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# THEORETICAL AND EXPERIMENTAL BASES FOR ENSURING THERMAL AND ACOUSTIC RESISTANCE OF STRUCTURAL ELEMENTS OF BUILDINGS AND SHIELDING OF ELECTROMAGNETIC RADIATION EMISSION

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An applied mathematical apparatus has been developed for predicting the thermal and acoustic resistance of building elements and the effectiveness of electromagnetic radiation shielding. Thermal resistance calculations take into account the influence of solar radiation and convective heat exchange on the outer surface of buildings. This makes it possible to rationalise the thermal protection of buildings and their energy efficiency. To predict the acoustic resistance of building structural elements, a multifactorial model of sound transmission through a protective layer has been improved, which has reduced the calculation error compared to known solutions. An applied calculation tool has been developed to predict the effectiveness of shielding electromagnetic radiation with building and facing materials. It is based on the relationships of electrodynamics of continuous media and is most suitable for multicomponent materials compared to semi-empirical formulas. Verification of the results obtained indicates an acceptable convergence of theoretical and experimental data. Given the presence of certain assumptions and simplifications in the calculations, in practical activities, a certain margin of effectiveness must be included in the protective properties of the designed materials and structures.

**Keywords:** thermal resistance, acoustic resistance, shielding effectiveness, electromagnetic radiation.

## Introduction

One of the important tasks of civil and industrial construction is to create normative conditions for people staying in buildings. These include temperature conditions, noise levels, electromagnetic fields and man-made radiation. The significance of these physical factors largely depends on the physical characteristics of building and facing materials. The thermophysical characteristics of building structural elements influence the process of creating comfortable conditions for people and are crucial for ensuring energy efficiency. The sound insulation properties of building facing materials and their ability to shield electromagnetic radiation contribute to the preservation of human health. Therefore, a lot of attention is paid to this issue. To optimise the selection of building and facing materials with the necessary and sufficient indicators of thermal and acoustic resistance and electromagnetic radiation shielding efficiency, it is advisable to make preliminary calculations to predict their values. However, mathematical relationships for these physical factors have a number of shortcomings, which increases the errors in the preliminary determination of the desired parameters. Known calculations of the thermal resistance of materials do not take into account solar radiation on the external surfaces of buildings and, in part, convective heat transfer. The mathematical apparatus for determining the acoustic resistance of materials is based on simplified sound absorption models, and multifactorial models are of no practical value due to the impossibility or complexity of determining certain coefficients. The same applies to the prediction of electromagnetic radiation shielding by structural elements of buildings. This determines the relevance of this study.

## An overview of literary sources

Requirements for temperature regimes, noise levels, electromagnetic fields and radiation are regulated by a number of European Union directives [1-3].

Research on the thermal regime of buildings is mainly aimed at improving energy efficiency. Works [4, 5] investigate the effectiveness of phase change substance structures, which allow the thermal regime of premises to be maintained at the proper level by heat transfer through exothermic processes. The thermal resistance of all existing building and facing materials is known, which simplifies the design process. However, heat transfer processes are more complex in layered structures. Studies [6, 7] provide calculation tools for determining the temperatures of the outer and inner surfaces of layered structures depending on the temperature gradient. However, such calculations are somewhat formal and do not take into account additional heat exchange due to solar radiation and convective heat exchange.

There are many thorough studies on the shielding of electromagnetic fields and radiation by various structural and facing materials. These are mostly composite materials [6, 7]. Predicting the effectiveness of such materials is difficult, so such work is entirely experimental. However, any experimental research requires a large amount of experimentation and expenditure of time and money. The use of semi-empirical Maxwell-Garnet, Lorentz, and Odelevsky relationships gives large errors even for two-component materials [8, 9]. Work [10] lays the foundations for the application of fundamental relations of electrodynamics of continuous media to predict the effectiveness of shielding electromagnetic radiation with building materials. This direction seems promising. Therefore, it is necessary to adapt the corresponding relations for applied use with the possibility of automating the calculation processes.

Many studies are devoted to solving problems of building acoustics. However, these are mainly experimental works [11, 12] that require the availability of reverberation chambers, impedance installations, etc. The work [13] considers existing models of sound transmission and absorption by sound-insulating materials. It is shown that currently only the Delany-Bazley model, in which the parameter is the specific resistance of air, has practical significance. This model gives a large calculation error, so it is advisable to consider the possibilities of practical application of more complex models of sound transmission and absorption. Research [14] indicates the possibility of reducing the number of model parameters by determining them through known parameters. This opens up the possibility of developing a calculation apparatus for determining the acoustic resistance of any material with a small error.

