knots and contact areas between the wood beams that act as thermal imperfections.

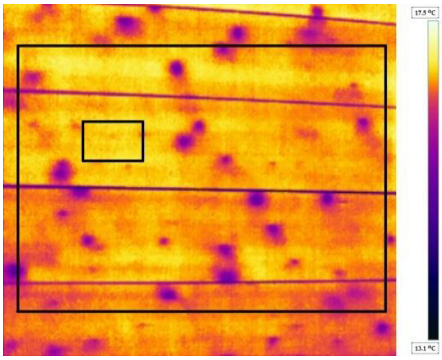

Fig. 4. Example of thermography image of the the external wall from the inside.

Table 1. Temperature statistics obtained from the thermography measurements in Fig. 4.

Large wall element	Max	17.1 °C
	Min	13.5 °C
	Average	16.6 °C
Small wall segment	Max	17.1 °C
	Min	16.5 °C
	Average	16.8 °C

3.2. Convection heat transfer

The convection heat transfer coefficient (h_{conv}) was determined by the tangent of a linear regression using intercept constrain (X,Y) = (0,0), as illustrated in Fig. 5. The value was found to be h_{conv} = 2.617 W·m^{-2}·K^{-1} with ±0.16 W·m^{-2}·K^{-1} confidence interval of 95% certainty. Measurements are predicted with 95% certainty to disperse around the mean (trend-line) with ±5.32 W·m^{-2}·K^{-1}.

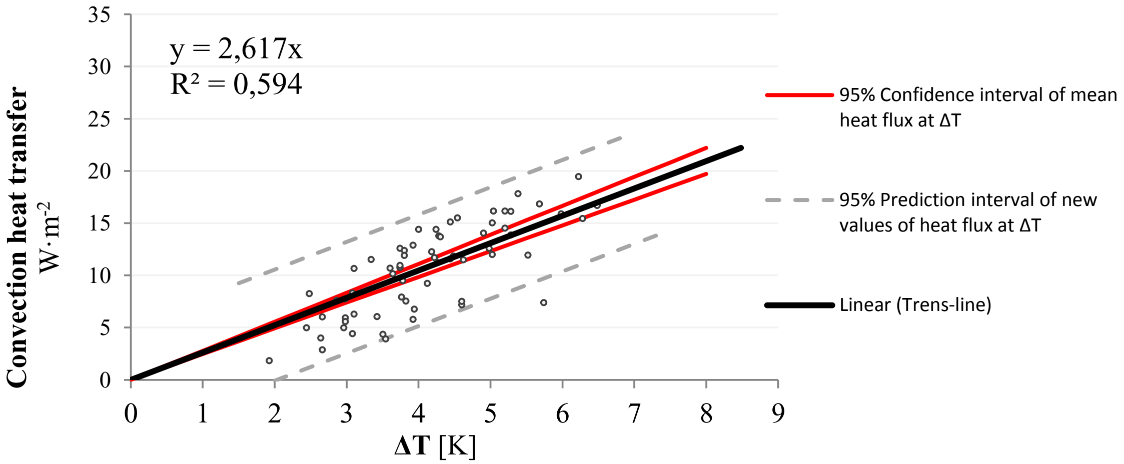

Fig. 5. The heat flux vs. the temperature difference between the interior surface of the small wall segment and the indoor ambient air. The convection heat transfer is calculated according to eq.5.

3.3. Conduction heat transfer coefficient

The conduction heat transfer coefficient (h_{cond}) of the wall was measured by two methods: by using HFMs (Fig. 6) and thermography of the small wall segment (Fig. 7). The conduction heat transfer coefficient measured by the HFMs was found to be h_{cond} = 0.712 W·m^{-2}·K^{-1} with ±0.008 W·m^{-2}·K^{-1} confidence interval of 95% certainty. Measurements are predicted with 95% certainty to disperse around the mean (trend-line) with ±7.98 W·m^{-2}·K^{-1}. The conduction heat transfer coefficient measured by the thermography was found to be h_{cond} = 0.74 W·m^{-2}·K^{-1} with ±0.03 W·m^{-2}·K^{-1} confidence interval of 95% certainty. Measurements are predicted with 95% certainty to disperse around the mean (trend-line) with ±3.06 W·m^{-2}·K^{-1}. The values obtained by the HFMs were found to be more dispersed but with lower confidence interval around the mean in comparison to values obtained by thermography.

