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WAVE AMPLITUDES OF TEMPERATURE AND HEAT FLUX IN THE SURROUNDINGS OF EXTERNAL WALLS

AMPLITUDY FALI TEMPERATURY I STRUMIENIA CIEPŁA W OTOCZENIU ŚCIAN ZEWNĘTRZNYCH

A b s t r a c t

In this paper, the thermal dynamic characteristics of exterior walls with variant concrete solutions of load-bearing layer were analysed. The main aim of this study was to compare the amplitudes of wave fluctuations of internal temperature and internal heat flux depending on the construction material used. Calculations were made for partitions with a structural layer made from lightweight concrete composites, autoclaved aerated concrete and reinforced concrete. Very good damping properties were obtained for the partitions made of concrete composites. The obtained data suggests that such solutions provide much smaller fluctuations of temperature and heat flux in comparison to materials with low specific heat.

Keywords: dynamic thermal characteristics, transfer matrix, lightweight concrete composites, heat flux

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

W niniejszej pracy poddano analizie zbiór danych dotyczących dynamicznych charakterystyk cieplnych ścian zewnętrznych o różnie dobranej pod względem materiałowym warstwie konstrukcyjnej. Głównym celem pracy było porównanie amplitud wahań fali temperatury wewnętrznej i wewnętrznego strumienia ciepła w zależności od użytego materiału warstwy nośnej. Rozpatrzono przegrody z warstwą konstrukcyjną wykonaną z rozmaitych lekkich kompozytów betonowych, betonów komórkowych oraz betonu zbrojonego. Bardzo dobre właściwości tłumiące przegrody uzyskano dla kompozytów betonowych. Otrzymane dane wykazują, że tego typu rozwiązania zapewniają zdecydowanie mniejsze wahania fali temperatury i strumienia ciepła w porównaniu do materiałów o niskim cieple właściwym.

Słowa kluczowe: dynamiczne charakterystyki cieplne, macierz przejścia, lekkie kompozyty betonowe, strumień ciepła

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1. Introduction

New, stricter requirements for energy savings make it necessary to look for customised solutions designed to improve the energy efficiency of buildings, which is the subject of numerous research projects both in Poland [1] and abroad [2].

The reduction in the value of thermal transmittance turns out to be insufficient to achieve the goal of almost zero-energy building design. Nowadays, new solutions are sought which can positively affect the reduction of energy consumption through the use of various types of heavy building materials. Tests performed in [3] show explicit differences in the energy consumption of buildings with differently set load-bearing and insulating layers as well as the influence of the thickness of heavy layers.

Due to the complex problem of non-stationary heat flow through the partitions, in conjunction with the effects of both sunlight radiation and ventilation in buildings, efforts are taken to determine parameters that could replace the thermal transmittance U which describes only stationary heat flux. For this purpose, a dynamic coefficient of thermal resistance is described [4]. This coefficient takes into account the effect of thermal mass in calculations of the real heat flux through the building partition. Another approach presented in [5] involves the use of a dimensionless global heat transfer coefficient which is based on harmonically varying conditions of temperature on both sides of the wall. This factor additionally takes into account the influence of solar radiation.

Apart from use of alternative energy sources and innovative installation solutions, the influence of materials used in construction is also worth considering. This problem was undertaken by Taylor [6] who compiled and compared all sorts of traditional building materials for interior finish used as an additional thermal mass. There were also some efforts taken to determine the heat capacity of various building materials depending on its density or thermal conductivity [7]. Studies were also performed to assess the relationship between the moisture of the material and the increase of its thermal conductivity λ and volumetric specific heat c_v [8].

In this paper, we tested the dynamic thermal characteristics [9] of typical two-layer walls with different load-bearing materials. We analysed which type of concrete composite was most effective with regard to energy savings.

2. Design conditions

2.1. Analysed wall

The calculation of amplitude fluctuation of temperature and heat flux on both sides of the partition was made on the basis of norm [10] which enables solving the Fourier equation in harmonically variable boundary conditions. The scheme of the tested partition is shown in Figure 1.

