

ESTIMATION OF THE RELIABILITY OF THE THERMAL RECEPTIVITY COEFFICIENT OF THE SURFACES OF TIMBER FRAME WALL MATERIALS

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ABSTRACT

A number of differences between the experimental results and the calculated thermal behaviour results of the timber frame walls have been obtained during the investigation carried out at summer operation conditions. The aim of the recent investigation is to determine at what stage in the calculation procedure the most significant errors in the estimation of the values of physical parameters might be made. The impact of errors on the further calculation reliability will be discussed as well. The methods of mathematical-statistics have been applied for establishing the parameters to characterize the sophisticated thermo physical processes.

The timber frame wall was used as the object of the experiment under unstable summer operation conditions. The calculations were performed according to the measured climatic input data (outside air temperature, solar radiation, wind speed, relative humidity, etc.) and the temperature distribution inside the tested wall.

The methodology for the calculation of the material's surface thermal receptivity coefficient Y is the object considered in the paper. Such methodology allows the estimation of the interaction between the physical parameters of different materials in the wall structure.

The investigation has resulted in the estimation of the parameter Y reliability. The modified Monte Carlo simulation, including analysis by the methods of the Paired t -Test, Tolerance intervals and Prediction intervals has been applied for the determination of the discussed reliability. Unstable processes of heat transmittance and interaction among the wall structural layers then have been described through parameter Y with adequate precision. The interaction was determined for the parameters included into the Y calculation equations, such as thermal conductivity λ W/mK, thermal resistance R m²K/W, the rate of thermal inertia D and materials' thermal receptivity coefficient s W/m²K. The relative errors between the mean Y_m and design $Y_{ds,0.9}$ values have been evaluated and the main dependences discussed.

Keywords: thermal receptivity, reliability, Monte Carlo simulation, timber frame wall

1. INTRODUCTION

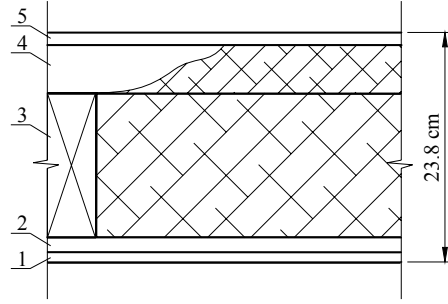
The number of the thermo-physical parameters (e.g. heat flux density, thermal inertia, time constant, thermal resistance, time lag, decrement factor, etc.) describes the thermal behaviour of the building envelope under unstable conditions. Precision in the calculation of the mentioned thermo-physical parameters depends on the precision of a particular material's value of the physical parameter (i.e. thermal conductivity, density, thickness, specific heat capacity and etc.) and on their interaction [1].

The review of the scientific publications has revealed [2-4] that the precise estimation of the variable parameters might be assured by the corresponding experimental input data (comprehensive temperature field and moisture content inside the building envelope). Such experimental input data [5] was employed to determine the precision of the thermal receptivity coefficient Y of the surfaces of the timber frame wall materials. In this case, the Monte Carlo simulation [6] was used to construct the necessary mathematical model.

The thermal receptivity coefficient of the materials' surfaces Y was used for the calculation of the heat transfer coefficient U of the building envelope [7]. It was found out that Y depends on the physical properties of materials and the oscillation period of outdoor air temperature.

The coefficient Y may be also found in the Russian Standard [8] in which it is used for the estimation of the thermal behaviour of the building envelope. It is also presented as a thermo physical property of building partitions in various articles and in European Standards [9, 10].

The thermal receptivity coefficient of the materials' surfaces Y has been well explored for the heavyweight building envelope [11], [12]. However the thermal behaviour analysis of the lightweight envelope, such as the timber frame walls, on the climatic conditions of a hot period in Eastern Europe was not found in the available databases of scientific publications. Therefore, the investigation aims at the precise calculation of the thermal receptivity coefficient Y of the surfaces of lightweight timber frame wall materials during a hot operation period. The timber frame wall with a rather complex structure yet nevertheless most frequently used in practice has been chosen for the investigation (Fig.1).



