Effect of Semitransparent Screen on Heat Transfer Through a Flat Wall

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Abstract. Evaluation the energy efficiency of houses under a transparent dome is a rather difficult task due to the complexity of taking into account numerous factors affecting heat transfer, in particular the greenhouse effect. In this paper, a relatively simple model for calculating the characteristics of heat transfer through the wall of a building with a dome, which takes into account the greenhouse effect, is proposed. It is shown that the presence of a semitransparent screen due to the greenhouse effect significantly changes the temperature of the building wall under the dome and the heat flux, which implies the importance of taking into account factors such as the optical properties of the screen, the temperature of the sky, and other climatic factors when calculating the thermal regime of dome systems.

1. Introduction
In connection with the growing interest in the construction of houses in the northern regions under a transparent dome, the task is to estimate the energy efficiency of such structures. The decrease in heat loss of houses under the dome in the cold season is due to additional thermal resistance of the air layer of the dome space, as well as additional accumulation of solar radiation energy (the greenhouse effect) in it. The prediction of the influence of various constructive solutions of the dome structure on energy saving is based on mathematical modeling of heat exchange in a multilayer system, which becomes more complicated in this case, since in addition to heat transfer by heat conduction and convection, radiative heat transfer must be taken into account in the presence of a screen with selective optical properties.

Available publications dealing with heat transfer with consideration of penetrating radiation through semitransparent enclosing structures at civil construction sites are mainly devoted to the study of the thermal regime in commercial greenhouses [1-7]. The mathematical models developed in these works are used to predict internal temperatures – in the air and in the soil, to calculate heat loss for various covering materials of the greenhouse and its design features. Taking into account infiltration, evaporation, the influence of plants, the concentration of carbon dioxide, outside climate variables and other factors in the simulation of the greenhouse regime requires the use of a complex mathematical apparatus. In particular, greenhouse modeling studies in the recent years have used TRNSYS software (TRaNsient SYstem Simulation program) [5,6], or computational fluid dynamics technique (CFD) and the discrete ordinate method [7]. At the same time, engineering estimates of the heat transfer characteristics in a multilayer dome system, taking into account such complex phenomena as the greenhouse effect, remain relevant.

In this paper, we propose a simplified model of heat transfer in a system of an opaque wall and a semitransparent screen onto which external radiation is incident. It can be used to make engineering
calculations of heat transfer taking into account the greenhouse effect and determine the influence of various thermal and optical factors.

2. Problem statement and solution method

Consider the element of the dome system in the form of a flat opaque wall and a semitransparent screen, between which there is an air layer (Fig. 1). The screen is considered transparent for incident external (short-wave) radiation and opaque for (long-wave) radiation emitted from the wall and the surrounding. At the external boundaries of the system, the condition of convective heat exchange with the surrounding air is set, with a temperature $T_0$ on the inner surface of the wall (room temperature) and with a temperature $T_a$ on the outer surface of the screen, respectively.

![Figure 1. Physical model and the system of coordinates.](image)

The statement of the problem includes the following balance relations. At the outer boundary of the screen, the heat flux density $q$ consists of the density of the convective heat flux $q_k^3$, as well as the resulting radiation flux in the short-wave $q_r^*$ and long-wave $q_r^2$ parts of the spectrum:

$$q = q_k^3 + q_r^2 + q_r^*$$

(1)

Using the laws of Newton-Richman, Stefan-Boltzmann and Kirchhoff, and considering the radiation of the sky to be similar to that of a black body with temperature $T_s$, (1) can be written as:

$$q = \alpha_a (T_3^4 - T_a^4) + \varepsilon_3 (\sigma T_3^4 - \sigma T_s^4) - \varepsilon_1 q_r^*$$

(2)

where $T_3$ is the screen temperature (the screen is considered thin enough to neglect the change in its temperature over the thickness), $\alpha_a$ is the convective heat transfer coefficient, $\sigma$ is the Stefan-Boltzmann constant, $\varepsilon_1$ and $q_r^*$ are the emissivity of the wall and the flux density of the incident radiation in the short-wave part of the spectrum, $\varepsilon_3$ is the emissivity of the screen in the long-wave part of the spectrum.

A relation similar to (1) can be written for the heat flux on the outer surface of the wall:

$$q = q_k^2 + q_r^1 + q_r'^*$$

(3)

The convective heat flux density is determined here from the formula for a closed air space:

$$q_k^2 = (T_2 - T_3) / R_2$$

(4)

where $T_2$ is the temperature of the outer surface of the wall, $R_2$ is the effective thermal resistance of the air layer, taking into account conduction and convection. Depending on the space form, its value can be expressed using well-known equation

$$R_2 = l / \lambda_k,$$

where $\lambda_k = f(Ra)$ is the effective coefficient of thermal conductivity, which depends on the Rayleigh number $Ra$, which in turn depends on the temperature difference $(T_2 - T_3)$ at the boundaries of the layer and its thickness $l$. But in this study, we limited ourselves to a simple variation of the of $R_2$-value.
The radiation flux density between the wall and the screen, taking into account that the radiation maximum at given temperatures is located in the long-wave part of the spectrum, is found from the formula for the resulting radiation flux of two gray surfaces:

\[ q_{23} = \frac{\varepsilon_2}{1/(\varepsilon_2 + 1/\varepsilon_3) - 1} \sigma T_2^4 - \sigma T_3^4, \quad (5) \]

where

\[ \varepsilon_{23} = \frac{1}{1 + \varepsilon_2 + 1/\varepsilon_3 - 1} \]

is reduced emissivity of the wall and screen; \( \varepsilon_2 \) and \( \varepsilon_3 \) are the emissivity of the screen and the wall in the long-wavelength part of the spectrum.

