## NOTATION

$A_S$ and $T_S$, integrated coefficients of absorption and transmission of solar radiation; n and $n_S$, refractive indices of the film and substrate; k and $k_S$, absorption coefficients of the film and substrate; A, integrated absorption coefficient; $\nu$, radiation frequency; $A_\nu$, $R_\nu$, $T_\nu$, spectral absorption, reflection, and transmission coefficients; $T_0$, temperature of an absolute blackbody; h, Planck's constant; $\sigma$, Stefan–Boltzmann constant; c, velocity of light in a vacuum; T, coefficient of transmission of light through a film into an infinitely thick substrate; r and t, Fresnel coefficients; d, thickness of the film; R and R', coefficients of reflection of light incident on the film from its free surface and from the substrate; $R_0$, reflection coefficient of the substrate; $a$, b, f, g, and m, extrapolation constants; $E_g$, gap width; and $\gamma$, absorption coefficient of the film.

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# EMISSIVITY OF ALUMINOSILICATE REFRACTORIES


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UDC 536.5



Experimental data was obtained on the dependence of the emissivity of refractories on temperature and chemical composition.


Industry currently produces and uses about 50 grades of aluminosilicate refractories. The content of the main components, alumina and silica, is usually regulated in these refractories. Since the refractories are made by different plants, the content of other oxides differs significantly and causes an appreciable change in the radiative properties of the products. Most experimental studies [1] have covered a limited range of refractory grades. No detailed analysis has therefore been made of the effect of chemical composition on the emissivity of refractories. There have also been no studies of the emissivity of refractories upon heating in air to temperatures above 1600°K.

The present article reports results of a study of the integral normal emissivity of different grades of aluminosilicate refractories (see Table 1) in relation to their chemical composition and temperature during heating in air in the temperature range 600-2100°K and during heating in vacuum, with a vacuum pressure to $10^{-3}$ mm Hg, in the temperature range 600-1800°K. The refractory specimens were bars measuring 35 × 35 × 3 mm or 40 × 40 × 5 mm, depending on the grade of refractory. The roughness parameters of the specimens were measured on an MIS-11 binary microscope.

The emissivity of the specimens in air was measured by the radiation method on the unit described in [2]. Here, the specimens were heated to 900°K by a tubular resistance furnace, while they were heated to temperatures in the range 900-2100°K by the flame from an oxygen–propane burner. The measurement of the radiant surface of the specimens was measured with Chromel–Alumel thermocouples with a thermoelectrode diameter of 0.2 mm. The measurements at the higher temperatures were obtained with PR-30/6 platinum-rhodium thermocouples. The thermocouples were placed in a groove so that they were located 0.4 and 0.8 mm from the surface and were covered with a layer of refractory paste. The layer of paste was applied so that it was flush with the radiant surface of the specimen. The temperature of the radiant surface was determined by extrapolating the thermocouple readings to the lowest level of the thermocouples in the specimen.

The main component of the unit used to measure the emissivity of the refractories in vacuum during heating (Fig. 1) was a vacuum chamber 1 which contained a molybdenum heating


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TABLE 1. Initial Characteristics of the Refractory Specimens

