Topic: Building Physics, Building Envelope and Materials

Overview of a research project of novel and rapid in-situ U-value measurements

Petteri Huttunen[1], Juha Vinha[1]

[1]Faculty of Built Environment, Tampere University, Tampere, Finland

*Corresponding email: petteri.huttunen@tuni.fi

Keywords:in-situ measurement, U-value, thermal transmittance

SUMMARY

A Finnish-German collaborative project was carried out in 2018-2020 with the objective to investigate the accuracy and reliability of a novel metering device for in-situ determination of U-values of envelope structures. A rapid and reliable in-situ measurement method would clearly be a desirable tool for surveying the actual energy performance of existing buildings. Series of experimental and computational studies around a novel measurement device were carried out in Rapid U project. Rapidness of the measurement is sought by scheduling the moment of measurement so that the outdoor temperature has been sufficiently stable and cold before the measurement. Several test building measurements were carried out for certain structures in real weather conditions. Numerical modelling was also used to estimate the total number of hours in a year when the conditions are theoretically possible for similar structures to be measured rapidly. Repeated test building measurements showed unfortunately significant variation in the results. However, on average the results were promising and according to the simulations there should be plenty of suitable hours per year for rapid U-value measurement in cold countries if certain error tolerance is allowed.

INTRODUCTION

A Finnish-German consortium was formed in 2018 with the aim to validate and develop the novel Rapid U U-value metering technology. The device was tested initially by Salford University. Upon success the instrument developer and Salford University submitted jointly this technology for competition in 2015 organized by BRE (Building Research Establishment, UK), which called for new concepts and prototypes for rapid ways to assess the U-values of existing buildings [1]. Fundamental idea in the use of the device is to measure a momentary heat flux at the interior surface of an exterior wall (or any envelope structure which separates indoor and outdoor air). By monitoring weather progress near the building, the measurement is scheduled for the moment where the structure under investigation is with a high probability very close to stationary state of the heat flux so that the representative heat flux can be used to calculate the thermal transmittance (U-value, W/(m^2K)) by measuring the momentary temperature difference across the structure also.

Inside the casing of the device there is 40 mm plastic insulation in addition to the electrical components. If the device is unpowered and placed against wall surface, the contact interface between the wall and the device will start to cool because of the insulation – assuming that there is considerably cold temperature on the outside of the wall. When the device is powered, it prevents this temperature fall by supplying the required heating power to maintain the interface at the same temperature with the uncovered surface of the wall. To carry out this, the device has temperature sensor at the interface, reference meter at the side (which comes to contact with the uncovered surface of the wall) and digital circuitry for adjusting the correct amount of heating power. Before the measurement the device itself must be settled in the indoor temperature. A rechargeable battery can be used for several measurements per charge. One U-value determination lasts typically 1-2 hours depending on how rapidly the PID-controlled heat production stabilizes. For recording the indoor and outdoor temperatures, separate temperature meters are needed. Figure 1 shows photographs of the device from top and bottom. The size of the device is about 10 cm x 10 cm x 5 cm. The device can also be used on rough or slightly curved surfaces with an adapter piece.

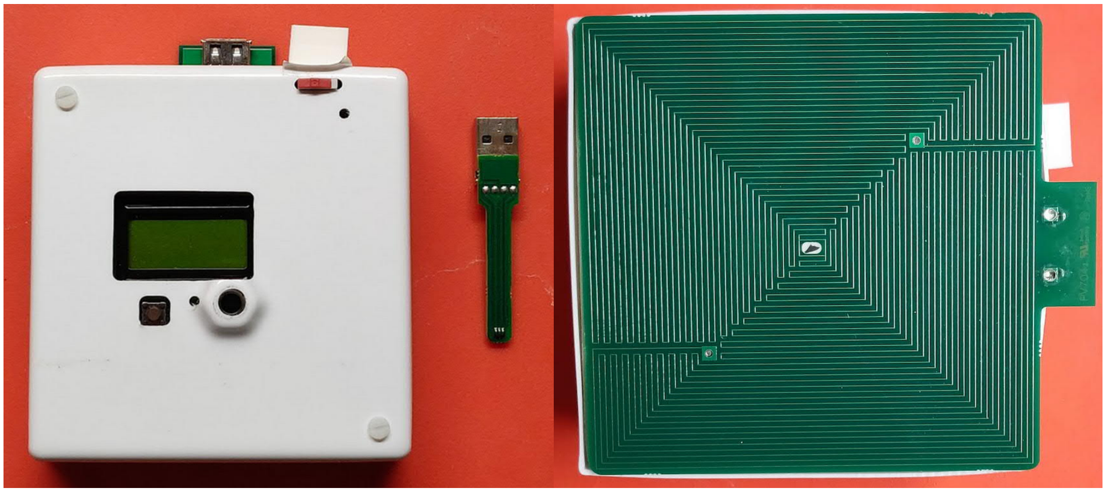

Figure 1. Left: The rapid U meter viewed from top side, where it has a digital screen, an indicator light and a threaded hole for the monopod stand. Next to the device is the reference surface temperature probe, which is connected to the device via USB-connector. Right: Bottom of the device, which is covered with heating coil.

