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ON ATTENUATION OF TEMPERATURE OSCILLATION BY THE ENCLOSURE OF THE BUILDING

O TŁUMIENIU FAL CIEPLNYCH PRZEZ PRZEGRODY ZEWNĘTRZNE BUDYNKÓW

A b s t r a c t

Overheating is becoming now a very important aspect of building use. While the main cause of overheating is usually oversized glazing area, to control overheating risk not only windows and insulating features but also heat wave damping characteristics of the external walls should be considered as an important and very useful factor.

Keywords: heat wave damping, overheating, thermal transmittance, green roof

S t r e s z c z e n i e

Przegrzewanie staje się coraz ważniejszym aspektem użytkowania budynków. Chociaż jego głównym źródłem są zwykle nadmierne przeszklenia, to w celu uniknięcia lub przynajmniej ograniczenia przegrzewania wnętrza budynku warto już na etapie projektowania wziąć pod uwagę nie tylko powierzchnię okien i właściwości izolacyjne obudowy, ale także zdolności przegród do tłumienia fal cieplnych.

Słowa kluczowe: tłumienie fal cieplnych, przegrzewanie, transmitancja cieplna, zielony dach

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1. Introduction

Overheating is becoming nowadays a very important aspect of a building use and also a significant part of the maintenance costs. It is relatively easy to minimize heating needs and usually the formal requirements are oriented on this aim. Because of the common pressure on energy saving a designer may easily find information how to decrease energy losses, maximize and efficiently use solar and internal heat gains. Unfortunately, actions aimed at decreasing heating needs may also lead to adverse effects in form of increased overheating risk, e.g. oversized window area. The measures how to protect building against overheating are not commonly known and understood, because of the complicated dynamic aspects of heat flow and energy storage in building shell.

For example, a flat, horizontal roof, that is commonly used in public utility buildings and big apartment houses, is in summer often a source of the big heat gains. Solar radiation, intensively absorbed by dark coloured bituminous roof coating, combined with high air temperature results in a high heat flow rate entering the building space. Space overheating basically caused by window solar gains could be at least reduced by minimizing amplitude of the internal heat flow rate and/or maximizing a time lag, i.e. phase difference between heat flow rate on one side and surface temperature on the other side.

2. Periodic thermal transmittance

One of the simplest and best known heat transfer dynamic model is a theory of harmonic heat waves, based on Fourier analysis of cyclic functions [1]. Due to a quasi-periodic course of ambient temperature this analytical approach fits in fact very well to the real conditions. The dynamic thermal characteristics of a building component describe the thermal behaviour of the component when it is subject to variable boundary conditions, i.e. variable heat flow rate or variable temperature on one or both of its boundaries. In International Standard EN ISO 13786 [2], only sinusoidal boundary conditions are considered: building boundaries are submitted to sinusoidal variations of temperature or heat flow rate. The properties considered are thermal admittances and thermal dynamic transfer properties, relating cyclic heat flow rate to cyclic temperature variations. Thermal admittance relates heat flow rate to temperature variations on the same side of the component. Thermal dynamic transfer properties relate physical quantities on one side of the component to those on the other side. Transmittance is a complex quantity defined as a complex amplitude of the density of heat flow rate through the surface of the component adjacent to zone *m*, divided by the complex amplitude of the temperature in zone *n* when the temperature in zone *m* is held constant. Component thermal transmittance from surface to surface may be expressed as [2, 3]:

$$Y_{si-se} = -\frac{q_{si}}{\theta_{se}} = -\frac{1}{Z_{12}} \tag{1}$$

where:

q_{si} – cyclic amplitude of the heat flow density on the internal roof surface
Θ_{se} – cyclic amplitude of temperature on external roof surface

Z_{12} – element of the heat transfer complex matrix $\boldsymbol{Z}$ (2), relating the complex amplitudes of temperature and heat flow rate on one side of a multi-layer component to the complex amplitudes of temperature and heat flow rate on the other side [1–3]:

$$Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} Z_{n,11} & Z_{n,12} \\ Z_{n,21} & Z_{n,22} \end{bmatrix} \cdot \begin{bmatrix} Z_{n-1.11} & Z_{n-1.12} \\ Z_{n-1.21} & Z_{n-1.22} \end{bmatrix} \cdot \ldots\ldots \cdot \begin{bmatrix} Z_{1.11} & Z_{1.12} \\ Z_{1.21} & Z_{1.22} \end{bmatrix} \tag{2}$$