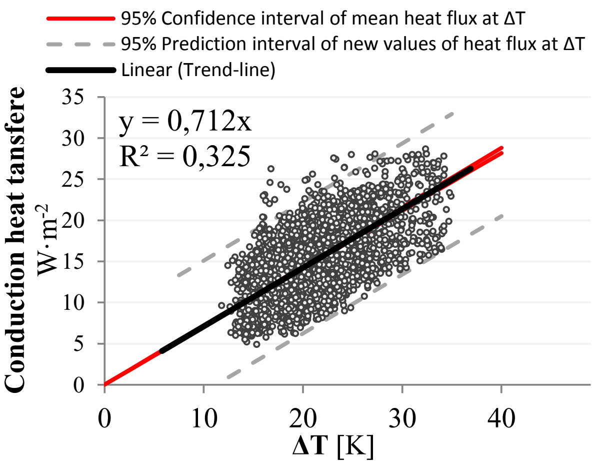

Fig. 6. Conduction heat transfer measured by the heat flux meters vs. the difference between the indoor and the outdoor wall surface temperatures, and the linear regression line (trend-line)

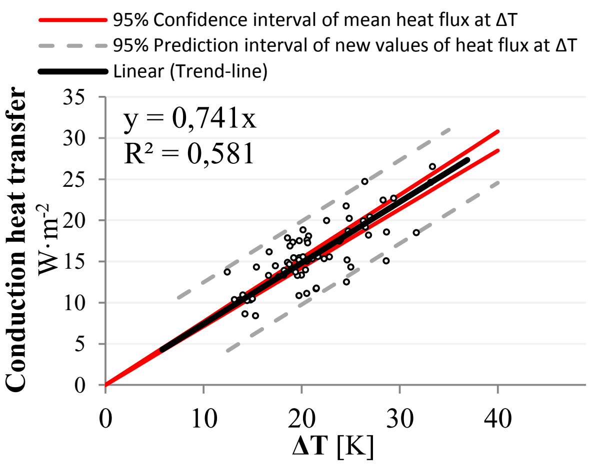

Fig. 7. Conduction heat transfer calculated by eq.6 vs. the difference between the indoor and the outdoor wall surface temperatures, and the linear regression line (trend-line).

3.4. Overall heat transfer coefficient

The overall heat transfer coefficient (*U-value*) of the wall was measured by two methods: by using HFMs (Fig. 8) and thermography of the large wall element (Fig. 9). The overall heat transfer coefficient measured by the HFMs was found to be *U* = 0.603 W·m^{-2}·K^{-1} ±0.006 W·m^{-2}·K^{-1} with confidence interval of 95% certainty. Measurements are predicted with 95% certainty to disperse around the mean (trend-line) with ±7.28 W·m^{-2}·K^{-1}. The overall heat transfer coefficient measured by the thermography was found to be *U* = 0.671 W·m^{-2}·K^{-1} ±0.02 W·m^{-2}·K^{-1} with confidence interval of 95% certainty. Measurements are predicted with 95% certainty to disperse around the mean (trend-line) with ±4.47 W·m^{-2}·K^{-1}. The values obtain by the HFMs were found to be more dispersed but with lower confidence interval around the mean in comparison to values obtained by thermography.

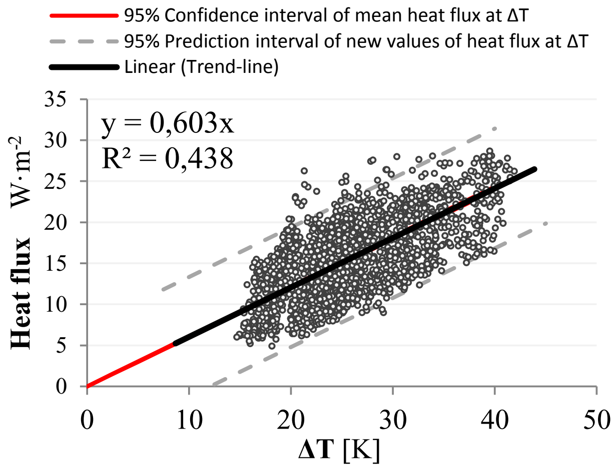

Fig. 8. Conduction heat transfer measured by the HFM vs. the difference between the indoor and outdoor temperatures, and the linear regression line (trend-line).

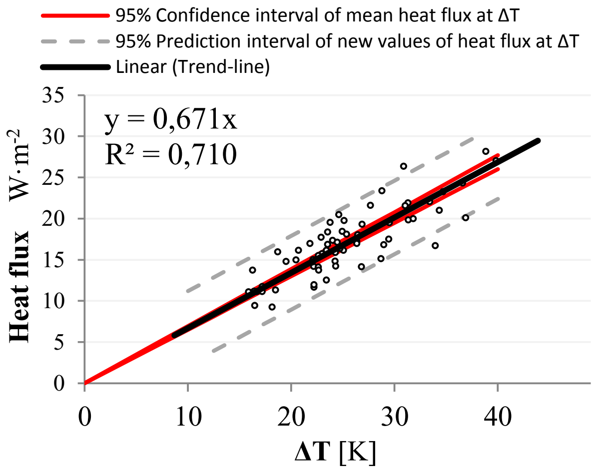

Fig. 9. Conduction heat transfer calculated by eq.7 vs. the difference between the indoor and outdoor temperatures, and the linear regression line (trend-line)

Table 2 summaries the values from the different measurements. The thermal conductivity measured by the two methods were found to differ with only 4%. The overall heat transfer coefficient of the large wall element, measured by thermography was found to be higher by 11.3% in comparison to the value obtain from the point measurements of the HFMs.