| Grade of refractory | Color | Roughness parameters | | Cemical composition, wt.% | Bulk density, g/cm³ |
|---|---|---|---|---|---|
| | | Ra, μm | Sm, μm | | |
| Fireclay ShA | white | 36 | 0,59 | $Al_2O_3 = 33$ | — |
| Dinas DK-1 (P) | yellowish-brown | 25 | 0,38 | $SiO_2 = 94$; $Fe_2O_3 = 1,7$ | 2,34 |
| Fireclay 40-30 | same | 22 | 0,76 | $Al_2O_3 = 35$ | 2,1 |
| Dinas DK-1 | » | 22 | 1,0 | $SiO_2 = 94$; $Fe_2O_3 = 1,7$ | — |
| Aluminosilicate | white | 22 | 1,08 | $Al_2O_3 = 28$ | — |
| Quartzite K98-100 | brown | 19 | 0,74 | $SiO_2 = 98$; $Al_2O_3 = 1,1$ $Fe_2O_3 = 0,6$ | — |
| Dinas DK | yellowish-brown | 18 | 0,56 | $SiO_2 = 94$; $Fe_2O_3 = 1,7$ | 2,34 |
| Fireclay | white | 13 | 0,56 | $Al_2O_3 = 28$ | — |
| Dinas DL-1,2 | pale brown | 12 | 0,27 | $SiO_2 = 91$ | 1,2 |
| Mullite MLS-62 | yellowish-brown | 12 | 0,28 | $Al_2O_3 = 62$; $Fe_2O_3 = 1,5$ | 2,23 |
| High-alumina MKS-74 | white | 11 | 0,32 | $Al_2O_3 = 72$; $Fe_2O_3 = 1,5$ | — |
| Dinas DS (P) | yellowish-brown | 10 | 0,24 | $SiO_2 = 93$; $CaO = 3$; $Fe_2O_3 = 1,7$ | — |
| Corundum KL-1,3 | white | 8 | 0,58 | $Al_2O_3 = 95$; $SiO_2 = 0,5$; $Fe_3O_4 = 0,4$ | — |
| Quartzite KVKB | pale brown | 7 | 0,20 | $SiO_2 = 97,5$; $Fe_2O_3 = 0,6$ | — |
| Dinas DS | yellowish-brown | 6 | 0,20 | $SiO_2 = 94$; $CaO = 3$; $Fe_2O_3 = 1,7$; | — |
| Mullite-silica | gray | 6 | 0,23 | $SiO_2 = 55$; $Al_2O_3 = 40$; $Fe_2O_3 = 1,9$; $MgO = 1$; $CaO = 0,4$ | — |
| Dolomite | light gray | 5 | 0,45 | $MgO = 25,3$; $CaO = 24,67$; $SO_3 = 12,55$; $Si_2O = 8,68$; $CO_2 = 8,30$; $Fe_2O_3 = 7,49$; $ZnO = 4,86$; $K_2O = 4,0$; $Al_2O_3 = 3,41$; $Na_2O = 0,74$ | — |

element 4. The vacuum in the chamber was created by mechanical vacuum and diffusion pumps. The refractory specimens were heated by the heat given off by the heating element during the passage of an electric current through it. The current was supplied by a TD-500 welding transformer. The temperature of the radiant surface of the refractories was measured with four VR-5/20 tungsten–rhenium thermocouples with a thermoelectrode diameter of 0.15 mm. The hot junctions of the thermocouples were positioned flush against the radiant surface. This arrangement, different from the case of the experiments in air, was dictated by the already-mentioned fact that specimen heating was done with an oxygen-propane burner in the latter case. The heating in vacuum was done by heat given off during the passage of an electric current through molybdenum foil. Under oxidative heating conditions, embedding the thermocouples to a certain depth in the refractory specimen protects them against oxidation at high temperatures. For vacuum heating conditions, conversely, embedding the thermocouples to a certain depth is related to the higher service temperatures of the thermocouple in this case — which shortens its life.

To simplify the picture, Fig. 1 shows two of the four thermocouples. Each of these thermocouples has a thermostatted cold junction. The values of thermo-emf from one thermocouple were recorded on a VK2-20 digital voltammeter, while the remaining three values were recorded on an N004M1 light-beam oscillograph with photographic paper 200 mm wide. The same oscillograph received a signal from a PPT-131 radiation detector. The temperature was determined from the arithmetic mean of the thermo-emf readings of three thermocouples.

