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Article

Energy Renovation of Buildings Utilizing the U-value Meter, a New Heat Loss Measuring Device

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Abstract: A new device with the ability to measure heat loss from building facades is proposed. Yet to be commercially developed, the U-value Meter can be used as stand-alone apparatus, or in combination with thermographic-equipment. The U-value meter complements thermographs, which only reproduce surface temperature and not the heat loss distribution. There is need for a device that measures the heat loss in a quantitative manner. Convective as well as radiative heat losses are captured and measured with a five-layer thermal system. Heat losses are measured in the SI-unit W/m^2K. The aim is to achieve more cost-effective building renovation, and provide a means to check the fulfillment of Building Regulation requirements with respect to stated U-values (heat transmission coefficients). In this way it should be possible to greatly reduce energy consumption of buildings.

Keywords: heat loss measuring; energy renovation; conductivity; thermal radiation

1. Introduction

1.1. Introduction to Energy Renovation

Building owners, particularly in temperate regions of the world, are able to decrease heating costs remarkably with a rational energy renovation of their buildings. This is proven by measurements of different houses, built in different decades of the past century. A few examples are described for houses from the Nineteen-twenties and the Nineteen-seventies in a case study later in this paper.

Heating accounts for some 40% of the total Danish energy consumption which, therefore, represents vast potential savings. The U-value meter is an ideal instrument by which to establish the locations of greatest heat loss on a facade, arming owners with the knowledge of where best to concentrate efforts to insulate and optimise savings. In this way overall costs of energy renovation can be reduced considerably, and an optimal relation between investment and savings achieved.

The mean ambient temperature in Denmark has increased by about 1.2 ℃ during a period of approximate 130 years [4]. The period encompasses a part of the industrial revolution which began during the second half of the 18th century. Energy renovation of as many houses as possible worldwide would benefit the environment by slowing and decreasing the consequent global heating.

A project with the aim of designing standardized solutions for energy renovation of facades is currently being planned. In the project the U-value meter will be utilized to measure representative U-values for a number of different residential houses built in a period from about the nineteen-forties to the nineteen-nineties representing over 90 percent of private houses in Denmark. The measurements will be compared to the U-value requirements for the respective construction periods. From this approach we are able to calculate the potential heat savings compared to the present U-value requirements, as per the Building Regulations (BR08). Furthermore, we can compare heat consumption before and after energy renovations where the developed standard solutions for the renovation of facades are used. The involved parties will, among others, be HT-Meter ApS., Saint-Gobain Isover A/S together with DTU, the latter being represented by the so called LavEByg network. The project aims to minimize the emission of CO_2 caused by unnecessarily large energy consumption for heating.

1.2. Introduction to U-value Meter

U-value measurements are made in laboratories today with the assistance of heat flux measurements and heat conductivity apparatus [3]. Such measurement methods are complicated and laborious because the target wall or window elements must be transported to the laboratory and mounted into the test arrangement designed for the experiment. Then controlled amounts of energy, resulting in rises in temperature, must be supplied to the test arrangement in order to initiate the essential heat transfer in the test piece.

Fourier's law representing heat conduction, represented by the following equation:

$$\Phi = k\Delta T/\Delta x \tag{1}$$

Equation (1) is a special 1D form of Fourier's law, which only applies to the steady-state. Laboratory measurements of U-values can take several hours or even days before a steady-state measurement can be obtained.

The time required to reach a steady state situation depends primarily on the thermal inertia of the test piece, *i.e.*, material based properties such as heat capacity, density, thermal conductivity and material thickness. After that measurements of the heat flux are typically carried out for a relatively long period of time. This is done by means of measurements in test arrangements which are large in volume, typically several cubic meters. The heat flux is measured by holding a constant temperature level on the heat receiving side, *i.e.*, the cold side of the test piece. If we have a test piece with only one layer of material, a glass pane for instance, then heat conductivity apparatus is sufficient to determine the material's practical heat conductivity.

The basis of finding these heat conductivities practically is therefore by means of laboratory based measurements on conditioned test specimens brought to steady state by means of a plate apparatus with a protective ring or with a heat flux meter per DS/EN 12,664 or DS/EN 12,667. The material is previously brought into moisture equilibrium in air with relative humidity of 35–50 percent. The results from the measurements refer to a mean temperature of 10 ℃. Common to the aforementioned measuring methods is the problem of a transition insulation factor at the bounding surfaces on the two sides of a test piece. The surface temperatures of the test piece are not identical to the air temperatures very near to its surfaces. This problem is addressed in different ways by state of the art technology and with reasonable accuracy [3].