Thus, the aim of the study is to develop theoretical principles for ensuring the thermal, acoustic and electromagnetic resistance of building structural elements and to verify the theoretical results.

## Presentation of the main material

Let us evaluate the effectiveness of thermal insulation of a building wall covered with a layer of heat-insulating material. We will consider a one-dimensional problem, i.e., assume that heat is transferred perpendicular to the wall surface, and the isotherms are planes parallel to it. In addition, we will assume that the conditions outside and inside the building, in particular, the temperature and direction of the air, do not change over time, i.e., the heat exchange is steady.

Previously, when performing such calculations, the influence of solar radiation was neglected, which under certain conditions can lead to noticeable errors in the estimation of heat losses. The heat flux density of the sun at its zenith is about 1000 W/m$^2$. The actual heat flux from the sun varies depending on the geographical latitude, season and time of day. In addition, the radiative cooling of the outer surface of the wall, which is a consequence of heat loss through long-wave radiation directed towards the sky, was not taken into account.

In winter, the higher temperature of the building wall heated by solar radiation increases the temperature difference between the outer surface of the wall and the atmospheric air and, as a result, the heat flow from the wall to the external environment. Conversely, thanks to solar heat gain, the temperature difference between the indoor air and the inner surface of the wall decreases, as does the corresponding heat flow from the indoor environment to the wall. This can be considered as the emergence of additional heat flows to the outdoor and indoor environments, respectively. Both are the result of absorbed solar energy.

Let us assume that the entire heat flow of solar radiation is absorbed only by the outer surface of the wall. Then the heat flux density from the internal environment to the wall, which corresponds to the heat loss of the wall:

$$q_{in} = \frac{t_i - t_{se}}{R_{si} + R_1 + R_2}, \tag{1}$$

where $t_i$– indoor temperature; $t_{se}$– temperature of the outer wall surface; $R_{si}$ – thermal resistance of the inner surface of the wall, associated with convection and radiation; $R_1$ and $R_2$ – thermal resistance of wall materials and thermal insulation, respectively.

In this case, the heat balance equation for the outer surface of the wall takes the form:

$$q_{in} + \alpha_{se} I_{sol} = q_{out} + q_{sky}, \tag{2}$$

where $\alpha_{se}I_{sol}$ – heat flow of absorbed solar radiation; $\alpha_{se}$ – the coefficient of solar energy absorption by the outer surface of the wall; $I_{sol}$ – density of solar radiation heat flux;

$$q_{out} = \frac{t_{se} - t_e}{R_{se}} \tag{3}$$

density of convective and radiative heat flux from the outer surface of the wall, caused by the temperature difference $t_{se}$- $t_e$; $t_e$– ambient temperature; $R_{se}$ – the corresponding thermal resistance of the outer surface of the wall;

$$q_{sky} = \frac{t_e - t_{sky}}{R_r} \tag{4}$$

heat flux density caused by radiative cooling of the outer wall surface at $t_e \neq t_{sky}$ ; $R_r$ – corresponding thermal resistance; $t_{sky}$ –imaginary temperature of the atmosphere.

From (1) – (4) we obtain an expression for calculating the reduction in heat loss from a wall after covering its outer surface with a layer of heat-insulating material:

$$\Delta q = \frac{1}{R_t(1-k)}(k(t_i - t_e + \frac{R_{se}}{R_r}(t_e - t_{sky})) - R_{se} I_{sol}(\alpha_{se}^w - (1-k)\alpha_{se}^i)), \tag{5}$$

where $R_t = R_{si} + R_1 + R_2 + R_{se}$ – total thermal resistance of the wall; $k = R_2/R_t$ ; $\alpha_{se}^w$ and $\alpha_{se}^i$ – solar energy absorption coefficients of the outer surface of uninsulated and insulated walls, respectively.

The thermal resistance of wall materials and thermal insulation according to Fourier's law is calculated using the following formulas:

$$R_1 = d_1/\lambda_1, \;\; R_2 = d_2/\lambda_2, \tag{6}$$

where $d_1$ and $d_2$ – thickness of the uninsulated wall and heat insulator, $\lambda_1$, $\lambda_2$ – thermal conductivity of the respective materials.

