Comparative analysis of thermophysical characteristics for screen insulation and building heat-insulating materials

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Abstract. Methods for calculating massive screen insulation consisting of metal sheets with sufficient volumetric heat capacity and air layers are presented. The comparison of the thermophysical characteristics of a massive screen system with the steel screens with building thermal insulation materials is given.

Introduction
In stationary processes of heating or cooling bodies, the most important is the coefficient of thermal conductivity, which characterizes the ability of a substance to transfer heat [1]. When studying the non-stationary processes of heating or cooling bodies, along with the thermal conductivity coefficient, the thermal diffusivity of the substance is used, which characterizes the rate of temperature equalization over the body volume and the volumetric heat capacity of the substance, which is the product of the specific heat capacity by the substance volume.

Main Part
A setup diagram for studying the properties and characteristics of massive screen insulation is shown in Figure 1. It represents a structure of steel sheets and air spaces between them.

![Figure 1](image_url). Screen scheme: $q$ — specific heat flux, W / m$^2$; $t_w$ — wall temperature, °C; $l$ — air gap; 2 — steel sheet; 3 — sample (body)
To find the effective thermal conductivity coefficient (this coefficient means the thermal conductivity coefficient of the entire system of screens with air spaces) [2], let us consider the ratio:

\[
\frac{R}{\lambda_{ef}} = n \frac{\delta_{air}}{\lambda_{air}} + n \frac{\delta_{st}}{\lambda_{st}},
\]

(1)

where \( R \) — is the total thickness of the screen system, \( m \); \( \lambda_{ef} \) — is effective thermal conductivity, \( W/(m \cdot K) \); \( \lambda_{air} = 3.21 \cdot 10^{-2} \) \( W/(m \cdot K) \) — is the air thermal conductivity coefficient; \( \lambda_{st} = 45.24 \) \( W/(m \cdot K) \) — is the thermal conductivity coefficient of steel; \( \delta_{air} \) and \( \delta_{st} \) — denote the thickness of one air layer and one steel screen, respectively; \( m \); \( n \) — is the number of layers, pcs.

From the relation (1), we express the effective thermal conductivity coefficient:

\[
\lambda_{ef} = \frac{R}{n \frac{\delta_{air}}{\lambda_{air}} + n \frac{\delta_{st}}{\lambda_{st}}}
\]

(2)

Substituting the corresponding values into the formula (2), we obtain, \( W/(m \cdot K) \):

\[
\lambda_{ef} = \frac{0.064}{\frac{0.006}{4} + \frac{0.01}{45.24}} = 0.085.
\]

To find the effective volumetric heat capacity (we mean the volumetric heat capacity of the entire system package of screens with air layers) [3], let us consider the equation of the sum of the volumetric heat capacities:

\[
(cp)_{ef}V_0 = (cp)_{air}V_{air} + (cp)_{st}V_{st},
\]

(3)

where \((cp)_{ef}\) — is effective volumetric heat capacity of the screen system, \( J/(m^3 \cdot K) \); \((cp)_{air}, (cp)_{st}\) — volumetric heat capacity of air and material of screens included in the system, \( J/(m^3 \cdot K) \), respectively; \( V_0, V_{air}, V_{st} \) — volume of the entire screen system, \( m^3 \), total air space, \( m^3 \), screen material volume, \( m^3 \) respectively. It is clear that these volumes are determined by the formulas:

\[
V_0 = RF; \quad V_{air} = \sum_i^n \delta_{air} \cdot F; \quad V_{st} = \sum_i^n \delta_{st} \cdot F,
\]

(4)

where \( F \) — is the screen surface area, \( m^2 \).

Substituting the values of these volumes into the formula (3), we get:

\[
(cp)_{ef}RF = (cp)_{air} \sum_i^n \delta_{air} \cdot F + (cp)_{st} \sum_i^n \delta_{st} \cdot F.
\]

(5)

We divide both sides of the equation by the surface area of the screening system — \( F, m^2 \) and get:

\[
(cp)_{ef} = (cp)_{air} \sum_i^n \delta_{air} + (cp)_{st} \sum_i^n \delta_{st}.
\]

(6)

This equation is the equation of the linear volumetric heat capacities sum for calculating the bulk screen systems. The equation characterizes the linear distribution of volumetric heat capacities included in the massive screening system [4, 5], referred to \( 1 \ m^2 \) screen area. In the future, for the calculations, we will use exactly this formula.

