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Article

Energy reduction in buildings in temperate and tropic regions utilizing a heat loss measuring device

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Global energy efficiency can be obtained in two ordinary ways. One way is to make improvement on the energy production and supply side, and the other way is, in general, to reduce the consumption of energy in society. This paper has focus on the latter and especially the consumption of energy for heating and cooling our houses. There is a huge energy-saving potential in this area for reducing both the global climate problems as well as economy challenges.

Heating of buildings in Denmark counts for approximately 40% of the entire national energy consumption. For this reason, a reduction of heat losses from building envelopes are of great importance in order to reach the Bologna CO_2-emission reduction targets. Upgrading of the energy performance of buildings is a topic of huge global interest these years [14]. Not only heating in the temperate and arctic regions are important, but also air conditioning and mechanical ventilation in the “warm countries” contribute to an enormous energy consumption and corresponding CO_2 emission.

In order to establish the best basis for upgrading the energy performance, it is important to make measurements of the heat losses at different places on a building facade, in order to optimise the energy performance. This paper presents a method for measuring the heat loss by utilising a U-value meter [2]. The U-value meter measures the heat transfer in the unit W/Km^2 and has been used in several projects to upgrade the energy performance in temperate regions. The U-value meter was also utilised in a EUDP project focusing on renovation of houses from the 1960s and 1970s. The U-value meter is now planned to be utilized in the tropics for measuring the thermal performance of facades with the aim to reduce the costs to air conditioning. In this context we introduce the initiation of a project between the National University of Singapore, Aalborg University, Denmark and HT-Meter, the latter as the U-value meter developer company.

Keywords: energy reduction of buildings, heat loss measuring; energy performance; heat loss measuring device; temperate and tropic regions, CO_2 emission, global climate, world economy.

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1. Introduction

1.1. Introduction to Energy Performance Upgrading

Around the world, building owners are able to decrease heating costs remarkably with a rational upgrading of the energy performance of their buildings. This is demonstrated by measurements of different houses, built in different decades of the past century. A few examples are described for houses from the 1960s and 1970s 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 the 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, the overall costs of upgrading the energy performance 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 ºC 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. Upgrading the energy performance of as many houses as possible worldwide would benefit the environment by slowing and decreasing the consequent global heating.

A EUDP project with the aim of designing standardised solutions for energy renovation of facades is currently in progress [6]. In the project, the U-value meter is utilised to measure representative U-values for a number of different residential houses built in the period from 1960s-1970s and representing over 90% of private houses in Denmark. The measurements will be compared with the U-value requirements for the respective construction periods. From this approach we are able to calculate the potential heat savings compared with the present U-value requirements, as per the Danish Building Regulations. Furthermore, we compare heat consumption before and after upgrading the energy performance where the developed standard solutions for retrofitting facades are used. The involved parties are, among others, HT-Meter ApS., Saint-Gobain Isover A/S together with DTU. The project aims to minimise the emission of CO_2 caused by unnecessarily large energy consumption for heating [2,6].

1.2. Introduction to U-value Meter

Measurements of U-values have traditionally been made in laboratories 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 $\Phi = k\Delta T/\Delta x$ (a special 1D form of Fourier’s law [5,17]) representing heat conduction, 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. The basis for finding heat conductivities practically is 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 in accordance with DS/EN 12664 or DS/EN 12667. The results of the measurements refer to a mean temperature of 10 ºC. 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].

With the newly developed U-value meter, such a process can be omitted and U-values can be measured directly on site. See Figure 1 for a picture of the U-value meter.

Figure 1. U-value measurement on outer wall. The figure also shows an insulated acclimation suitcase, in which the meter is placed between the individual measurements.

This apparatus is based on a principle where the heat is ‘trapped’ by a heat absorption sensor (copper plate) when it leaves the outdoor surface of the test piece. A copper plate is used, as the absorption sensor due to its high thermal diffusivity and high conductivity [2,3].

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 by a highly insulating material, with 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% 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 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 (i.e. U-value) 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 U-value meter, the problems of transition insulation factor and surface temperature are eliminated, creating more accurate results. 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 facing the test piece. On the opposite side, i.e. facing away from the heat absorption sensor, a reflecting layer is placed 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, of relatively thick dimensions, and low thermal conductivity and diffusivity as basic thermal properties [2,3].

With this invention a very good accuracy is achieved for measuring transmission coefficients (U-values). The accuracy of the results lies between +/–5% from the ‘correct’ result according to information from different manufacturers of building components, tested *via* laboratory.

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 for several reasons: first of all, the moisture content changes in a building element, an outer wall for instance, during the years in which the element is a part of the building. Moisture levels influence the U-value, depending on 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 significantly [2,3].