1. Plaster, $d=0.01\text{m}$;
2. OSB (Oriented strand board), $d=0.015\text{m}$;
3. Timber frame with mineral wool inside, $d=0.15\text{m}$;
4. Cross beam with mineral wool inside, $d=0.05\text{m}$;
5. Gypsum plasterboard, $d=0.013\text{m}$;

Figure 1. The cross sections of the tested wall.

Table 1. The physical parameters of the tested materials.

Materials	Thickness of the layer d , m	Thermal conductivity λ , W/(mK)	Density ρ , kg/m ³	Specific heat capacity c , J/(kgK)
Plaster	0.01	0.8	1700	1100
OSB (Oriented strand board)	0.015	0.08	900	1700
Mineral wool	0.15	0.039	40	840
Mineral wool	0.05	0.036	100	840
Gypsum plasterboard	0.013	0.22	800	1050

As the Table 1 demonstrates, the materials of which the tested wall is composed combine a wide range of physical parameters.

2. THE MATHEMATICAL MODEL FOR THE ESTIMATION OF THE THERMAL RECEPTIVITY COEFFICIENT OF MATERIALS' SURFACES Y

The Monte Carlo simulation method was modified for the calculation of the descriptive statistics (mean, variance, standard error, etc.) of the thermo-physical variable parameters. The modified methodology is presented below.

In general, variable vector X is a function of a few stochastic variables $\xi_1, \xi_2, \dots, \xi_n$:

$$X = g(\xi_1, \xi_2, \dots, \xi_n) \quad (1)$$

Thus, the mean of vector X_m and the variance $\sigma^2 X$ are to be calculated by taking into account the covariance between $\xi_1, \xi_2, \dots, \xi_n$ in to consideration:

$$X_m = g_m(\xi_1, \xi_2, \dots, \xi_n) + 0,5 \sum_{i=1}^n \left(\frac{\partial^2 g}{\partial \xi_i^2} \right)_m \sigma^2 \xi_i + \sum_i \sum_j \left(\frac{\partial^2 g}{\partial \xi_i \partial \xi_j} \right)_m \text{cov}(\xi_i, \xi_j) \quad (2)$$

The variance of the variables can be estimated by the following equation (2):

$$\sigma^2 X = \sum_{i=1}^n \left(\frac{\partial^2 g}{\partial \xi_i} \right)_m^2 \sigma^2 \xi_i + \sum_{i=1}^n \left(\frac{\partial g}{\partial \xi_i} \right)_m \left(\frac{\partial^2 g}{\partial \xi_i^2} \right)_m \alpha \xi_i + \sum_i \sum_j \left(\frac{\partial g}{\partial \xi_i} \right)_m \left(\frac{\partial g}{\partial \xi_j} \right)_m \text{cov}(\xi_i, \xi_j) \quad (3)$$

The designed values of the variable parameters can be estimated with the 90% quantile and 90% 1-tailed confidence interval supposing that the distribution is normal [13]:

$$X \in [m + z_p \sigma] \quad (4)$$

where: m – mean value; σ – standard deviation; and quantile – $z_{0,90}=1.28$.

The geometrical interpretation of the analysed thermo-physical parameter distribution (4) is presented in Fig.2.

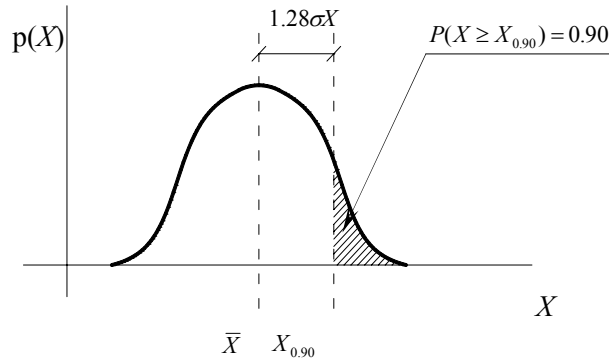


Figure 2. Geometrical interpretation of the analysed thermo-physical parameter distribution.

