

Software development of thermal resistance calculator for thermal insulation parameters determines dielectric building structures

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Abstract

The article presents the specifics of the software implementation of the thermal resistance calculator named “ThermoResist”. The developed thermal resistance calculator calculates the thermal resistance of the wall, window, attic floor, and roof in accordance with the State Building Regulations of Ukraine. The programming language C# was chosen to implement computation procedures and the thermal resistance calculator interface. Calculations were performed under the assumption that the contributions of different thermal resistance mechanisms to the total thermal resistance of dielectric building materials are additive.

Keywords

thermal resistance, calculator, heat transfer processes, dielectric building structures

1. Introduction

Digitization of all spheres of public life and industry requires the development of appropriate tools [1]. One of the most important branches of industry in Ukraine is the construction industry because after the war it will be necessary to rebuild hundreds of destroyed cities and villages, to rebuild thousands of houses. Thermal insulation of buildings is an important part of construction. Both civil engineers and ordinary workers in the construction industry will carry out such work. The training of specialists in the construction industry is carried out by institutions of higher and professional pre–higher education. That is why the ability to perform thermal insulation calculations is an important component of the professional competence of civil engineers. The creation of thermal insulation begins with its calculations. Such calculations are usually carried out manually. At the same time, there are thermal resistance calculators that

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are advisable to use in the process of calculating the thermal insulation parameters of buildings and structures.

To calculate the parameters of thermal insulation, one can use general-purpose application software, automated design systems, or existing thermal conductivity calculators. The use of software of the specified categories has its advantages and disadvantages; in particular, they do not take into account the peculiarities of heat transfer in dielectric materials. In dielectrics, heat transfer processes occur due to phonon-phonon interaction without the participation of free electron diffusion [2, 3]. Therefore, it would be more appropriate to use a specialized software tool – a thermal resistance calculator for dielectric building materials.

The article aims to reveal the features of software implementation and the user interface of the thermal resistance calculator for dielectric building materials.

2. Computation method

One of the urgent and at the same time the most difficult problems of thermal physics is the task of researching energy transfer processes [4, 5, 6]. Data on thermal conductivity allow for obtaining important information for thermal physics. Dielectrics have several mechanisms that determine thermal conductivity, and a number of processes that limit the effectiveness of each of the mechanisms [7, 8, 9, 10]. The development of industrial technologies contributed to the creation of high-precision methods of thermal conductivity research, which made it possible to obtain more complete information about the nature of the forces acting in dielectric materials. However accurate quantitative prediction of thermal conductivity due to the complexity of describing specific mechanisms of heat transfer for real dielectrics is a difficult task. In the classical Debye model, the thermal conductivity Λ of dielectrics can be presented by the expression [2, 11]:

$$\Lambda = \frac{\hbar}{2\pi^2 v^2 k_B T^2} \int_0^{\omega_D} l(\omega) \omega^4 \frac{e^{\hbar\omega/k_B T}}{(e^{\hbar\omega/k_B T} - 1)^2} d\omega \quad (1)$$

where v is the sound velocity, ω_D is the Debye frequency, k_B is the Boltzmann's constant, $l(\omega)$ is the phonon mean free path, and \hbar is the Planck's constant.

At the same time, today there are considerable deviations between the results of experimental studies of the dielectric materials thermal conductivity and classical theoretical predictions. At present, there is no generally accepted theoretical model that can effectively determine the contributions of different heat transfer mechanisms to the thermal conductivity of dielectrics [7, 8, 12, 13, 14]. Therefore, in practice, a simplified idea of the possibility of independent separation of the contributions of each of the phonon scattering mechanisms to the total thermal resistance and determination of the combined phonon relaxation time τ is often used [15, 16, 17]:

$$\tau^{-1} = \sum_i^n \tau_i^{-1} \quad (2)$$

where τ_i is the relaxation time for each of the phonon scattering mechanisms in the dielectric.

The possibility of using such a simplification in the inverse functions for kinetic coefficients was also theoretically substantiated in works [18, 19]. According to the results of these works,

if a quantity is a direct correlation function (in our case thermal conductivity) goes to infinity, then it is necessary to consider the behavior of its inverse quantity (inverse correlation function in our case is thermal resistance) and add to its thermodynamic value terms that describe spatiotemporal dispersion and additional corrections. If the inverse value goes to zero, then all correction terms are added to this zero value.

