Estimation of the effect of the blackness coefficient on the error in determining the emissivity of materials

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Abstract. The article considers the influence of the blackness coefficient on the emissivity of various materials. Determining the precise values of the thermal conductivity and heat exchange is of crucial importance to solve problems of power supply and to ensure optimal temperature conditions of premises since the choice of materials for the manufacture of various buildings, structures and their structural elements depends on the heat exchange. The emissivity of materials, in particular, the values of the blackness coefficients in the calculation of radiation heat exchange plays a significant role in the formation of the thermal balance. The contribution to the total heat exchange from radiation processes can be significant and vary significantly for different temperature conditions. This study demonstrates that the error in estimating the radiative heat flux depends on the type of spectral characteristic of its emissivity, and the use of the integral blackness coefficient can significantly increase the error in determining the heat flow from the surface of objects, including construction materials.

1. Introduction

Accurate measurement of thermal conductivity and heat exchange is becoming increasingly important when solving problems of energy-saving and ensuring optimal temperature conditions. It is the heat exchange that determines the thermal insulation and heat exchange properties of the materials used to make the supporting and enclosing structures of buildings and structures, as well as the temperature conditions in the premises.

Obtaining measurement information is necessary not only for construction and heat exchange tasks but also for creating reliable methods and tools for determining the necessary parameters of materials, such as the emissivity and the blackness coefficient. When assessing the heat exchange processes, not only the thermal conductivity but also the thermal radiation of objects plays an important role. The values of the basic parameters of the heat exchange, being an important process for many applications, determine the intensity of the heat exchange – one of the most global natural processes. The data reliability of the values which are essential for all spheres of human activity can only be ensured by measurements. The temperature variation of different objects is determined by the heat exchange processes occurring between them. One of the determining parameters of these processes is the blackness coefficient. In that case, it is the temperature formed in the premises which is necessarily associated with the exchange of the heat flows between both the heat carriers and the environment.

The heat flow density of a real radiating element, in most cases, cannot be described within the framework of classical laws and depends on the temperature of the object, the spectral region of the observed radiation, as well as on the material and state of the radiating surface. In general, the blackness coefficient of an object is determined by a variety of processes and is a complex composition of volumetric properties of materials. For example, the presence of microasperities on the surface can be
represented as the appearance of small "black bodies" that increase the radiating surface and, as a result, the value of the blackness coefficient.

Thus, the formation of the surface heat flow and the energy exchange processes between the material and its environment is a complex multiparametric process, and for assessing its value and contribution to other processes, it is necessary to take into account the characteristics of each specific material.

2. Materials and Methods

When evaluating the thermal balance, the change in the value of the blackness coefficient from the spectral composition of the studied radiation should be taken into account, since this value can be considered constant only for strictly grey bodies, in all other cases, at a given temperature, the change in the blackness coefficient with the change in the wavelength should be expected, and these changes can be significant. Table 1 shows the values of the spectral coefficient for some of the most popular constructional materials.

To evaluate the thermal radiation of a real body in a narrow spectral range, it is recommended to estimate the difference from the black body radiation by the spectral coefficient of blackness, and it should be assumed that it changes when the spectral range changes. Since the thermal radiation is characterized by a continuous spectral distribution, the integral estimation of the coefficient will be determined by the integral blackness coefficient, and based on the above, these values are not equal for the vast majority of materials. The distribution of the heat flow from the object occurs in all directions, but for the real radiating elements the degree of blackness also changes when the viewing angle changes, so the hemispherical integral blackness coefficient is most often used to evaluate the heat exchange properties of surfaces.

At present, unfortunately, there is no unique result of how the blackness coefficient for non-black bodies can change when the radiation wavelength or surface state changes. Even for the most studied materials, such as nickel or tungsten, the difference in the results of measurements of their blackness coefficients reaches 20%, although it has been observed that at large values of the coefficients, these differences decrease [1, 2]. This situation demonstrates that taking into account only the integral coefficient of blackness, a formal assessment of the heat flow from the material surface can lead to significant violations of the veracity of the result. According to the data in Table 1, the heat flow values for different values of the blackness coefficients can be determined and the corresponding changes in the calculations can be evaluated. It should be noted that the data shown in Table 1 are different for various sources, so they are difficult to be compared.

