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Section: Energy for Buildings

Sensitivity analysis of the proposed method for determining dynamic heat flux lost through the building envelope

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Abstract

Energy consumption of the building depends on transmission heat loss through the building envelope and ventilation heat loss, gains from solar radiation and internal gains such as from people or household appliances, as well as the efficiency of HVAC system. To evaluate the energy performance of building, it is necessary to collect all the available information about building construction and installations. The focus of this study was on transmission heat losses. For determination of the building energy load in dynamic conditions, the new method was proposed, which makes use of modified external air temperature. In order to calculate this temperature, the Exodus method (modification of the Monte Carlo method) was used, to obtain the dynamic heat flux which penetrates the building envelope. Based on the chosen method, authors developed their own computation procedure. It gives full access to source code and unrestricted (in terms of research objectives) structure of the model. The program calculates the dynamic heat flux penetrating multilayer walls used in the central-eastern Europe. This paper presents the sensitivity analysis of heat fluxes on a group of selected factors. The effect on the heat flux lost through the building envelope was studied for such factors as: wall orientation, layer thickness variation and changes in the physical properties of the individual layers. The variability in heat flux, which depends on the wind speed and solar radiation, and therefore the heat transfer coefficient on the external building surface was also examined.

Keywords: heat loss; transmission heat transfer coefficient; energy consumption measurements; thermal diagnostics of buildings.

Nomenclature

A	area of the building envelope (m^2)
c_p	specific heat capacity (J/kgK)
H_T	transmission heat transfer coefficient (W/K)
l	length of linear thermal bridge (m)
t_e^*	modified external temperature (°C)
t_e	external air temperature (°C)
R_T	thermal resistance of the total structural element of the envelope (m^{2}K/W)
R_i	thermal resistance of *i*-th layer of the element (m^{2}K/W)
R_s	thermal resistance of the surface (m^{2}K/W)
U	thermal transmittance (W/m^{2}K)
Q	quantity of heat (W)
q	heat flux (W/m^2)
Greek symbols	
α	coefficient of heat transfer of the outside air film of construction (W/m^{2}K)
η	efficiency
λ	thermal conductivity (W/mK)
ρ	density (kg/m^3)
χ	point thermal transmittance of thermal bridge (W/K)
Ψ	linear thermal transmittance of thermal bridge (W/mK)

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Subscripts	
e	external
est.	estimated value
g	gain
h	heat, heating system
i	number of element, internal
j	number of point thermal bridge
k	number of linear thermal bridge
l	loss
m	measured value
s	solar
us	unheated spaces
v	ventilation

1. Introduction

Buildings account for approximately 40% of the total energy consumption in Europe, mainly for heating and cooling purposes. It is expected that, in coming years, a large number of buildings will be retrofitted, due to the 2010/31/EU directive [1]. Walls and roofs of the building envelope play an important role in heat transfer between the exterior and the interior spaces of the building. Therefore they have a significant effect on heat loss and energy consumption [2–3]. That is why, the insulation efficiency of building envelope can be one of the most important area where energy saving can be achieved [4].

2. Transmission heat loss

The focus of this study was on transmission heat losses. For determination of the building energy load in dynamic conditions, the new method was proposed. In this part of the article the background on heat loss through building elements due to transmission is presented. Then the key stages of the proposed method are described.

2.1. Background

Transmission heat loss through the building envelope is a sum of conductive, convective and radiative heat flows through building elements. The most widely used parameters for building envelope thermal performance are thermal resistance *R*-value and thermal transmittance *U*-value. Calculation method to obtain these factors is compliant with the regulation ISO 6946 Building components and building elements – Thermal resistance and thermal transmittance [5].

