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MEASUREMENT OF THERMAL RADIATION AND OPTICAL PROPERTIES OF REFRACTORY OXIDES AND THEIR MELTS UNDER CO_2 LASER RADIATION HEATING

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ABSTRACT

The use of CO_2 laser radiation for heating of refractory oxides in the air virtually eliminated all the restrictions limiting the temperature of studying their thermal radiation characteristics. But the conditions of intensive surface heating necessitate the consideration of a number of new factors when determining the emissivity and reflectivity. Owing to the partial transparency of the oxides, these radiation properties measured during heating are not determined unambiguously by the surface temperature, but depend on the flux of the heating laser radiation. Under these conditions, the emissivity is not a thermophysical property in its generally adopted sense, and it cannot be related to a definite temperature. The temperature indicated by a pyrometer does not characterize the surface temperature, but has only the meaning of an "effective" parameter. Only in quasi-steady states corresponding to definite values of the heating radiation flux will the dependence of the thermal radiation characteristics on the effective temperature be unambiguous. The maximum temperature of investigations with laser heating is limited by condensation of products of oxide evaporation in the air surrounding a sample. Special experiments involving the attenuation of the probe radiation on the condensate droplets in air adjoining the sample have shown the dimensions and concentration of the droplets to depend both on the sample and on the intensity of the laser radiation.

The features of the change in the radiation characteristics in solidification after the heating radiation has been switched off are considered.

The possibility of determining the wavelength and temperature dependencies of the absorption coefficient of oxide melts from the results of measuring the spectral distribution of the intensity of radiation of an optically infinite layer is analyzed.

INTRODUCTION

Polycrystalline refractory oxides and materials based on them are employed in various fields of high-temperature equipment as thermal insulating and heat protective materials. Such materials quite often serve in an oxidizing medium under conditions of an intensive heat load when the temperature reaches 3500-4000 K and there is an ablative layer of a melt on their surface. Information on the thermal radiation characteristics of ceramics oxides is required for calculations of radiation and combined radiation and conduction heat transfer in the thermal insulation of various high-temperature apparatus. Information on the optical properties of melts is required for calculating the temperature fields in the technological processes of growing single crystals and in installations for melting oxides or cutting them by concentrated radiation. At room temperature, refractory oxides are good insulators and in their optical properties relate to the class of semitransparent substances. There is a region of high transparency between the long-wave edge of the electron absorption band whose peak is in the ultraviolet region of the spectrum and the short-wave edge of the first fundamental absorption band in the infrared region due to vibrations of the atoms in the lattice. In this region, the single crystals of the oxides have a very low absorption coefficient k that does not exceed 10^{-3} - 10^{-4} cm^{-1}. With elevation of the temperature, the absorption coefficient increases practically over the entire region of the spectrum as a result of broadening of both bands. As an example, figure 1 summarizes the absorption coefficient for the best studied of the refractory oxides - aluminium oxides - at three temperatures: 300, 2200, and 2900 K. The first two curves relate to the solid phase, and the third to the liquid phase (the melting point is about 2320 K). The values of k recommended by Lingart *et al.* (1982) have been taken as the base ones for the solid phase. The results of Musatov *et al.* (1977) have been used for the shortest wavelength region at 300 K, and those of Bakhir *et al.* (1977) at 2200 K. The curve showing the absorption coefficient of the melt has been plotted according to the results of Bakhir *et al.* (1977) for the infrared region, and of Mularz and Yuen (1972) for the ultraviolet and visible region. The portions of the curves for a region for which there are no experimental data, or they are uncertain are shown by dashed lines.

Examination of Fig. 1 reveals that in the region of high transparency, the absorption coefficient changes by several orders of magnitude with the temperature. The absorption coefficient of an aluminium oxide melt is known much more poorly than that of a crystal. The discrepancies of the results obtained for a melt in the few available publications are three and more orders of magnitude (Lingart *et al.*, 1982). The absorption coefficient of melts have generally been calculated from the results of measuring the thermal radiation characteristics of flames and a plasma into which aluminium oxide particles have been introduced.