To estimate the thermal resistance of the inner wall surface with sufficient accuracy, typical values for most practical applications can be used, as given in EN ISO 6946:2022. Thus, in the case of horizontal air flow, $R_{si}$ = 0.13 (m$^2$×K)/W, vertical upward flow – 0.10 (m$^2$×K)/W, vertical downward flow – 0.17 (m$^2$×K)/W. The data given in the standard are calculated for the emissivity of the inner surface of the wall ε = 0.9, the average temperature of the inner surface and the surrounding environment 20°C.

The thermal resistance of the outer surface of the wall, caused by convection and radiation, can be found from the ratio:

$$1/R_{se} = 1/R_{ce} + 1/R_{re}, \tag{7}$$

where $R_{ce}$ – thermal resistance associated with convection; $R_{re}$ – thermal resistance associated with radiation.

In entry (7), it is taken into account that in the equivalent electrical circuit, these resistors are connected in parallel because the corresponding processes occur independently of each other.

To evaluate $R_{ce}$, EN ISO 6946:2022 offers a simple ratio:

$$1/R_{ce} = 4 + 4v, \tag{8}$$

where $v$ – air velocity near the outer surface of the wall.

According to [15], where the results of direct measurements were compared with calculations based on known models, (8) leads to a significant error in the determination of $R_{ce}$. At the same time, adequate results were obtained using the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) model, according to which [15]:

$$\frac{1}{R_{ce}} = 18,6(0,25v_{10})^{0,605}, \tag{9}$$

where $v_{10} \geq 2$ m/s– air velocity at a height of 10 m and a distance of 0.3 m from the wall.

To find the expression for $R_{re}$, we take into account that, according to Stefan-Boltzmann's law, the density of the radiative heat flux from the outer surface of the wall is determined by the formula:

$$q_{r,out} = \varepsilon\sigma(T_{se}^4 - T_e^4), \tag{10}$$

where $\varepsilon$ – the emissivity of the outer surface of the wall; $\sigma$ – Stefana-Boltzmann constant; $T_{se}$ and $T_e$ – corresponding thermodynamic temperatures.

After comparing (10) and (3) with (7) taken into account, we obtain:

$$\frac{1}{R_{re}} = \frac{\varepsilon\sigma(T_{se}^4 - T_e^4)}{T_{se} - T_e} = \varepsilon\sigma(T_{se} + T_e)(T_{se}^2 + T_e^2). \tag{11}$$

Note that the approximate formula for $1/R_{re}$, given in EN ISO 6946:2022, can be obtained from (11) by linearisation at $T_{se} - T_e << \overline{T}_{se,e}$, where $\overline{T}_{se,e}$ – mean value $T_{se}$ and $T_e$.

Finally, to calculate $R_{se}$ from (7), (9), (11), we have:

$$R_{se} = \frac{1}{18,6(0,25V_{10})^{0,605} + \varepsilon\sigma(T_{se} + T_e)(T_{se}^2 + T_e^2)}. \tag{12}$$

To account for the contribution of radiation cooling of the outer surface of the wall to heat loss, the sky is considered as a grey body with characteristic $t_{sky}$. In this approximation, for the density of the corresponding heat flux, we have:

$$q_{sky} = F_{se-sky}\varepsilon\sigma(T_{se}^4 - T_{sky}^4), \tag{13}$$

where $F_{se-sky}$ – angular radiation coefficient between the wall and the sky; $T_{se}$ and $T_{sky}$ – thermodynamic temperatures.

Comparing with (4), we get:

$$R_r = \frac{T_e - T_{sky}}{F_{se-sky}\varepsilon\sigma(T_{se}^4 - T_{sky}^4)}. \tag{14}$$

If we assume $T_{se} \approx T_e$, then expression (14) can be transformed similarly to (11):

$$R_r = \frac{1}{F_{se-sky}\varepsilon\sigma(T_e + T_{sky})(T_e^2 + T_{sky}^2)}. \tag{15}$$

The simplified linearised expression for $R_r$ given in EN ISO 52016-1:2022 may lead to a noticeable calculation error if the relationship $T_e - T_{sky} << \overline{T}_{e,sky}$ is not satisfied, where $\overline{T}_{e,sky}$ is the average value of $T_e$ and $\overline{T}_{e,sky}$.