The thermal transmittance is not a characteristic of the structure alone but varies due to the prevailing conditions of radiation and air movement. It can be calculated from:

$$U = \frac{1}{R_T} = \frac{1}{R_{si} + \sum_i R_i + R_{se}} \tag{1}$$

According to ISO 6946 in the absence of information on boundary conditions for horizontal surfaces R_{si} is usually taken as 0.13 m^{2}K/W and R_{se} as 0.04 m^{2}K/W.

Thermal resistance values of each layer material, reported by manufacturers, are normally evaluated at standard laboratory conditions. However, when placed in the real building, materials are exposed to different climatic conditions, especially humidity, so their actual thermal performance may differ from reported ones. Furthermore, thermal bridges occurring in the building envelope are difficult to define properly. Moreover, it is very common for older buildings to have the relevant, technical documentation missing. In this situation building envelope properties are estimated on the basis of the year of building construction (values required by the relevant regulations in the particular year). These factors may result in deviations when predicting the thermal and the energy performance of the whole building [2, 6, 8].

In the literature there are some modifications of obtaining these factors. The methodology in [9] enables to determine the limit values of building envelope heat transfer coefficients on the basis of A/V (total façade area to building volume) ratios and other design parameters affecting indoor thermal comfort such as orientation, window type, optical and thermophysical properties of the building envelope. In [10] the dynamic *R*-value is proposed, which shows variation in the thermal resistance of walls over different seasonal periods. This means that the normal *R*-value remains constant while dynamic *R*-value varies depending on internal and external environments. This may be particularly helpful when designing building envelopes for varying conditions. In [11] Bellamy presented the method to determine the dynamic *U*-factor and the equivalent *U*-factor, which account for effects of thermal mass, solar heat gains and insulation, and can be obtained, by either experimental or analytical method.

For existing buildings the thermal properties of envelope components (*R*-value, *U*-value) can be determined by in-situ measurements according to the ISO 9869, but it presents many difficulties. Both problems are of accurate measurements of temperatures and heat flux, because of different types of sensors and their proper location. The major difficulty, however, is to deal with the thermal transient conditions. But, here the problem of thermal bridges evaluation is still valid. Therefore, the heat flow meter method in many cases is used along with thermovision techniques [12–13] despite the fact it does not fully solve the problem.

To obtain envelope components thermal performance for real buildings the mathematical models as shown e.g. by Roels in [14] and Bacher *et al*. in [15] can be applied, but they are not easy to use and require well prepared experimental setup with detailed data acquisition.

In [16–18] other approaches are presented, based on simulation methods, neural networks or long-term measurements, but they required access to software licenses, deep knowledge in mathematics and long-term data availability. The availability of long-term measured data on climatic variables and building parameters are the basis for predicting, analyzing and simulating the building thermal behavior.

The accurate prediction requires detailed input data and understanding of time-dependent temperature distribution within the external wall structures. However, in the real cases that kind of data is still very rare. That is why the methods mention above are mostly used for academic purposes.

Therefore, there is a need to develop a new method to determine the transmission heat losses based on the results of short in-situ measurements which can be successfully used in practice by engineers and energy auditors.

2.2. Proposed method

The proposed method enables to determine the total building transmission heat transfer coefficient, which takes into account the impact of thermal bridges, as in the Equation (2) [19]:

$$H_T = \sum_i A_i U_i + \sum_k l_k \psi_k + \sum_j \chi_j \tag{2}$$

The articles [20–23] present the idea of the proposed method. The method makes use of the short measurement of heat consumption in a building and is based on the energy balance. Transmission heat transfer coefficient is calculated form Equation (3) written in a form for double short measurements.

$$H_T^{est.} = \frac{\left(\bar{\dot{Q}}_{h,m}(\bar{t}_{e1}) - \bar{\dot{Q}}_{h,m}(\bar{t}_{e2})\right)\cdot \eta_{h,total} + \Delta\bar{\dot{Q}}_{vhl} + \Delta\bar{\dot{Q}}_{ihg} + \Delta\dot{Q}_{shg} + \Delta\dot{Q}_{usl}}{\bar{t}^*_{e2} - \bar{t}^*_{e1}} \tag{3}$$