The system of equations (1)-(5) is closed by the equation for the heat flux density on the inner side of the wall \( q = q_k^1 \):

\[ q = \frac{T_0 - T_2}{1/\alpha_0 + R_1}, \quad (7) \]

where \( R_1 \) is the thermal resistance of the wall, and \( \alpha_0 \) is the coefficient of convective heat exchange. The radiation in (7) is not taken into account due to the negligible temperature difference on the inner surface of the wall and the surrounding.

The solution of the system of nonlinear equations (2)-(7) can be obtained by using engineering software, in particular, in the Mathcad environment.

3. Analysis of results

The calculations were carried out for the following values of the governing parameters: air temperature on the inner surface of the wall \( T_0 = 20^\circ C \), ambient temperature \( T_a = 0^\circ C \). The values of the coefficients \( \alpha_0 \) and \( \alpha_a \) assumed to be 8W/(m\(^2\)K) and 20W/(m\(^2\)K), which corresponds approximately to the conditions of heat exchange indoors and on external walls for moderate wind [8-9].

The results obtained indicate a significant effect of semitransparent screen on heat transfer under conditions of external incident radiation. Fig. 2-4 demonstrate the change in temperature of the external surface of the wall \( T_2 \) (Fig. a) and heat flux density \( q \) (Fig. b) depending on the flux of incident external radiation \( q^* \).

\[ R_1 = 1, \; R_2 = 1, \; \varepsilon_1 = 0.9, \; \varepsilon_2 = 0.9, \; \varepsilon_3 = 0.9, \; 1 - T_s = -5^\circ C, \; 2 - T_s = -30^\circ C. \; \text{Hereinafter, solid lines - calculation with a screen, dashed lines - calculation without a screen.} \]

The presence of the screen leads to a significant increase in the wall temperature (solid lines) compared to the case of its absence (dashed lines). As the density of the incident external radiation increases, this trend increases, while the heat flux through the wall decreases, and when a certain value \( q^* \) is reached, its inversion occurs, that is, heat begins to enter indoor.

The marked nature of heat transfer depends on a number of factors. As already mentioned, the radiation of the sky is considered as the radiation of a black body at a temperature \( T_s \), which, depending on the cloudiness, is usually 5-30 degrees lower than the air temperature on the earth's surface. As can be seen from Fig. 2, this factor significantly affects the heat exchange. Because of radiation cooling, the temperature of the wall surface at the same ambient temperature may differ by several degrees (for example, at the taken values of \( R_1 = 1, \; R_2 = 1 \) by three degrees), and the heat flux by 30%.

**Figure 2.** Effect of the sky temperature on the heat transfer.

\[ \begin{align*}
R_1 &= 1, \; R_2 = 1, \; \varepsilon_1 = 0.9, \; \varepsilon_2 = 0.9, \; \varepsilon_3 = 0.9, \; 1 - T_s = -5^\circ C, \; 2 - T_s = -30^\circ C. \; \text{Hereinafter, solid lines - calculation with a screen, dashed lines - calculation without a screen.} \\
\text{The presence of the screen leads to a significant increase in the wall temperature (solid lines) compared to the case of its absence (dashed lines).} \\
\text{As the density of the incident external radiation increases, this trend increases, while the heat flux through the wall decreases, and when a certain value } q^* \text{ is reached, its inversion occurs, that is, heat begins to enter indoor.} \\
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\end{align*} \]
The effect of incident radiation on the heat transfer depends on the ratio of the thermal resistance of the wall and the air space (Fig. 3). For the same total resistance of the building envelope ($R_1 + R_2$), the greenhouse effect is more expressed.

![Figure 3. Effect of thermal resistance on the heat transfer.](image)

$T_s = -10^0C, \varepsilon_1 = 0.9, \varepsilon_2 = 0.9, \varepsilon_3 = 0.9$. 1 – $R_1 = 0.5$, $R_2 = 1.5$, 2 – $R_1 = 1.5$, $R_2 = 0.5$.

The next factor that plays an important role in heat transfer in the dome system is the optical properties of the screen. Modern technologies allow, for example, to increase the reflectance of semitransparent screen in the infrared region, without changing the transmittance in the visible region of the spectrum. These technologies (low-e glass) are used to reduce energy loss by radiation through the windows in building [10]. An increase in the reflection coefficient of the screen in the long-wavelength part of the spectrum (accordingly, a decrease in the emissivity of the screen) due to a decrease in radiation cooling leads to a noticeable increase in the wall temperature and a change in the heat flux (Fig. 4).

![Figure 4. Effect of optical properties of the screen on heat transfer.](image)

$T_s = -10^0C, R_1 = 1$, $R_2 = 1$, $\varepsilon_1 = 0.9, \varepsilon_2 = 0.9$, $1 – \varepsilon_3 = 0.5$, $2 – \varepsilon_3 = 0.9$. when the thermal resistance of the air layer ($R_2$) prevails over the thermal resistance of the wall ($R_1$), resulting in greater wall heating and in heat loss decreasing or heat input indoor (lines 1).

4. Conclusion

Based on a simple model of heat transfer in a two-layer medium with a semitransparent screen, it is shown that the greenhouse effect plays important role in heat exchange in the dome system. A significant increase in the wall temperature under the influence of penetrating radiation, and, consequently, large temperature differences between the surfaces in the dome system will lead to complex intense convection in the dome space, which is beyond the scope of this study. It was found that attention should be paid to taking into account such factors as the optical properties of the screen and wall, the sky temperature, the ratio of the thermal resistance of the wall and the air space when calculating the thermal regime of the building under the dome. Thus, the development of more accurate thermal models of dome systems...
requires detailed information about the spectral optical properties of the semitransparent screen and walls of the building, incoming solar radiation and climatic factors in a given terrain.

5. References

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