The absorption coefficient of other refractory oxides (of magnesia, titania, zirconia, hafnia) in the solid phase have been studied to a much smaller degree. The measurement temperature does not generally exceed 2100 K (Cabannes and Billard, 1987). The absence of information on $k = f(\lambda,T)$ at higher temperatures is due to a considerable extent to the difficulties of producing such

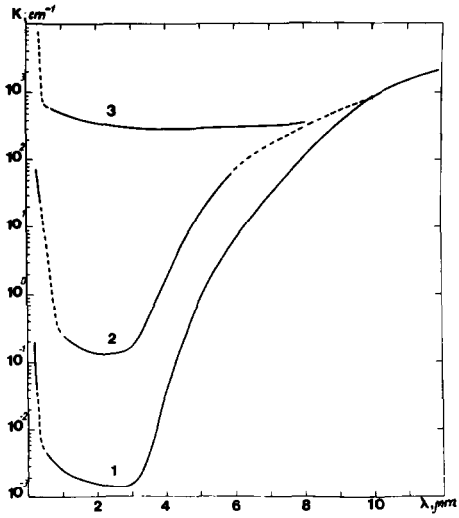

Fig. 1. Absorption coefficient of aluminium oxide at various temperatures: 1-300 K; 2-2200 K; 3-2900 K.

temperatures in an oxidizing atmosphere. No data are available on the optical properties of melts of these more refractive oxides. It should be noted that the overwhelming majority of the materials employed in high-temperature engineering that are made from refractory oxides are polycrystalline ceramic materials with a certain porosity. They relate to the class of semitransparent volume scattering materials. Their optical properties, when a transport equation is used to describe the propagation of the radiation, are characterized not only by absorption coefficient k and refractive index n, but also by the coefficient β and phase function γ of volume scattering. The magnitude of the latter depends on the direction of the incident and scattered radiation. The temperature fields and energy fluxes in such materials can be calculated strictly by simultaneously using the radiation transfer equation and energy conservation equation if one knows all four optical characteristics indicated above as functions of the temperature and wavelength.

At present, however, such information is not available for any materials. The calculations themselves can be performed only for one-dimensional cases, and even here many simplifying assumption must be introduced (Galaktionov *et al.*, 1988 a). The rule in practice is either to use approximate methods of solving the transfer equation (the two-flux approximation, diffusion approximation) that require fewer characteristics describing the optical properties (generally three), or to use averaged radiation characteristics - the reflectivity and emissivity. But both can be obtained only experimentally, and this signifies that studies must be conducted up to temperatures of 3500-4000 K in an oxidizing atmosphere. Up to recently, such temperatures were obtained only in solar or arc image furnaces. With such heating, however, studying of the radiation characteristics is hindered by the high reflection of the oxides in the region of the spectrum of solar and arc radiation. This makes it difficult to register the flux of the intrinsic radiation of the material being studied and lowers

the upper temperatures. In this connection, the use of the radiation of CO_2 lasers with a wavelength of about 10.6 μm for heating is very promising. This radiation is in the region of opacity (the region of high absorption with $k \propto 10^3$ cm^{-1}) of virtually all refractory oxides. At present, there is no problem in obtaining a power of several kilowatts for such lasers under laboratory conditions, and this power can be utilized very efficiently because of the low magnitude of reflection at 10.6 μm (several per cent).

Notwithstanding the great possibilities and obvious advantages of using CO_2 laser radiation for heating oxides, we cannot meanwhile consider that procedure of studying the optical properties and radiation characteristics under the conditions of such heating as completely developed. The first experiments involving the use of laser heating for studying the radiation characteristics of oxides were apparently conducted in 1977 (Bober and Karow, 1977). This work was further developed by Bober *et al.* (1980). But the results of these works were obtained without considering the influence of the features of temperature field formation in refractory oxides under the condition of intensive laser heating, and therefore contain a number of errors to which attention has been drawn (Petrov and Chernyshev, 1987).

TEMPERATURE FIELDS IN OXIDE CERAMICS UNDER LASER RADIATION HEATING

Consider the temperature distribution in a ceramic oxide material under conditions of surface heating by laser radiation. At the Laboratory of the Optical Properties of Substances of the Institute for High Temperature to date there has been developed a quite complete, but very complicated mathematical model describing the heating of such a material by powerful laser radiation. It takes account of the transfer in the material of both its intrinsic thermal and laser radiation, melting, shrinkage and closing up of the pores, ablation, the dependence of the thermophysical and optical properties of the solid phase and melt on the temperature, and of the optical properties dependence also on the wavelength (Galaktionov *et al.*,1988 b; Galaktionov and Stepanov, 1990).