In the harmonic approximation [20], heat waves propagate in the crystal without interacting with each other. In this case, the arbitrary distribution of phonons does not become equilibrium even in the absence of a temperature gradient, since the mechanism of phonons relaxation to an equilibrium state is absent. The heat flow in this case exists indefinitely, and the thermal conductivity is infinite $\Lambda = \text{inf}$, due to the absence of thermal resistance $W = 0$ ($\Lambda = 1/W$). But, as the experiment shows, the thermal conductivity of dielectrics is a finite value. Even in ideal crystals, the existence time of phonons is limited by the processes of phonon scattering, which arise as a result of the interaction potential anharmonicity of a real dielectric.

Thus, phonon anharmonicity is a necessary condition for finite thermal conductivity [2, 20]. In the framework of three-phonon interaction [2, 15], it is customary to distinguish N -processes and U -processes. N -processes during collisions do not change the value of the average quasi-momentum and by themselves do not lead to the occurrence of thermal resistance $W_N = 0$. After the U -process, there is a change in the direction of heat energy transfer, which ultimately leads to the emergence of thermal resistance $W_N = 0$ and repair of the phonons equilibrium distribution. In contrast to atomic crystals for dielectrics, in addition to phonon–phonon scattering, there are additional mechanisms of phonon scattering, in particular, boundary scattering of phonons, etc. [4, 7, 8, 15, 16]. That is, for dielectrics it is possible to write $\Lambda = 1/\sum W_i$ [3, 4] and assume that the contributions of different phonon scattering mechanisms to the total thermal resistance W are additive [8, 21]. Considering that different mechanisms of phonon scattering are present in dielectrics, the thermal resistance of the dielectric can be determined as:

$$W = \sum_{i=1}^n \frac{1}{W_i} \quad (3)$$

where W is the total thermal resistance, W_i are components of the total thermal resistance associated with different mechanisms of phonon scattering in dielectric materials [4, 21].

The formulas presented in works [22, 23, 24, 25, 26, 27] are used to calculate the values of thermal resistance for dielectric building materials. Calculations are performed under the assumption that the contributions of different phonon scattering mechanisms to the total thermal resistance of dielectric building materials are additive [2, 8].

For full thermal resistance W_R of thermally homogeneous and non-homogeneous opaque enclosing structures:

$$W_R = \frac{1}{\alpha_{in}} \sum_{i=1}^n \frac{\delta_i}{\lambda_i} \frac{1}{\alpha_{ext}} \quad (4)$$

where α_{in} is the heat exchange coefficient of the internal surface of the structure with the internal air; α_{ext} is the heat exchange coefficient of the outer surface of the structure with the outside air; δ_i is the thickness of the i -th material layer; λ_i is the coefficient of thermal conductivity of the i -th material layer.

For the thermal resistance W_{inc} of structures with defined values of the linear heat transfer coefficient of thermal-conducting inclusions:

$$W_{inc} = \frac{F_{tr} + \sum_{i=1}^n F_i}{\frac{F_{tr}}{W_{tr}} + \sum_{i=1}^n \frac{F_i}{W_i} + \sum_{j=1}^m \lambda_j L_j} \quad (5)$$

where W_{tr} is the reduced heat transfer resistance of the transparent area which is taken depending on the characteristics of the double-glazed units (the distance between the layers of glass, the type of gas filling and the degree of blackness of the glass surface), F_{tr} is the area of the translucent part (m^2), W_i and F_i are thermal resistance and the area of the i -th opaque element, n is the number of opaque structural elements with certain values of W_i and F_i , k_j is the linear coefficient of thermal conductivity of the j -th inclusion, L_j is the linear size of the j -th opaque inclusion of the translucent structure, m is the number of opaque structural inclusion for which k_j must be determined.

In their article, Zahorodko et al. [28]. compare the performance of quantum-enhanced and classical machine learning algorithms in an experiment [28].

3. Results and discussion

Starting with the design of the thermal resistance calculator, we will analyze the functionality and interface of the most common programmes for this purpose. A search for relevant software found such software products as Rockwool U-value Calculator, Kingspan U-value Calculator and others. The Rockwool U-value Calculator is available on the website [29]. This software tool provides an opportunity to calculate the thermal resistance of walls, roof and floor.

Advantages of the Rockwool U-value Calculator:

- variability of structural and thermal insulation materials;
- intuitive interface;
- multilingual interface.

Disadvantages:

- non-compliance with the State Building Regulations of Ukraine (Rockwool U-value Calculator calculates thermal conductivity, but we need to calculate thermal resistance);
- uncontrollability (the owners of the resource can close access to this resource at any time, and its use in the educational process will become impossible).

The next software tool is the Kingspan U-value Calculator [30]. After registering the user on the website, he can choose the desired type of building and type of wall, determine the material of the internal equipment of the wall, the material and thickness of the main material, the type of mortar, the material of thermal insulation and its thickness, the thickness of the air layer, the material and thickness of the external decoration. This calculator has the same disadvantages as the previous one:

- thermal conductivity is calculated, not thermal resistance;
- lack of control over the resource on which the Kingspan U-value Calculator is located;
- a set of thermal insulation materials from Kingspan.