In European standard EN ISO 13792 [4] periodic approach is advised as a simplified method of calculation of the space temperature in summer without mechanical cooling. Combined thermal characteristics of the component under steady and periodic conditions may be expressed as a decrement factor ie. ratio of the modulus of the periodic thermal transmittance to the value of the steady-state thermal transmittance *U*. The decrement factor is given by:

$$f = \frac{\left|Y_{si-se}\right|}{U} \tag{3}$$

In further research work thermal transmittance *Y* and decrement factor *f* were used as a concise description of dynamic roof characteristic that includes information regarding heat flow amplitude and time lag between the waves of external temperature and internal heat flow. Although the above equations look pretty simple, calculations on complex quantities (with real and imaginary parts) are possible only in a computer programme. *D'Thermal* programme [5] was used to run the computations needed for this paper.

3. Lightweight roof transmittance

Flat roof exposure to solar radiation on a summer day results in a very high external surface temperature, inducing in this way heat wave that flows across the roof. A space under the roof will be effectively protected against overheating not only when ceiling flux amplitude is minimized but also when it is shifted in time up to the moment when ambient air temperature is significantly decreased. This effect is efficiently used in so called passive cooling, that improves thermal conditions within the space without any extra demand on energy. Expected minimum time lag for the apartment roof is 10 hours and in case of a cold store even 12 hours [6].

Below lightweight roof structure was taken as a reference roof case:

- bituminous multi-layer coating, 1cm,
- thermal insulation, 5 to 25 cm
- corrugated metal sheet, 0,1 cm.

Thermal transmittance of the reference roof under steady state boundary conditions (*U* value) depends only on its thermal resistance (Fig.1). Under periodic conditions so called thermal diffusivity and thermal resistance should be considered. In case of the considered light structure, increased insulation thickness results in significant reduction of *U*-value, small decrease of decrement factor value and slightly increased phase shift (transmittance

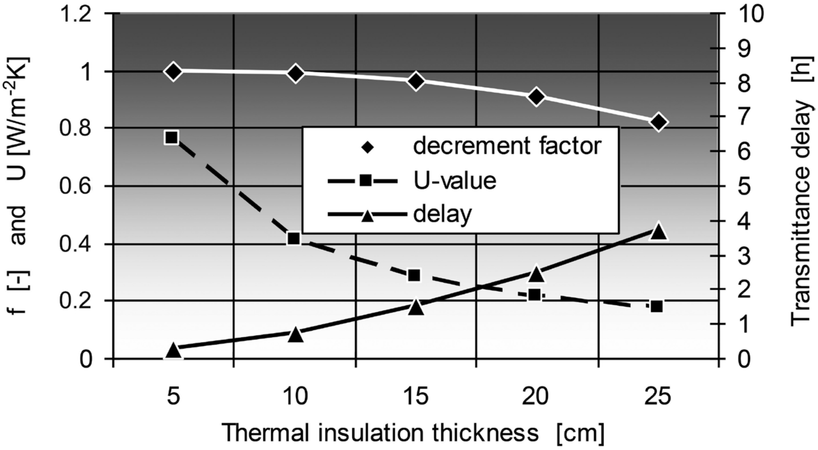

Fig. 1. Lightweight roof decrement factor, *U* value and time lag versus insulation thickness

Rys. 1. Zależność dekrementu tłumienia, współczynnika U i przesunięcia fazowego od grubości izolacji termicznej

delay). It means that during the hot summer day internal heat flux amplitude will be reduced but its maximum will happen in best case 3.7 h after the sun culmination, when ambient temperature is still very high. At this moment of a day even a relatively small extra energy gains could intensify thermal discomfort in the space. In this situation an expensive and energy consuming mechanical cooling would be the only chance to reduce space overheating.

It means that increased thermal resistance of a roof is not a right or rather sufficient measure to avoid overheating. In Fig. 2 lightweight roof with 10 cm thermal insulation was turned into a green roof when a vegetation substrate layer was added to its top.

Very thick (25 cm) substrate layer with density equal to 1800 kg/m^3 practically did not increase thermal resistance of the roof (*U* value curve), but it reduced dramatically decrement factor and magnified time shift up to 10 hours. If solar temperature culmination time is at 13.00, heat flow rate at the inner surface of the roof would reach its maximum at 23.00. At this moment ambient temperature is always relatively low, even after a very hot day, so intensive ventilation would effectively reduce internal operative temperature. Intermediate 10 cm thick substrate layer does not improve damping effects of this roof in a satisfactory way; decrement factor value is equal to 0.567 and phase shift is 4.09 h.

In Fig. 3 the obtained results of the increased insulation layer are set against the influence of the substrate layers.