Disregarding the details of this model, let us consider as an example the results of calculating the temperature distributions when heating an aluminium oxide ceramics in vacuum by CO_2 laser radiation. Figure 2 presents curves showing the temperature distribution in ceramics with a density of 1.1 g/cm^3 (a porosity of 73%) at different instants when heating with two different flux: q_1=2 kW/cm^2 and q_2=6 kW/cm^2. It was assumed that the initial thickness of the ceramics layer is 1 cm and that its right-hand boundary on which no laser radiation impinges is adiabatically insulated. It can be seen that the temperature of the surface that is irradiated grows very rapidly. The melting point (2320 K) is reached in the first and second cases during $2.3 \cdot 10^{-2}$ and $4.8 \cdot 10^{-3}$ s, respectively. There is a very steep temperature profile in the near-surface layer. The temperature gradients before melting here are 8360 and 13000 K/mm.

Though the density of molten aluminium oxide is about 30%

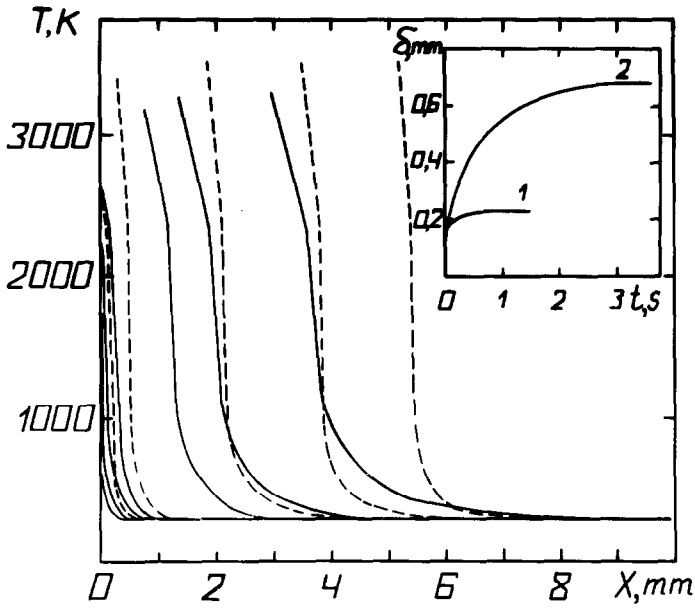

Fig. 2. Temperature distribution in layer of alumina ceramics when heating with various q at different instants t:
Solid lines: q = 2 kW/cm^2, t = 3.2·10^{-3}; 9.2·10^{-3}; 0.023; 0.051; 0.4; 0.8, and 2.0 s;
Dashed lines: q = 6 kW/cm^2, t = 9.2·10^{-3}; 0.05; 0.4;0.8, and 1.2 s;
The insert shows the time dependence of the melt thickness δ: 1 - q = 6 kW/cm^2; 2 - q=2 kW/cm^2.

lower than the density of a single crystal, in melting the surface moves to the left because of closing up of the pores. The surface begins to move rapidly when temperatures are reached at which the rate of evaporation becomes noticeable. Finally, in some time after the beginning of heating, the speed of the front boundary becomes virtually constant, and the temperature field becomes close to a quasi steady one.

It can be seen from Fig.2 that at different values of q, both before melting and after it, the temperature gradients in the near-surface layer appreciably differ. The melt thickness also differs. In the quasi-steady state it is 0.67 and 0.23 mm, respectively. The temperature curves show that at the same surface temperature we obtain a different temperature distribution in the surface layer, and this should result in differences in the energy irradiated by the material. There must also obviously be the relevant differences in the reflectivity because the temperature may greatly affect the optical properties, chiefly the absorption coefficient.

To establish what thickness of the near-surface layer determines the radiation characteristics, we must know the optical properties of the material. For the alumina ceramics being considered, the absorption coefficient in the region of high transparency (e.g., at 1.15 μm) in the solid phase near the melting point is k = 0.16 cm^{-1}, while the scattering coefficient is β = 250 cm^{-1}; in the melt, on the other hand, the absorption coefficient is about 300 cm^{-1}. The results obtained by Crosbie

(1980) allow us to consider that the thickness of the layer determining the radiation characteristics will be 0.17 mm for the indicated values of the optical properties in a melt, and over 1.2 mm in the solid phase. The last value has been obtained by extrapolating the dependence of the emissivity on the optical thickness for a scattering albedo of $\omega = 0.99$ given by Crosbie (1980). We obtained $\omega = 0.99936$ provided that the entire layer has a temperature of 2300 K. With a view to the lowering of the temperature with depth, ω will be still greater.