Because in the BRE competition the device and related concept was acknowledged, further research has been carried out by Finnish-German collaboration. The consortium consisted of Arcada University of Applied Sciences, Tampere University (called Tampere University of Technology in 2018, abbreviated TUT hereafter), Raksystems (Nordic construction engineering office), FIW München (German institute for thermal insulation materials research) and DEN (Deutsches Energieberater-Netzwerk, the network of German building energy consultants/assessors). The roles in the consortium were divided so that TUT and FIW München carried out experimental work in laboratory (FIW) and test building (TUT) in addition to computational studies where the rest of the consortium partners focused on practical tests of the device in actual buildings in Finland and Germany. In this paper we show and discuss only the results of the research measures by TUT, which aimed to produce new information like guidelines and instructions related to when the rapid U-value measurements could be done reliably with the studied device based on weather data and forecast, i.e., mainly the coldness of outdoor temperature. Experimental work carried out by FIW focused on measurements in hot-box laboratory equipment and their final report of the project can be downloaded at [2]. Comparable competing technologies exist, such as the excitation pulse method (EPM) [3] and the method introduced by Sørensen [4]. Advantages of the Rapid U technology are low costs and theoretical simplicity compared to the EPM method, which requires dynamic heat pulse generation and solving differential equations. Major difference between Rapid U and the Sørensen's device is that in the latter the heat flux is measured from the exterior surface of the structure.

METHODS

Six reference wall types were chosen, which were used in the computations to estimate the rapid measurability U-values in different situations. The following walls were decided so that they would represent the most typical buildings both in Finland and Germany:
- W1: Solid brick wall, 360 mm, U-value: 1.30 W/(m^2K)
- W2: Light timber frame structure with 150 mm insulation, U-value: 0.22 W/(m^2K)
- W3: Concrete sandwich wall, 90 mm insulation, U-value: 0.36 W/(m^2K)
- W4: Brick-wool-brick wall, 100 mm insulation, U-value: 0.28 W/(m^2K)
- W5: Brick cavity wall, 100 mm air as insulation, U-value: 1.33 W/(m^2K)
- W6: Perforated brick wall, 360 mm, U-value: 1.00 W/(m^2K)

One dimensional two-year long hygrothermal numerical simulations for these structures were carried out by using Comsol Multiphysics (v.5.6) software with its built-in Building Materials - module. In the beginning of the project only thermal simulations were made with no coupled effect of moisture, but it was quickly seen in the early comparisons of simulations that the moisture transfer must be included in the simulations because of its significant effect on heat fluxes especially with brick structures. The models were implemented so that the effects of driving rain and short-wave direct and diffuse solar radiation were taken into account. Since there are differences in Finnish and German weather, which could affect the number of suitable moments for rapid U-value measurement, two reference years were used in the studies, a Finnish building physical test year Jokioinen (60° 48' 13.835" N 23° 29' 8.729" E) and German reference year Holzkirchen (47° 52' 51.806" N 11° 41' 59.128" E). Suitable building physical material properties were chosen from the WUFI material database and previous Finnish research publications such as [5], where the Finnish building physical test reference years were also determined in 2013.

For analysing the *measurability* at different moments of time in different wall structures with different thermal history before the hypothetical attempted heat flux measurement for rapid U-value determination, we defined the time-dependent *apparent U-value* as:

$$U_{app}(t) = \frac{q(t)}{\Delta T(t)} \tag{1}$$

Where $q(t)$ is the heat flux (W/m^2) at the interior surface at time t and $\Delta T(t)$ is the temperature difference (°C) at the corresponding moment of time. Thus, the simulation results were post-processed by extracting the heat flux values at every time step in the simulation (8760 one-hour time steps per year) to compute apparent U-values for every time step and to compare those to the reference U-values (computed with same material properties in stationary state). Obviously, the closer the apparent U-value is to the reference value, the closer the situation is to the stationary state and a rapid U-value determination at that moment would be possible. However, because the apparent U-value is almost never exactly the same as the reference U-value, certain discrepancies must be tolerated. Three different arbitrarily chosen tolerances were chosen in order to determine whether a certain moment of time is suitable for measurement or not (i.e., *measurable*). These tolerances and corresponding results of measurable hours per year with different structures according to the computations are shown and analyzed in following chapters of this article.