For our particular case, the formula will take the form:

\[
(cp)_{ef} = n(cp)_{air}\delta_{air} + n(cp)_{st}\delta_{st}.
\]

(7)

Let us express the effective volumetric heat capacity from this equation

\[
(cp)_{ef} = \frac{[n\,(cp)_{air}\delta_{air} + n\,(cp)_{st}\delta_{st}]}{R}.
\]

(8)

We substitute the data into the formula (8) and obtain the effective volumetric heat capacity, \( J/(m^3 \cdot K) \):
The thermal diffusivity is determined by the known expression:

\[ a = \frac{\lambda}{c \rho}. \]  

Substituting the data into the formula (9), we obtain, m²/s:

\[ a = \frac{0.085}{19.45 \cdot 10^5} = 0.44 \cdot 10^{-7}. \]

The results obtained are included in Table 1.

### Table 1.
The comparison of thermophysical characteristics of a massive screens system (four flat steel screens) with air layers at \( t_c = 100 \, ^\circ\text{C} \) with monolithic: steel plate, concrete, cinder block, air with the same size \( R, \text{m} \)

| Material Name          | \( \lambda, \text{W/(m-K)} \) | \( (c\rho), \text{J/(m}^3\text{K)} \) | \( a, \text{m}^2/\text{s} \) |
|------------------------|-------------------------------|-----------------------------------|-------------------|
| Massive screen system  | 0.085                         | 1.95\cdot10^6                    | 0.044-10^{-6}     |
| Steel plate            | 45.24                         | 3.1\cdot10^6                     | 12.5-10^{-6}      |
| Concrete               | 1.28                          | 2.6\cdot10^6                     | 0.5-10^{-6}       |
| Slag concrete          | 0.43                          | 1.9\cdot10^6                     | 0.24-10^{-6}      |
| Air                    | 0.032                         | 955                              | 33.6-10^{-6}      |

Table 1 shows a comparison of the thermophysical characteristics between massive screening system with steel screens with other materials.

From the comparison (see Table 1), it can be concluded that the effective thermal conductivity coefficient of the massive screening system (steel screens with air layers) is less than the thermal conductivity coefficients’ values of all the materials under consideration, except for air and expanded polystyrene, and the system under consideration acquired the properties of a heat-insulating material [6, 7]. The value of the effective thermal conductivity coefficient of the screen system \( \lambda_{ef} \) is less than the thermal conductivity coefficient of steel by 532 times, concrete by 15 times, cinder concrete by 5 times, but more than the thermal conductivity of air by 2.66 times.

Thermal diffusivity \( \alpha_{ef} \) of screen systems are less than the thermal diffusivity of steel by 284 times, the thermal diffusivity of air by 764 times, concrete by 113 times, slag concrete by 5.5 times, expanded polystyrene by 5.7 times.

Also, at present time, an important role is played by the heat losses reduction from external barriers, therefore, it is important to use high-quality thermal insulation materials. Knowledge of the thermophysical properties (TPP) makes it possible to choose a heat-insulating material with the best heat-insulating characteristics, which will reduce heating costs and reduce heat losses of the building. To study the TPP, a sample was made from a mineral wool plate with the dimensions of 250 \( \times \) 250 \( \times \) 50 mm. The sample is a mineral wool heat-insulating plate, which contains basalt fiber, which has excellent fire-retardant and thermal insulation properties. A distinctive feature of the mineral plate is its high thermal insulation efficiency.

The experimental research procedure runs as follows. The test sample is placed in a device for implementing the method. The temperature of the test sample is measured using an additional thermocouple installed in the middle of the sample surface from the side of the heater to detect the temperature wave formed before the stationary mode onset. The coefficient of thermal conductivity, coefficient of thermal resistance, density of the stationary heat flux determination reveals the temperature wave on the surface of the material under study from the side of the heater. Using the obtained experimental data, the required thermophysical characteristics are determined by the formulas.

In the initial period, the sample temperature was 19 °C. Before the stationary thermal regime onset the sample was heated from the initial temperature of 19 °C to 40 °C in 24 min. Starting from 24
minutes until the end of the measurement, the sample temperature from the side of the heater was \( T_h = 40 ^\circ C \).