When calculating $R_r$ using formula (15) for the angular radiation coefficient between the wall and the sky $F_{se-sky}$, values in accordance with EN ISO 52016-1:2022 are used. Thus, for an unshaded vertical wall, the standard gives $F_{se-sky} = 0.5$. The use of a radiative angle coefficient of 0.5 for vertical surfaces in energy modelling is a common approach. It assumes a constant apparent temperature of the atmosphere regardless of the direction of heat flow of long-wave radiation from the atmosphere, which simplifies the calculation process. At the same time, this flow varies from maximum in the vertical direction to minimum in the horizontal direction. Thus, this approach cannot be considered fully representative, which must be taken into account when analysing the calculation results.

The solar energy absorption coefficients of the outer wall surface $\alpha_{se}^w$, $\alpha_{se}^i$ and the emissivity ε are tabulated values. To determine the solar radiation heat flux density $I_{sol}$ for a given location and season, widely available climate databases are used.

The apparent atmospheric temperature $T_{sky}$ is usually unknown from climate data. It makes sense to estimate it in accordance with EN ISO 52016-1:2022, which proposes a value $T_e - T_{sky}$ of 11 K for temperate latitudes. It should be noted that the standard takes into account a climate classification based solely on latitudes, distinguishing between subpolar, temperate and tropical zones. Calculations using the simplified model given in the standard are not always adequate for temperate regions with humidity fluctuations. At the same time, the use of known empirical relationships to determine the apparent temperature of the atmosphere is not justified because they were obtained for specific meteorological conditions by measurements at specific locations.

Various semi-phenomenological acoustic models combining empirical data with theoretical results can be used to design materials with high noise reduction indices, especially in the low frequency range, to describe the interaction of sound with porous materials. Among them, the Johnson–Champoux–Allard–Lafarge (JCAL) model [14] is the most accurate in describing sound propagation in porous media over a wide frequency range.

The sound absorption coefficient $\alpha$ is determined by the expression:

$$\alpha = 1 - |R|^2 = 1 - \left| \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0} \right|^2 , \tag{16}$$

where $R$ – sound reflection coefficient; $\rho_0$ – air density; $c_0$ – speed of sound in air;

$$Z_s = Z_c \coth(kl) \quad \text{– surface acoustic impedance;} \tag{17}$$

$$Z_c = \sqrt{\rho(\omega) K(\omega)} \quad \text{– characteristic impedance;} \tag{18}$$

$$k = \omega \sqrt{(\rho(\omega))/(K(\omega))} \quad \text{– complex wave number;} \tag{19}$$

$l$ – thickness of the porous layer; $\omega$ – cyclic frequency of a sound wave; $\rho(\omega)$ – complex density; $K(\omega)$ – complex dynamic modulus of volumetric elasticity of porousmaterial.

According to the JCAL model:

$$\rho(\omega) = \frac{\alpha_\infty \rho_0}{\phi} \left[ 1 - i \frac{\phi \eta}{k_0 \rho_0 \alpha_\infty \omega} \sqrt{1 + i \frac{4 k_0^2 \rho_0 \alpha_\infty^2 \omega}{\eta \Lambda^2 \phi^2}} \right], \tag{20}$$

$$K(\omega) = \frac{\gamma P_0 / \phi}{\gamma - (\gamma - 1) \left[ 1 - i \frac{\phi \eta}{k_0' \rho_0 P_r \omega} \sqrt{1 + i \frac{4 k_0'^2 P_r \rho_0 \omega}{\eta \Lambda'^2 \phi^2}} \right]^{-1}} . \tag{21}$$

As can be seen from (20) and (21), these values depend on six non-acoustic parameters, namely: open porosity $\phi$, high-frequency tortuosity limit $\alpha_\infty$, viscous $\Lambda$ and thermal $\Lambda'$ characteristic lengths, and viscous $k_0 = \eta/\sigma$ and thermal $\sigma$ permeabilities associated with air flow $k_0'$ resistance. Other air characteristics included in (20), (21) – $\eta$ (dynamic viscosity), $\gamma$ (adiabatic constant), $P_0$ (atmospheric pressure), $P_r$ (Prandtl number) – are tabulated values, $i$ – imaginary unit.

The main limitation of the model lies in determining these parameters, only some of which can be measured directly. In addition, the complex nature of the relationships complicates their practical application.

The practicality of the model can be improved while maintaining accuracy by taking into account the correlation between porosity and airflow resistance, which are determined experimentally with minimal error, with the four remaining non-acoustic parameters.