1.3. Main Processor

One of the main objectives of the processor in the U-value device is to solve Fourier's heat transfer equation for a steady-state situation [1,5]. This equation, in differential form, can be expressed as:

$$\Phi = k \cdot dT/dx \qquad (1)$$

where dT/dx is the temperature gradient through a homogenous material, in the direction of the heat transfer [5]. The equation represents 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 s. The energy is transmitted to and captured by the heat absorption sensor through a '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 means of two separate processes (convective heat transmission and thermal radiation)

The heat transmission coefficient, or U-value, is obtained this way: The summarised energy in the heat absorption sensor will raise the temperature in the sensor to a level corresponding to the new level of internal energy [18], governed by the product:

$$m_{cu} \cdot c_{cu} \cdot \Delta T_{cu} \qquad (2)$$

where m_{cu} is the mass and c_{cu} is the specific heat capacity of the heat absorption sensor. ΔT_{cu} is the temperature rise in the heat absorption sensor during the measuring period [2,3].

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:

$$\Sigma(\Phi_c + \Phi_r)_i \Delta t_i \qquad (3)$$

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:

$$1/U = \Sigma dX_i/k_i + R_{in} + R_{out} \qquad (4)$$

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 [2]. The equation:

$$\Sigma(\Phi_c + \Phi_r)_i \Delta t_i \cdot A = m_{cu} \cdot c_{cu} \cdot \Delta T_{cu} \qquad (5)$$

where A is the area (m²) of the heat absorption sensor plate is the main equation, and it is solved taking the following relation from [2,3] into account:

$$\Phi = (\Phi_c + \Phi_r) \cdot A = U \cdot A \cdot (T_{in} - T_{out}) \qquad (6)$$

T_{in} and T_{out} are the absolute indoor and outdoor temperatures, respectively. From (6) we are able to get the U-value expression as:

$$U = (\Phi_c + \Phi_r)\cdot A/(T_{in} - T_{out})\cdot A \quad (7)$$

By multiplying numerator and denominator with the measuring time Δt (= 20s) and utilising the relations given by (5) noting that $\Delta t = \Sigma\Delta t_i$, we get:

$$U = m_{cu}\cdot c_{cu}\cdot\Delta T_{cu}/(T_{in} - T_{out})\cdot A\cdot\Delta t \quad (8)$$

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.

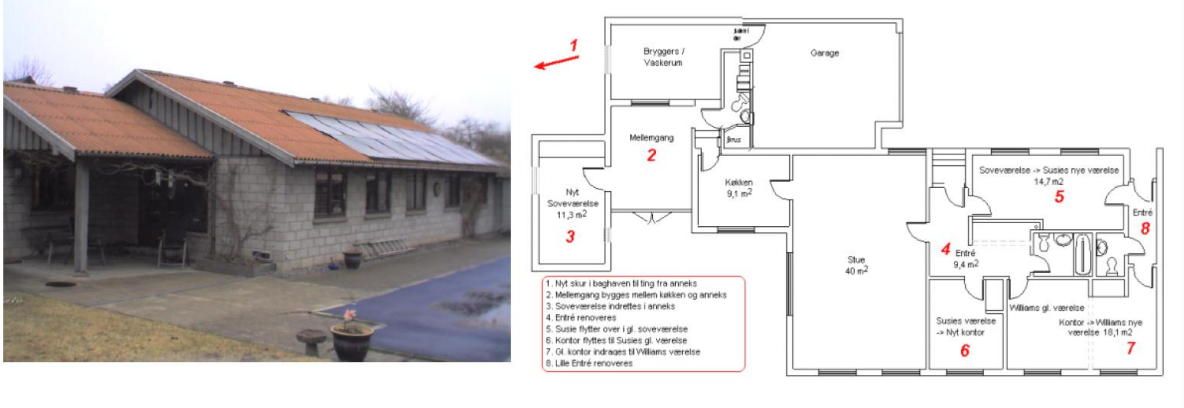
It is beyond the scope of this presentation to present in detail the form of the related data processing algorithm in the main processor, including output validation. However, the data processing aims to solve the above described thermo-physics. For further information see [2].

2. EUDP project

In Denmark, there is a great energy saving potential in houses built in the 1960s and 1970s. Special scrutiny is given to these houses since they account for a large part of the total residential dwellings [15,16]. In principle, it is possible to upgrade the energy performance of all types of housing up to modern requirements. It just depends on a sufficient increase of insulation in facades and ceiling, replacing traditional double-glazing with energy-saving glazing of low U-value (<1.1 W/m^2K), mounting draught-exclusion strips around doors and windows, optimising heating systems, changing to energy saving light sources and, crucially, on willingness to pay up-front costs for hidden benefits [10,12,13].