The thermal conductivity coefficient is calculated by the formula:

\[
\lambda = \frac{q \cdot \delta}{T_h - T_r} = \frac{16.6 \cdot 0.05}{40 - 17} = 0.036 \text{ W/m}^2 \text{K}
\]

where: \( q \) – is the density of the stationary heat flux passing through the sample under study, W/m\(^2\); \( \delta \) – is sample thickness, m; \( T_h \) – is the heater temperature, \(^\circ C\); \( T_r \) – is the refrigerator temperature, \(^\circ C\).

The thermal resistance coefficient is calculated by the formula:

\[
R = \frac{T_h - T_r}{q} = \frac{40 - 17}{16.6} = 1.385 \text{ (m}^2 \text{K)/W,}
\]

where \( T_h \) – is the heater temperature, \(^\circ C\); \( T_r \) – is the refrigerator temperature, \(^\circ C\); \( q \) – is the density of the stationary heat flux passing through the sample under study, W/m\(^2\).

The oscillation amplitude of the temperature half-wave is calculated by the formula:

\[
\vartheta_h = 0.5(T_{max} - T_{min}) = 0.5(41 - 17) = 12 ^\circ C
\]

where \( T_{max} \) – is the maximum temperature of the test sample from the side of the heater, \(^\circ C\); \( T_{min} \) – is the minimum surface temperature of the test sample from the side of the heater, \(^\circ C\).

Thermal activity is calculated by the formula:

\[
B = \frac{q_{max} \cdot \vartheta_h}{9_a} = \frac{85.6}{7.13} = 7.13 \text{ W/(m}^2\text{C)},
\]

where \( q_{max} \) – is the maximum heat flux density, W/m\(^2\); \( \vartheta_a \) – is the temperature half-wave amplitude, \(^\circ C\).

The volumetric heat capacity of the test sample is calculated by the formula:

\[
cp = \frac{B^2 \cdot \vartheta_a}{2 \pi \cdot \lambda} = \frac{7.13^2 \cdot 1980}{0.036 \cdot 2 \cdot 3.14} = 445227,62 \text{ J/(m}^3\text{K)},
\]

where \( B \) – denotes thermal activity, W/(m\(^2\)C); \( \vartheta_a \) – is the time of temperature measurement from the side of the heater before the onset of stationary mode, s.; \( \lambda \) – is the coefficient of thermal conductivity, W/m\(^2\).

The thermal diffusivity is calculated by the formula:

\[
a = \frac{\lambda}{cp} = \frac{0.036}{445227,62} = 0.08 \cdot 10^{-6} \text{ m}^2/\text{s},
\]

where \( \lambda \) – is the coefficient of thermal conductivity, W/m\(^2\); \( cp \) – is volumetric heat capacity of the test sample, J/(m\(^3\)K).

An experimental study was also carried out at a different temperature regime of heating.

In the initial period, the sample temperature was 17 \(^\circ C\). Before the stationary thermal regime onset, the sample was heated from the initial temperature of 17 \(^\circ C\) to 40 \(^\circ C\) in 25 min. Starting from 25 minutes until the end of the measurement, the sample temperature from the side of the heater was \( T_h = 40 ^\circ C \).

The growth of the thermophysical properties of the sample was carried out according to the method described above. The obtained thermophysical properties of the heat-insulating mineral plate using two experiments are shown in Table 2.

**Table 2. Thermophysical properties of a heat-insulating mineral plate**

| Value | Experimental data |
|-------|------------------|
|       | I experiment     | II experiment |
| 1. \( T_h \), \(^\circ C\) | 40              | 40            |
| 2. \( T_s \), \(^\circ C\) | 17              | 19            |
The obtained experimental values of the thermal conductivity coefficient $\lambda = 0.036$ W/(m·K) and $\lambda = 0.035$ W/(m·K) were compared with the passport data of the thermal conductivity coefficient of the test sample, which are equal to $\lambda = 0.036…0.07$ W/(m·K). The discrepancy is no more than 10%, that is, the proposed method for determining the TPP of a heat-insulating material makes it possible to accurately determine the thermal conductivity coefficient.

Summary
A significant decrease in the effective thermal diffusivity coefficient of a structure made of steel screens with air spaces is explained by the high thermal resistance of the air layer [8, 9] and the high volumetric heat capacity of the steel layer.

The performed physical and mathematical research confirms the possibility of using massive screen systems with steel screens as protection against thermal effects in stationary and non-stationary modes [10].

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