The measurement of heat consumption is carried out in two short periods during heating season. When choosing the same e.g. Monday-Sunday periods, it is possible to assume that internal heat gains, which occurred during measurement periods are similar, thus possible to be eliminated from the equation. This is a great advantage, because internal heat gains and people behavior are very hard to define [16]. They can be also estimated from the questionnaire given to the residents of the building, but the outcome from this type of survey is always quite low [16]. The total efficiency of the heating system can be estimated or calculated based on thermal diagnostics for heating system procedures. The other values from the equation (heat gain and loss components) are obtained based on estimation or measurements e.g. Blower Door testing when calculating the air change, solar radiation measurements for solar hear gains calculation etc.

In the proposed method the modified external temperature t_e^* was used instead of the external air temperature and takes into account the operation of solar radiation and wind on the building and the effect of resistance and heat capacity of the elements of building envelope on transient heat transfer, thus allowing to reduce the time of measurements. The exemplary series of modified external temperature t_e^* along with the external air temperature t_e are shown in Figure 1.

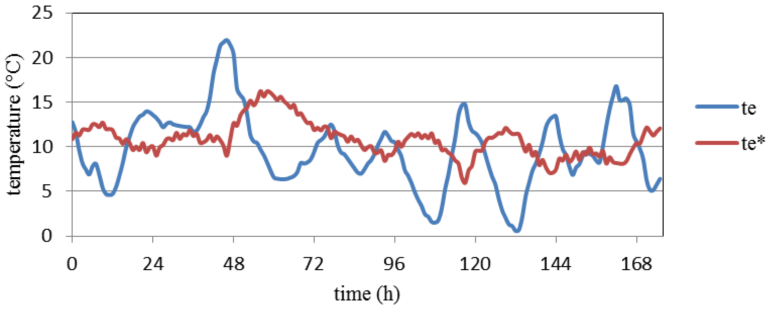

Fig. 1. External air temperature and modified external temperature

In order to calculate this temperature, the Exodus method (modification of the Monte Carlo method) was used, to obtain the dynamic heat flux which penetrates the building envelope. Based on the chosen method, authors developed their own computation procedure, which gives full access to source code and unrestricted (in terms of research objectives) structure of the model [24–25]. The program, implemented in Matlab, calculates the dynamic heat flux penetrating multilayer walls used in the central-eastern Europe. The temperature of the inner surface of the outer envelope components of the building, obtained by the program, is then used to determine the modified external temperature which together with the measured heat flux transferred from the source to the heating system allows the calculation of heat losses that occurred in the real building. The developed method has been verified by measurements carried out in buildings and using Ansys CFX simulation program [24–25].

In contrast to the calculation method mention earlier in the text, the proposed method takes into account real measurement data of the analyzed building so can be more accurate. Comparing to existing simulation methods and mathematical models or neural networks, due to the low cost and short data acquisition, it can be successfully applied in practice and used in existing, inhabited buildings. The proposed method is developed as part of the in-situ thermal diagnostic of buildings and it uses some data obtained within other diagnostic procedures.

Building's thermal diagnostics comprises the recognition and assessment of essential, individual elements that affect the heat consumption in a building. Those elements are: building envelope, heat and cold sources, heating, ventilating and air conditioning systems, indoor environment and features relating to the way of the building use. Diagnosing element by element should be practical and reliable and should give a clear representation of the above-mentioned elements so that the determined energy quality of the building as a whole is stated. Some of those procedures were created at the Silesian University of Technology, Department of Heating, Ventilation and Dust Removal Technology, in the strategic research project "Integrated system for reducing energy consumption in the maintenance of buildings" financed by the Polish National Centre for Research and Development (NCBR) [26].