The outlet windows of the vacuum chamber were made of KRS-5 glass, with a longwave transmission range up to 40 μm. The thin lens of the objective of the PPT-131 detector was made of fluorite. The provision of an additional axial optical window in the chamber allowed the PPT-131 detector to be calibrated with a tubular blackbody substituted for the molybdenum foil during calibration. The thin-walled graphite radiating cavity of the blackbody was secured

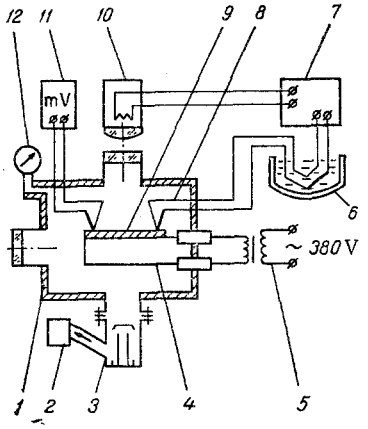


Fig. 1. Diagram of experimental unit for studying the emissivity of refractories during heating in vacuum: 1) vacuum chamber; 2) vacuum pump; 3) diffusion pump; 4) heating element; 5) transformer; 6) thermostat; 7) light-beam oscillograph; 8) thermocouple; 9) specimen; 10) radiation detector; 11) VK2-20 voltmeter; 12) vacuum gauge.

in the same manner as the foil — to copper electrodes by means of special contact clamps. As in the case of the molybdenum heater, the cavity of the blackbody was heated by passing an electric current from the transformer through the graphite tube.

Signals were recroded simultaneously on photographic paper when we measured heat flow from the PPT-131 detector and thermo-emf from the thermocouples. The integral emissivity of the specimens was determined as the ratio of the specimen heat flux density to the heat flux density of the blackbody at the same temperatures.

The error of the emissivity determination consisted of random and unexcluded systematic errors associated with the measuring equipment and procedure. The ranges of the components of the systematic errors were the permissible errors of the main and auxiliary measuring equipment.

According to GOST 8.011-72, the unexcluded systematic error of integral emissivity is determined from the formula

$$\Theta = 1{,}1\,(\Theta^2_{E/E_0} + \Theta^2_T + \Theta^2_R + \Theta^2_\lambda)^{1/2}, \tag{1}$$

where $\Theta_T$ = ±1.1% at a specimen temperature of 1700°K; $\Theta_R$ = ±0.4%; $\Theta_\lambda$ = ±0.4%.

The systematic error of the ratio of the integral heat flux densities is

$$\Theta_{E/E_0} = 1{,}1\,(\Theta^2_E + \Theta^2_{E_0})^{1/2}. \tag{2}$$

The error of the integral heat flux was calculated from the equation

$$\Theta_E = \Theta_{E_0} = 1{,}1\,[(4\Theta_T)^2 + \Theta^2_0 + \Theta^2_P]^{1/2}, \tag{3}$$

where $\Theta_0$ = ±0.2%; $\Theta_P$ = ±0.01%.

In measuring the temperature of the radiating cavity of the blackbody, $\Theta_T$ = ±1%.

We took the arithmetic mean of the observations as the measurement result when we analyzed the experimental data. The standard deviation was evaluated from the formula

$$\Delta Sa = \Big[\sum_{i=1}^{n} (x_i - \bar{a})^2/n\,(n-1)\Big]^{1/2}. \tag{4}$$

In thermophysical experiments, $\alpha$ = 0.95 was taken as the value of the reliability coefficient. This value corresponds to a Student's coefficient $t_{\alpha(n)}$ = 2.45.