There exist some test arrangements that can be brought to a building where the heat loss or a thermal conductivity is being researched. For instance US Patent 4,173,894 describes a temperature sensing device adapted to maximize heat transfer from a selected location to the device and US Patent 6,257,761 claims an insulating measuring apparatus which forces heat flow in one direction within a constant temperature region. Incorporated is an electronically controlled heating device used to form a region of constant high temperature on one side of the insulating material causing the majority of heat transfer to concentrate in a longitudinal heat flux, which flows across the thickness of a test piece effecting a one-dimensional heat transfer. Others patented types worth a mention include those mentioned in US 4,647,221, DE 19,516,480, US 4,236,403, FR 2,671,185 and EP 0,065,433 [3].

None of these apparatus or arrangements provides a measuring device for heat transmission coefficients or thermal conductivities where an air gap is provided between the surface of the test piece and a sensor plate (heat absorption sensor) as is achieved by the U-value meter. Furthermore, several of those mentioned force heat through the test piece *via* different electronic equipment techniques. Others measure an electrical resistance between the surfaces of the test piece according to the temperature difference of the two surfaces and gain an estimate of the heat transmission coefficient calculated from this observed electrical resistance. A rather inaccurate result is obtained this way.

Finally, on most of the reported existing apparatus, it is necessary to mount some of the test equipment on the test piece leaving some cracks or drill holes on the object. For all of the existing apparatus there is direct contact between the heat absorption sensor (sensor plate) and the surface of the test piece, thereby seriously affecting the result due to the transition insulation factor caused by the air gained insulating effect near the surfaces [3].

2. Description of the U-value Meter

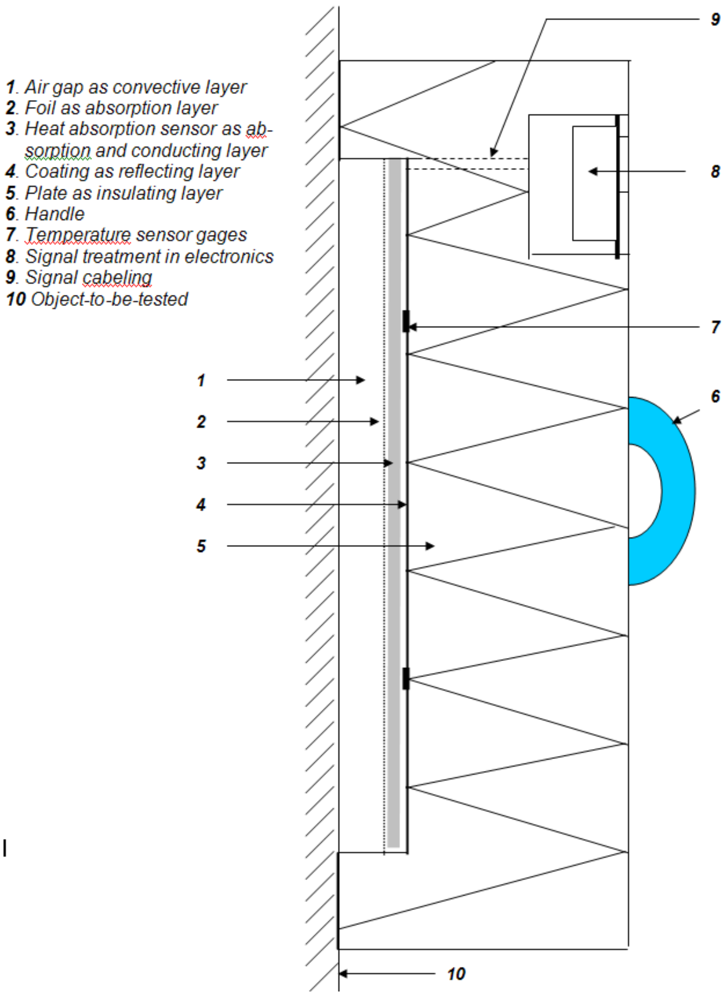
2.1. U-value Meter

A picture of the U-value meter is shown on Figure 1. The U-value meter utilized during energy renovation of buildings is explained in more detail in the following, where references are made to Figure 2.

This apparatus is based on a principle where the heat is ‘trapped’ by a heat absorption sensor (copper plate) {3} when it leaves the outdoor surface of the test piece. A copper plate is used, as the absorption sensor {3} due to its high thermal diffusivity and high conductivity.

Figure 1. Picture of U-value meter in use.

Figure 2. U-value meter, shown in principle [3].



The temperature of the heat absorption sensor is measured continuously over a short period of time, and from the relative increase of energy the U-value can be calculated. The system is separated from the surrounding environment with a highly insulating material {5}, of low thermal diffusivity and low conductivity.