A significant factor in the measurability of structures is the stability of the indoor temperature, which was observed in both the test measurements in actual buildings and in the computational analyses. Researchers of DEN found that in the German buildings the heating systems are typically adjusted so that heating is frequently turned off to save energy. Dynamically changing indoor temperature was thus essential in the numerical analyses. In addition to perfectly stable 21 °C indoor temperature situation three changing temperature schemes were used also, where the indoor temperature changed diurnally according to a sine function, which had its maximum at noon (21.1 °C, 21.5 °C or 22 °C) and minimum at midnight (20.9 °C, 20.5 °C or 20 °C).

Figure 2. North side of the building physical test building in Tampere, Finland, with six test wall structures installed in the test openings.

For the test building measurements, a different set of wall structures was chosen since one aim was also to gather data on how the device would perform in practice on modern low U-value structures. Also, the structures were designed for producing comparative results on hygrothermal performance of exterior walls to be analyzed in future projects. The test building has 10 test openings (5 on the north side and 5 on the south side) for test walls structures (size 1.2 m x 2.5 m), which will be exposed to realistic weather once installed in the opening. Inside the building are adjusted typical indoor temperature and humidity conditions. Although there was a large number of temperature and humidity probes installed inside the structures, in this paper we discuss only the results regarding the heat fluxes and U-value determination. In total, 10 test walls were constructed, 2 identical ones for both the north and the south side of the building. The test wall structure types were:

- TB-W1: Brick-wool-brick, 100 mm insulation, reference U-value = 0.288 W/(m^2K)
- TB-W2: Wood panel façade, 150 mm insulation, reference U-value = 0.268 W/(m^2K)
- TB-W3: Wood panel façade, 300 mm insulation, reference U-value = 0.139 W/(m^2K)
- TB-W4: Brick cladding, 150 mm insulation, reference U-value = 0.247 W/(m^2K)
- TB-W5: Brick cladding, 300 mm insulation, reference U-value = 0.133 W/(m^2K)

The insulation material in all test building structures was low-density fiberglass. The load bearing structure in other structures than TB-W1 was light-weight timber frame. Figures 2 and 3 show photographs from the test building with installed test walls.

Figure 3. Two devices for rapid in-situ U-value measurement attached to test walls with adhesive tape.

RESULTS

Due to the lack of space only a small portion of the result data from the project can be shown in this article. However, the most important findings are related to the changing indoor temperature and the acceptable error of the measurement. In figures 4 and 5 are visualized how the total number of measurable hours per year decreases as the amplitude of diurnally changing indoor temperature increases. Measurable hour is defined here as a theoretical moment of time (a time step in calculations) when the heat flux on the interior surface corresponds closely to the exact U-value. Figure 4 shows results where the moment t is considered measurable if $U_{app}(t)$ does not deviate more than 5 % of the U_{ref}. Figure 5 shows similar results, but where a less strict tolerance is used: $U_{app}(t)$ must be $U_{ref} \pm (0.05\ \mathrm{W/(m^2K)} + 5\ \%$ of the $U_{ref})$.

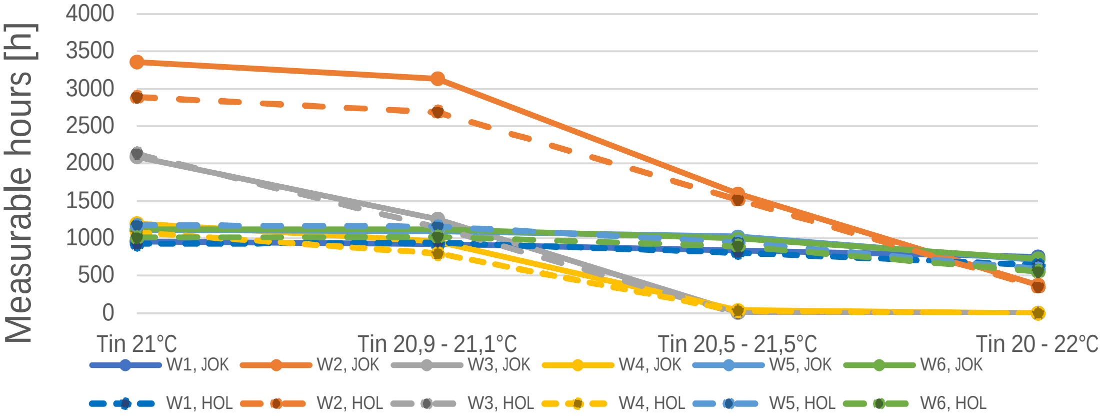

Figure 4. Measurable hours per year for structures W1-W6 oriented north in both climates (JOK = Jokioinen, HOL = Holzkirchen). Measurability tolerance: $U_{app} = U_{ref} \pm 5$ *% of the* U_{ref}

