A composite substrate of dissimilar materials temperature determination in the process of infrared heating in vacuum

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Abstract. The problem of determining the temperature of a substrate of dissimilar materials fragments in the process of infrared heating in vacuum solution, obtained using the algebraic method of calculating radiant fluxes, is presented.

During the infrared heating of a substrate consisting of two different materials in vacuum [1–3] a temperature difference arises due to the difference in their thermophysical properties. In this case it is about the radiant interaction of several surfaces with different temperatures and emissivities [4, 5]. Such a problem can be solved by the algebraic method.

Let us consider an approach to solving such a problem using the example of a basic computational scheme shown in figure 1, which includes a working chamber with a heating module (a halogen lamp and a reflector) placed in it and a heated object in the form of a composite substrate consisting of two fragments with different properties.

![Figure 1. The computational scheme: 1 – heater, 2.1 – component, 2.2 – substrate, 3 – working chamber, 4 – inner surface of the reflector, 5 – outer surface of the reflector.](image)

The reflector and the camera are water-cooled surfaces. Taking into account the difference in the properties of the inner and outer surfaces of the reflector, there is a total of 6 surfaces with different properties. Preparation of a system of equations for 6 surfaces in a general form is as follows:

\[
Q_{ref1} = \varphi_{21}Q_{ef21} + \varphi_{22}Q_{ef22} + \varphi_{31}Q_{ef3} + \varphi_{14}Q_{ef4} - \left(\varphi_{121} + \varphi_{122} + \varphi_{13} + \varphi_{14}\right)Q_{ef1}
\]

\[
Q_{res1} = \varphi_{121}Q_{ef1} + \varphi_{321}Q_{ef3} + \varphi_{A1}Q_{efA} - \left(\varphi_{21} + \varphi_{213} + \varphi_{214}\right)Q_{ef21}
\]

\[
Q_{res2} = \varphi_{122}Q_{ef1} + \varphi_{322}Q_{ef3} + \varphi_{A2}Q_{efA} - \left(\varphi_{221} + \varphi_{223} + \varphi_{224}\right)Q_{ef22}
\]
where the ratio for effective fluxes \( Q_{ef,i} \), fluxes of self-radiation \( Q_{0,i} \) and the resulting fluxes \( Q_{res,i} \) \[6\] is

\[Q_{ef,i} = Q_{0,i} + R_{i}Q_{res,i} = E_{0,i}F_{i} + R_{i}Q_{res,i},\]

where \( E_{0,i} \) is the integral surface density of a blackbody radiation flux at the temperature of the \( i \)-th surface; \( F_{i} \) is the \( i \)-th surface area; \( R_{i} \) is the \( i \)-th surface relative reflectivity

\[R_{i} = \frac{1-\varepsilon_{i}}{\varepsilon_{i}},\]

where \( \varepsilon_{i} \) is the \( i \)-th surface emission coefficient.

For the whole system, there is an obvious correlation

\[Q_{res1} + Q_{res2} + Q_{res2} + Q_{res4} + Q_{res5} = 0 \quad (\ast).\]

The most important step for solving the problem is the determination and calculation of essentially significant view factors. After solving this problem, the computational system of equations, taking into account the relations presented, takes the form

\[(1 + R_{1})Q_{res1} - \varphi_{21,1}R_{21}Q_{res21} - \varphi_{22,1}R_{22}Q_{res22} - \varphi_{31}R_{3}Q_{res3} - \varphi_{41}R_{4}Q_{res4} = -E_{01}F_{1} + \varphi_{21,1}E_{0,21}F_{21} + \varphi_{22,1}E_{0,22}F_{22} + \varphi_{31}E_{0,3}F_{3} + \varphi_{41}E_{0,4}F_{4},\]

\[-\varphi_{12,1}R_{1}Q_{res1} + (1 + R_{1})Q_{res21} - \varphi_{32,1}R_{3}Q_{res3} - \varphi_{42,1}R_{4}Q_{res4} = -E_{01}F_{1} - E_{0,21}F_{21} + \varphi_{32,1}E_{0,3}F_{3} + \varphi_{42,1}E_{0,4}F_{4},\]

\[-\varphi_{12,2}R_{1}Q_{res1} + (1 + R_{2})Q_{res22} - \varphi_{32,2}R_{3}Q_{res3} - \varphi_{42,2}R_{4}Q_{res4} = -E_{01}F_{1} - E_{0,22}F_{22} + \varphi_{32,2}E_{0,3}F_{3} + \varphi_{42,2}E_{0,4}F_{4},\]

\[-\varphi_{13}R_{1}Q_{res1} - \varphi_{21,3}R_{21}Q_{res21} - \varphi_{22,3}R_{22}Q_{res22} + (1 + (1 - \varphi_{33})R_{3})Q_{res3} - \varphi_{43}R_{4}Q_{res4} - \varphi_{53}R_{5}Q_{res5} = \varphi_{13}E_{01}F_{1} + \varphi_{21,3}E_{0,21}F_{21} + \varphi_{22,3}E_{0,22}F_{22} - (1 - \varphi_{33})E_{0,3}F_{3} + \varphi_{43}E_{0,4}F_{4} + \varphi_{53}E_{0,5}F_{5},\]

\[-\varphi_{14}R_{1}Q_{res1} - \varphi_{21,4}R_{21}Q_{res21} - \varphi_{22,4}R_{22}Q_{res22} - \varphi_{34}R_{3}Q_{res3} + (1 + (1 - \varphi_{44})R_{4})Q_{res4} = \varphi_{14}E_{01}F_{1} + \varphi_{21,4}E_{0,21}F_{21} + \varphi_{22,4}E_{0,22}F_{22} + \varphi_{34}E_{0,3}F_{3} - (1 - \varphi_{44})E_{0,4}F_{4},\]

\[-\varphi_{35}R_{3}Q_{res3} + (1 + R_{5})Q_{res5} = \varphi_{35}E_{0,3}F_{3} - \varphi_{53}E_{0,5}F_{5}.\]

