Methods for determining thermophysical properties of heat protective protections of buildings and high-temperature installations

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Abstract. The paper presents two methods for determining the thermal and physical properties of thermal barriers, differing in the range of operating temperatures and the object of which they are an integral part. The first method is based on a non-destructive approach to determining the thermal resistance of the external fencing of buildings, providing comfortable living conditions. The second method is based on taking into account the volumetric absorption of radiation by porous materials used in high-temperature installations, and the quasi-stationary heating mode. The presence of these two factors makes it possible to determine the absorption coefficient of a material located in the field of high-temperature radiation.

1.1. Introduction
It is known that existing heat-shielding fences are subject to unsteady environmental influences, as is the case with buildings for various purposes, or intense heat radiation in high-temperature and heat-technological installations (HTI). Therefore, during operation, they lose their heat-shielding properties. To determine the magnitude of these losses, methods are needed that, firstly, do not destroy the structure of the building’s enclosure and, secondly, take into account the volumetric nature of the absorption of radiation in the enclosures of these installations. The information obtained in this way can be useful in carrying out energy-saving measures in order to increase the energy efficiency of the heat-technological process.

2. Non-destructive method for determining the thermal resistance of the external fence of the building

2.1. The need to develop this method
The task of determining the thermophysical properties (TPP) of the outer enclosures of buildings is especially relevant in housing construction companies, since the properties of building materials depend on the conditions of their operation and affect the operation of heating, ventilation and air conditioning systems. It is clear that the correctly selected properties of the material provide many years of preservation of the structure and the conservation of thermal energy by reducing heat loss to the environment. However, it should be borne in mind that buildings built in different years and according to different building codes and rules (SNiP) were operated in different time and weather conditions. Therefore, the walls of existing buildings differently lost their heat-shielding properties, because unequally subjected to periodic moistening and drainage. Due to the reduction or loss of the initial heat-
shielding properties of the external fences, it is necessary to increase the heat load on the heating system of the building in order to maintain comfortable conditions in its premises. It follows from this that, firstly, the actual TPP values of the external walls of buildings can differ from the values calculated by SNiP. Secondly, we need a method that allows, without destroying the walls of the building, to determine their real thermal resistance, and thirdly, on the basis of the data obtained, make the correct selection of energy-saving measures that eliminate the decrease in the heat-shielding properties of the outer fences due to their wear.

2.2. The need to develop this method

The method is based on the method of calculating the thermal resistance of wall heat transfer under conditions of stationary one-dimensional heat conduction, the essence of which is described in [1], and two literature sources [2] and [3]. The first source is dedicated to the definition of zones with a one-dimensional temperature field in the outer enclosure, and the second to the experimental determination of heat losses through the outer enclosure of room A231 located in the building of the NRU MPEI. For the successful implementation of this method, it is necessary to form the initial data using the work [3] and the algorithm presented below.

- By analogy with Figure 1 to determine in the outer fence under study a region with a one-dimensional temperature field;
- Using the heat flow and temperature sensors, set the values of these values in the area with a one-dimensional temperature field, both on the inner and outer surfaces of the outer fence (see Figure 2-4).
- Calculate the thermal resistance of the wall according to the formula \( R = \frac{\Delta t}{q} \), where \( \Delta t \) is the temperature difference on the inner and outer surface of the wall.

![Figure 2.1. Single window fencing. Dark color marks the area with a one-dimensional temperature field [2]](image1)

![Figure 2.2. The change in temperature of the inner surfaces of the elements of the external fence and the heating device in time](image2)

![Figure 2.3. The change in local temperature values on the external surfaces of the elements of the external fence in time](image3)
If it is not possible to determine the specific heat flux instrumentally for some reason, it is recommended to use the empirical formula to determine the heat transfer coefficient on the inner surface of the wall under conditions of free convection. With a known room height and knowledge of the heat transfer coefficient, the specific heat flux is determined from the Newton-Richmann law.

**Figure 2.4.** Thermograms of the external surface of the building [2]

**Figure 2.5.** Room A321. The place of temperature measurement is marked with a pencil. The thickness of the outer wall to the right of the window is 0.72 m, and to the left - 0.84 m, in the niche - 0.42 m.