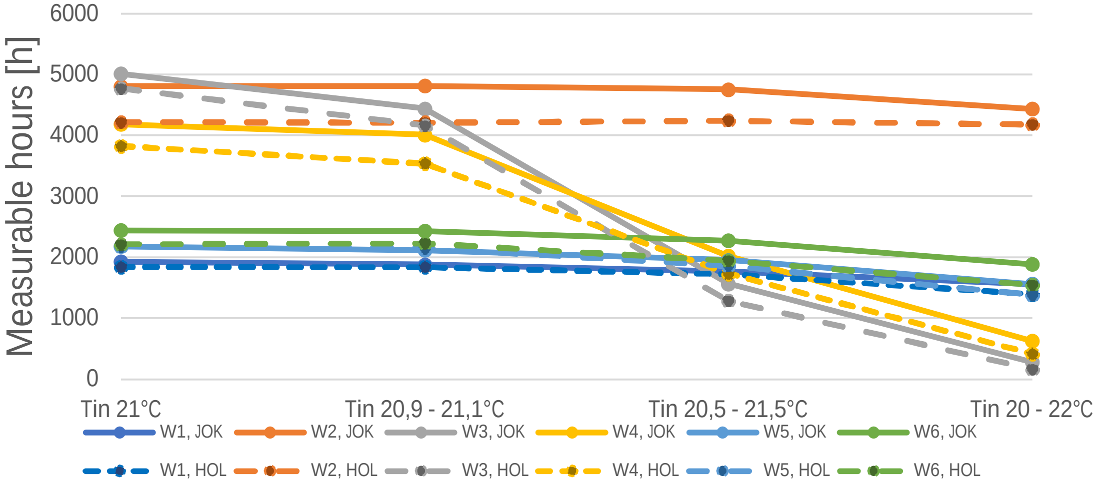

Figure 5. Measurable hours per year for structures W1-W6 oriented north in both climates (JOK = Jokioinen, HOL = Holzkirchen). Measurability tolerance: $U_{app} = U_{ref} \pm 0.05$ *W/(m^{2}K) ± 5 % of the* U_{ref}

From figures 4 and 5 can be seen that the number of theoretically possible moments for rapid measurements in Jokioinen (Finland) and Holzkirchen (Germany) is close to each other. If a measurement error around ± 0.05 W/(m^{2}K) due to thermal nonstationarity is accepted, a lightweight decently insulated (150 mm fiberglass) timber-frame wall has plenty of measurable hours per year and almost any moment in winter is theoretically suitable even if the indoor temperature is not especially stable. Using the same, less strict measurability tolerance, indoor temperature instability does not seem to affect on the measurability of other structure types, except for the W3, which is the concrete sandwich. It was concluded that the most difficult structures for rapid measurement are structures, that are heavy (i.e., have thermal mass) and in addition have somewhat more thermal insulation than e.g., an uninsulated solid brick wall. Table 1 shows the averaged U-value measurements from the test building. Measurements were carried out from March to May 2020 when temperature difference was typically less than 20 °C.

Table 1. Averaged U-value measurement results. N (meas.) = total number of measurements. SD = standard deviation.

Structure	North/South	N (meas.)	U_{avg}	U_{ref}	SD
TB-W1	N	28	0.251	0.288	0.144
TB-W1	S	31	0.289	0.288	0.152
TB-W2	N	32	0.391	0.268	0.120
TB-W2	S	38	0.272	0.268	0.072
TB-W3	N	38	0.201	0.139	0.054
TB-W3	S	32	0.248	0.139	0.084
TB-W4	N	37	0.283	0.247	0.068
TB-W4	S	33	0.248	0.247	0.080
TB-W5	N	41	0.199	0.133	0.064
TB-W5	S	32	0.166	0.133	0.067

Figure 6 shows an example of the individual U-value results from one structure (TB-W2, wood panel façade with timber frame, 150 mm insulation).