Heat transfer occurs by thermal radiation, conduction and convection and the apparatus is designed to ensure that these constituent energy components are collected by the sensor plate. In fact, in the case of windows, radiation alone can account for as much as 70 percent of its total heat loss. However, this value can be reduced drastically with a low emissivity coating: windows with and without these coatings can be handled by the U-value meter.

Heat conduction is the molecular oscillation transport whereas radiation is electromagnetic energy transport. In the U-value meter it is chosen to transform the heat conduction (conduction in a solid) to convection in a fluid (an air gap {1} in front of the copper plate is included to do this). That is to say the transfer process to the heat absorption sensor is changed from conduction to convection through the air gap. It is important to ensure that the temperature of the heat absorption sensor is identical with the outdoor temperature just before a heat transmission coefficient measurement is initiated [3].

The heat absorption sensor is coated with a material of high heat absorption capacity to secure a quick and effective heat transfer from test piece to heat absorption sensor. Heat transfer occurs by convection as well as thermal radiation *via* the described air gap. Following this procedure, there is no ongoing heat transfer from the surface of the test piece to the heat absorption sensor by direct contact.

By the new 'air gap' technique, developed with this invention, the problems of transition insulation factor and surface temperature are eliminated, creating more accurate results (see section 3 for results and uncertainties). At the same time, geometrical inaccuracies at the surface of the test piece are eliminated by the air gap. These would, by direct contact, cause irregular heat conduction between the two surfaces, *i.e.*, between the test piece and the copper plate.

The coating is placed on the side of the heat absorption sensor {3} facing the test piece. On the opposite side of the heat absorption sensor, apart from the test piece, is placed a reflecting layer {4}, to ensure energy transmitted to the heat absorption sensor is trapped and kept inside during the test.

Behind the reflecting foil is a heat insulating layer {5}, of relatively thick dimensions, and low thermal conductivity and diffusivity as basic thermal properties.

With this invention a very good accuracy is achieved for measuring of transmission coefficients (U-values). The accuracy of the results is between +/–5 percent from the 'correct' result according to information from different producers of building components, tested *via* laboratory. See Sections 3 and 4 about measurement results, uncertainties and limitations.

The measurements are done much quicker, *via* this invention, than we have seen previously. Furthermore the measurements can be done *in situ* instead of in a laboratory. There is no requirement to mount test equipment on the test piece. A steady state heat loss process is normally achieved for at least the light building components, fenestration and doors. The Meter is not suited for heavy walls, due to the fact that the heat transfer process in building envelope components—generally speaking—is not in a steady state.

The period of measuring is only 20 seconds and afterwards approximately half a minute to get thermal balance before moving to the next measurement location. The apparatus is relatively small, around 270 mm × 270 mm × 90 mm and, weighing less than 1.5 kilogram, is entirely mobile. It is also very user friendly.

Another advantage of the invention is that the U-values are measured on site and in real time, giving current information of transmission coefficients for a particular building as opposed to the 'new building element' U-value. This is important of several reasons: first of all in a building element, an outer wall for instance, the moisture content changes during the years in which the element has been a part of the building. Moisture levels will influence the U-value, depending of the relative humidity and the type of material in focus. Furthermore the insulation in an outer wall can ‘fall down’ a bit during the years resulting in poorly distributed insulation. For windows the glazing can puncture and the insulating effect is reduced significant.

In summary:

1. A steady state heat loss process is utilized
2. The transition insulation factor problem is solved, by measuring implicitly *via* air gap/convector techniques
3. An enthalpy based physical measuring principle is utilized
4. Practical, current U-values (heat transmission coefficients) are measured
5. No need to measure in the laboratory but outside the building
6. The measurements are rapid
7. Mobile equipment weighing less than 2 kg
8. Easy to operate apparatus
9. No need for to mount equipment on the test piece.

On the side of the heat absorption sensor {3} apart from the test piece, is mounted a number of temperature sensor gauges {7}. These sensor gauges are able to measure the temperature rise in the sensor plate {3} with an accuracy of 1/1000 K. Therefore a temperature rise during a 20s meter application is sufficient. The sensors are of the type ETG-50B/E and are nickel based. ETG-Series gauges are fabricated with high-purity nickel foil sensing grids, and are used to monitor temperatures in strain gauge work and related applications. These gauges are open-faced construction with a 1 thou (0.03 mm) tough, flexible polyimide backing. The temperature measuring interval is –195 ℃ to + 230 ℃. The sensors are mounted to the sensor plate {3} with hightemperature epoxy adhesives for best performance. The temperature sensors are protected after mounting with suitable protective coating and are applied just after gauge installation. M-M Protective Coatings is used.