Low value of the decrement factor means that only a small fraction of the heat wave induced by absorbed solar radiation will be transmitted to the space through the roof. Once again it was proved that in case of the dynamic heat flow ground layer (white curve) is more effective than thermal insulation (black curve).

Influence of the physical properties of the ground (or so called substrate) on the roof damping characteristics has been analyzed below.

Substrate specific heat was kept at same level in each case, water content thermal capacity was not included.

Table 1

Assumed substrate density ρ and thermal conductance λ

ρ	λ
[kg/m³]	[W/mK]
1800	0.9
1500	0.7
1000	0.5
500	0.25

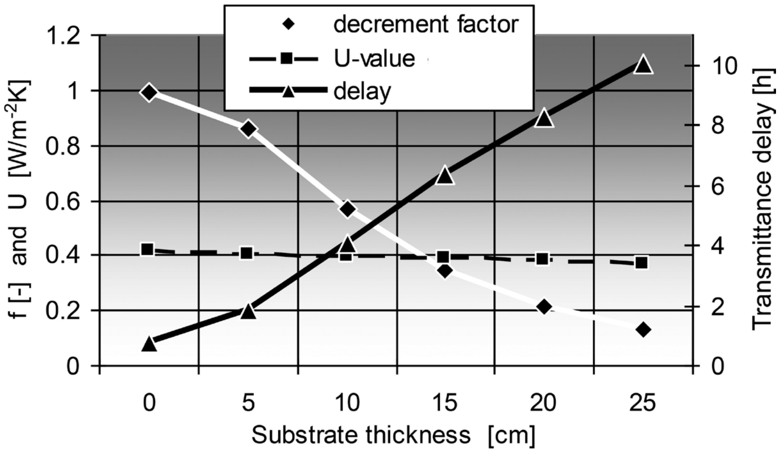

Fig. 2. Decrement factor, U value and time lag versus substrate thickness

Rys. 2. Zależność dekrementu tłumienia, współczynnika przenikania ciepła i przesunięcia fazowego od grubości substratu

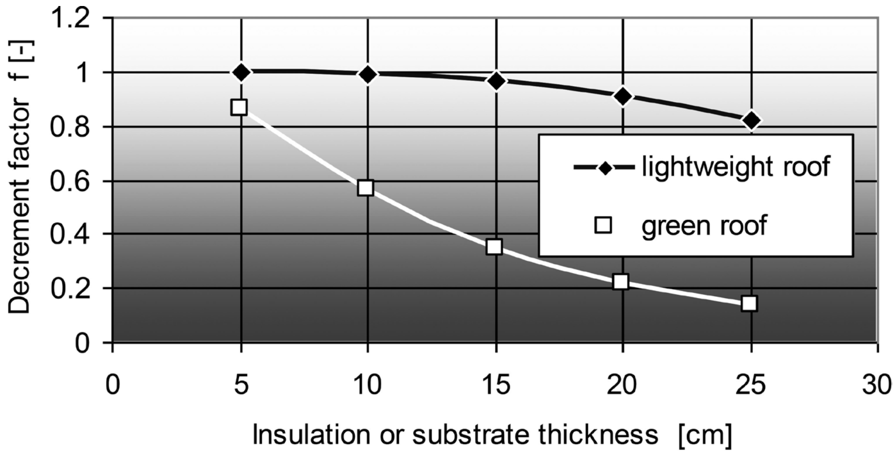

Fig. 3. Decrement factor vs. insulation or substrate thickness

Rys. 3. Dekrement tłumienia w zależności od grubości izolacji i substratu

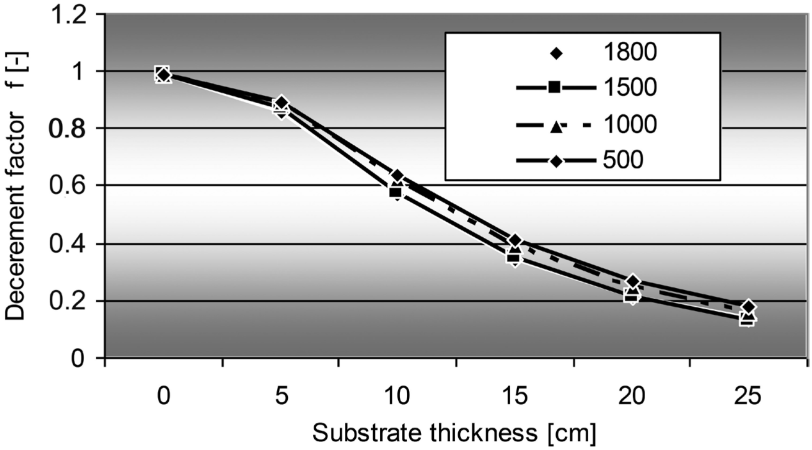

Fig. 4. Decrement factor of the lightweight green roof versus substrate density and thickness