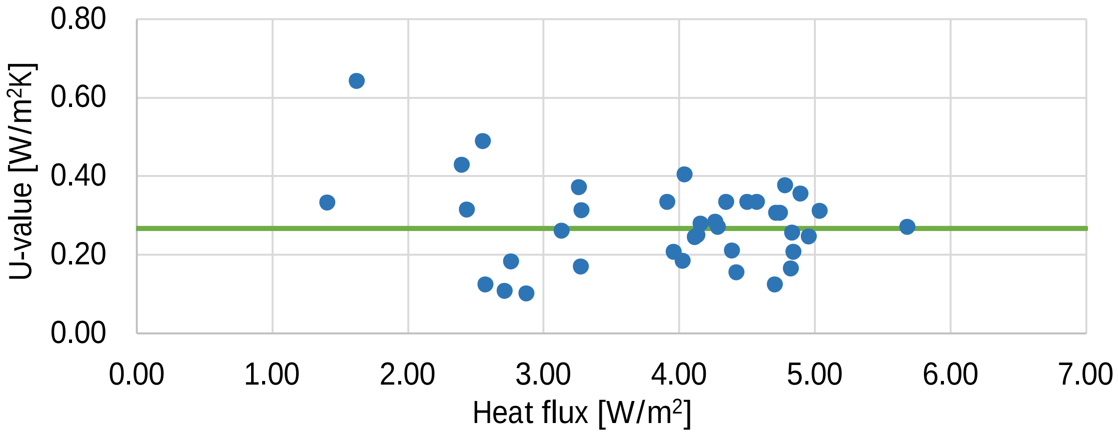

Figure 6. Test building U-value measurement results from structure TB-W2 (south orientation) as a function of resulted heat flux. Green line = U_{ref} =0.268 W/(m^2K).

Clearly, low temperature difference means low heat flux and higher deviation in the results. Some structures in table 1 show very good agreement between U_{ref} and averaged result from U-value measurements. In general, structures with higher U-value had better agreement between measurements and expected values. Standard deviation is the highest with brick-wool-brick structure, although it had quite good results on average. Unexpectedly, the averaged values are better from the south side while it was expected that solar radiation and rain would disturb the south side more. The reference U-value is, however, calculated and based on tabulated values of thermal material properties.

DISCUSSION

The concept behind the device studied in this project is very ambitious and much more development is required if it was to be used in e.g., quality control purposes. However, when surveying an old building with unknown thermal properties it could be useful when several relatively cheap devices would be used in different locations of the envelope and several measurements would be carried out from the same points. A newer generation version of the device exists, which has shown faster heat flux stabilization times and whose circuitry produces less heat. In any case, the U-value measurement requires reasonable temperature difference over the structure.

CONCLUSIONS

Rapid in-situ U-value measurement would be very desirable for researchers, real-state owners, building energy consultant etc. but it has several difficulties which require more research. The small device, which was studied in this project can offer some advantages over e.g., the well-known standardized method described in [6], but at least at its current development state requires dozens of measurements per location for reliable result.

ACKNOWLEDGEMENT

The research was funded by BusinessFinland (public organization under the Finnish Ministry of Employment and the Economy) and the Finnish Ministry of Environment. Both organizations are gratefully acknowledged.

REFERENCES

[1] BRE. 2017. Solid wall heat losses and the potential for energy saving. Rapid measurement device test report - Summary. https://www.bre.co.uk/filelibrary/pdf/projects/swi/Rapid-measurement-test-report-SUMMARY-v2.2.pdf (2017. viewed 2022-02-09)

[2] Sprengard, C. and Schreiber C. 2020. Forschungsbericht FO-2018/07, FIW München. https://doi.org/10.2314/KXP:1776156374

[3] Rasooli, A. & al. 2016. A response factor-based method for the rapid in-situ determination of wall's thermal resistance in existing buildings. *Energy and Buildings*, 119, pp. 51-61.

[4] Sørensen, L.S. 2010. Energy Renovation of Buildings Utilizing the U-value Meter, a New Heat Loss Measuring Device. *Sustainability*, 2(2), pp. 461.

[5] Vinha, J. & al. 2013. Effects of climate change and increasing of thermal insulation on moisture performance of envelope assemblies and energy consumption of buildings (only abstract in English). Tampere University of Technology. https://urn.fi/URN:ISBN:978-952-15-2949-8

[6] ISO. Thermal Insulation – Building elements – In-situ measurement of thermal resistance and thermal transmittance. ISO 9869. 1994.