The results obtained from the proposed method, in addition to information on the actual transmission heat losses that occur in buildings, will allow to define the required heat source power and to evaluate the heat source oversizing, which is one of the tasks of the thermal diagnostics and inspection of heat source, required by the regulation [3]. Moreover, the transmission heat transfer coefficient, obtained by the proposed method, along with other elements received from diagnostic procedures, can be further used to perform an energy audit or energy performance certificate [3], which should improve their accuracy, and may be a hint for building managers and investors how to optimize the thermal modernization of existing buildings.

3. Sensitivity analysis

The most important element of the whole execution of the proposed method is to take into account the transient conditions, especially if the measurements carried out in buildings, are required to be brief. This article focuses on a part of the method, based on the computational procedure implemented in Matlab. The aim was to examine the sensitivity of transmission heat fluxes, calculated in Matlab, on a group of selected factors.

The effect on the heat flux lost through the building envelope was studied for such factors as: wall orientation, layer thickness variation and changes in the physical properties of the individual layers. The variability in heat flux depending on the heat transfer coefficient on the external building surface was also examined. The analysis was made for typical Polish multilayer wall constructions, which were chosen due to [27]. The considered walls together with their layers physical parameters are shown in the Table 1.

Table 1. Considered wall constructions for sensitivity analysis

Wall	Material	Thermal conductivity λ (W/mK)	Width (m)
1	Plaster	0.82	0.015
	Solid brick	0.77	0.25
	Plaster	0.82	0.015
2	Plaster	0.82	0.015
	Reinforced concrete	0.77	0.12
	Styrofoam	0.045	0.10
	Reinforced concrete	0.77	0.25
	Plaster	0.82	0.015

The first part of the experiment concentrated on input parameters which are entered to the model based on possessed knowledge. Some faults may occur when calculating heat flux at dynamic conditions if the wall orientation is given wrongly, because it influences solar radiation on the analyzed building component. Other values which may corrupt the calculations are layer thicknesses or physical parameters such as λ (thermal conductivity) which do not match the actual state. The typical meteorological data taken for the analysis were created by the Polish Ministry of Infrastructure and Development [28]. The data chosen were of the period from the 1st of January to 31st of March, as those are the middle months of the heating season in Poland, thus it is the perfect period for heat loss analysis.

To begin with, wall orientation deviation was considered on the calculated heat flux. The relative error dependency on the deviation from the base direction, located at the S, W, N or E was checked for both analyzed walls. The results are shown on Figure 2.

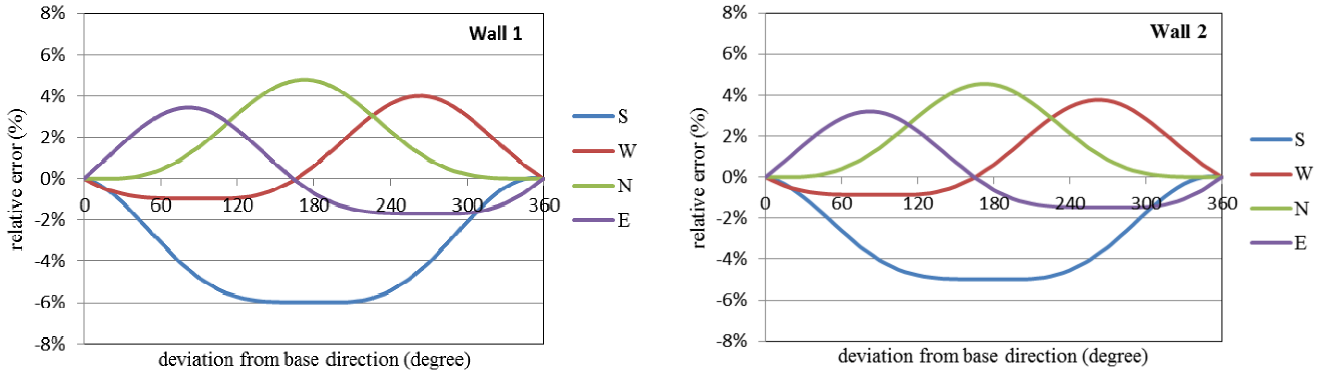

Fig. 2. Illustration of relative error dependency on the deviation from base direction (located at the S, W, N, E) for both analyzed walls