**Table 1.** Room parameters A231 of the MPEI building

| Parameter       | Room | Window | Niche | Central beam | Side beam |
|-----------------|------|--------|-------|--------------|-----------|
| Depth           | 6.48 | 0.12   | 0.18  | 6.48         | 6.48      |
| Height          | 4.18 | 3.80   | 0.85  | 0.42         | 0.42      |
| Width           | 3.61 | 2.00   | 1.18  | 0.31         | 0.10      |

2.3. **Comparison of thermal resistance values of the outer fence obtained in different ways**

- The required heat transfer resistance of the outer wall, corresponding to sanitary and hygienic comfortable conditions:
  \[ R_{tr.min}(n, t_{in}, t_{out}, \Delta t_{in}, \alpha_{in}) = \frac{n(t_{in} - t_{out})}{\Delta t_{in} \alpha_{in}} \]  
  \[ (2.1) \]
  \[ => R_{tr.min}(1.25, -30, 4, 8.7) = 1.58 \]  
  \[ (2.2) \]

- Thermal resistance \( R \) of the outer wall (according to the expected composition) and heat transfer resistance \( R_0 \):
  \[ R = \frac{0.64}{0.81} + \frac{0.03}{0.93} + \frac{0.05}{0.07} = 1.537 \]  
  \[ (2.3) \]
  \[ => R_0 = R + 1/8.7 + 1/23 = 1.695 \]  
  \[ (2.4) \]

In equation (2.4), the first term is the thermal resistance of the brickwork, the second is the total thermal resistance of the external and internal plaster, the third is the thermal resistance of the insulation. \( R_0 > R_{tr.min} \).

- The heat transfer coefficient on the inner surface of the outer wall of the room (in Mathcad notation):
4. Listing of a function developed in the Mathcad environment for calculating the heat transfer coefficient in conditions of free convection

- Heat flux density on the inner surface of the outer wall of the room:
  \[ q(t_{in}, t_{in,w}, H) = \alpha(t_{in}, t_{in,w}, H)(t_{in} - t_{in,w}) \]  
  \Rightarrow q(25, 20, 4.18) = 14.223  

- Thermal resistance of the outer wall of the room:
  \[ R_w(t_{in}, t_{in,w}, t_{out,w}) = \frac{t_{in,w} - t_{out,w}}{q(t_{in}, t_{in,w}, H)} \] 
  \Rightarrow R_w(25, 20, -2.4.18) = 1.547

It can be seen that the values of \( R_w \) obtained in (2.3) and (2.6) are very close.

2.4. Conclusion on the 2nd section:
A non-destructive method has been developed for determining the actual thermal resistance of the external fence and it has been established that the thermal resistance of the external wall in building A of the NRU MPEI, obtained by calculation by the proposed method, coincided with values identified by the methods of the obsolete SNiP-3-79. This means that, firstly, during the operation of the building, the thermal resistance of its walls did not deteriorate. Secondly, the methodology has received its experimental confirmation. Thirdly, it was established that the walls of the MPEI building do not meet modern requirements for heat transfer resistance.

3. Bases of the method for determining thermophysical properties of porous materials applicable at HTI

3.1. Mathematical model of the temperature field of a porous plate heated by radiation

The heat equation, taking into account the presence of a heat source due to volumetric absorption of the radiation incident on it, has the following form:

\[ \frac{d}{dX} \theta(X, Fo) = \frac{d^2}{dX^2} \theta(X, Fo) + kA(1 - R)e^{(\frac{\sigma}{\rho u} X^2)} \]  

As the initial and boundary conditions, we use equations (3.2) - (3.4):

\[ eq1 = \theta(X, Fo) = 1 \]  
\[ eq2 = \frac{d}{dX} \theta(X, Fo) \bigg|_{X = 0} = 0 \]  
\[ eq3 = \frac{d}{dX} \theta(X, Fo) \bigg|_{X = 1} = 0 \]

The following dimensionless complexes and simplexes are involved in the equations: \( X = x/\delta \) --
complex in space; \( F_0 = at / \delta \) – time complex or Fourier number; \( Bu = k \delta \) is the optical density of the porous plate; \( f_0 = D a / \delta^2 \) – characteristic time; \( \theta = t / t_0 \) is the temperature simplex; \( q_{\text{pad}} = A e^{(-D/\tau)} \) – is the incident radiation flux that changes in time; \( q_v = kq_{\text{pad}}(1 - R) \exp(-kx) \) – heat source due to volumetric absorption of incident radiation;

