Technique of measuring the emissivity coefficient

V A Arkhipov, V D Gol’din, I K Zharova and K GPerfilieva
National Research Tomsk State University, 36 Lenina Avenue, Tomsk 634050
Russian Federation

E-mail: k.g.perfiljeva@yandex.ru

Abstract. The experimental setup and the variant of calculation-experimental technique of measuring the emissivity coefficient of heat-shielding materials surface are presented.

1. Introduction
Despite the wide use of heat-shielding materials in elements of high-energy equipment, for example, in the systems of thermal protection and gas flow ducts of propulsion setups [1-3], one of the relevant problems is receiving reliable data about thermophysical properties of heat-shielding materials in the range of temperatures, close to thermal degradation temperature. In the conditions of high temperatures alongside with conductive and convective component, the emissivity of a surface of heat-shielding materials can make an essential contribution in the study of heat exchange. The devices realizing radiation, calorimetric and non-stationary methods are used for measuring the emissivity coefficient of various materials surface in the wide range of temperatures. [4]. The analysis of experimental methods of determination of the emissivity coefficient has revealed a number of advantages of non-stationary methods of measurement [5, 6]. One of the advantages is possible adaptation of the devices to non-standard conditions of heat exchange research without the loss of measurement accuracy.

This paper presents the variant of a technique [7] of measuring the emissivity coefficient of heat-shielding materials surface. The technique is based on temperature measurement of a sample in the course of its cooling in the vacuum chamber and on the use of the apparatus of inverse heat transfer problems. An increased accuracy of the emissivity coefficient and a decreased time of the measurements are provided due to heating of a sample directly in the vacuumized chamber and accounting of non-uniformity of a temperature field in the sample.

2. Setup and technique of measuring the emissivity coefficient
Measurements of the emissivity coefficient were carried out on experimental setup (figure 1). The sample of the studied material was made in the shape of the cylinder which face surfaces are covered with a foil with high coefficient of reflection. Previously the sample was entered into the heater in the form of the hollow cylinder with an incandescence electric coil on an external surface. To provide sufficient cooling intensity of the sample due to radiant heat exchange (in compliance with Stephan-Boltzmann law of radiant thermal stream of $q_r \sim T^4$), the side surface of the sample was heated up to 500 K. After reaching the necessary temperature, the sample was taken out of the heater by means of the movable rod mounted in the center of the basis.
Figure 1. Scheme of experimental setup for measuring the emissivity coefficient. 1 – glass cap; 2 – metal base; 3 – sealing gasket; 4 – vertical post; 5 – cylindrical heater; 6 – clamp; 7 – movable rod; 8 – disk; 9 – sample; 10 – thermocouples; 11 – adjustable stop; 12 – multiplexing device; 13 – nipple; 14 – taps; 15 – triplet coupler; 16 – vacuum meter; 17 – vacuum hose; 18 – fluoroplastic inserts; 19 – laboratory autotransformer; 20 – single-channel measuring instrument regulator "OVEN TRM 01"; 21 – computer.

In the course of cooling in the vacuumized chamber the sample temperature was controlled by two tungsten-rhenium thermocouples. Thermocouples were placed on a symmetry axis of the sample and on its side surface. The additional thermocouple on the side surface of the sample allows considering non-uniformity of its heat up at the initial moment of cooling.

The emissivity coefficient is defined from the solution of the inverse heat conduction problem [6–8]:

$$\frac{\partial T(r,t)}{\partial t} = a \left( \frac{\partial^2 T(r,t)}{\partial r^2} + \frac{1}{r} \frac{\partial T(r,t)}{\partial r} \right)$$

with boundary conditions

$$\frac{\partial T(0,t)}{\partial r} = 0, \quad \lambda \frac{\partial T(R,t)}{\partial r} = -e \cdot \sigma \cdot T^4(R,t),$$

initial condition
and experimental conditions

\[ T(0, t) = T_i(t), \quad T(R, t) = T_s(t), \]

where \( t \) is the time; \( r \) is the space coordinate (in the cylindrical system of coordinates); \( T(r, t) \) is the sample temperature; \( a = \lambda / (\rho \cdot c) \) is the thermal diffusivity coefficient, \( \rho, c, \lambda \) are the density, heat capacity and thermal conductivity coefficient of material of the sample; \( R \) is the sample radius; \( \varepsilon \) is the emissivity coefficient; \( \sigma = 5.6687 \cdot 10^{-8} \text{ W m}^{-2}\text{K}^{-4} \) is the Stephan-Boltzmann constant; \( T_i(t), T_s(t) \) are the measured values of temperature on symmetry axis and on an side surface of a sample, respectively.