As it can be clearly seen, the less isolated wall construction the bigger the impact on inconsistent wall orientation estimation. Incorrect estimation of the wall orientation of e.g. 15 degrees did not significantly affect the heat flow. Generally, the impact of wall orientation in analyzed period of time is quite low (up to 6%), because of small amount of solar radiation and short days that occur during the winter season in Poland. It would be more meaningful for whole year investigation. Of course, the influence of the orientation of the building in the overall heat balance is much larger, because it affects the amount of direct solar radiation coming through transparent components, as windows and balcony doors, and increases the indoor temperature.

The next stage of the analysis focused on layer thickness variation. For both considered walls different options were checked. The first wall was not insulated, so it was examined, what if the insulation layer was added with thickness up to 5 cm. The insulation thickness of the second wall was 10 cm in a real case, so the variations were investigated from the case with 5 cm of the styrofoam to 15 cm layer. The ±5 cm variation was chosen, because it my happen in a real wall construction inspection, especially for old buildings, if there is no documentation preserved. The results of relative error dependencies on the deviation from base insulation layer thickness for both analyzed walls are shown on Figure 3.

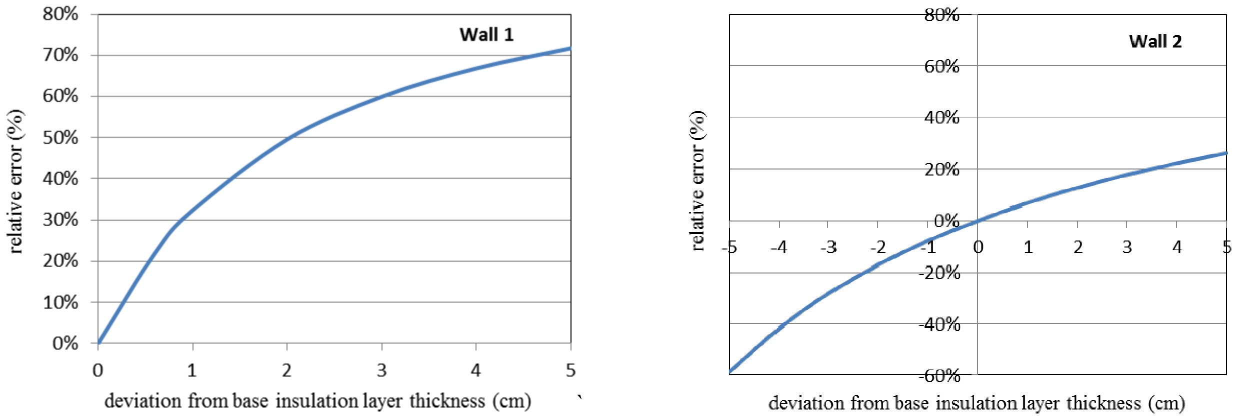

Fig. 3. Illustration of relative error dependency on the deviation from base insulation layer thickness for both analyzed walls

Because the first wall was not insulated at all, additional insulation layer has a great impact on the determined heat flux. Even 1 cm of styrofoam result in serious change in heat flux (21.9%), whereas additional 5 cm consequences in huge 71.7% difference. For the second wall however, increasing insulation does not result in such big differences as for the first one, 5 cm of extra insulation results in 26.5% change. It means that if the insulation layer is present, enlarging it further, reduces the transmission heat flux, but not as rapidly as in the absence of insulation. When lowering the insulation layer for the second wall it has larger impact – 1 cm less modify the heat flux for 7.7%, whereas 5 cm results in almost 58.7% difference.