The calculations were made for seven wall solutions which differed in the kind of load-bearing material. Each of the analysed variants must also meet the minimum requirements of thermal insulation in accordance with [11]. The thickness of all layers was constant. This

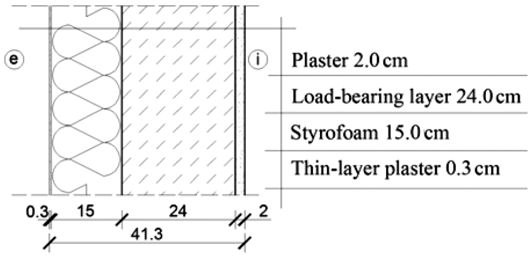

Fig. 1. Scheme of the analysed wall

allowed to comparison the influence of the tested concretes on the amplitudes regardless of the thickness of the materials. The surface resistance of the boundary layer was also taken into account. The parameters of the partition are shown in Table 1.

Table 1

Parameters of the particular layers of the external wall

No.	Layer	*d* m	λ W/(m·K)	ρ kg/dm³	c_v MJ/(m³·K)
1	plaster	0.020	0.40	1.00	1.00
2	load-bearing layer	0.240	tab. 2	tab. 2	tab. 2
3	styrofoam	0.150	0.04	0.03	0.042
4	thin-layer plaster	0.003	1.00	1.80	1.80

The analysis was made for the seven different concretes presented in Table 2. The data of the dynamic thermal characteristics, with a particular emphasis on the periodic thermal transmittance and internal area heat capacities, were discussed in [12].

The first four materials shown in Table 2 indicated by symbols LEC and LYT are concretes based on expanded clay aggregate and fly ash aggregate respectively. Composites based on lightweight aggregates are an interesting alternative to normal concrete, and they still have untapped potential in Poland. The usefulness of clay raw materials for the production of lightweight aggregates from the south-eastern area of Poland were investigated by Panna et al. [13].

The specific heat of the load-bearing materials is presented in relation to the volume instead of weight because it accurately reflects the relationship between the wall thickness and heat capacity in comparison to the mass of the wall.

The analysed composites were made in two variants: non-aerated (N) and aerated (A). These concretes were made for the purpose of currently ongoing research project. The properties of air-entrained concretes were the subject of multi-faceted research conducted by Kulová et al. [14]. The authors conducted tests of air-entrained composites with the addition of brick powder.

The study also included the simulation of partitions with a load-bearing layer made of autoclaved aerated concretes. The influence of bulk density and moisture on the thermal parameters of autoclaved aerated concrete has been discussed by Unčík et al. [15]. Physical properties of the autoclaved aerated concretes and reinforced concrete were determined based on [16].

Table 2

Parameters of the particular load-bearing layers and *U* coefficients of whole partitions

No.	Material	λ W/(m·K)	ρ kg/dm³	c_v MJ/(m³·K)	U – whole partition W/(m²·K)
1	LEC/N	0.73	1.35	1.76	0.232
2	LYT/A	0.32	1.03	1.55	0.212
3	LEC/N	1.07	1.86	1.78	0.238
4	LYT/A	0.66	1.50	1.70	0.231
5	Reinforced concrete	1.70	2.20	1.85	0.243
6	Autoclaved aerated concrete 600	0.21	0.60	0.50	0.195
7	Autoclaved aerated concrete 400	0.14	0.40	0.34	0.176

2.2. Calculation method

According to the algorithm shown in [5], the transfer matrixes Z were calculated for all seven variants and different fluctuation periods. On this basis, it was possible to bind the complex amplitudes of temperature and heat flux on one side with the conditions on the opposite side of the partition – this is illustrated by the following equation:

$$\begin{bmatrix} \hat{\Theta}_e \\ \hat{q}_e \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \cdot \begin{bmatrix} \hat{\Theta}_i \\ \hat{q}_i \end{bmatrix} \tag{1}$$

The above equation enables defining the magnitude of the complex amplitude of temperature and heat flux, if the values on the other side are known. The complex amplitudes allow defining the magnitude of the amplitude of the harmonically changing function (the module of the complex number) and the faze shift (the argument of the complex number). The complex amplitudes are presented in the exponential form of a complex number in the following form:

$$\hat{\Theta}_{\pm} = \left|\hat{\Theta}\right| \cdot e^{\pm i\psi} \tag{2}$$

$$\hat{q}_{\pm} = \left|\hat{q}\right| \cdot e^{\pm i\varphi} \tag{3}$$

It is assumed that the temperature on both sides of the partition oscillates around the average value and that the heat flux fluctuates around the value equal to:

$$\overline{q} = U \cdot \left(\Theta_i - \Theta_e\right). \tag{4}$$

On this basis and in this study, we put different starting conditions on one side of the partition and then analysed the acquired data from the other side, depending on the variant of load-bearing material.