To evaluate the critical parameters of the model through $\phi$ and $\sigma$, we will use the ratio [14]:

$$\alpha_\infty = 1 - 11 \cdot \ln\phi, \; \Lambda = \sqrt{\frac{8\eta(1 - 11 \cdot \ln\phi)}{\sigma\phi}}, \; \Lambda' = 2\Lambda,$$

$$k_0' = \frac{\phi^2}{1 - \phi} 10^{-10}. \tag{22}$$

Then expressions (20) and (21) can be written as:

$$\rho(\omega) = a(1 - i\frac{\sqrt{1+ib}}{2b}), \tag{23}$$

$$K(\omega) = \frac{d}{1 - f(1 - im\sqrt{1+in})^{-1}}, \tag{24}$$

where

$$a = \frac{\rho_0(1 - 11 \cdot \ln\phi)}{\phi},\ b = \frac{n\omega}{2\sigma},\ d = \frac{P_0}{\phi},\ f = 1 - \frac{1}{\gamma},$$

$$m = \frac{(1-\phi)\eta}{\phi\rho_0 \operatorname{Pr}\omega},\ n = \frac{\phi^2\sigma}{8m(1-\phi)\eta(1 - 11\cdot\ln\phi)}10^{-10}. \tag{25}$$

Let us represent (16) as:

$$\alpha = \frac{4t\operatorname{Re}(Z_s)}{|Z_s|^2 + 2t\operatorname{Re}(Z_s) + t^2}, \tag{26}$$

where $t = \rho_0 c_0$; $\operatorname{Re}(Z_s)$ – actual part $Z_s$. Since the analytical expression for $\alpha$, which can be obtained from (26) using (17)–(25), is extremely cumbersome, so let us write the final formula using intermediate values. Let us introduce the following notation:

$$P = \sqrt{1+ib},\ Q = \sqrt{1+in}. \tag{27}$$

For the real Re and imaginary (Im) parts *P* and *Q* we have:

$$\operatorname{Re}(P) = \sqrt{\frac{\sqrt{1+b^2}+1}{2}},\ \operatorname{Im}(P) = \sqrt{\frac{\sqrt{1+b^2}-1}{2}}, \tag{28}$$

$$\operatorname{Re}(Q) = \sqrt{\frac{\sqrt{1+n^2}+1}{2}},\ \operatorname{Im}(Q) = \sqrt{\frac{\sqrt{1+n^2}-1}{2}}. \tag{29}$$

Then:

$$\rho(\omega) = a\left(\left(1 + \frac{\operatorname{Im}(P)}{2b}\right) - i\frac{\operatorname{Re}(P)}{2b}\right), \tag{30}$$

$$K(\omega) = \frac{d\left(1 + m\left(\operatorname{Im}(Q) - i\operatorname{Re}(Q)\right)\right)}{1 - f + m\left(\operatorname{Im}(Q) - i\operatorname{Re}(Q)\right)}. \tag{31}$$

Next, we calculate $\sqrt{\rho(\omega)K(\omega)}$ , $\sqrt{\frac{\rho(\omega)}{K(\omega)}}$ and using the ratio:

$$\coth(x+iy) = \frac{\sinh(2x) - i\sin(2y)}{\cosh(2x) - \cos(2y)}, \tag{32}$$

Let's calculate:

$$\coth\left(\omega l\sqrt{\frac{\rho(\omega)}{K(\omega)}}\right). \tag{33}$$

After finding $Z_s$ for (17) – (19), we isolate $\operatorname{Re}(Z_s)$ and calculate $|Z| = (\operatorname{Re}(Z)) + (\operatorname{Im}(Z))$ , which are necessary for calculating $\alpha$.

Complete sequential substitution of all formulas leads to multicomponent expressions for $\operatorname{Re}(Z_s)$ and $|Z_s|^2$ due to nested radicals, hyperbolic functions, and operations with complex numbers. In practice, it is advisable to use mathematical packages such as MatLab, Mathematica or Maple for analytical calculations. For numerical calculations, it is optimal to use Python with the NumPy and SciPy libraries for working with complex numbers and hyperbolic functions.

Sequence of calculations:

1. Calculate *P* and *Q*.

2. Find $\rho(\omega)$, $K(\omega)$.
3. Calculate $Z_s$.
4. Find $\alpha$.

This will allow you to quickly obtain the desired result and select the most suitable ratio of input data for designing sound-absorbing material with the required efficiency.

Calculations for shielding electromagnetic radiation should be based on the fundamental relationships of electrodynamics in continuous media. This allows you to take into account the electrophysical parameters of the material and determine the main indicators of the structure – the coefficients of reflection, absorption and transmission of electromagnetic waves.