Rys. 4. Zależność dekrementu tłumienia lekkiego stropodachu zielonego od gęstości i grubości warstwy substratu

Relation between substrate density, thickness and roof decrement factor was shown in Fig. 4. Despite the big differences between ground density and thermal conductivity in all the considered cases, the changes of the decrement factor are moderate. This conclusion is very important because of the structural reasons. The mechanical load of the ground on the lightweight roof increases significantly the strengths within the structure and finally investment costs.

Water content influence (not considered in the above calculations) because of the big specific heat and increased thermal conductance of water may be of the significant importance for substrate damping efficiency.

Case of the poorly insulated green roof was chosen to compare substrate layer and insulation damping efficiency. In reality both measures would be most probably used at same time. In case of a roof with 20 cm thermal insulation and 15 cm substrate layer, transmittance modulus is 0.094 W/m^{2}K, time lag 8,15 h, decrement factor value is 0.206 while U = 0.208 W/m^{2}K. Green roof of this kind would be then a very well insulated barrier for heat losses in winter and a good passive protection against overheating in summer.

4. Heavyweight roof transmittance

In common building practice heavyweight concrete roofs are widely used since decades. So it would be important to indicate also in this case the most efficient solution to prevent overheating in the spaces under the roof. As the reference heavyweight case the standard roof with 12 cm concrete structure and 10 cm thermal insulation was taken.

The similar as before shown damping effect may be observed in case of the heavyweight roof structure. Increased thermal insulation thickness leads only to insignificant decrement factor reduction, while added substrate layer decreases heat wave transfer for a few times. It should be then stated that also in case of heavyweight concrete structure additional substrate layer could be an effective measure to reduce overheating risk in the spaces under the roof.

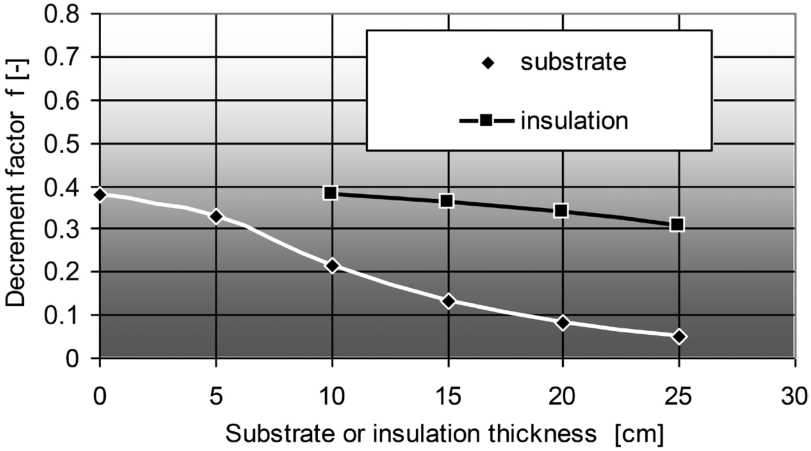

Fig. 5. Decrement factor of the heavyweight roof versus substrate or thermal insulation thickness

Rys. 5. Zależność dekrementu tłumienia stropodachu masywnego od grubości warstwy substratu lub izolacji termicznej

5. Conclusions

Effective **passive protection** against overheating is still a new challenge for the building designers. So very often in intended low energy buildings total yearly energy consumption is significantly growing, due to oversized cooling needs. A substrate layer of a green roof, because of its thermal capacity could be an important factor of overheating protection, not only in case of the popular lightweight flat roofs but also for heavyweight concrete structures. Massive substrate layer allows to decrease intensity but most of all to shift in time the heat wave induced by absorbed solar radiation. Delayed energy flux transmitted by the green roof could be easily counterbalanced by intensive space ventilation during the night. In this way green roof wins another important usability and helps to decrease in a passive way overheating risk.

Carried out simulations allow also to answer reasonably an often asked question how to modernize an existing roof to reduce summer overheating. Often applied measure, in form of increased thermal insulation, is not an effective solution in this case.

Denotations

Y_{ij} – thermal transmittance
q_{si} – cyclic amplitude of the heat flow density on the internal roof surface
Θ_{se} – cyclic amplitude of temperature on external roof surface
Z_{12} – element of the heat transfer complex matrix
f – decrement factor
U – thermal transmittance

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