3. Analysis results

3.1. Variant I

In the first variant, the external temperature was set at –10°C while the temperature inside was constant at 20°C. On this basis, the amplitudes of internal heat flux were compared. The results of the test are shown in Figure 2. The thermal diffusivity of the analysed concretes is presented in Figure 3.

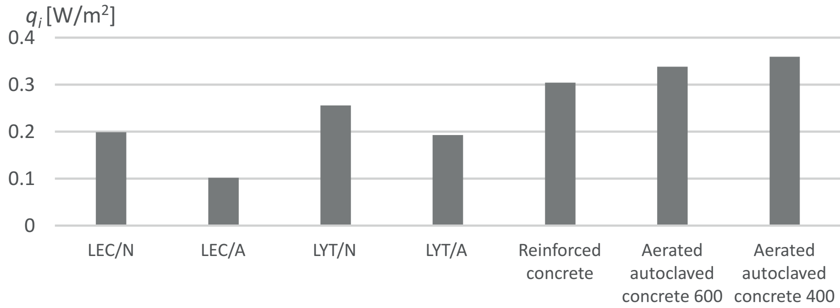

Fig. 2. The amplitudes of the internal heat flux for the 24-hour fluctuation period

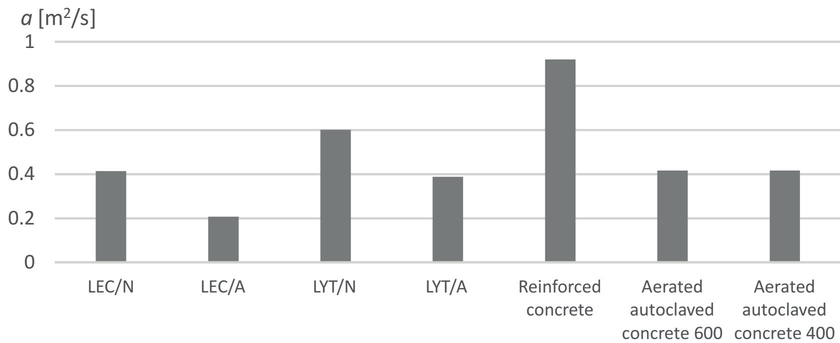

Fig. 3. Thermal diffusivity of the tested load-bearing materials

The results indicate that materials with a high specific heat and reduced thermal diffusivity enable achieving a constant temperature at considerably lower heat flux jumps on the internal surface of the partition due to temperature fluctuation on the external side of the wall. Lightweight concretes of which the thermal conductivity λ had significantly lower values than reinforced concrete, have enabled a reduction of the heat flux amplitudes on the inner side of the partition. Despite their low thermal diffusivity, the autoclaved aerated concretes do not reduce the q_i peaks as efficiently as lightweight concretes and their values are comparable to normal reinforced concrete.

3.2. Variant II

In the second variant, the external temperature was set at 25°C and its fluctuation at 5°C. The average internal temperature was again set at 20°C; however, this time we set a constant value of internal heat flux. This enabled comparison of the samples with regard to fluctuation of the temperature inside, as shown in Figure 4.

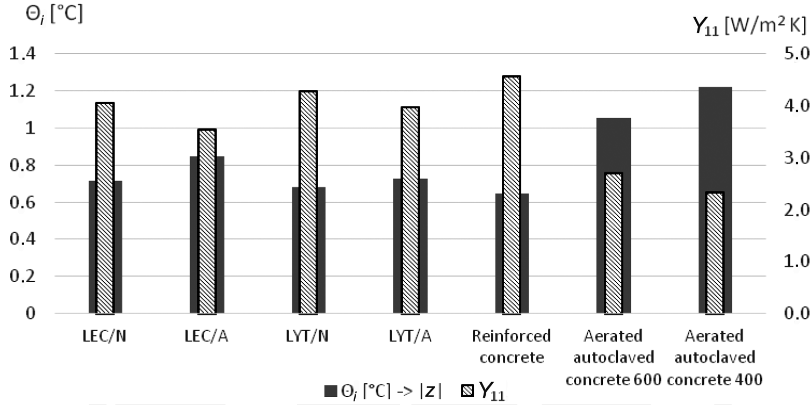

Fig. 4. The amplitudes of the internal temperature and internal admittances for the 24-hour fluctuation period

Again, the materials with higher specific heat obtained more favourable values of amplitudes. The largest fluctuations were observed for autoclaved aerated concretes of which the amplitude reached as much as 1.2°C with only 5°C external temperature variations. The specific heat c_v has a greater impact on the variation of temperature fluctuation than the thermal conductivity coefficient λ. This is the reason why the lowest fluctuation was observed for the partition with normal reinforced concrete. The relationship between internal admittance and temperature amplitude is clearly seen – the higher the value of the internal heat admittance, the lower the values of temperature fluctuation.