If we adopt the appraisals of the thickness of the emitting (and reflecting) layer and compare them with the results of calculating the temperature distribution in the course of heating (Fig. 2), we shall see that up to melting at a surface temperature of 2300 K the radiation characteristics are determined by the layer whose thickness is greater than that of heated layer at both values of q.

The temperature difference is about 240 and 860 K in a melt with heating from q_1=2 kW/cm^2 and q_2=6 kW/cm^2, respectively, at a thickness of 0.17 mm. This is substantially lower than the temperature difference at the thickness of the emitting layer in the solid phase with a surface temperature close to the melting point.

REFLECTIVITY AND EMISSIVITY OF CERAMICS UNDER SURFACE HEATING BY LASER RADIATION

Petrov and Chernyshev (1987) were the first to show, and the above appraisals confirm this, that the radiation characteristics (reflectivity and emissivity) in the surface heating of oxide ceramics by laser radiation are not physical constants that can be related to the surface temperature, but depend on the flux of the heating radiation. We can speak of the magnitude of the reflectivity R without distorting the generally adopted meaning of this term, but we do not know the temperature to which this quantity should be related. We cannot speak of the emissivity ε in its conventional meaning because of radiation from nonisothermal layers.

The same relates to the values of the temperature T measured by optical pyrometers. The measured value of the temperature, which we shall call the effective one, corresponds to the temperature of a blackbody whose radiation at the wavelength of the pyrometer has the same intensity as the radiation reaching the pyrometer from a layer with an optically infinite thickness adjoining the surface of the sample being studied. All this introduces major complications into the use of laser heating for determining the radiation characteristics of refractory oxide.

Let us consider the influence of the flux q in greater detail. Figure 3 gives as an example the results of our experiments involving the measurement of the normal-hemispherical reflectivity R when heating samples of polycrystalline magnesium oxide of technical purity with an admixture of 1% of calcium oxide in air by CO_2 laser radiation. The reflectance was measured at a wavelength of 1.15 μm corresponding to the region of high transparency, while the reduced values of the effective temperature T_{1ef} correspond to the radiation at a wavelength of

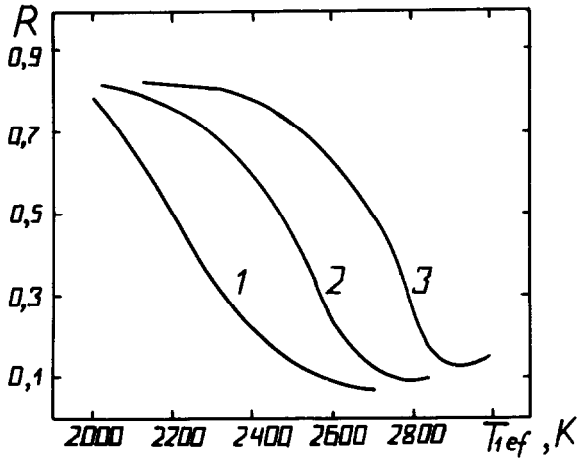

Fig. 3. Dependence of reflectivity of MgO for λ =1,15 μm on T_{1ef} at various q's: 1 - q = 870 W/cm^2; 2 - q=1100 W/cm^2; 3 - q = 1370 W/cm^2.

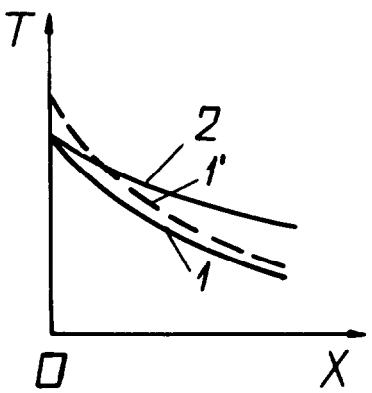

Fig. 4. To the influence of the flux on the reflectivity: 1, 1' - q_1; 2 - $q_2<q_1$.