At the first stage, the maximum temperatures on the substrate fragments that are achievable with a given system geometry, selected materials and a known heater are calculated. In this case, we neglect the conductive interaction between the substrate fragments. After that, we find the temperature variation on the various elements of the treated surface in time.

1) Determining the maximum heating temperatures of the substrate and the component \( T_{21,\max} \), \( T_{22,\max} \). In this case, \( Q_{res1} = \rho_{heat} \cdot T_{res21} = 0 \), \( Q_{res2} = 0 \), \( T_{3} = T_{4} = T_{5} = T_{cool} \) from where we determine \( E_{cool} = \sigma_{0}T_{cool}^{4} \). Unknown: \( Q_{res3}, Q_{res4}, Q_{res5}, T_{1}, T_{21}, T_{22} \).

The unknown variables \( E_{01}F_{1}, E_{0,21}F_{21}, E_{0,22}F_{22}, Q_{res3}, Q_{res4}, Q_{res5} \) can be determined by using the Cramer’s rule, the unknown value of \( Q_{res5} \) can be determined from the correlation (\( \ast \)), taking into account the values of the view factors \( \varphi_{ij} \), the emission coefficients \( \varepsilon_{i} \) or the relative reflectivities \( R_{i} \), the known temperatures and areas.

2) Calculating the temperature variation of the given elements in time \( [7] \). \( T_{21} \) is set from \( T_{cool} \) to \( T_{21,\max} \) and \( T_{22} \) is set from \( T_{cool} \) to \( T_{22,\max} \). At the first step we take \( T_{21} = T_{22} \), at the second step we focus on the results of the first step. In this case, \( Q_{res1} = \rho_{heat} \). \( T_{21} \rightarrow E_{0,21} = \sigma_{0}T_{21}^{4}, T_{22} \rightarrow E_{0,22} = \sigma_{0}T_{22}^{4}, T_{3} = T_{4} = T_{5} = T_{cool} \), from where we determine \( E_{cool} = \sigma_{0}T_{cool}^{4} \). Unknown: \( T_{1}, Q_{res21}, Q_{res22}, Q_{res3}, Q_{res4}, Q_{res5} \).

The transformations of the system, taking into account changes in known and unknown quantities, are carried out by analogy with the first version of calculating the maximum temperatures.
Taking into account the values of the view factors $\varphi_{ij}$, emission coefficients $\varepsilon_i$ or relative reflectivities $R_i$, known temperatures and areas, we determine the unknowns and get $Q_{res21} = f(T_{21})$ and $Q_{res22} = f(T_{22})$.

We describe $Q_{res21} = f(T_{21})$ with its corresponding trend line $Q_{res21}(T_{21})$. Then from the ratio $Q_{res21}(T_{21})dt = c_{21}m_{21}dT$

through integration we get the dependency $T_{21} = f(\tau)$ and describe it with the corresponding trend line $T_{21} = T_{21}(\tau)$.

Similarly, for $Q_{res22} = f(T_{22})$, we get $T_{22} = f(\tau)$ and describe it with the corresponding trend line $T_{22} = T_{22}(\tau)$.

After that, we recalculate for the case of $T_{21}$ and the $T_{22}$ values corresponding to it in time according to the data obtained at stage 1 to obtain the final $T_{21, res} = T_{21, res}(\tau), T_{22, res} = T_{22, res}(\tau)$. If there is a large discrepancy, repeat the second iteration again as the third iteration using the results of the second iteration to calculate the third, etc., until satisfactory results are obtained.

The calculation was carried out for a model consisting of two elements - a component with a size of 10x10x2mm, placed on a substrate with a size of 150x150x2mm. The resulting dependency of the substrate elements temperature variation in time is presented in figure 2.

![Figure 2](image.jpg)

**Figure 2.** The estimated assessment of the substrate and the component temperature change nature in the process of infrared heating with a 1500 Watt halogen lamp; $t_1$ – component $F_{21}$ (10x10x2mm), surface emission coefficient $\varepsilon_{21}=0.55$; $t_2$ – substrate $F_{22}$ (50x150x2mm), surface emission coefficient $\varepsilon_{22}=0.7$.

The developed methodology allows us to model the process of infrared heating of composite substrates consisting of fragments with different thermophysical characteristics, taking into account their relative position, shapes and sizes, thermophysical properties, the heater parameters, characteristics of the reflector and the working chamber, to obtain a calculated estimate of temperature extremes.

The experimental studies on modes optimization can be carried out after the calculated determination of the optimal parameters of the infrared heating process, which will speed up and cheapen the process of developing equipment and optimizing modes.

**References**

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