During a EUPD project [6] with participants from the Technical University of Denmark, Saint-Gobain, Weber, Isolink, HT-Meter and others, measurements were made on typical residential houses from the 1960s and 1970s. As an example Table 1 presents measurement results (U-values) for a 145 m^2 house built in 1964, located at Christianshøjvej, Kirke Værløse, Denmark. The house was partly rebuilt and extended in 2005. Outer walls are made of solid aircrete blocks. Some of the outer walls were insulated (inside) during the conversion in 2005. Heating of the house was done via a new condensing natural gas boiler. The U-measurements were made on 6 April 2011 between 9:30 AM and 12.10 PM by the U-value Meter (software version 1.60) together with a RayTek laser/infrared temperature measuring device. Weather conditions were calm, with wind speed < 5 m/s, no rain and with outdoor temperatures ranging from 8.0 ºC at 9:30 AM and increasing to 10.0 ºC at 12:10 PM. The U-vale measurements were accompanied by thermography, and a few examples of these are shown in Figures 3 to 5. A plan drawing of the house is shown in Figure 2.

Figure 2. One of the test houses involved in the EUDP project.



T_{in} is higher than T_{out} for the situations in figures 3 to 5. Figure 3 and 4 are thermographics taken from outside the building and figure 5 is from inside the building. The dark shaded (blue/violet) areas on figure 3 and 4 represents cold surfaces and therby more heat insulated than the yellow/orange areas with higher outside surface temperatures caused by poor insulation.

Figure 3. Poorly insulated window/door section along a corridor that connects the main house with an annex. The U-value is measured to be U-value=1.44 (Id 1, the wood parapet). The outer wall next to the wind/door section was measured to be U-value=0.80 (Id 2). See Table 1 for measured U-values.

Figur 4. Gable (west) with window to the bedroom. This room`s outer wall was previously insulated from inside. However, a thermal bridge interruption was omitted along the floor concrete slab and therfore the socket shows orange on the thermography to the right. The U-value was measured to 1.03 (Id 19) compared with the insulated outerwall U-value=0.32 (Id 22), see Table 1.

At the thermography on figure 5, the dark shaded areas also represents cold surfaces, but with *low* heat insulation. The low insulation gives rise to low surface temperatures inside. The yellow and orange areas represent better insulated areas and therefore capable to keep the heat inside the room which in turn results in higher surface temperatures.

Figur 5. The transition between the wall and the floor is acceptable. No leaks were registered in this door. The dark shades of the door indicate cold surfaces and a relatively large heat loss through the door. That corresponds to a high U-value, which is confirmed by Table 1, where the door is measured to U-value = 1.72 (Id 9) compared with the outer wall’s U-value = 0.89 (Id 11).

Table 1. Measurements of U-values for a typical Danish residential house from 1960s

Id	**Object**	**T_{in} (°C)**	**Remark**	**U-value (W/m^2K)**
1	Parapet	21.9	2 thin wooden boards with air/insulation between. 3 cm thick in total	1.44
2	Outer wall	23.0	Measured at 70 cm height	0.80
3	Outer wall	22.4	Measured at 1.5 m height	0.84
4	Outer wall	23.3	Measured at 1.5 m height	0.88
5	Pane	23.3	Measured at the middle of the pane	1.24
6	Outer wall	23.3	Measured at 1.5 m height	0.87
7	Outer wall	23.5	Measured at 1.5 m height	0.81
8	Outer wall	23.5	Measured at 1.5 m height	0.85
9	Exterior door	22.0	Door made of 4 cm thick wood (possibly teak)	1.72
10	Pane	22.3	Measured at the middle of the pane	1.30
11	Outer wall	22.3	Measured at 1.5 m height	0.89
12	Beam	22.3	Window lintel (lightweight concrete)	1.12
13	Edge of wall	22.3	No significant peripheral effects were measured	0.91
14	Exterior door	22.0	Door made of 4 cm thick wood (possibly teak)	1.78
15	Wall	22.4	Wall between the garage and living room	0.32
16	Outer wall	20.5	Outer wall of utility room/laundry room (facade)	0.26
17	Outer wall	20.5	Outer wall of utility room/laundry room (gable)	0.29
18	Outer wall	20.5	Outer wall of utility room/laundry room (gable)	0.29
19	Socket	21.9	Measured at the center of the base	1.03
20	Outer wall	22.7	Built-in cupboard stood up against this wall. Measured at 40 cm height	0.36
21	Pane	22.7	Measured at the middle of the pane	1.16
22	Outer wall	22.7	Measured at wall section below the window	0.32
23	Outer wall	22.7	Measured at 40 cm above socket level	0.20
24	Outer wall	22.7	Measured 80 cm above bottom of wall	0.23