3. Analysis of the model problem solving results

The proposed experimental-calculating method was tested by numerical solution of the model problem of determination of the emissivity coefficient of heat-shielding materials. Characteristics of material: density is \( \rho = 2350 \text{ kg/m}^3 \); heat capacity is \( c = 1000 \text{ J/(kg \cdot K)} \); and thermal conductivity coefficient is \( \lambda = 1.4 \text{ W/(m \cdot K)} \). Radius of a cylindrical sample is \( R = 0.015 \text{ m} \), and initial temperature is 293 K.

Based on the results of the numerical solution of the heat conduction problem, it was determined that the temperature on the outer surface of sample \( T(R, 0) = 1000 \text{ K} \), and on the symmetry axis \( T(0, 0) = 513 \text{ K} \) were reached under the action of a constant heat flux \( q = 9.4 \cdot 10^4 \text{ W/m}^2 \) in for 86 seconds. Initial temperature distribution at sample cooling is defined on the basis of the ratio [9]

\[ T(r, t) = T(0, t) + \left[ T(R, t) - T(0, t) \right] \left( \frac{r}{R} \right)^2. \]

On the basis of the solution of the inverse heat transfer problem (1)–(4) the value of the emissivity coefficient at sample cooling was defined in vacuum. At the same time, the values of \( T(R, t) \) and \( T(0, t) \) obtained by solving of the direct problem of heat transfer with the introduced perturbations simulating the random error of the experiment were taken as the “experimentally measured” temperature in condition (4). The initial value of the emissivity coefficient \( \varepsilon = 0.80 \) was accepted. Target value of the emissivity coefficient was defined numerically by minimization of functionality

\[ J = \frac{1}{n} \sum_{i=1}^{n} \left[ \left( T(0, t_i) - T_i^e(t_i) \right)^2 - \left[ T(R, t_i) - T_s^e(t_i) \right]^2 \right] (t_i - t_{i-1}) , \]

where \( t_i \) is the cooling time of the sample; \( n \) is the number of points over time \( (i = 1, 2, \ldots, n) \); \( T(0, t_i), T(R, t_i) \) are the calculated temperature values on the symmetry axis and on the sample side surface at \( i \)-th fixed moments of time; \( T_i^e(t_i), T_s^e(t_i) \) are the “experimental” values of temperature on the symmetry axis, and on the sample side surface at \( i \)-th fixed moments of time.

Based on the results of calculating experiment we have found the specified value of the emissivity coefficient \( \varepsilon = 0.805 \).

4. Conclusion

The proposed calculation-experimental technique increases accuracy of determination of the emissivity coefficient. This becomes possible due to heating of a sample from the heat-shielding materials directly in the vacuumized chamber and to increased informativeness of measurements caused by additional thermocouple.
Acknowledgments
This research was supported by “The Tomsk State University competitiveness improvement program”.

References
[1] Polezhaev Yu V and Yurevich F B 1976 Thermal protection (Moscow: Energy) p 390 [in Russian]
[2] Polezhaev Yu V and Shishkov A A 1992 Gasdynamic experiments of thermal protection. Reference book (Moscow: Promedec) p 248 [in Russian]
[3] Blokh A G, Zhuravlev Yu A and Rizhkov L N 1991 Radiation heat exchange: Reference book (Moscow: Energoatomizdat) p 432 [in Russian]
[4] Ed. by Shtyndlin A Ye 1974 Radiating properties of solid materials. Reference book (Moscow: Energy) p 472 [in Russian]
[5] Arkhipov V A, Gol’din V D, Zharova I K, Kurilenko N I and Mamontov G Ya 2012 Thermophysics and Aeromechanics 19(6) 750–760 [in Russian]
[6] Arkhipov V A, Gol’din V D, Zharova I K. and Kurilenko N I 2012 Instruments 2(140) 43–46 [in Russian]
[7] Arkhipov V A, Gol’din V D, Zharova I K and Kurilenko N I 2012 Method for measuring the emissivity coefficient of heat-shielding materials surface Patent RU 2468360, (Int.Cl.: G01N 25/18, G01K 7/02) [in Russian]
[8] Aliľanov O M 1988 Inverse heat transfer problems (Moscow:Masininstroenie) p 280 [in Russian]
[9] Lykov A V 1971 Heat and mass transfer: Reference book (Moscow: Energy) p 560 [in Russian]