| Material     | 1.0 μm | 1.7 – 2.2 μm | 5.1 – 6 μm | 8.0 – 14.0 μm | \( \varepsilon_\Sigma \) |
|--------------|-------|--------------|------------|--------------|-----------------|
| Concrete     | 0.65  | 0.90         | 0.90       | 0.95         | 0.94            |
| Iron         | 0.35  | 0.10 – 0.30  | 0.05 – 0.25| 0.05 – 0.20  | 0.60            |
| Cast iron    | 0.65  | 0.78         | 0.64       | -            | -               |
| Brick red    | 0.10  | 0.10 – 0.20  | 0.60 – 0.80| 0.70         | 0.92            |
| Paint        | 0.30  | 0.60         | 0.97       | 0.94         | 0.97            |
| Ceramics     | 0.40  | 0.50         | -          | 0.65         | -               |
| Fireclay     | 0.10  | 0.10         | 0.70       | 0.90         | 0.75            |
Even a very modest analysis of the data provided in the literature shows not only a significant change in the spectral blackness coefficient when the spectral interval changes, but also a change in the value of its meaning for the same parameters in different sources [3]. Very often, the information about the spectral characteristics of the material emissivity is not available at all, and for various applications, an integral coefficient is used, the value of which can also change. This ambiguity of information is caused by a variety of processes forming the degree of the blackness coefficient of the object, and changing the value of the blackness coefficient will inevitably lead to an error in the estimation of the emissivity and, respectively, a faulty assessment of the thermal balance. It is clear that depending on the type of material and the state of its surface, the approximation of radiative properties using the integral blackness coefficient can be justified. For example, Figure 1(a) shows the spectral characteristics of the blackness coefficient to \( \varepsilon \) foam concrete, to calculate the emissivity of which the integral factor is justified because the spectral blackness coefficient is slightly less than for concrete, but the spectral characteristic changes \( \varepsilon \) insufficiently over the spectral range. A sharp rise of the value \( \varepsilon \) in the short-wave part of the spectrum can not significantly lead to the thermal balance for temperatures of the order of 300 K, since the emissivity of thermal radiation in this region of the spectrum for this radiating element tends to zero. A different situation is presented in Figure 1 (b). For this material, the use of the integral blackness coefficient cannot be justified, since the changes are observed not only in the region of low emissivity but also in the region close to its maximum value (for temperatures of the order of 300 K, the maximum is in the region of 9.6 microns). For materials of this type, it should be expected not only an increase in the error of calculating the emissivity when using the integral value \( \varepsilon_{\Sigma} \), but even the choice of its specific value becomes problematic. Regarding the above, the problem of estimating the possible error in calculating the emissivity of different materials, including construction materials, is relevant, which is especially important for accounting the heat balance and heat supply of various premises in cold climatic conditions when taking into account the real value of the blackness coefficient [4, 5]. Comparison of the above dependencies allows assuming a different value of the error in estimating the emissivity when using the average values of the blackness coefficients.

![Figure 1](image1.png)

**Figure 1.** The spectral characteristic of the blackness coefficient: (a) – aerocrete; (b) – brick red

Figure 2 shows the spectral characteristics for the blackness coefficient of paint such as white enamel and fireclay construction material. The dependence graphs show significant changes in the blackness coefficient when changing the spectral range, and the values of this parameter in the region of maximum emissivity meanings at room temperatures can only be guessed. However, even the known regions of the characteristic show that the parameter changes are complex, but they tend to increase \( \varepsilon \) with rising wavelength, which is typical for dielectrics.
3. Results and Discussion

For a comparative assessment of the integral emissivity $R$, the shares of emissivity $\Delta R_i$ in each spectral interval were calculated when the wavelength changes, taking into account Planck's law for thermal radiation and the blackness coefficients $\varepsilon_i$ for each spectral interval, and then the results were summarized under the ratio (1)

$$R = \sum_{i=1}^{N} \varepsilon_i \cdot \Delta R_i,$$

where $N$ is the number of summed sections.

Calculations of the spectral emissivity $R_{i\lambda}$ and the generalization $\Delta R_i$ to the selected spectral range were performed using the standard method for determining the share of radiation in a given spectral range for the thermal radiating elements. The distribution of emissivity for a selective thermal emitter has a continuous spectrum and when selecting the spectral interval $\Delta R_i$, the areas with a close value of the blackness coefficient are selected [6-8].

To calculate the emissivity of the selected materials, a fairly conditional division of radiation into spectral intervals was used by the values known for these materials $\varepsilon_i$. The obtained results of $R_1$ when summing the radiation of some spectral sections for the temperature of 300°K are presented in Table 2.