The reliability of the thermo-physical parameters (e.g. thermal conductivity λ , layer thickness d , thermal resistance R , thermal inertia D and the material's thermal receptivity s) found in the methodology used for the calculation of the thermal receptivity coefficient of materials' surfaces Y [10] was estimated in previous research [14]. The results of these estimations (variance σ^2 , standard deviation σ and design value) are presented in Table 2.

The mathematical model for the calculation of the thermal receptivity coefficient of materials' surfaces Y has been developed according to the layers' position in the wall and the physical properties of materials of the layers. The model is presented in equations (5)-(9) and the graphical interpretation in Fig.3. The active zone of the temperature wave oscillations has been determined inside the 1st and 2nd layers. Actually, the rate of thermal inertia $D=0.372$ has increased to $D=1.403$ after the temperature wave has passed the 3rd layer (mineral wool, $d=0.15$). It means that the temperature wave amplitude has decreased nearly twice, meanwhile the oscillations at the 4th and 5th layers remained regular.

The thermal receptivity coefficient of the external layer (i.e. plaster) surface Y_1 has been defined by the following equation:

$$Y_{1m} = \frac{R_{1m} s_{1m}^2 + Y_{2m}}{1 + R_{1m} Y_{2m}} \quad (5)$$

The coefficient Y_2 of OSB (Oriented strand board) layer has been defined as follows:

$$Y_{2m} = \frac{R_{2m} s_{2m}^2 + Y_{3m}}{1 + R_{2m} Y_{3m}} \quad (6)$$

The coefficient Y_3 of mineral wool ($d=0.15m$) layer has been found out by the below given formula:

$$Y_{3m} = \frac{R_{3m} s_{3m}^2 + s_{4m}}{1 + R_{3m} s_{4m}} \quad (7)$$

As the oscillation of the temperature wave has decreased near by twice (Fig.3), the coefficient Y_4 of the mineral wool ($d=0.05m$) layer was adequate to the thermal receptivity of the layer material s_4 :

$$Y_{4m} = s_{4m} \quad (8)$$

The coefficient Y_5 of the internal layer (gypsum plasterboard) has been defined in the same way as in the deeper layer. Consider:

$$Y_{5m} = s_{5m} \quad (9)$$

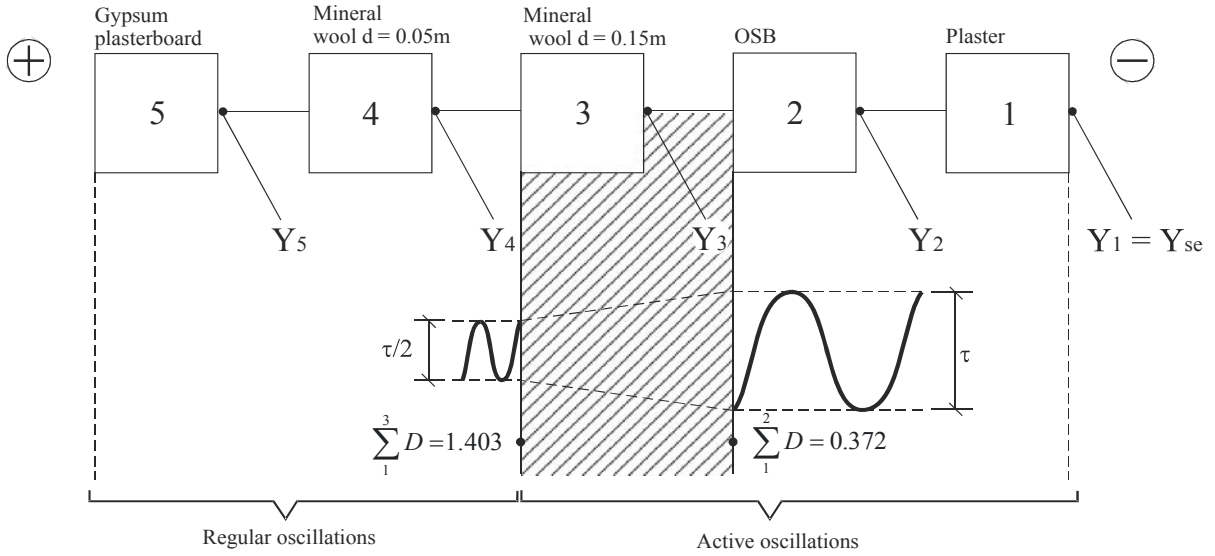


Figure3. Graphical interpretation of the estimation model of the coefficient Y .

The equations for the estimation of descriptive statistics of the thermal receptivity coefficient of materials' surfaces Y have been compiled by applying the Monte Carlo modification described above in equations (1) to (4).

The variance $\sigma^2 Y_1$ of the external layer (plaster) has been defined by the following equation:

$$\begin{aligned} \sigma^2 Y_1 &= \left(\frac{\partial Y_1}{\partial R_1} \right)_m^2 \sigma^2 R_1 + \left(\frac{\partial Y_1}{\partial s_1} \right)_m^2 \sigma^2 s_1 + \left(\frac{\partial Y_1}{\partial Y_2} \right)_m^2 \sigma^2 Y_2 + 2 \left(\frac{\partial Y_1}{\partial R_1} \right)_m \left(\frac{\partial Y_1}{\partial s_1} \right)_m Cov(R_1, s_1) = \\ &= A_1^2 \sigma^2 R_1 + B_1^2 \sigma^2 s_1 + C_1^2 \sigma^2 Y_2 + 2 A_1 B_1 \times Cov(R_1, s_1) \end{aligned} \quad (10)$$

Further consider:

$$A_1 = \left[\frac{s_{1m}^2 (1 + R_{1m} Y_{2m}) - Y_{2m} (R_{1m} s_{1m}^2 + Y_{2m})}{(1 + R_{1m} Y_{2m})^2} \right] \quad (11)$$

$$B_1 = \left[\frac{2 R_{1m} s_{1m}}{1 + R_{1m} Y_{2m}} \right] \quad (12)$$

$$C_1 = \left[\frac{(1 + R_{1m} Y_{2m}) - R_{1m} (R_{1m} s_{1m}^2 + Y_{2m})}{(1 + R_{1m} Y_{2m})^2} \right] \quad (13)$$

$$Cov(R_1, s_1) = \left[\left(-\frac{d_{1m}}{\lambda_{1m}^2} \right) \left(\frac{\pi c_1 \rho_1 / z}{\sqrt{2 \pi c_1 \rho_1 \lambda_{1m} / z}} \right) \right] \times \sigma^2 \lambda_1 \quad (14)$$

The variance $\sigma^2 Y_2$ of the OSB (Oriented strand board) layer has been defined by the following equation:

$$\begin{aligned}\sigma^2 Y_2 &= \left(\frac{\mathcal{G}Y_2}{\mathcal{G}R_2} \right)_m^2 \sigma^2 R_2 + \left(\frac{\mathcal{G}Y_2}{\mathcal{G}s_2} \right)_m^2 \sigma^2 s_2 + \left(\frac{\mathcal{G}Y_2}{\mathcal{G}Y_3} \right)_m^2 \sigma^2 Y_3 + 2 \left(\frac{\mathcal{G}Y_2}{\mathcal{G}R_2} \right)_m \left(\frac{\mathcal{G}Y_2}{\mathcal{G}s_2} \right)_m \text{Cov}(R_2, s_2) = \\ &= A_2^2 \sigma^2 R_2 + B_2^2 \sigma^2 s_2 + C_2^2 \sigma^2 Y_3 + 2A_2 B_2 \times \text{Cov}(R_2, s_2)\end{aligned}\quad (15)$$