The overall protection efficiency indicator, which is determined by the fraction of electromagnetic radiation that has passed through the structure,

$$SE_T = 10\log\left(\frac{1}{T}\right), \tag{34}$$

shielding effectiveness due to reflection

$$SE_R = 10\log\left(\frac{1}{1-R}\right) \tag{35}$$

and absorption

$$SE_A = SE_T - SE_R \tag{36}$$

electromagnetic radiation can be calculated if the relevant coefficients of transmission *T*, reflection *R*, and absorption *A* of the electromagnetic wave falling on the screen are known.

Given that any building or cladding structure has a finite thickness, at least double reflection from the front and inner surfaces must be taken into account. In general, the structure is multilayered. Then it can be shown that:

$$R = R_{12}\left(1+\left(1-R_{12}\right)^2\exp\left(-4\alpha d\right)\cdot\left(1-R_{12}^2\exp\left(-4\alpha d\right)\right)^{-1}\right), \tag{37}$$

$$T = \left(1-R_{12}\right)^2\exp\left(-2\alpha d\right)\cdot\left(1-R_{12}^2\exp\left(-4\alpha d\right)\right)^{-1}, \tag{38}$$

$$A = \left(1-R_{12}\right)\left(1-\exp\left(-2\alpha d\right)\right)\cdot\left(1-R_{12}\exp\left(-2\alpha d\right)\right)^{-1}. \tag{39}$$

where $R$ – multiple reflection coefficient; $R_{12} = \dfrac{(n-1)^2+k^2}{(n+1)^2+k^2}$.– reflection coefficient from the structure; $n$ – refractive index of an electromagnetic wave; $k$ – extinction coefficient (coefficient of radiation attenuation in a material); $d$ – thickness of the structure; $\alpha = (\omega\kappa)/c$ – amplitude coefficient of electromagnetic radiation absorption; $\omega$ – cyclic radiation frequency; $c$ – speed of light in a vacuum.

Taking into account multiple reflections from the internal surfaces of the structure significantly affects the values of *R*, *T* and *A* under the condition: $d < 3\delta$, where $\delta = 1/\alpha$ is the thickness of the layer at which the wave amplitude decreases by a factor of *e*. If the screen parameters and radiation frequency are such that this condition is not met, then the reflection from the rear surface can be neglected altogether. Then, for the reflection and transmission coefficients from (37) and (38), we find:

$$R = R_{12}, \tag{40}$$

$$T = (1-R_{12})\exp(-2\alpha d). \tag{41}$$

The absorption coefficient A in this case is calculated accordingly (39).

Taking into account (39), (40) and (41) for shielding efficiencies, we obtain:

$$SE_T = 10\log\left(\frac{(n+1)^2+\kappa^2}{4n}\right) + 20\alpha d\log e, \tag{42}$$

$$SE_R = 10\log\left(\frac{(n+1)^2+\kappa^2}{4n}\right), \tag{43}$$

$$SE_A = SE_T - SE_R = 20\alpha d\log e. \tag{44}$$

To find the coefficients $n$ and $\kappa$ , we will use the following relationship:

$$\sqrt{\hat{\varepsilon}} = n + i\kappa, \tag{45}$$

where

$$\hat{\varepsilon} = \varepsilon' + i\varepsilon'' = \varepsilon + i\left(\sigma/(\omega\varepsilon_0)\right) \tag{46}$$

- the complex dielectric permittivity of a structural material containing electrically conductive additives; $\varepsilon$ is the dielectric permittivity, and $\sigma$ is the electrical conductivity of the material, the values of which depend on the volume content of the electrically conductive additive; $\varepsilon_0$ is the electrical constant. From (45) and (46) it follows that:

$$n = \left(\frac{\varepsilon' + (\varepsilon'^2 + \varepsilon''^2)^{1/2}}{2}\right)^{1/2}, \tag{47}$$

$$\kappa = \left(\frac{-\varepsilon' + (\varepsilon'^2 + \varepsilon''^2)^{1/2}}{2}\right)^{1/2}. \tag{48}$$

Thus, knowing the values of dielectric permeability and electrical conductivity of a material with different contents of the electrically conductive component, it is possible to calculate the dependence of shielding efficiency on the volume content of the additive and the frequency of the incident electromagnetic wave.

The thermal, acoustic and electromagnetic resistances of common materials were calculated and compared with experimental data.