In addition to insulation layer thickness analysis, physical parameters of the insulating material were also examined. The analysis concerned the second wall. Different physical parameters of insulation layer were set instead of the real ones, preserving their thickness. Three types of mineral wool, and one other styrofoam were considered, as shown in the Table 2.

From the results shown in Table 2 it can be seen, that the most important parameter affecting the heat flux is thermal conductivity. Mineral wool (1) results in very small relative error (almost zero) despite of very different specific heat capacity and density specification. New styrofoam gave higher relative error (8.4%) even though the only difference between it and the base one was 0.005 W/mK in thermal conductivity. The huge difference was observed for mineral wool (3) with the relative error 17.3%.

Table 2. Physical parameters of insulation materials taken to the analysis and the relative error dependency on the deviation from base physical parameters of insulation layer

Insulation layer	Physical parameters			Relative error (%)
	Thermal conductivity λ (W/mK)	Specific heat capacity c_p (J/kgK)	Density ρ (kg/m^3)	
Styrofoam (1 – base case)	0.045	1460	30	–
Styrofoam (2)	0.040	1460	30	8.4%
Mineral wool (1)	0.045	750	70	0.2%
Mineral wool (2)	0.041	1030	156	6.6%
Mineral wool (3)	0.035	1030	35	17.3%

The second part of the research was focused on external heat transfer coefficient α_e (the inverse of R_{se}). Two approaches were considered: values set due to the regulation for unknown conditions [5] or calculated based on real conditions, which actually occur during the analyzed period. The aim was to check how the coefficient of heat transfer of the outside air film of construction influence the total heat flux lost through the building components.

In the analyzed period of time (1st of January to 31st of March), the average wind speed was 3 m/s and the average temperature –1 °C with the mean R_{se} = 0.06 m^{2}K/W. The R_{se} recommended in ISO 6946 [5] in the absence of information on boundary conditions is calculated for 10 °C and 4 m/s and equals 0.04 m^{2}K/W. For the first wall the relative error in calculating the heat flux was 11.7% and for the second one only 6.8% in the situation where real values were replaced by the standardized one. The results confirm that the lower the wall thermal resistance the higher the impact of heat transfer coefficient on the external building surface, so the higher difference in heat flux is observed.

4. Conclusion

In the article the proposed method which enables to determine the total building transmission heat transfer coefficient, was demonstrated. The method was presented in respect to different existing approaches [1–2, 4, 6–18]. The main focus of the article was to perform the sensitivity analysis of heat fluxes on a group of selected factors such as: wall orientation, layer thickness variation and changes in physical properties of the individual layers. The heat flux was calculated for dynamic conditions, using authors' computation procedure. The program, implemented in Matlab, is based on Exodus method.

The analysis gave following results. During winter period in Poland, incorrect estimation of the wall orientation, surprisingly, did not significantly affect the heat flux penetrating analyzed walls, even if it was completely opposite to the real one (research did not take into account transparent components). The factor which had the major impact on heat flux was insulation layer thickness. Therefore, for obtaining reliable results of heat losses, the most important part is to ensure that the thickness of the layers, especially insulation, is set up correctly. The less insulated the wall the higher impact of a mistake in layer thickness estimation. Physical parameters, mainly thermal conductivity, should be estimated as confidently as possible. Thus, the technical documentation should be studied, and in the absence of the complete data, building technology from this period of time should be considered. The external heat transfer coefficient α_e (the inverse of R_{se}) is more important when analyzing building components without the insulation layer, because it has a great shear in the whole thermal resistance calculation, and therefore it affects significantly the determined heat flux.

Only the small part of the proposed method was presented in the article. Currently whole method for determining transmission heat transfer coefficient is validated. The next step will contain transmission heat transfer estimation based on the energy balance methodology in a group of existing buildings with different type of the envelope construction along with the usage of the other part of thermal diagnostic of buildings procedures.

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