The analysis results show that it is impractical to use the mentioned thermal resistance calculators, since the method of their calculations does not correspond to the State Building Regulations [27]. That is, a significant drawback of these calculators is the use of another method of calculation.

A feature of thermal resistance calculations performed by civil engineers in Ukraine is that the calculation method and main coefficients are described in the State Building Regulations [27]. In these calculations, thermal resistance is calculated as the body's ability to prevent the spread of heat.

A feature of thermal resistance calculations performed by civil engineers in Ukraine is that the calculation method and main coefficients are described in the State Building Regulations [27]. In these calculations, thermal resistance is calculated as the body's ability to prevent the spread of heat, that is, as a process that is the inverse of thermal conductivity. Having analyzed the main calculations performed during the design of the thermal insulation coating of buildings and structures, it is possible to distinguish 4 main types of enclosing structures, and, accordingly, 4 main types of calculations [27]:

- calculation of the thermal resistance of the wall;
- calculation of the thermal resistance of the window;
- calculation of the thermal resistance of the attic floor;
- calculation of the thermal resistance of the roof overlap.

These calculations do not have fundamental differences, but use different limit values of thermal resistance coefficients and different structural and thermal insulation materials. Accordingly, the developed thermal resistance calculator must have appropriate functional modules. In addition, it is necessary to allocate an additional block of initialization of tabular data, which initializes the critical values of thermal resistances for various types of enclosing structures depending on the climatic zones of Ukraine. Let's consider these functional modules in more detail.

The *initial data initialization module* activates those critical values of thermal resistance that are characteristic of the relevant climatic zone of Ukraine. There are two such zones in Ukraine. In order to simplify this process, the user is given the opportunity to select the area in which the designed building will be constructed, and depending on the area, the program determines the climatic zone, and only after that activates the required values of thermal resistance for this zone. The specified thermal resistance values are output to the appropriate controls on the form. In the same module, basic classes are initialized and basic class instances are created.

The *module for calculating the wall thermal resistance* accepts the following input data (selected by the user using drop-down lists): material and thickness of the main wall, material, and thickness of thermal insulation, material, and thickness of internal plaster, material, and thickness of external cladding. In the handbooks, the coefficients of thermal conductivity of most building materials are given, but in this module, you can choose only those materials

that are used for the construction and thermal insulation of the wall. For example, there is no roofing material in the list of materials for walls (it is not used for waterproofing walls).

The *module for calculating the window thermal resistance* uses different input data, according to the materials used to make the windows. The tabular value of the thermal resistance of the window is different from that of the wall.

The *module for calculating the attic floor thermal resistance* simulates the corresponding calculations performed by the civil engineer. The user uses the drop-down lists to select the material of the main floor, the material of thermal insulation, and the material of the interior of the building, and with the help of sliders (TrackBar) sets the thickness of the corresponding structural elements. The programme calculates the thermal resistance and displays its value in the text field. Depending on whether the calculated value of thermal resistance corresponds to the permissible value for the given climatic zone, the text field is painted in green or red.

The *module for calculating the roof overlap thermal resistance* differs from the previous one only in a different set of materials (main support, thermal insulation, etc.), as well as in other values of heat exchange coefficients with the environment and the internal environment.

In the process of developing the thermal resistance calculator, an object-oriented approach was applied, according to which all information about a certain phenomenon of reality is concentrated in the object.

The class diagram of the “ThermoResist” programme is shown in figure 1.