The thermal resistance was determined for basalt fibre in the form of slabs with a thickness of 50, 100 and 150 mm (Table 1).

Table 1

Comparison of experimental and calculated material resistances based on basalt fibres

| Method | Thermal resistance, $m^2 \cdot K/W$ | | |
|---|---|---|---|
| | 50 mm | 100 mm | 150 mm |
| Calculation | 1,30 | 2,60 | 3,95 |
| Experiment | 1,35–1,38 | 2,75–2,85 | 4,15–4,26 |

As can be seen from Table 1, the convergence of theoretical and experimental results is acceptable. At the same time, it should be noted that the experimental determination of thermal parameters may not be entirely accurate due to large errors in all calorimetric measurements.

A comparison of theoretical and experimental data was also used for basalt products (Table 2).

Table 2

Comparison of experimental and calculated noise reduction indices for basalt product

| Method | Noise reduction indices, dB | | |
|---|---|---|---|
| | 50 mm | 100 mm | 150 mm |
| Calculation | 46 | 58 | 64 |
| Experiment | 40–43 | 52–55 | 59–62 |

The results obtained also indicate acceptable convergence between theoretical and experimental data. The calculations give slightly overestimated data compared to the experiment. This can be explained by the partial penetration of sound around the sample, which is especially characteristic of low-frequency sound.

A comparison of calculated and experimental data on electromagnetic radiation shielding was carried out for metal-silicate materials with different contents of electrically conductive material (copper powder). This is due to the fact that the shielding coefficients depend on the volume content of the conductive filler (Table 3).

Table 3
Dependence of the protective properties of a 5 mm thick metal silicate material on the volume content of the electrically conductive filler. Frequency of electromagnetic radiation 20 GHz

| Method | Electromagnetic radiation transmission coefficient | | | | |
|---|---|---|---|---|---|
| | 0,16 | 0,17 | 0,18 | 0,19 | 0,20 |
| Calculation | 0,060 | 0,045 | 0,020 | 0,008 | 0,005 |
| Experiment | 0,050–0,055 | 0,040–0,045 | 0,023–0,025 | 0,003–0,005 | 0,004–0,005 |

In Table 3, 0.016–0.020 is the volume fraction of the electrically conductive filler in the dielectric matrix.

The experimental data presented are highly consistent with the calculated data. The experimental conditions excluded the penetration of electromagnetic radiation past the shielding surface. However, it should be noted that the nominal maximum error of the device is 2.7 dB (36%).

The calculations given for determining the thermal resistance of the structure, sound insulation properties and effectiveness of electromagnetic radiation shielding show acceptable agreement with experimental data for common building materials. It should be noted that discrepancies with the experiment exist due to the mandatory presence of certain simplifications and assumptions in the calculation apparatus. Reference data on the thermal resistance of standard building and facing materials are always rounded up. The calculations involve a semi-infinite plane, while real objects have finite dimensions and boundaries between individual elements. To calculate sound absorption properties, it is assumed that the material is completely homogeneous and has the same porosity and airflow resistance. In reality, even materials of the same type have differences in surface impedance. In calculations of electromagnetic radiation shielding, it was assumed that the electromagnetic wave falls perpendicular to the surface, and the electrophysical properties of the material are uniform throughout its depth.

Considering the above, when using predicted calculations in design, it is necessary to include a certain margin in the design, considering the calculated data to be underestimated by 10–12%, which corresponds to the average discrepancies with experimental data.

## Conclusions

1. When calculating the thermal resistance of building elements, the influence of solar radiation and convective heat transfer from the external surfaces of buildings is taken into account. The initial data on these influences are generally reference data based on the latitude of the location, the orientation of the building, etc.
2. The determination of the acoustic resistance of structures is based on the most adequate model of sound absorption by materials (JCAL) with the adaptation of this model for practical application. The advantage of the developed approach is the correct determination of the corresponding model coefficients using data that can be measured unambiguously or is reference data.
3. Determining the effectiveness of shielding electromagnetic radiation with structural elements using the electrodynamics of continuous media gives a smaller error compared to known semi-empirical formulas.
4. When using calculation methods to predict the thermal and acoustic resistance and electromagnetic radiation shielding of materials and structures, certain simplifications and assumptions should be taken into account. Therefore, when solving applied problems, a certain margin of 10–12% should be included in the calculations, which corresponds to the average discrepancies with experimental data.