Where the coefficients A_2 , B_2 , C_2 and $\text{Cov}(R_2, s_2)$ have been expressed by:

$$A_2 = \left[\frac{s_{2m}^2 (1 + R_{2m} Y_{3m}) - Y_{3m} (R_{2m} s_{2m}^2 + Y_{3m})}{(1 + R_{2m} Y_{3m})^2} \right] \quad (16)$$

$$B_2 = \left[\frac{2R_{2m} s_{2m}}{1 + R_{2m} Y_{3m}} \right] \quad (17)$$

$$C_2 = \left[\frac{(1 + R_{2m} Y_{3m}) - R_{2m} (R_{2m} s_{2m}^2 + Y_{3m})}{(1 + R_{2m} Y_{3m})^2} \right] \quad (18)$$

$$\text{Cov}(R_2, s_2) = \left[\left(-\frac{d_{2m}}{\lambda_{2m}^2} \right) \left(\frac{\pi c_2 \rho_2 / z}{\sqrt{2\pi c_2 \rho_2 \lambda_{2m} / z}} \right) \right] \times \sigma^2 \lambda_2 \quad (19)$$

The variance $\sigma^2 Y_3$ of the mineral wool layer ($d=0.15\text{m}$) have been defined by:

$$\begin{aligned}\sigma^2 Y_3 &= \left(\frac{\mathcal{G}Y_3}{\mathcal{G}R_3} \right)_m^2 \sigma^2 R_3 + \left(\frac{\mathcal{G}Y_3}{\mathcal{G}s_3} \right)_m^2 \sigma^2 s_3 + \left(\frac{\mathcal{G}Y_3}{\mathcal{G}s_4} \right)_m^2 \sigma^2 s_4 + 2 \left(\frac{\mathcal{G}Y_3}{\mathcal{G}R_3} \right)_m \left(\frac{\mathcal{G}Y_3}{\mathcal{G}s_3} \right)_m \text{Cov}(R_3, s_3) = \\ &= A_3^2 \sigma^2 R_3 + B_3^2 \sigma^2 s_3 + C_3^2 \sigma^2 Y_2 + 2A_3 B_3 \times \text{Cov}(R_3, s_3)\end{aligned}\quad (20)$$

Where the coefficients A_3 , B_3 , C_3 and $\text{Cov}(R_3, s_3)$ have been expressed as follows:

$$A_3 = \left[\frac{s_{3m}^2 (1 + R_{3m} s_{4m}) - s_{4m} (R_{3m} s_{3m}^2 + s_{4m})}{(1 + R_{3m} s_{4m})^2} \right] \quad (21)$$

$$B_3 = \left[\frac{2R_{3m} s_{3m}}{1 + R_{3m} s_{4m}} \right] \quad (22)$$

$$C_3 = \left[\frac{(1 + R_{3m} s_{4m}) - R_{3m} (R_{3m} s_{3m}^2 + s_{4m})}{(1 + R_{3m} s_{4m})^2} \right] \quad (23)$$

$$\text{Cov}(R_3, s_3) = \left[\left(-\frac{d_{3m}}{\lambda_{3m}^2} \right) \left(\frac{\pi c_3 \rho_3 / z}{\sqrt{2\pi c_3 \rho_3 \lambda_{3m} / z}} \right) \right] \times \sigma^2 \lambda_3 \quad (24)$$

The coefficients Y_4 of the mineral wool layer ($d=0.05\text{m}$) and Y_5 of the internal layer (gypsum plasterboard) have been defined by the following equations:

$$\sigma^2 Y_4 = \sigma^2 s_4 \quad (25)$$

$$\sigma^2 Y_5 = \sigma^2 s_5 \quad (26)$$

The parameters $\sigma^2 s_4$ and $\sigma^2 s_5$ have been estimated in previous research [14].