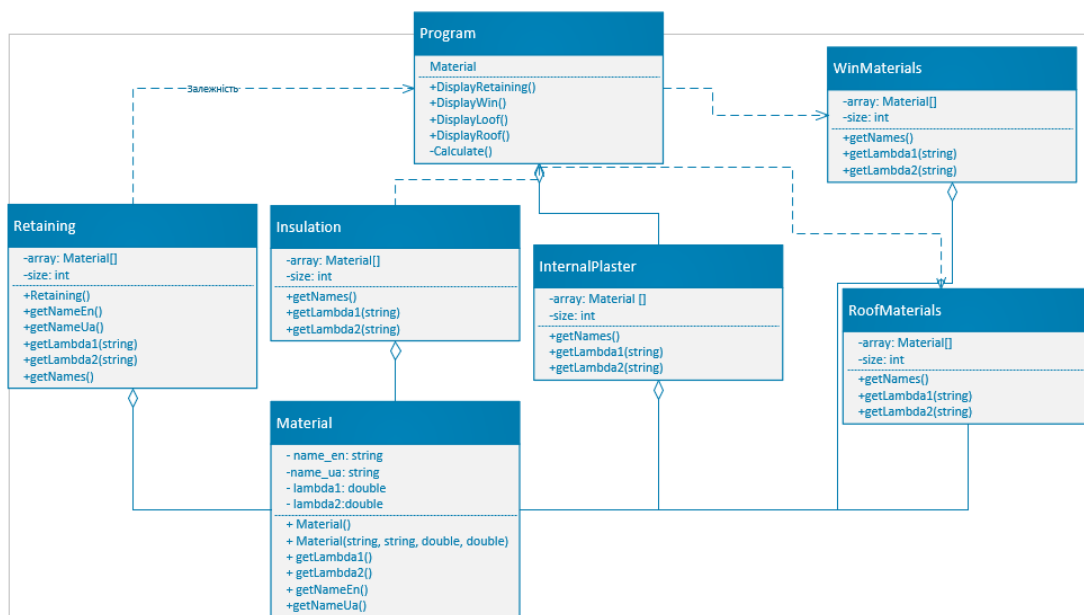


Figure 1: Class diagram of the “ThermoResist” thermal resistance calculator programme.

The programming language C# was chosen for the implementation of the programme. The creation and compilation of the software code was carried out in the Microsoft Visual Studio 2022 programme development environment. System requirements of the programme:

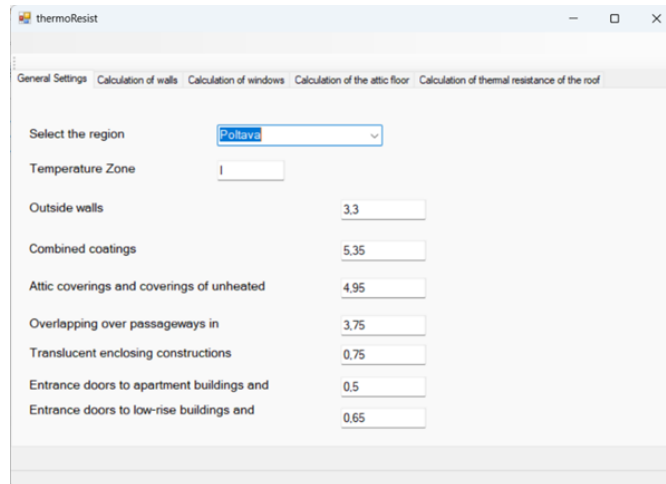


Figure 2: “ThermoResist” thermal resistance calculator interface.

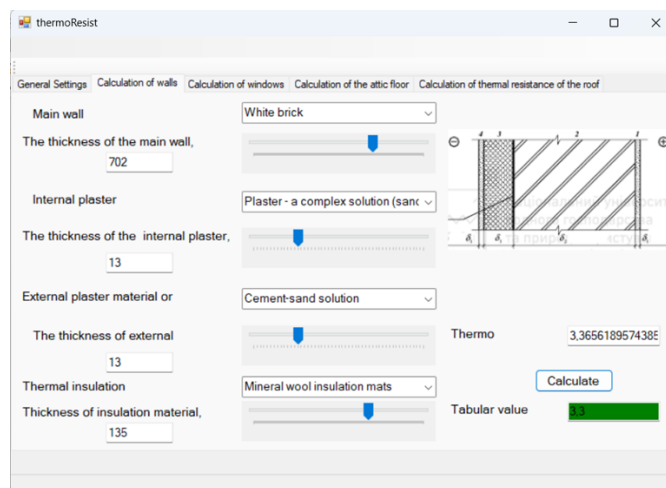


Figure 3: Calculation of the thermal resistance of the wall using the “ThermoResist” programme.

- monitor resolution 800x600;
- Microsoft Windows 10/11 operating system;
- .NET Framework 4.0 and higher.

The output of calculation results is accompanied by the coloring of the text field in green. This means that the thermal resistance of the wall has an acceptable value.

4. Conclusions

Digitization of society involves digitalization of all aspects of social life. The developed “ThermoResist” thermal resistance calculator for dielectric building structures has an intuitive in-

interface, a methodology, and a sequence of calculations that comply with the State Building Regulations in Ukraine. Thanks to this, basic computer user skills are enough to use this calculator, so it can be used by both students and civil engineers. Unlike many software products, it calculates thermal resistance according to the methodology given in the State Building Regulations and enables to calculation of the thermal resistance of the following categories of structures: walls, windows, attic floor, and roof according to indicators, specified in the State Building Regulations. The presented results will be useful for implementation in the educational process.

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