Measured values are used in a system of equations where care is taken of the thermal properties of the heat absorption sensor plate {3}, the mass, outdoor temperature, the increase of temperature in the sensor plate, the heat capacity and a nonlinear convective transfer coefficient and furthermore the properties of the test piece section, area, temperatures near the two sides and the measuring time. Measuring signals are treated by the processor in the electronics {8}, and a result on the U-value is the outcome and shown in the display.

2.2. Main Processor

One of the main objectives of the processor is to solve Fourier’s heat transfer equation for a steady-state situation [3]. This equation, in differential form, can be expressed as:

$$\Phi = k \cdot dT/dx \tag{2}$$

where dT/dx is the temperature gradient through a homogenous material, in the direction of heat transfer. The equation is representing the heat loss in Joules per second for each square meter of the test piece. The apparatus is intended mainly for existing buildings where a steady-state heat flow is already obtained. The heat loss expressed by the above differential equation is integrated by the processor during a fixed measuring period of 20 seconds. The energy is transmitted to and captured by the heat absorption sensor through the previous described 'five layer thermal system'. The total transport of energy from the surface of the test object to the surface of the heat absorption sensor takes place by two separate processes:

I. By convective heat transmission:

$$\Phi_c = h \cdot (T_{air} - T_{cu}) \tag{3}$$

where h is the convective heat transmission coefficient and T_{air} and T_{cu} are the absolute temperatures of the air gap and heat absorption sensor surfaces, respectively.

II. By thermal radiation, where the approximate equation for the radiative heat flux (*i.e.*, radiative heat transfer per unit area) between the surfaces bounding the air gap is:

$$\Phi_r = \frac{\sigma \cdot (T_{testpiece}^{\ 4} - T_{cu}^{\ 4})}{\dfrac{1}{\varepsilon_{testpiece}} + \dfrac{1}{\varepsilon_{cu}} - 1} \tag{4}$$

where σ is the Stefan-Boltzmann's constant, $T_{test\ piece}$ and T_{cu} are the absolute temperatures of the 'test piece' and 'heat absorption sensor' surfaces and $\varepsilon_{test\ piece}$ and ε_{cu} their corresponding thermal emittances [5]. A configuration factor (F) could be omitted due to it's value of unity. It should be mentioned that the process of heat transfer to the heat absorption sensor is governed by a nonlinear process, which is taken care of in the processor as well.

The heat transmission coefficient, or U-value, is obtained this way: The summarised energy in the heat absorption sensor will rise the temperature in the sensor to a level corresponding to the new level of internal energy, governed by the product:

$$m_{cu} \cdot c_{cu} \cdot \Delta T_{cu} \tag{5}$$

where m_{cu} is the mass and c_{cu} is the specific heat capacity of the heat absorption sensor {3}. ΔT_{cu} is the temperature rise in the heat absorption sensor during the measuring period.

Therefore the rise in level of internal energy should equal the amount of energy transmitted to the heat absorption sensor which can be expressed like this:

$$\Sigma(\Phi_c + \Phi_r)_i \Delta t_i \tag{6}$$

where Φ_c is the convective heat flux and Φ_r the radiative heat flux. Δt_i is 1 s intervals over which the sensor energy integration is performed. The energy is integrated over the measurement period, *i.e.*, 20 s. The heat transmission coefficient through a multilayer slab with thermal resistances at the inner and outer surfaces is defined by:

$$1/U = \Sigma dX_i/k_i + R_{in} + R_{out} \tag{7}$$

where R_{in} and R_{out} are the interface resistances from the air layer at the inner and outer surfaces respectively. dX_i is the thickness in meter of layer number 'i' in a composite construction, and k_i is that layer's corresponding heat conduction coefficient in [W/m·K]. We also need to take the area of the heat absorption sensor plate into consideration. The equation:

$$\Sigma(\Phi_c + \Phi_r)_i \Delta t_i \cdot A = m_{cu} \cdot c_{cu} \cdot \Delta T_{cu} \quad (8)$$

where A is the area (m^2) of the heat absorption sensor plate is the main equation, and it is solved taking the following relation from [2,3] into account:

$$\Phi = (\Phi_c + \Phi_r) \cdot A = U \cdot A \cdot (T_{in} - T_{out}) \quad (9)$$

T_{in} and T_{out} are the absolute indoor and outdoor temperatures, respectively. From (9) we are able to get the U-value expression as:

$$U = (\Phi_c + \Phi_r) \cdot A / (T_{in} - T_{out}) \cdot A \quad (10)$$

By multiplying numerator and denominator with the measuring time Δt (= 20s) and utilize the relations given by (8) noting that $\Delta t = \Sigma \Delta t_i$, we get:

$$U = m_{cu} \cdot c_{cu} \cdot \Delta T_{cu} / (T_{in} - T_{out}) \cdot A \cdot \Delta t \quad (11)$$

Therefore, before a measurement is started, we need to know the temperatures on both sides of the test object *i.e.*, T_{in} and T_{out} respectively. The apparatus is able to measure T_{out} automatically.