The standard deviation of the coefficient Y for any layer σY_n can be defined as follows:

$$\sigma Y_n = \sqrt{\sigma^2 Y_n} \quad (27)$$

The designed value of the thermal receptivity coefficient of materials' surfaces $Y_{ds,0.90}$ can be estimated according to the equation (4):

$$Y_{ds,0.90} = Y_m + 1.28\sigma Y_n \quad (28)$$

The standard deviation σY_n displays the quantity of the thermal receptivity coefficient of materials' surfaces Y . In the analysed case, more important it is to have the quality expression of distribution of variables, i.e. the coefficient of variation ($\delta(\%)$), in order to compare the results obtained in the different layers.

The coefficient of variation for any analysed variable can be expressed by:

$$\delta X = \left(\frac{\sigma X}{X_m} \right) \times 100 \quad (29)$$

where X_m is the mean and σX is the standard deviation of any analysed variable vector.

The relative error e (%) between the mean Y_m and the designed $Y_{ds,0.9}$ values can be defined as follows:

$$e = \left(\frac{Y_{0.90} - Y_m}{Y_{0.90}} \right) \times 100 \quad (30)$$

3. RESULTS

The input data of the experiment [5] (e.g. climatic conditions, microclimatic parameters inside the tested cell and the physical parameters of the tested materials) has been applied for the structured mathematical model (see Chapter 2). The descriptive statistics $\sigma^2(Y_n)$, $\sigma(Y_n)$ and $\delta(Y_n)$ calculated with the use of the mentioned model are presented in Table 2. The largest values of $\delta(Y_n)$ have been determined for the mineral wool layers (Table 2). The parameters (R , s) that are included in the equations (5-9) have been estimated with the low precision for the mentioned layers [14] and it could be the reason for a wide distribution of the estimated Y values. The problem is that the results of the calculation of the designed values $Y_{ds,0.90}$ directly depends on $\delta(Y_n)$ (28), and therefore, the precision of the unstable heat transmittance cannot be determined by common mathematical tools. It requires a wide range of analysis in order to modify the existing mathematical expressions.

Table 2. Descriptive statistics of the analysed thermo-physical parameter Y estimated by the Monte Carlo simulation method.

Estimated descriptive statistics	Layer of the analysed wall				
	Gypsum plasterboard	Mineral wool $d=50\text{mm}$	Mineral wool $d=150\text{mm}$	OSB (Oriented strand board)	Plaster
Variance of the variables					
$\sigma^2 Y, (\text{W}/(\text{m}^2\text{K}))^2$	8.601E-03	1.804E-04	6.122E-05	1.394E-03	1.390E-03
Standard deviation of the variables					
$\sigma Y, \text{W}/(\text{m}^2\text{K})$	0.093	0.013	0.0078	0.037	0.037
Coefficient of variation of the variables					
$\delta Y, \%$	2.256	2.804	2.569	1.988	1.177
Designed values of the variable parameters with the probability 0.90					
$Y_{ds,0.90}, \text{W}/(\text{m}^2\text{K})$	4.229	0.496	0.315	1.925	3.214

The designed values $Y_{ds,0.90}$ of the thermal receptivity coefficient Y have been estimated with the use of the developed mathematical model. They were compared with the mean values Y_m and then the relative errors e (%) were determined (Fig.4). As it was expected, the largest relative errors were obtained for the mineral wool layers, but they did not exceed the limit of engineering requirements.