The exemplary distributions of the internal temperature fluctuations for a longer variation period of 168 hours are shown in Figure 5. The presented results for autoclaved aerated concrete of class 600, non-aerated concrete based on expanded clay and reinforced concrete indicate that concretes based on lightweight aggregates can represent a good alternative to normal concrete. The differences between the amplitudes of both variants are nonsignificant and are definitely preferable to the values for the ACC variant.

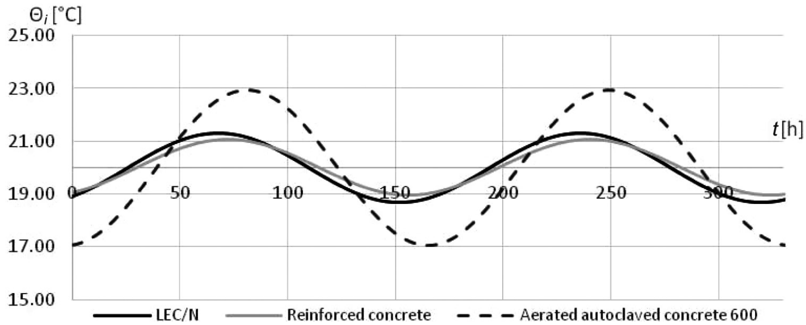

Fig. 5. Plot of internal temperature for the 168-hour fluctuation period

3.3. Required heating power

The heating power required to maintain a constant internal temperature was calculated for the examined partitions. The power value was estimated as the sum of the average heat flux (static heat flow) and the product of thermal transmittance for the period of 24 hours and the amplitude of external temperature (quasi-dynamic heat flow), described by the formula:

$$\Phi = U \cdot \Delta\Theta + Y_{12} \cdot \hat{\Theta}_e \quad (5)$$

The formula binds the average value of heat flux density with the fluctuation of heat flux caused by the variation of the temperature (harmonic fluctuation). We assumed that the outdoor temperature was –10°C, its amplitude was equal to 10°C and that the internal temperature was 20°C. The results are shown in Figure 6.

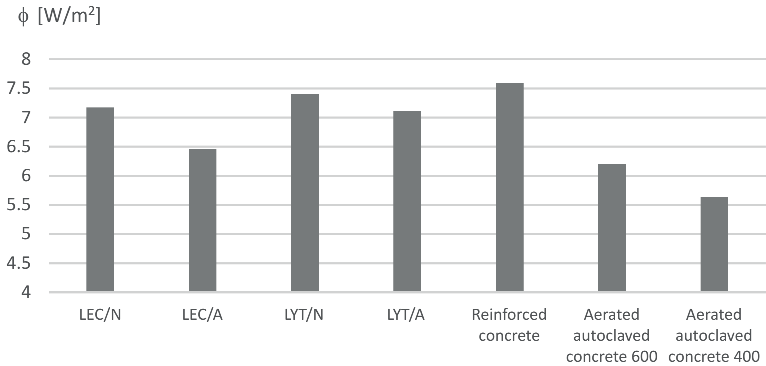

Fig. 6. Required heat power needed for maintaining constant temperature for fluctuations of 24 hours

It is worth mentioning that the required heating power in the case of the use of partitions with aerated autoclaved concretes was similar to partitions with lightweight composite concretes, although the thermal transmittance values for composites are between 0.212 and 0.238 W/(m^2·K) and for AAC, it is 0.195 W/(m^2·K).

4. Conclusions

The results of investigation into the dynamic properties of partitions and amplitudes of temperature and heat flux presented in this paper clearly indicate the need for a much more in-depth analysis than an assessment based solely on the comparison of the thermal transmittance of each variant. Although the comparison concerned only a few kinds of concrete composites, the obtained differences between each of the variants are clear. Materials of high specific heat such as lightweight concrete composites based on fly ash aggregate enable the significant reduction of the internal fluctuation of temperature, which, especially in low energy buildings [17], may be important for the overall energy efficiency of the building. Therefore, dynamic thermal analysis in the real climate conditions in which the building will function may be very useful.

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