2.3. Measuring Procedure

The measuring procedure for the U-value Meter is outlined in a detailed way below:

1. If the Meter is taken outdoors from an indoor environment the Meter has to be acclimatized to the outdoor temperature for a period of minimum half an hour. The display will show 'Waiting', until the Meter is in thermal equilibrium with its surroundings. While waiting, the Meter can display the difference between the reference sensor and the heat absorption sensor temperatures.
2. After acclimatization the user is prompted to key in the indoor temperature. After that the user is asked to hold the reference sensor up in the air, and the outdoor temperature is measured for half a minute. During data acquisition these temperature values are given as input to the main processor. In fact, the outdoor temperature is continuously measured by the reference sensor and can be displayed at any time while the apparatus is turned on.
3. When thermal equilibrium is reached, the display says 'Ready' and the user can initiate the measurement. If the user, by accident, turns the Meter towards the sun or puts his hand on the heat absorption sensor, causing a thermal rise in the heat absorption sensor, the processor will show the message 'Waiting…' again, indication lack of thermal balance. Thermal equilibrium is reached when the temperature difference between the heat absorption sensor and the reference sensor is below 0.3 °C.

4. When the user holds the Meter against the test piece, the main processor starts to count the time and the measuring process is going on for the entire measuring period (20 seconds). The display shows 'Measuring…' and displays the temperature rise of the heat absorption sensor, while the measurement goes on.
5. Immediately after the measurement is finished, the display says 'Calculate…' for a few seconds and the U-value is presented afterwards.
6. The user can store the results in an internal memory by pressing the button 'Memory'.
7. The Meter will display 'Waiting…' until the heat absorption sensor is back in thermal equilibrium with the outdoor temperature, and after that a new measurement can begin.

2.4. Data Processing

The signal treatment and data processing in the electronics (see item 8 on Figure 2) consist of the following six main parts:

1. Low energy Battery Management. A single 9 V battery or 6 × 1.5 V batteries (rechargeable or single use) supplies current to all the features of the apparatus. Rechargeable batteries can be charged in the apparatus. Charger is supplied.
2. Dot Matrix Display. The display is a green LED-display enabling to read in daylight as well as in dark if the measurements take place during the night.
3. Main processor. This is where all the calculations are done, *i.e.*, solving the formulas according to the principles described in section 2.2. The main processor is governed by software (approximate 800 lines of coding language C). Also the measuring procedure, including warnings *etc*. described in section 2.3 is handled in the processor.
4. In-System Programming Interface. An adapter enabling programming of the apparatus' main processor utilizing the coding language C.
5. Data Acquisition System. Governing the data flow to and from the main processor.
6. Thermal Sensor 4 point interface. Adaptor for signals from the four main sensors, placed on the heat absorption sensor and for the reference sensor as well.

It is beyond the scope of this presentation in further detail to present the form of the related data processing algorithm in the main processor, including output validation. But, the data processing aims to solve the thermo-physics described in Section 2.2, by means of signal input to the processor, obtained *via* the described five layer thermal system.

3. Measurement Results and Uncertainties

Measurements were made at a number of buildings during the last five years, partly in parallel with the development of the apparatus and attached software. A few examples on measurements are shown below. U_1, U_2 and U_3 in example 1 are measured over three days in February 2006 (and at different times during the day). U_2 and U_3 were measured in the evening around 9 pm. U_1 was measured in daylight at about noon (1 pm).

The expected U-values are the classified values for the windows and a calculated value according to DS 418 [7], and made on the basis of knowledge of the structure including insulation. The measured U-values are a little above the expected values.

Example I	**U_1**	**U_2**	**U_3**	**Expected U**	**Age**
Terrace door	1.35	1.33	1.31	1.20	6 years
LowE-glazed window	1.24	1.27	1.30	1.20	6 years
Outer wall	1.04	0.97	0.94	0.90	32 years

This could be due to ageing of the materials ('collapse' of insulation) and/or the windows could be measured near the edges where the heat loss is slightly larger. Furthermore, the deviations are due to uncertainties in the apparatus (hardware and software) and the thermo-physical principle that could be lacking fine adjustment. The variations between the individual measurements could be due to different weather conditions. The outdoor temperatures varied only slightly (from 6–8 °C). In all cases there was cloudy weather.

