Verification of agro-production building structures affecting the quality of indoor environment in the summer season

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Abstract

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This contribution focuses on the evaluation of the effect of aerated concrete external wall of a hall falling within the category of special-purpose agricultural buildings in terms of the phase shift of temperature oscillation. The assessment was performed by precise and approximate calculation procedures and was then compared with the results obtained from the values actually measured under the operating conditions.

Keywords: phase shift of temperature oscillation; temperature damping; external cladding

The building energy balance is affected by different thermo-physical phenomena generated by the interaction between solar radiation and different parts of the building envelope. These components should be closely linked with a unified aim to provide an improvement on the energy balance of the building (Fuliotto et al. 2010). Internal air temperature is influenced by variations in outdoor conditions such as temperature, solar radiation or meteorological situation. Other important parameters are wall overall heat transfer coefficient, internal heat gains or losses caused by devices such as lighting, occupancy, etc. Many articles related to this topic are focused on energy storage using heat accumulation in purpose-designed structures (Khudhair, Farid 2004; Heim 2010). At the present time, the phase shift of temperature oscillation is a lack in understanding thermal characteristic of buildings, which can present the semblance of a considerable influence on the thermal comfort of interior users during the summer period. The surface of the building envelope is heated by exposure to the increased external air temperature or direct sunlight, and at the same time the increased temperature from the surface is gradually spread towards the interior. Heat conduction occurs due to the exchange of energy

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between micro-particles in solids but also in the air (Řehánek 2002). The phase shift expresses the time during which the max. external air temperature increases the max. temperature on the inner surface of the building structure. This means that the phase shift of temperature oscillation in individual parts of the building envelope Ψ indicates the level of thermal stability of the internal environment. The higher its value, the greater thermal stability will exist in the internal space. The objective of the presented research was to verify the computing methods for determining the temperature damping of the external cladding in the agricultural manufacturing building in relation to the actually reached parameters obtained during summer "tropical days".

MATERIAL AND METHODS

The selected part of the external wall of the hall in a special-purpose agricultural building was assessed in terms of the phase shift of temperature oscillation in the summer season. Computational models were used to validate the results under practical operating conditions.

The external wall of the building is designed with light-weight aerated concrete blocks with a thickness of 300 mm and both of its sides are of lime-cement plaster 15 mm thick. The composition of the envelope structure and thermal properties of the wall layers are shown in Table 1.

The assessment in the computing part was done by precise calculations according to Šklover et al. (1966) and Halahyja et al. (1985), the output of which are relationships presented in a complex form. The results of this calculation are compared with a commonly used approximate equation (Chmúrny 2003; Vaverka 2006), followed by the assessment.

During the verification of the phase shift of the temperature oscillation, seven consecutive "tropical days" (from August 19, 2011 to August 26, 2011) were taken into account. Such a long period can already be considered sufficiently substantiated in terms of the exposure of the considered building to high temperatures. During the verification of the phase shift of the temperature oscillation in the selected east-oriented external wall, the period from August 24, 2011 (from 2.00 p.m.) to August 26, 2011 (till 2.00 p.m.) was taken into account due to the assumed time delay between the achievement of max. waveform ambient temperatures and inner surface temperatures. The actual assessment of the phase shift of the temperature oscillation was carried out only for the interval of one day (August 25, 2011 from twelve midnight to twelve midnight). Numerous results obtained were compared with the actually measured values. The measurements were made with a temperature and relative humidity logger Comet 3121 (Comet System Ltd., Rožnov pod Radhoštěm, Czech Republic) and a surface temperature logger DS 18 B20 (Department of Electrical Engineering, Automation and Informatics, Slovak University in Nitra, Nitra, Slovak Republic).

RESULTS AND DISCUSSION

Numerous expression of the phase shift of temperature oscillation

Precise calculation

(1) Temperature damping of a three-layer construction in a complex form (Šklover 1966)

$$\begin{aligned}\Theta_3 = \frac{s_2}{s_3}\left[\frac{s_1}{s_2}\times N\times\cosh\left(\frac{\overline{s}_2}{\lambda_2}\times d_2\right)+M\times\sinh\left(\frac{\overline{s}_2}{\lambda_2}\times d_2\right)\right]\times\\ \times\left[\sinh\left(\frac{\overline{s}_3}{\lambda_3}\times d_3\right)+\frac{\overline{s}_3}{h_e}\times\cosh\left(\frac{\overline{s}_3}{\lambda_3}\times d_3\right)\right]+\\ +\left[\frac{s_1}{s_2}\times N\times\sinh\left(\frac{\overline{s}_2}{\lambda_2}\times d_2\right)+M\times\cosh\left(\frac{\overline{s}_2}{\lambda_2}\times d_2\right)\right]\times\\ \times\left[\cosh\left(\frac{\overline{s}_3}{\lambda_3}\times d_3\right)+\frac{\overline{s}_3}{h_e}\times\sinh\left(\frac{\overline{s}_3}{\lambda_3}\times d_3\right)\right]\end{aligned} \tag{1}$$

where:

$\lambda_1, \lambda_2, \lambda_3$ – thermal conductivity of the layers (W/m.K)

s_1, s_2, s_3 – heat absorption capacity of the wall structure layers (W/m^2.K)

d_1, d_2, d_3 – thickness of the layers (m)

h_e – surface coefficient of heat transfer on the external side of the structure (W/m^2.K)

M, N – parameters indicating the ratio of heat flows and thermal amplitudes

whereby

$$s_j = 0.00853\times\sqrt{\lambda_j c_j \rho_j} \tag{2}$$

$$\overline{s}_j = s_j\times\sqrt{i} \tag{3}$$

where:

s_j – heat absorption capacity (W/m^2.K)

c_j – specific heat capacity (J/kg.K)

ρ_j – bulk density (kg/m^3)

Table 1. Thermo-technical properties of building materials (STN 73 0540-3 2002)

Layer	Material	Thickness of layer (m)	Bulk weight (kg/m^3)	Thermal conductivity (W/m.K)	Specific heat capacity (J/kg.K)
1.	lime-cement plaster	0.015	2,000	0.99	790
2.	light-weight aerated concrete block	0.300	550	0.19	840
3.	lime-cement plaster	0.015	2,000	0.99	790

(2) Phase shift of temperature oscillation Ψ_1°

$$\overset{\circ}{\psi}_1 = \text{argum}(\Theta) = \text{arctg}\frac{b}{a} + k\pi \tag{4}$$

where: $k = 0$ at $a > 0$, $b > 0$
$k = 1$ at $a < 0$, $b < 0$
$k = 2$ at $a > 0$, $b < 0$

where:

argum (Θ) – complex shape of the phase shift of temperature oscillation (–)
k – coefficient (–)
a – abscissa of a complex number (–)
b – ordinate of a complex number (–)

Then,
Ψ_1° = 10.09 (h).

Approximate calculation

We determined the phase shift of temperature oscillation Ψ_2° by an approximate calculation in a time scale through the equation

$$\overset{\circ}{\psi}_2 = \frac{1}{15}\left[40.5\sum_{j=1}^{n} D_j - \text{arctg}\frac{\alpha_i}{h_i + U_{si}\sqrt{2}} + \text{arctg}\frac{U_{se}}{U_{se} + h_e\sqrt{2}}\right] \tag{5}$$

where:

$$D_j = R_j s_j \tag{6}$$

where:

R_j – thermal resistance of a layer (m^2.K/W)
U_{si}, U_{se} – heat absorption capacity of individual surface layers (W/m^2.K)
h_i – heat transfer coefficient at internal surface (W/m^2.K)
h_e – heat transfer coefficient at external surface (W/m^2.K)
D_j – thermal inertia (–)
s_j – heat absorption capacity (W/m^2.K)

Then,
Ψ_2° = 11.63 (h).

Temperature harmonic fluctuation is schematically described in Fig. 1.

Phase shift of temperature oscillation expressed according to actually measured values

After the time period of six consecutive tropical days (from August 19, 2011 to August 24, 2011) during which the temperature value exceeded 30°C, the courses of external and internal temperatures as well as temperatures of the circumferential wall on the internal surface were measured during the next 48 hours.

Based on the values measured during the first interval of 24 h (from August 24, 2011 from 2.00 p.m. to August 25, 2011 till 2.00 p.m.) and the second interval of 24 h (from the August 25, 2011 from 2.00 p.m. to August 26, 2011 to 2.00 p.m.), the following data were evaluated.

(1) Average daily temperature of external air θ_{eDm} according to the equation

$$\theta_{eDm} = \frac{1}{144}\left(\theta_{e1} + \theta_{e2} + \ldots\right) \tag{7}$$

where:

θ_{e1}, θ_{e2} – daily temperatures of external air (measured in the intervals of 10 min, it means 144 measurements in 24 h)

Average daily temperature of external air measured from the registered records:

θ_{eD1m} = 27.16°C (first interval of 24 h)
θ_{eD2m} = 26.50°C (second interval of 24 h)

(2) Average daily temperature of the internal surface on the considered wall $\theta_{si,m}$ according to the equation

$$\theta_{si,Dm} = \frac{1}{144}\left(\theta_{si,1} + \theta_{si,2} + \ldots\right) \tag{8}$$

where:

$\theta_{si,1}$, $\theta_{si,2}$ – daily temperatures on the internal surface (measured in the interval of 10 min, it means 144 measurements in 24 h)