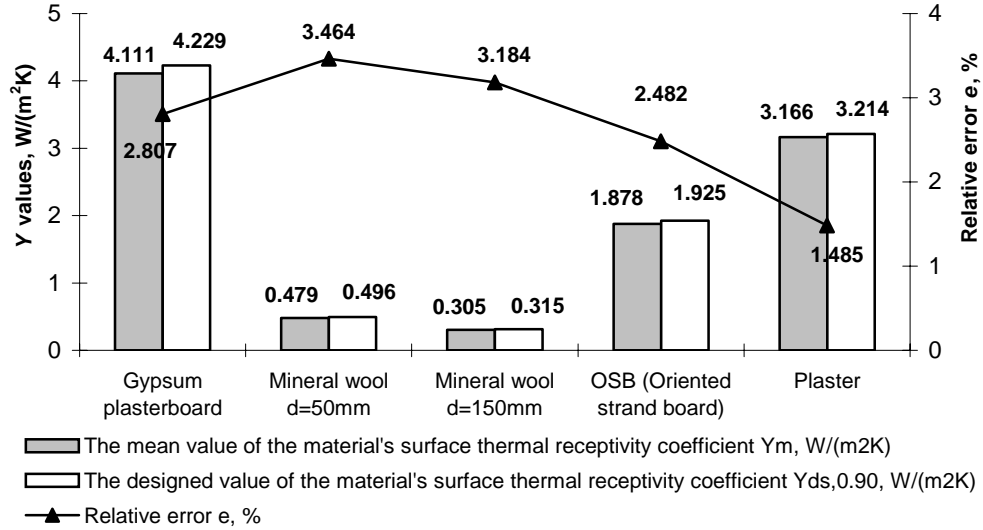


Figure 4. Reliability of the designed values $Y_{ds,0.90}$ of the wall layers.

4. CONCLUSIONS

In the case of the adjacent layers the errors δY cannot be summarized on the basis of the estimation of the reliability of the thermal receptivity coefficient of the timber frame wall materials' surfaces Y . The $\delta Y=2.569\%$ was estimated for the mineral wool layer ($d=150\text{mm}$). This layer reduces the temperature oscillations nearly twice. The $\delta Y=2.804\%$ was determined for the mineral wool layer ($d=50\text{mm}$) that remains in the regular zone of temperature oscillations taking into account the error of the mineral wool layer ($d=150\text{mm}$). The accumulative parameters (s and Y) have been calculated with desirable precision even when the layer had low thermal capacity (Table 1). The least value $\delta Y=1.177\%$ influenced by the total error of inner layers (Y_3 and Y_2) was determined for the plaster layer (Y_1). The investigation showed that the impact of the interaction between the layers on the reliability of Y was insignificant. To conclude, in most cases, the reliability for the thermal receptivity coefficient Y depends on the variation of the values of the materials' physical parameters.

The investigation lead to the conclusion that the largest relative errors between the mean Y_m and the design values $Y_{ds,0.9}$ were obtained for both layers of the mineral wool (3.184% and 3.464%). The distribution of the thermo-physical parameter values of the layers with low thermal conductivity and low thermal capacity reduce the calculation reliability of the tested wall's thermal behaviour.

LIST OF SYMBOLS

- s – material's thermal receptivity coefficient, $W/(m^2K)$;
- s_m – the mean value of the material's thermal receptivity coefficient, $W/(m^2K)$;
- $\sigma^2 s$ – variance of the material's thermal receptivity coefficient, $(W/(m^2K))^2$;
- λ – thermal conductivity of a material, $W/(mK)$;
- $\sigma^2 \lambda$ – variance of the thermal conductivity coefficient of a material, $(W/(mK))^2$;
- R – thermal resistance of the layer, m^2K/W ;
- R_m – the mean value of the thermal resistance of the layer, m^2K/W ;
- $\sigma^2 R$ – variance of the thermal resistance of the layer, $(m^2K/W)^2$;
- c – material's specific heat capacity, $J/(kgK)$;
- ρ – material's density, kg/m^3 ;
- z – oscillation period of outside air temperature, hours;
- d – thickness of the layer, m;
- D – the rate of thermal inertia, –;
- Y – thermal receptivity coefficient of a material's surface, $W/(m^2K)$;

Y_m – the mean value of the thermal receptivity coefficient of a material surface, $W/(m^2K)$;
 σY – standard deviation of the thermal receptivity coefficient of a material's surface, $W/(m^2K)$;
 $\sigma^2 Y$ – variance of the thermal receptivity coefficient of a material's surface, $(W/(m^2K))^2$;
 δY – coefficient of variation of the thermal receptivity coefficient of a material's surface, $W/(m^2K)$;
 $Y_{ds,0.90}$ – thermal receptivity coefficient of a material's surface with 90% quantile, $W/(m^2K)$;

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