Another example of measurements is given below on a three-storeyed building at Technical University of Denmark (DTU). These measurements were made the 6th April 2006 during the daytime, and with only 10 minutes between the individual measurements.

Example II	**U_1**	**U_2**	**Expected U**	**Age**
Double-glazed window	3.00	3.15	2.80	36 years
Outer wall	0.41	0.42	0.40	36 years

These measured U-values are slightly above the expected U-values. The above mentioned reasons for the divergence could be valid here as well. See the next section about limitaitons.

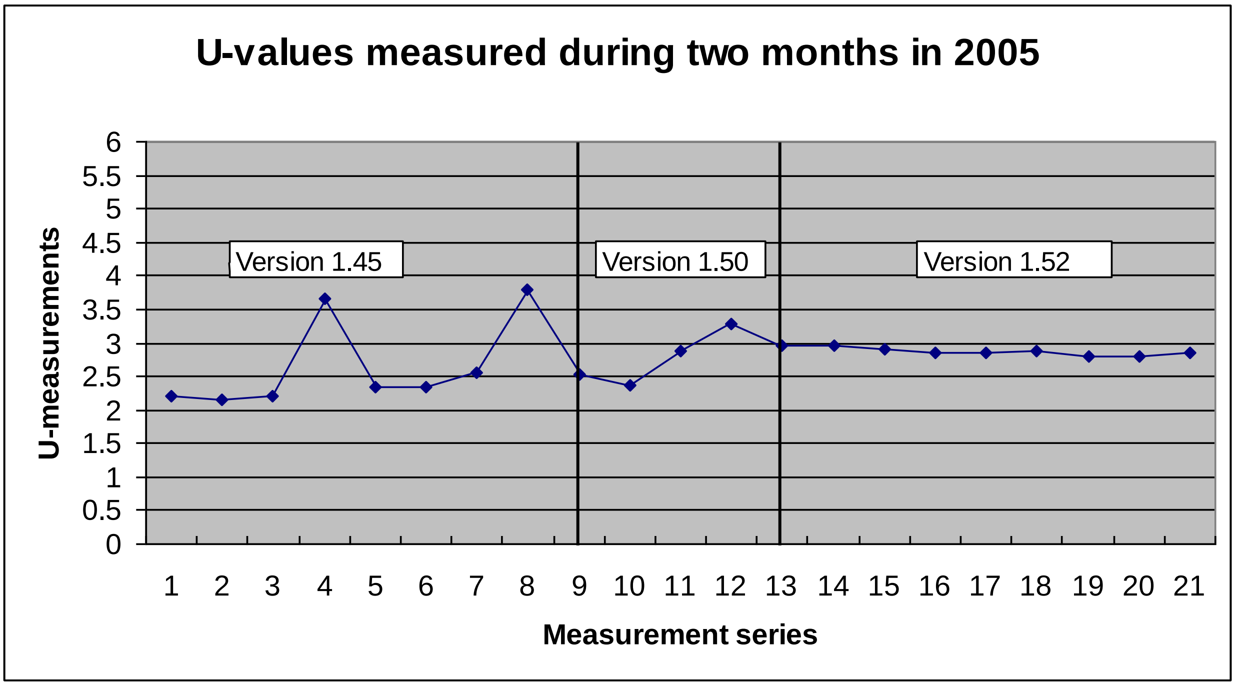
A third example of measurements is a double-glazed window in a house. The measured window was about 25 years old and the window was measured several times during the start of 2005. For each of the measurements the T_{in} and T_{out}, RH (Relative Humidity), weather conditions *etc*. were recorded. All the data are shown in Table 1 below. Updated software versions, and slightly adjusted measuring procedures were made during this series of measurements, finally resulting in much more uniformity in the results (see Figure 3). One of the main adjustments was that a more correct radiative heat transfer model was included into the software where both the temperatures of the heat absorption sensor and the surface of the test object were included and the interaction of radiative energy due to slight difference in temperatures. Furthermore a correction factor was included if the heat absorption sensor was not 100% acclimatized with the surroundings.

Example III	**U_{mean}**	**Expected U**	**Age**
Double-glazed window	2.87 (ver. 1.52)	2.80	25 years

The data belonging to the successive measuring series in Figure 3 are listed in Table 1, including important environmental data about the temperatures T_{in} and T_{out}, RH% (Relative Humidity), weather conditions (wind and sky) *etc*.