The final formula for calculating the random error has the form

$$\Delta a = t_{\alpha(n)} \Delta Sa. \tag{5}$$

The result with the random error range is

$$a = \bar{a} \pm \Delta a. \tag{6}$$

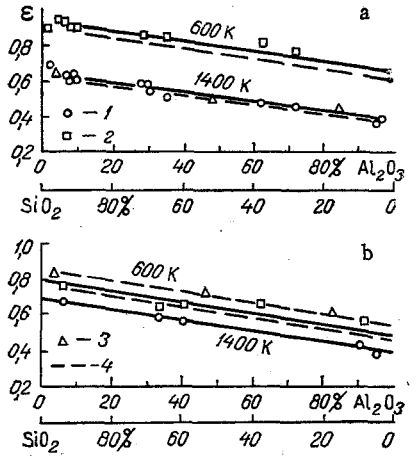


Fig. 2. Effect of the content of $Al_2O_3$ and $SiO_2$ on the emissivity of aluminosilicate refractories during heating in air (a) and in vacuum (b): 1, 2) our data; 3) data from [1]; 4) calculation from Eqs. (9) and (10).

The relative random error was calculated as

$$\xi = (\Delta a/a)\,100\ \%. \tag{7}$$

The random error calculated using Eqs. (4)-(7) was 1.32%.

The total error of measurement of integral emissivity was the sum of the random and unexcluded systematic errors:

$$\delta_{\Theta,\xi} = 1{,}1\,(\Theta^2 + \xi^2)^{1/2}. \tag{8}$$

Its numerical value was ±8.6%.

Tables 2 and 3 show experimental data on the integral emissivity of the specimens in relation to temperature for heating in air and vacuum, respectively. All of the results are for stabilized values of emissivity in repeated heatings of the same given specimens.

It can be seen from Tables 2 and 3 that the emissivity of the refractories decreases most sharply with an increase in temperature in the range 600-1400°K during heating in air. Temperature has less of an effect on emissivity during heating in vacuum. The oxides which are included in the composition of the refractories are semiconductors with ionic-covalent bonding. The lesser effect of a temperature increase on emissivity during heating in vacuum is attributable to dissociation of the oxides due to an insufficient supply of oxygen. Heating in vacuum is always accompanied by darkening of the light specimens. An increase in the concentration of defects during evacuation due to the absence of certain oxygen atoms in the lattice of the oxide crystals increases the capacity for internal ionization and thereby changes the conditions of quantization of valence electrons. No drastic changes in the emissivity of the refractories occur in either case of heating at temperatures above 1400°K. This can be explained by an examination of spectral emissivity. At 600°K, most of the spectral radiation density is associated with the longwave region above 4 μm. In this region, the spectral emissivity of the refractories is much greater than in the shortwave region. An increase in temperature is accompanied by a shift in the radiation maximum to the shortwave region and, due to the low spectral emissivity in this region, the integral emissivity of the refractories is sharply reduced.

At temperatures above 1400°K, most of the radiant energy of the refractories is found in the shortwave region up to 4 μm. Here, the values of spectral emissivity stabilize.

Figure 2 shows the effect of the contents of the main components on the emissivity of aluminosilicate refractories. It is evident from the figure that the integral emissivity of the refractories decreases with an increase in alumina content for all temperatures. Conversely, an increase in silica content is accompanied by an increase in emissivity. Silica is among a group of oxides with defects of the anti-Frenkel type, characterized by oxygen atom vacancies in the crystalline lattice and the simultaneous presence of interstitial oxygen atoms

TABLE 2. Integral Normal Emissivity of Refractories in Relation to the Temperature during Heating in Air