Dimensional quantities included in dimensionless complexes and simplexes: \( R \) is the radiation reflection coefficient, \( k \) is the absorption coefficient (extinction). In the formulas \( T \) (tau large) it is \( f_0 \), \( t_0 \) is the initial temperature of the porous plate. The translucency of the plate is due to its porous structure. The attenuation of radiation in the plate occurs according to Bouguer’s law. We neglect convective heat transfer in the \( x=0 \) plane due to its smallness compared to radiation from an external source. In the plane X=\( \delta \), adiabatic conditions.

Heat transfer through intrinsic radiation and heat conduction inside the plate is taken into account by effective TPS determined experimentally.

### 3.2. Analytical solution

The system of equations (3.1) - (3.4) can be solved analytically using the programs Matlab, Mathematica or Maple. Below is the solution procedure in Maple notation.

- We use the `dsolve` function \( \{ \ldots \}, \ldots \) to find a solution to the system of differential equations (2.1) - (2.4):

\[
sol = \text{dsolve}(\{eq0,eq1,eq2,eq3\}, \theta(X,F_0))
\]

- The solution has the form:

\[
\theta(X,F_0,R,A,Bu,f_0,m) = 1 + \frac{\Phi \cdot Bu - A \cdot Bu \cdot (R - 1) \left( \exp\left(\frac{-f_0}{\tau}\right) - \exp\left(-\frac{Bu \cdot \tau - f_0}{\tau}\right)\right)}{Bu} d\tau
\]

\[
\Phi = \sum_{n=1}^{m} (2(R - 1) A \cdot Bu^2 \exp\left[\frac{\pi^2 n^2 \tau^2 - (F_0 - \pi^2 n^2 + Bu) \cdot \tau - f_0}{\tau}\right] \left[\exp(Bu) + (-1)^n\right] \cos(n \pi X)
\]

Using the `unapply` (...) function, we define the form of the function that will describe the temperature field in spatial and temporal coordinates:

\[
\theta = \text{unapply}\left(1 + \int_{0}^{f_0} \frac{1}{Bu} \left( \sum_{n=1}^{m} \frac{1}{\pi^2 n^2 + Bu^2} \left(2(R - 1) A \cdot Bu e^{\frac{\pi^2 n^2 \tau^2 - (F_0 - \pi^2 n^2 + Bu) \cdot \tau - f_0}{\tau}} \left(-e^{Bu} + (-1)^n\right) \cos(n \pi X)\right) Bu \right)
\]

\[
- Ak(R - 1) \left( e^{\frac{T}{\tau}} - e^{\frac{-Bu - \tau - f_0}{\tau}} \right) d(z,X,F_0,R,A,k,Bu,T,m)\right)
\]

- Visualization of the solution using the `plot` (...) function with the following input data:

\[
\text{plot}(\{(\theta(0,F_0,R,A,k,Bu,T,m), \theta(0.5,F_0,R,A,k,Bu,T,m), \theta(1,F_0,R,A,k,Bu,T,m)\}, F_0 = 0..0.5)
\]
3.3. Analysis of the results and conclusions

From Figure 3.1 it follows that at $Fo > 0.4$ a quasistationary heating regime occurs. In this case, the heating rate at all points of the plate is the same. This fact can be used to experimentally determine the thermophysical properties of a porous material. In Figure 3.2 shows how this can be done in Mathcad.

3.4. Conclusion on the 3rd section:
1. A mathematical model of the temperature field of a porous plate heated by a time-varying radiant flux taking into account the volumetric mechanism of its absorption has been developed.
2. To determine the adequacy of the developed model for the real process, it is necessary to conduct an experiment and compare its results with the calculated model data.
3. We believe that due to the competent selection of the coefficients $A$ and $D$ (which are essentially adaptation coefficients, which are part of the formula of the radiant flux that changes over time) and transfer coefficients (responsible for the thermophysical properties of the material), will evaluate the reliability of the simulation results.
4. Experimental determination of the temperature field of a porous material heated by a variable radiant flow