Table 2. Summary of the results.

	Conduction heat transfer coefficient $W·m^{-2}·K^{-1}$		**Thermal conductivity** $W·m^{-2}·K^{-1}$	**Overall heat transfer coefficient**[1] (*U-value*) $W·m^{-2}·K^{-1}$	
	Mean	95% confidence interval	Mean	Mean	95% confidence interval
Heat flux meters	0.712	±0.008 (1%)[2]	0.1	0.603	±0.006 (1%)[2]
Thermography small wall segment	0.741	±0.03 (4%)[2]	0.104	0.624	±0.02 (3%)[2]
Thermography large wall element	---	---	---	0.671	±0.02 (3%)[2]
Difference	4%		4%	3%[3], 11.3%[4]	

[1] For 140 mm massive wood thickness.
[2] The percentage of the confidence interval of the mean value.
[3] The percentage of the small wall segment of heat flux meters.
[4] The percentage of the large element wall to heat flux meters.

4. Discussion

In this study, infrared thermography was used to measure and calculate the overall heat transfer coefficient of 0.6 m^2 external wall element that was exposed to the outdoor weather conditions. The hypothesis was that linear regression over sufficient number of measurement would obtain relative accurate results even if large errors are expected in each of the individual measurement values due to the use of steady state equations in a non-steady state heat flow profile through the wall. Conductivity and overall heat transfer coefficient were measured both by using thermography and HFMs on a small wall area with similar temperature uniformity. The results from the two methods were found to be compatible with small differences of 4% and 3%, respectively for the conductivity and overall transfer coefficient, which suggest that thermography could be as accurate as HFMs.

The results indicate that steady state heat flow during a measurement period is not necessary if the number of measurements are large enough. The conduction and overall heat transfer coefficient was found to have a low confidence interval around the mean even though that large dispersion of heat flow values was observed. The high dispersion is the results of the non-steady state thermal conditions. The values obtained by the heat flux meters were found to be more dispersed but with lower confidence interval around the mean in comparison to values obtained by thermography. In this study, thermography measurements were taken in a low rate of up to three measurements per day. Higher sampling rate may reduce the confidence interval around the mean, increase accuracy and potentially even reduce the period of measurement.

The advantage of thermography over the use of HFMs is the ability to do qualitative and quantitative analysis over large areas of building elements, capturing non-uniformities, points of imperfections and linear thermal bridges. In this study areas of contacts between wood beams and areas with wood knots were found to increase the overall heat transfer coefficient by 11.3% in comparison to the values obtained from small measurement areas with uniform temperature.

In this study, the convection heat transfer coefficient was a key factor for obtaining accurate results. It was calculated by using both the HFM and infrared thermography and was to be 2.63 $W \cdot m^{-2} \cdot K^{-1}$ for the test object in this study. This value seems to be in the lower range of values according to the literature [20]. However, it is a difficult value to compare between studies as each study is subjected to specific conditions that may affect the results [20], i.e., wind velocity, wall texture, tilt, temperature and near objects. There is no indication that the value of the convection heat transfer obtain in this study is fault, since low confidence interval were obtained around the mean, which indicate high accuracy.

The method describe in this study applied on 140 mm thick massive wooden wall. The applicability of the method on other type of wall elements is yet have to put into test, for example cavity wall and wall elements that constructed with several material, e.g., wood and insulation. The method should also tested for wall elements with higher thermal efficiency and for different outdoor conditions.

5. Conclusions

- This study describes a quantitative method to measure the thermal properties of buildings by thermography combine with HFM.
- The results of this study showed that thermography can be used to measure thermal properties of buildings envelope even in a non-steady state heat flow conditions.
- In this method the value of the convective heat transfer coefficient is measured separately for each building element, since it has large effect on the results. The convective heat transfer coefficient is measured simultaneously with the conductivity of the building element, by using both thermography and HFMs.
- To obtain small measurement error it is important to have sufficient number of measurements. In this study 65 measurements were taken, resulting in a 3% to 4% error.
- Thermography has the advantage of measuring surface temperature over a large area of a building element, thus providing more representative data compared to spot measurements. In this study 11% higher overall heat transfer coefficient was obtained in comparison to spot measurements by HFMs, probably due to the ability of thermography to capture areas of imperfections, point and linear thermal bridges.

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