The table should be read in groups of data connected to each of the three software versions (1.45, 1.50 and 1.52), because of large differences in the results. See Figure 3 for justification of this statement. Some huge peak U-values appear in the table (more evident on Figure 3). These values were due to a failure in the radiative heat transfer model, coded in the software. Furthermore it was caused by the acclimatization procedure of the Meter (and thereby the heat absorption sensor) lacking consistency. These problems were solved in version 1.52.

Figure 3. U-value series measured on a double-glazed window. Data from Table 1.



Note: Versions relates to software development. The Version 1.52 compared to version 1.45 and 1.50 include an updated radiative model and an adjusted measuring procedure which secure a better acclimatization of the heat absorption sensor.

Table 1. Data attached to a U-value series measured on a double-glazed window.

$U_{measured}$	Date (2005)	Day/night	Wind	Sky	T_{in}	T_{out}	RH %	Note
2.20	12. Jan.	Night	Mod. blowing	Cloudy	21.0	4.2	73	Ver. 1.45
2.14	13. Jan.	Night	Slight blowing	Cloudy	20.6	3.6	70	Ver. 1.45
2.20	14. Jan.	Daytime	Calm	Cloudy	20.2	1.4	81.5	Ver. 1.45
3.67	14. Jan.	Night	Calm	Starry	20.6	–4.0	80	Ver. 1.45
2.33	15. Jan.	Daytime	Calm	Clear sky	20.6	–1.6	73.5	Ver. 1.45
2.34	16. Jan.	Daytime	Slight blowing	Cloudy	22.2	1.4	72	Ver. 1.45
2.56	17. Jan.	Daytime	Slight blowing	Cloudy	21.0	2.0	82	Ver. 1.45
3.80	18. Jan.	Night	Calm	Haze	20.8	–1.4	78.5	Ver. 1.45
2.53	21. Jan.	Daytime	Slight blowing	Hail shower	20.0	0.4	72.5	Ver. 1.45
2.36	23. Jan.	Daytime	Slight blowing	Slight cloudy	19.8	–1.2	78	Ver. 1.50
2.87	26. Jan.	Night	Calm	Cloudy	19.4	–4.4	69.5	Ver. 1.50
3.29	27. Jan.	Night	Calm	Cloudy	20.2	–2.4	76	Ver. 1.50
2.95	29. Jan.	Night	Calm	Cloudy	20.4	–3.8	72.5	Ver. 1.52
2.97	5. Feb.	Night	Calm	Starry	21.2	–2.0	71.5	Ver. 1.52

Table 1. *Cont.*

$U_{measured}$	Date (2005)	Day/night	Wind	Sky	T_{in}	T_{out}	RH %	Note
2.90	6. Feb.	Daytime	Mod. blowing	Cloudy	20.8	–2.6	71	Ver. 1.52
2.85	7. Feb.	Daytime	Calm	Unclouded	21.0	–3.7	75	Ver. 1.52
2.84	7. Feb.	Night	Calm	Starry	20.0	–5.2	73	Ver. 1.52
2.89	8. Feb.	Night	Calm	Starry	18.2	–5.0	65	Ver. 1.52
2.80	13. Feb.	Daytime	Mod. blowing	Cloudy	19.3	–2.5	81	Ver. 1.52
2.80	3. Mar.	Daytime	Slight blowing	Cloudy	20.4	–16	68	Ver. 1.52
2.84	8. Mar.	Night	Calm	Slight cloudy	20.8	–2.1	70.8	Ver. 1.52

Note: Wind speeds: Calm: 0–1 m/s; Slight blowing: 2–4 m/s; Mod. blowing: 5–10 m/s

4. Limitations of the U-value Meter

Real house walls never operate at steady state conditions and therefore a single external heat flux measurement can lead to significant errors. For example, when an east-facing wall after a cold night is exposed to solar radiation, the heat flow at the outer surface can be into the building rather than out of the building. That phenomena can be checked *via* the U-value meter and, if present, measurements are omitted.

Stormy weather is a problem as well because of its disruptive effect on the heat transmission from the outer surface of the object to the heat absorption sensor. A measurement was made during a snowstorm with wind speed above 20 m/s. The U-value of a double-glazed window was measured to just 1.80 W/m^{2}K instead of the expected 2.80 W/m^{2}K. Wind speeds below 10 m/s do not influence the heat transfer environment near the facade very much, and measurements can be done with good accuracy.

Solar radiation direct on a façade before a measurement will result in variations. This is due to the heating of the surface which tell nothing about the heat loss through the façade, But, the Meter will measure any heat reaching its heat absorption sensor, and therefore the sun generated heat will disturb the results.