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## ТЕОРЕТИЧНІ ТА ЕКСПЕРИМЕНТАЛЬНІ ЗАСАДИ ЗАБЕЗПЕЧЕННЯ ТЕРМІЧНОГО ТА АКУСТИЧНОГО ОПОРІВ КОНСТРУКТИВНИХ ЕЛЕМЕНТІВ БУДІВЕЛЬ ТА ЕКРАНУВАННЯ ЕЛЕКТРОМАГНІТНИХ ВИПРОМІНЮВАНЬ

Розроблено прикладний математичний апарат для прогнозування термічного та акустичного опорів елементів будівель та ефективності екранування електромагнітних випромінювань. Розрахунки термічного опору враховують вплив сонячної радіації та конвективний теплообмін зовнішньої поверхні будівель. Це надає можливість раціоналізувати термозахист будівель і їх енергоефективність. Для прогнозування акустичного опору конструктивних елементів будівель вдосконалено багатофакторну модель проходження звуку крізь захисний шар, що знизило похибку розрахунків порівняно з відомими рішеннями. Розроблено прикладний розрахунковий апарат для прогнозування ефективності екранування електромагнітних випромінювань будівельними та облицювальними матеріалами. Він базується на співвідношеннях електродинаміки суцільних середовищ й найбільш прийнятний для багатокомпонентних матеріалів, порівняно з напівемпіричними формулами. Верифікація отриманих результатів свідчить про прийнятну збіжність теоретичних та експериментальних даних. Враховуючи наявність у розрахунках певних припущень і спрощень, у практичній діяльності у захисні властивості проєктованих матеріалів і конструкцій необхідно закладати певний запас ефективності.

**Ключові слова:** термічний опір, акустичний опір, ефективність екранування, електромагнітне випромінювання.

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## THEORETICAL AND EXPERIMENTAL BASES FOR ENSURING THERMAL AND ACOUSTIC RESISTANCE OF STRUCTURAL ELEMENTS OF BUILDINGS AND SHIELDING OF ELECTROMAGNETIC RADIATION EMISSION

An applied mathematical apparatus has been developed for predicting the thermal and acoustic resistance of building elements and the effectiveness of electromagnetic radiation shielding. Thermal resistance calculations take into account the influence of solar radiation and convective heat exchange on the outer surface of buildings. This makes it possible to rationalise the thermal protection of buildings and their energy efficiency. To predict the acoustic resistance of building structural elements, a multifactorial model of sound transmission through a protective layer has been improved, which has reduced the calculation error compared to known solutions. An applied calculation tool has been developed to predict the effectiveness of shielding electromagnetic radiation with building and facing materials. It is based on the relationships of electrodynamics of continuous media and is most suitable for multicomponent materials compared to semi-empirical formulas. Verification of the results obtained indicates an acceptable convergence of theoretical and experimental data. Given the presence of certain assumptions and simplifications in the calculations, in practical activities, a certain margin of effectiveness must be included in the protective properties of the designed materials and structures.

**Keywords:** thermal resistance, acoustic resistance, shielding effectiveness, electromagnetic radiation.

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*Розроблено прикладний математичний апарат для прогнозування термічного та акустичного опорів елементів будівель, а також ефективності екранування електромагнітних випромінювань будівельними й облицювальними матеріалами з урахуванням впливу сонячної радіації, конвективного теплообміну та особливостей поширення хвиль у багатокомпонентних середовищах. Розроблено математичний апарат для прогнозування ефективності шумопоглинання, у тому числі для низькочастотного звуку та інфразвуку. Надано розрахунки щодо проєктування резонансних панелей, виходячи з реальних амплітудно-частотних характеристик звуку. Верифікація результатів показала задовільну збіжність теоретичних і експериментальних даних, що підтверджує можливість практичного застосування розроблених моделей.*

Табл. 3. Бібліогр. 15 назв.

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*An applied mathematical apparatus has been developed for predicting the thermal and acoustic resistance of building elements, as well as the effectiveness of shielding electromagnetic radiation with building and facing materials, taking into account the influence of solar radiation, convective heat transfer, and the peculiarities of wave propagation in multicomponent media. A mathematical apparatus has been developed for predicting noise absorption efficiency, including for low-frequency sound and infrasound. Calculations for the design of resonant panels based on real amplitude-frequency characteristics of sound have been provided. Verification of the results showed satisfactory convergence of theoretical and experimental data, confirming the possibility of practical application of the developed models.*

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