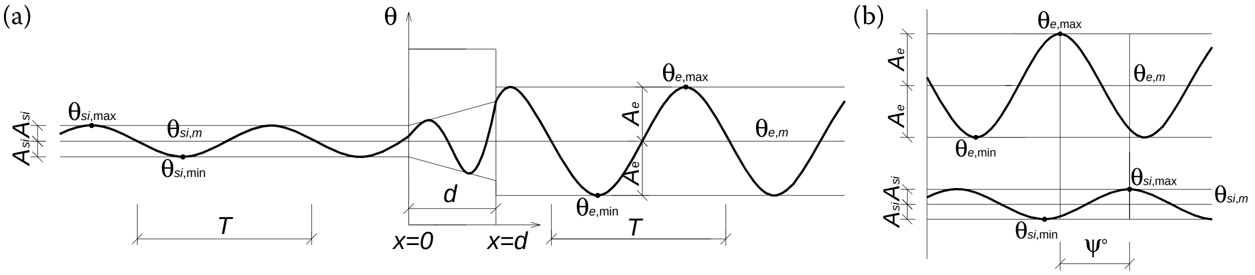

Fig. 1. Schematic description of temperature harmonic fluctuation:
(a) thermal damping; (b) phase shifts of thermal oscillations Ψ in the wall structure
A_{si} – temperature amplitude on the internal surface of the structure (K); A_e – external air temperature amplitude (K); T – time (h); $\theta_{si,\min}$ – min. internal surface temperature (°C); $\theta_{si,\max}$ – max. internal surface temperature (°C); $\theta_{si,m}$ – medium internal surface temperature (°C); $\theta_{e,\min}$ – min. external air temperature (°C); $\theta_{e,\max}$ – max. external air temperature (°C); $\theta_{e,m}$ – medium external air temperature (°C); ψ° – phase shift of temperature oscillation (–); d – wall thickness in the x-direction (mm)

The average daily temperature of the internal surface on the considered wall measured from the registered records:

$\theta_{si,D1m}$ = 28.24°C (first interval of 24 h)
$\theta_{si,D2m}$ = 28.58°C (second interval of 24 h)

(3) Temperature of internal air $\theta_{i,m}$ was found by a similar procedure:

$\theta_{i,D1m}$ = 28.85°C (first interval of 24 h)
$\theta_{i,D2m}$ = 29.17°C (second interval of 24 h)

For illustration, the courses of the measured values with a subsequent definition of the assessed area are shown in Fig. 2.

The phase shift of temperature oscillation was determined from the measured data $\Psi = t_2 - t_1 = 3.30$ h (Fig. 3).

A number of researches focused on the impact of the building envelopes on heating and cooling loads of the buildings assuming the indoor air temperature is constant (Bojic et al. 2001; Li, Chen 2003). According to Gong et al. (2005), even though a building is naturally ventilated in summer, its mean indoor air temperature is considered as a constant, being only 1.5°C higher than the outdoor air temperature. However, when a building is naturally ventilated, the indoor air temperature also varies periodically because of the impact of the outdoor air temperature and ventilation rate (Yam et al. 2003). Therefore, it cannot be considered as a constant in analysing air-conditioned buildings. In summers, non-air-conditioned interiors of halls in special-purpose agricultural buildings cause considerably nonstationary conditions that negatively affect qualitative parameters of the work environment. According to Zhou et al. (2007), the use of a heavy wall with external insulation is predicted to have the lowest amplitude of indoor air temperature and such wall is