Moisture in the material is another limitation in the application of the Meter. This is due to the evaporation of the moisture from surface. The evaporation requires energy, and a part of the heat loss is consumed during this evaporation process, resulting in lower measured U-values. Taking repeated measurement at different points in time may average some of the variability out off course. For this to work it may also be critical to minimize the sun exposure to the measure surface.

5. Case Study

It is well known that in Denmark there is a great energy saving potential in houses built in the nineteen-sixties and seventies. Special scrutiny is given to these houses since they account for a large part of the total residential dwellings. In principle it is possible to energy renovate all types of housing up to modern requirements. It just depends on a sufficient increase of insulation in facades and ceiling, replacing traditional double-glazed panes with energy saving panes of low U-value (<1.1 W/m^2K), mounting draught-exclusion strips around doors and windows, optimizing heating systems, changing to energy saving light sources and, crucially, on willingness to pay up-front costs for hidden benefits. A few examples of energy renovation projects made in Denmark are described below.

5.1. Houses from the Nineteen-Twenties

Measurements of heat loss were made after a thorough renovation of a 161 sqm, brick-house from 1927, located in Køge (Zealand, Denmark), showed cost reductions beyond expected. The yearly saving was DKK 22,300 (USD 4,460) instead of a first calculated saving of DKK 16,000 (USD 3,200). With respect to the financing of the renovation the net saving the first year (2007) was DKK 13,800 (USD 2,760) compared to estimated saving of DKK 7,500 (USD 1,500). The energy renovation was made during a demonstration project with parties from Rockwool, DTU, Danfoss and the Danish secretary of energy-marking. The oil consumption was reduced by 3,050 litres in the first year [1]. The saving potential will of course increase with increasing oil prices.

During the first year after the renovation was made, the oil prices did rise from 6.40 DKK/litre to 7.60 DKK/litre. This is the reason of more savings than calculated. The cost related to heating was reduced by 57 percent.

In the house located in Køge, the same indoor temperature as before the energy renovation was maintained, but at the half price! This demonstrates that an investment into energy renovation is one of the most profitable you can make to a house [1].

An extra advantage of the improvements is that the indoor environment will benefit by the heat loss reduction. For example draughts will be reduced. The costs related to the energy improvements in the house was DKK 157,000 (USD 31,400) including VAT. The improvements consisted of an increase of insulation thickness of the outer wall, ceiling and slope walls. The windows were improved by secondary windows with energy saving glass. The radiators were equipped with Danfoss thermostatic controlled valves [1].

5.2. House from the Nineteen-Seventies

A house build in 1972, located in Næstved, is energy renovated as part of a demonstration project in which Rockwool A/S was one of the parties. A consulting group connected to the project consists of members from DTU and SBi. DTU has since 2005 carried out energy measurements and calculations on temperature, moisture-level, gas and power consumption. The tasks of SBi have been to make the subsequent indoor climate investigations and to make measurements using track-gas [1].

The following improvements were made: insulation of the facades, foundations and ceiling, renovation of part of the roof, renovation and renewal of windows and outer doors, replacement of gas boiler, install of ventilation plant.

Before the energy renovation the energy consumption was approximate 233 kWh/m^2 per year. After the renovation will be as low as 90 kWh/m^2 per year and, on the whole, at the level of houses built according to the new Danish energy rules in the Building Regulations (BR08). The savings on the heat expenditure will be at approximate DKK 20,000 (USD 4,000) per year. A part of this can be used to financing the costs related to the energy renovation. Furthermore, the house has been more airtight and the air exchange is now controlled by the ventilation plant, instead of previous random leaks in the facades and roof [1].

6. Conclusions

A new heat loss measuring device, called a U-value meter, has been developed. The device was invented in 2001 and the first application to the Danish Patent Office took place in March 2002. A Danish patent has been granted in 2009 (Patent number 176,757). An international patent application has been filed in March 2003. The development of the apparatus took place in the period 2003–2008. The device can be utilized as a stand-alone apparatus, or in combination with thermograph-equipment. The latter should be in order to get a picture of the distribution of hot and cold locations of a buildings facade. But, since a thermograph only gives a picture of the surface temperatures, and not the heat loss distribution, there arises a need for a heat loss measuring device. The device measures heat losses through the facades in the SI-unit [W/m^{2}K]. Thermal conductance as well as the radiative heat losses are captured and measured by the device's five-layer thermal system. By means of the measuring device, it is possible to achieve a more cost-effective building renovation. It is possible to check whether heat transmission coefficients (U-values) meet the requirements as stated in the Building Regulations. The corresponding potential in reduction of energy consumption can be calculated.

References and Notes

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