Based on the measured U-values in Table 1, thermography and measurements of surface areas for the different types of structures and building elements (outer walls, exterior doors, windows etc.), it is possible to calculate the potential savings in energy (Q) for heating. If the upgraded energy performance complies with the current requirements to U-values stipulated in the Building Regulations is implemented [7,8,9], we can write:

$$Q = \Sigma\Phi_i \cdot t = \Sigma U_i \cdot A_i \cdot (T_{in} - T_{out}) \cdot t \qquad (9)$$

U_i and A_i are U-values and areas, respectively, for the building elements (windows, exterior doors, outer walls). t represents the time (could be set to a year) if we use an average indoor temperature and the year mean temperature. The Q-equation (9) is calculated for measured U_i as well as for required U_i-values, and the difference (ΔQ) represents the saved of energy.

The budget for upgrading the energy performance of this house was about DKK 470,000 (USD 94,000). The energy consumption (heat and electricity) totalled as much as DKK 39,000 (USD 7,800) per year (including heat for a pool). Natural gas for heating in year 2009/2010 totalled 1,906 m^3 (heating of house excl. pool) corresponding to 145 kWh/m^2 which is much more than required to a new house today in Denmark (approximately 65-70 kWh/m^2 [9]). A small part of the house (a corridor and a bedroom) was heated by electricity with consumption in 2010 of 1,354 kWh. Indoor temperature (year average) was 22 ºC. The saving potential on heating (gas consumption alone) was DKK 10,800 (USD 2,160) per year corresponding to approximately 60% saved on the heat expenses for the main house, disregarding the swimming pool. This saving potential corresponds to the below listed measures for upgrading the energy performance [6]:

- Outer walls including sockets are insulated with 195 mm mineral wool which is plastered.
- One exterior door replaced by a modern entrance door with low U-value. The other exterior door is removed and the opening closed and insulated as the rest of the façade.
- House entrance was insulated with 100 mm insulation
- Gables and foot of roof were insulated with good connection to the ceiling insulation
- Digging up soil around the concrete foundation and in top, new foundation blocks made of lightweight concrete are established and insulated with phenolic foam (PF).
- The existing windows (with low-energy glazing) are moved out to align with the façade.
- Installation of mechanical ventilation (balanced) aggregate with heat recovery
- Airtightening of the ceiling and between ceiling and outer walls.
- Insulation of bedroom (previously insulated from inside to a certain level)

Every upgrades of energy performance must be conducted with special care to the actual building physics. The upgrades should off course not introduce new problems such as increased moisture level in the building [11].

A number of other measurements were made on different buildings during the last seven years, partly in parallel with the development of the apparatus and integrated OS software. Other examples on measurements are presented in [2]. In the same reference you can find a discussion of the limitations and uncertainties of the U-value meter.

3. Planned measurements in tropic regions

A research cooperation about thermal performance of facades in tropics is initiated with SERIS (Solar Energy Research Institute) at NUS in Singapore. After a number of phone meetings concerning proposals, agreements (including scope of work), non-disclosure agreement etc., a first meeting in Singapore is planned together with SERIS. U-value measures a façades and an introduction course on how to use the U-value meter will cover the main parts of the meeting. A strategy for the coming measurements of the thermal performance of facades will be outlined. A number of houses in Singapore are the focus of the measurements. The measured U-values will be the basis for future proposals of thermal improvements of different types of facades, panes etc. The outcome of the project will be published in interested journals and/or at conferences by the end of the cooperation.

4. Conclusions

Energy efficiency, energy reduction and upgrading of the energy performance was investigated. 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 was granted in 2009 (Patent number 176757). An international patent application was filed in March 2003. The device can be utilised as a stand-alone apparatus, or in combination with thermography equipment, the latter in order to get a picture of the distribution of hot and cold locations of a building facade. However, since thermography only gives a picture of the surface temperatures, and not the heat loss distribution, the need arises for a heat loss measuring device. The device measures heat losses through the facades in the SI unit [W/m^{2}K]. 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 stipulated in the Danish Building Regulations. The corresponding potential reduction of the energy consumption can be calculated. A huge energy saving potential for residential houses is demonstrated during a EUDP project in a temperate region (Denmark). The initiation of a project in a tropic climate in cooperation with NUS is introduced.

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