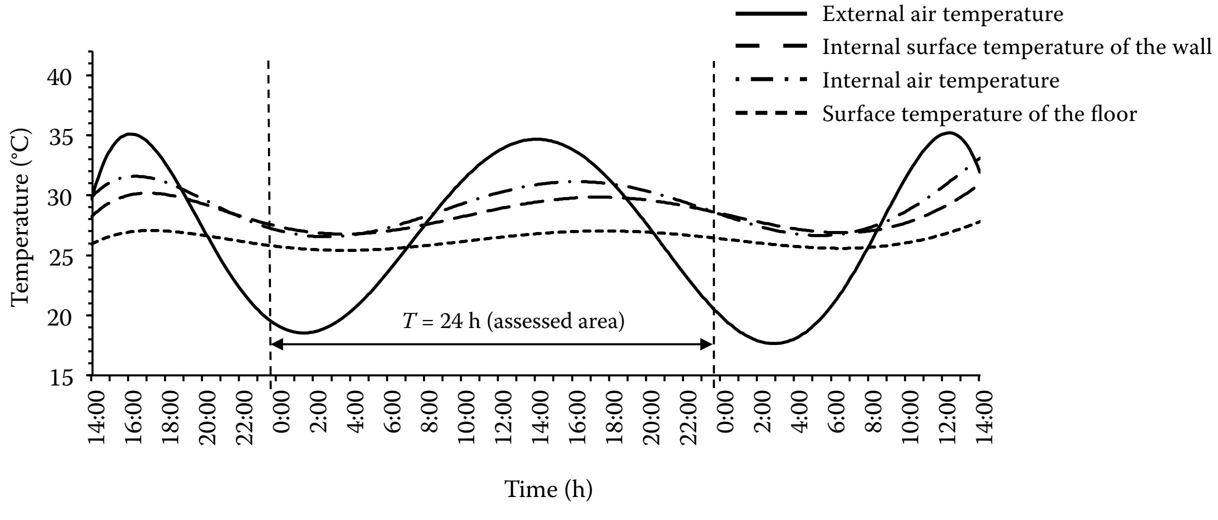

Fig. 2. Trend lines of courses of parameters measured from August 24, 2011 to August 26, 2011

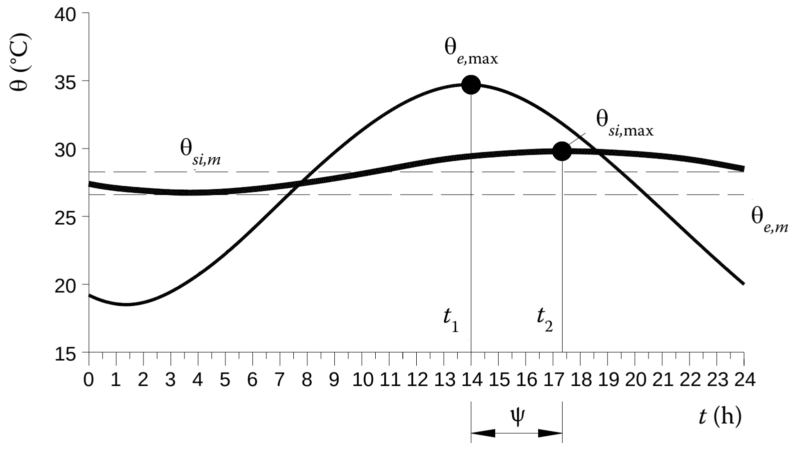

Fig. 3. Scheme of the course of measured external temperatures θ_e and internal surface temperatures of the wall θ_{si} t – time (h); t_1 – time to reach the max. external air temperature (h); t_2 – time to reach the max. internal surface temperature (h); for abbreviations see Fig. 1

suitable for naturally ventilated buildings. The fluctuation of internal air temperature decreases, and the time needed to reach the max. temperature extends with a decreasing amount of internal thermal mass. But the effect becomes negligible when the time constant of the system is more than 20 hours.

In the case of the structure considered in this study, the mean temperature of the inner surface of the outer thermally uninsulated wall was higher than the average ambient temperature. For that reason, considerably different results were obtained of the phase shift of temperature oscillation between the calculation methods and direct measurements in operating conditions. The reasons for this finding can be analysed as follows:

(1) A direct effect was observed of sunlight on the external wall. In the case of the assessed east-oriented wall, intense solar radiation is evident from the morning hours already. Sun rays fall on the wall plane almost at a 90° angle, which causes a fast increase of external surface temperature. The effect of solar radiation is combined with a very important role of the cloud occurrence.

(2) A high average internal air temperature was observed. In this case, the average internal air temperature was higher than the average external air temperature. In terms of the heat balance, especially the size of areas of transparent elements, their inclination from the horizontal plane and their orientation towards the compass points participates in the increase of internal air temperature.

(3) Furthermore, another important factor is the quality of the storage capacity in the upper parts of the building structure envelope and the intensity of natural ventilation during high daily temperature of the outside air. In terms of the heat balance, only the floor structure can be assigned to a greater cooling effect if it is placed directly on the ground (Fig. 2).

CONCLUSION

The results of our measured values significantly distort non-stationary effects difficult to predict (the variability of external climatic conditions, method, and ventilation rate). This has been demonstrated by a multiple difference between the results obtained from the precise calculation procedure and the results obtained from the values measured under the operating conditions.

The phase shift of temperature oscillation indicates the thermal stability of the interior of the building as well as the justification of the need to install an air conditioner to cool the interior ("summer energy buildings").

More accurate results in assessing the quality of the envelope in terms of thermal technology, and in assessing the effect of the phase shift of temperature oscillation on the thermal stability of the indoor environment in individual parts of buildings can be achieved by advanced computational methods (e.g. Computational Fluid Dynamics – CFD), which enable the calculation of airflow with respect to the complexity and non-linearity of the radiation changes. This being the case, the difference between the air and surface temperatures computed and the data measured is generally less than 1 K.

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