**Table 2. The calculation of the emissivity for the spectral intervals**

| Material    | $\Delta R_{1\lambda}$ W m$^{-2}$ (up to 1.7 μm) | $\Delta R_{2\lambda}$ W m$^{-2}$ (1.7 – 4.0 μm) | $\Delta R_{3\lambda}$ W m$^{-2}$ (4.0 – 8.0 μm) | $\Delta R_{4\lambda}$ W m$^{-2}$ (8.0 – 14.0 μm) | $\Delta R_{5\lambda}$ W m$^{-2}$ (more than 14.0 μm) | $R_{1\lambda}$ W m$^{-2}$ | $\varepsilon_\Sigma$ | $R_{2\lambda}$ W m$^{-2}$ |
|-------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------|----------------|----------------|
| Concrete    | 1.80 $10^{-3}$                              | 1.53                                          | 71.17                                         | 168.45                                        | 192.47                                        | 433.62          | 0.94            | 431.46          |
| Brick red   | 0.27 $10^{-3}$                              | 0.34                                          | 56.85                                         | 124.21                                        | 121.56                                        | 303.12          | 0.92            | 422.28          |
| Iron        | 0.96 $10^{-3}$                              | 0.44                                          | 12.67                                         | 20.90                                         | 44.06                                         | 78.07           | 0.60            | 275.01          |
| Fireclay    | 0.28 $10^{-3}$                              | 0.55                                          | 53.39                                         | 174.42                                        | 198.29                                        | 426.65          | 0.75            | 344.25          |

Here, for comparison, the values of the integral emissivity $R_2$ obtained using the integral blackness coefficient are given.

The results presented in Table 2 showed the different values of the calculated parameter for different methods of determination. The estimation of absolute $\Delta R$ and relative $\delta$ errors in the emissivity of materials is given in Table 3. The value $R_1$ was taken as the true value.
Table 3. The absolute and relative error of emissivity for different calculation methods $\varepsilon$

| Material  | $R_1$, W m$^{-2}$ | $R_2$, W m$^{-2}$ | $\Delta R$, W m$^{-2}$ | $\delta$, % |
|-----------|-------------------|-------------------|-------------------------|-----------|
| Concrete  | 433.62            | 431.46            | 2.16                    | 0.50      |
| Brick red | 303.12            | 422.28            | 119.16                  | 39.30     |
| Iron      | 78.07             | 275.01            | 196.94                  | 250.00    |
| Fireclay  | 426.65            | 344.25            | 82.40                   | 19.30     |

The obtained values illustrate the instability of the estimated values of the emissivity in different methods of calculating it since the theoretical calculation requires a precise value of the spectral blackness coefficients, the information of which is not available in most cases, and the use of the integral coefficient is justified only for materials with close values of the blackness coefficients in the spectral region where the emissivity is close to the maximum.

Based on the analysis and the results obtained, it can be implied that to reduce the error of heat exchange results, an experimental determination of the blackness coefficient for a given material and specific measurement conditions should be used.

It is known that the most reliable results of the blackness coefficient measurements are provided by the calorimetric measurement method [10, 11]. In the experimental determination of the blackness coefficients, the relative measurements are usually used based on the calibration dependence of the values of the heat flow density in the gap between two surfaces on the value of the blackness coefficient $\varepsilon_1$. $\varepsilon_2$ can be determined using standard samples with the known blackness coefficients. Figure 3 shows the calculated dependences of changes in the surface heat flow density for $T_1 = 290$ K and $T_2 = 310$ K. When $\varepsilon_1 \neq \varepsilon_2$, the relation (2) is used

$$q_c = \frac{\varepsilon_1 A}{1 + \frac{\varepsilon_1}{\varepsilon_2} - \varepsilon_1}.$$  \hspace{1cm} (2)

The resulting dependence is shown in Figure 3, Graph 1. It can be seen that for $\varepsilon_2 \rightarrow 1$, the graph reaches a linear dependence. If $\varepsilon_1 = \varepsilon_2$, the dependence $q_c$ takes the form of dependence 2 in Figure 3 by the relation (3)

$$q_c = \frac{\varepsilon_1 A}{2 - \varepsilon_1}.$$  \hspace{1cm} (3)

![Figure 3. Dependence of the heat flow density $q = f(\varepsilon_1)$](image-url)
At large values of $\varepsilon_1$, the sensitivity of $q_\varepsilon$ to changes of $\varepsilon_1$ increases noticeably. The calculations show that the greater the degree of blackness, the stronger the influence of its changes on the value of heat flow [12].

4. Conclusion
As shown by the analysis, the only reliable way to determine the values of the blackness coefficient for real radiation sources is to measure it on samples of the materials or coatings. For this reason, it is necessary to emphasize the importance of experimental determination of the blackness coefficient value, since the theoretical calculation for each specific case requires simultaneous consideration of several parameters and development of a model of their interaction. The assessment of heat flow and heat balance in the heat exchange under the specified conditions of measurement should be made taking into account the non-linearity of the heat flow characteristics when changing the blackness coefficient for a specific type of material, taking into account their operating conditions.

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