| Grade of refractory | Temp. T, °K | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 2000 | 2100 |
| Dinas DK-1 | 0,95 | 0,82 | 0,73 | 0,63 | 0,58 | 0,55 | 0,54 | 0,53 | — |
| Dinas DS (P) | 0,94 | 0,82 | 0,71 | 0,66 | 0,64 | 0,62 | 0,60 | 0,59 | — |
| Dinas DS | 0,93 | 0,80 | 0,70 | 0,65 | 0,63 | 0,61 | 0,60 | 0,59 | — |
| Dinas DL-1,2 | 0,93 | 0,79 | 0,70 | 0,62 | 0,61 | 0,59 | 0,58 | 0,57 | — |
| Dinas DK (P) | 0,92 | 0,78 | 0,67 | 0,61 | 0,58 | 0,56 | 0,55 | 0,54 | — |
| Fireclay ShB | 0,91 | 0,75 | 0,66 | 0,61 | 0,59 | 0,58 | 0,57 | 0,56 | 0,55 |
| Aluminosilicate | 0,89 | 0,78 | 0,66 | 0,61 | 0,57 | 0,55 | 0,54 | 0,53 | 0,52 |
| Quartzite K98-100 | 0,88 | 0,83 | 0,79 | 0,76 | 0,70 | 0,66 | 0,62 | — | — |
| Quartzite KVKB | 0,87 | 0,75 | 0,65 | 0,61 | 0,56 | 0,53 | 0,51 | 0,50 | — |
| Fireclay 40-30 | 0,85 | 0,74 | 0,63 | 0,57 | 0,50 | 0,47 | 0,44 | 0,41 | — |
| Mullite MLS-62 | 0,83 | 0,72 | 0,62 | 0,54 | 0,49 | 0,45 | 0,43 | 0,42 | 0,41 |
| High-alumina MKS-72 | 0,77 | 0,65 | 0,54 | 0,49 | 0,46 | 0,43 | 0,42 | 0,41 | — |
| Corundum ML-1,3 | 0,55 | 0,46 | 0,40 | 0,38 | 0,36 | 0,35 | 0,34 | 0,33 | — |

TABLE 3. Integral Normal Emissivity of Refractories in Relation to the Temperature during Heating in Vacuum

| Grade of refractory | Temp. T, °K | | | | | | |
|---|---|---|---|---|---|---|---|
| | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 |
| Dinas DK-1 | 0,77 | 0,74 | 0,71 | 0,69 | 0,68 | 0,67 | — |
| Mullite MLS-62 | 0,68 | 0,65 | 0,64 | 0,63 | 0,62 | 0,61 | — |
| Fireclay ShA | 0,65 | 0,63 | 0,62 | 0,61 | 0,60 | 0,59 | — |
| Mullite-silica | 0,65 | 0,62 | 0,60 | 0,57 | 0,55 | 0,54 | — |
| Dolomite | 0,58 | 0,75 | 0,56 | 0,55 | 0,54 | 0,53 | — |
| Corundum KL-1,3 | 0,40 | 0,39 | 0,38 | 0,38 | 0,37 | 0,35 | 0,35 |

Alumina is among the group of oxides with only oxygen vacancies. Thus, silica has a greater capacity for internal ionization and, thus, has a higher emissivity.

The combined effect of temperature and chemical composition on the emissivity of the refractories during heating in air is described by the linear relation

$$\varepsilon = 1 - 0{,}0002T - 0{,}25M_{Al_2O_3}. \quad (9)$$

For the conditions of heating in vacuum, this relation has the form

$$\varepsilon = 1 - 0{,}008\sqrt{T} - 0{,}25\,M_{Al_2O_3}. \quad (10)$$

It can be seen from Fig. 2 that the greatest differences between the experimental and theoretical data is seen for heating in vacuum. The estimate of emissivity for temperatures in the middle of the range 600-1400°K agrees satisfactorily with the experimental data.

## NOTATION

Ra, arithmetic mean value of deviation of surface irregularities; Sm, mean spacing of surface irregularities; T, temperature; $\Theta_T$, $\Theta_R$, error of measurement of temperature and roughness parameters; $\Theta_\lambda$, error caused by selectivity of refractory-specimen radiation and by absorption of optical windows and lens of radiation-detector objective; $\Theta_E$, $\Theta_{E_0}$, error of measurement of radiation fluxes from refractory specimen and absolute blackbody; $\Theta_o$, $\Theta_P$, errors of graphical analysis of test results and record of measured quantity; $x_i$, result of observations; n, number of observations; $\varepsilon$, integral emissivity; $M_{Al_2O_3}$, mass fraction of alumina; $\bar{\alpha}$, arithmetic mean observation.

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