4.1. Description of the experimental setup
Experimental studies were carried out on the setup shown in Figure 4.1.

Figure 4.1. Experimental setup: 1 – electric heater ENDEVER EP-20W. Power 1000 W; 2 – Brick fireclay lightweight general purpose SHL-0.4 No. 8; 3 – asbest cardboard 6 mm; 4 – chromel-copel thermocouples DTPL021-0.5 / 5, model 021 with insulation MKRts tube, thermoelectrode diameter 0.5 mm, thermocouple length 5 m, measuring range: -40 ... + 600°C; 5 – analog input module MBA-8; 6 – Converter interfaces RS-485 << =>>> USB AC4; 7 – laptop

The test sample is placed above the radiation source, the distance between the radiation panel and the fireclay brick is about a centimeter. Using special devices supporting the object of study at a given distance from the radiating heating surface, it is possible to have an air gap, which, in turn, is designed to reduce the influence of heat conduction and convective heat transfer on the total heat flux emanating
from the surface of the radiation. Five thermocouples placed in the following manner are preliminarily installed in the test sample:

- Three on a surface close to the radiation source (input 5-7);
- One in the middle of the test sample (input 3);
- One on the back (far) surface of the sample in relation to the radiation source (input 4);

In order to create a one-dimensional temperature distribution in a sample heated by radiation, the side surfaces of the sample are shielded with asbestos board - heat-insulating material - 6 mm thick. Thermocouples DTPL021-0.7 / 1.5 are connected to the analog module MBA-8, which, in turn, is connected via an USB adapter to an AC4 converter with an RS-485 interface. After the analog module, the values of the measured values, which are recorded at intervals of 10 seconds, are displayed on the laptop monitor.

Installation starts only after checking the correctness of the connections made and begins with the inclusion of a laptop and a source of thermal radiation. The radiation flux heating the material under study is described by the function:

\[ q = Be^{-D/\tau} \]

The experiment continues until the system reaches a level close to the hospital, that is, until insignificant changes in temperature over time. The results of the experiment are recorded in a table in which the time and temperature values from each thermocouple are recorded. Since the surface of the brick, which receives the heat flux of radiation from the slab, is facing down, according to [4], its heat transfer by convection is less than that of a vertical surface by 30% and 60% compared to a horizontal surface that gives off heat up. Therefore:

- the convective component of the heat flux can be estimated by the formulas presented in paragraph 10.2 [4];
- since PrGr3 <1000, it means that the fraction of the convective component in the total heat flux is small and the sample is heated mainly by radiation and thermal conductivity;
- the value of the first (radiant) component of the heat flux is several orders of magnitude higher than the value of the second (conductive) component of the heat flux.

Thus, the heating of the test sample is carried out mainly by radiation.

4.2. Results and their analysis

In Figure 4.2 – 4.3 presents the results of two experiments.

![Figure 4.2 - A fragment of the results of the 1st experiment, presented in tabular and graphical form in Excel document format](image)

A comparison of the temperature curves of the 1st and 2nd experiments in the frontal (t1s and t2s) and central (t1c and t2c) planes of the studied object showed a slight 5% difference. The temperature curve \( t_s + B1\exp(-D1/\tau) \) was obtained analytically and corresponds to the initial stage of heating the bricks in its center.

Unfortunately, it was not possible to reach the site associated with the quasi-stationary heating mode due to the automatic shutdown of the heater upon reaching the critical temperature. Because of this feature, the proposed method could not be fully verified. You can see only the initial stage of heating, which coincides with the analytical solution.
4.3. Conclusions on the 4th section

1. Experimental data on the temperature field formed in a porous plate upon heating by radiation were obtained.

2. Positive results of verification of data on physical and mathematical modeling were obtained only for the initial stage of heating a porous material by radiation.

3. The presence of a critical temperature in the heater makes it necessary to reformulate the boundary conditions in the frontal plane of the sample, i.e. to the replacement of boundary conditions of the second kind by boundary conditions of the first kind. Such a change in the condition of the problem will be used in the next message, because it requires the development of a special function that describes the peculiarity of temperature changes over time on the surface of the material under study.

4.4. Conclusion

The main results of the work:

- Non-destructive method for determining the thermal resistance of the exterior wall of a building.
- Model of the temperature field, taking into account the volumetric nature of the absorption of radiation by the material when heated by an alternating flow.
- Quasistationary method for determining the absorption rate of a porous material.
- Results of verification of data obtained by mathematical and physical modeling.

References

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