0.55 μm registered by a pyrometer. For heating up to T_{1ef}=2000 K, the values of reflectivity for all heating fluxes q are 2-4% lower than its value at room temperature. The reflectance begins to diminish quite markedly from a definite value of the temperature

T_{1ef}, and to a greater extent when the value of the flux is greater. It is exactly this nature of the behavior of R that is affected by the specific features of semitransparent scattering materials. If we do not consider the results of the cumbersome numerical calculations of radiation and conduction heat transfer, these specific features can be explained by Fig.4.

At the instants when in heating with various heating fluxes, the temperatures of the surface ($x = 0$) are equal (curves 1 and 2), owing to the steeper profile of $T = f(x)$ at large q's the temperature at each point x_1 of an optically infinite layer, except for the surface $x = 0$ itself, is lower. Appraisals show that, for instance, to achieve a melting point of 3100 K on the surface at q_1 = 1370 W/cm^2, 1.04 s are needed, and at q_2=945 W/cm^2 this time is 3.3 s. The temperature differences at distance of 0.3 mm from the surface are 420 and 320 K, respectively. Since $T = f(x)$ for q_1 is lower at any values of x, the absorption coefficient is also lower at each corresponding point. The scattering coefficient mainly determined by the porosity and refractive index depends only slightly on the temperature. This is why at the same surface temperature with larger values of q a material at any wavelength, including that of a pyrometer (0.55 μm), emits less, while its reflectivity is larger. For the intensity of radiation at 0.55 μm at q_1 to become equal to that at q_2, heating must be continued, and this can be done at the temperature distribution 1′ (Fig. 4). It must be remembered, however, that elevation of the temperature is attended not only by an exponential increase of Planck's radiation intensity $I_p=f(T)$, but also by an increase in the absorption coefficient k by a certain power law. Since the spectral volumetric emission coefficient of radiation is $j = k(T)n^2I_p(T)$, to ensure the equality of T_{1ef} a smaller increment of the surface temperature is needed in heating with higher values of q than to ensure the equality of R because the temperature field affects the decrease in R only as an increase of the absorption coefficient k. This is why with equality of T_{1ef} during heating with various values of q, the reflectivity will be higher with larger heating fluxes (Fig. 3).

Consequently, neither the reflectivity nor the emissivity of ceramics in heating by laser radiation are related unambiguously to the temperature being measured, but depend on the flux q. The measured value of the temperature at the same surface temperature, in turn, also depends on q. If, on the other hand, we wait for a stable quasi-steady temperature distribution, the dependence of the radiation characteristics on an effective temperature, e.g. on T_{1ef} will be a stable value for each q that will grow with increasing q. It is exactly these values as a function of q that can be employed for calculating heat transfer in apparatus using oxide thermal insulation if, naturally, steady conditions also set in there with surface, e.g., convective heating.

DETERMINING THE WAVELENGTH AND TEMPERATURE DEPENDENCE OF THE ABSORPTION COEFFICIENT OF A MELT

After the melting point is reached on a surface during

heating by laser radiation, melting and a growth in the melt thickness begin. When a quasi-steady state is reached, a constant thickness of the melt sets in. In many cases, it is sufficient for the melt to be considered as an optically infinite one. This can be taken advantage of to determine its absorption coefficient. The expression for intensity of monochromatic radiation from a nonisothermal optically infinite layer in the direction of a normal to the surface has the form:

$$I = (1-\rho)\int_0^L I_p(T(x))k(T(x))\exp\left\{-\int_0^x k(T(\xi))d\xi\right\}dx$$

In this expression, L is the thickness of the melt layer, ρ is the reflectivity of the surface, x is the space coordinate of the melt layer, I is the intensity of the monochromatic radiation emerging from the melt layer, and I_p is the local intensity of the equilibrium Planck radiation.

The use of the results of measuring the intensity for a single wavelength to find the temperature dependence of the absorption coefficient will yield nothing because both $k(T)$ and $T(x)$ are unknown. This inverse coefficient problem of radiation transfer is similar to the problem of multiwave pyrometry when neither the temperature nor the emissivity are known. We must choose the forms of $T = f(x)$ and $k = f(\lambda,T)$ and select coefficients of these relations which ensure the best (in the meaning of the method of least squares) agreement of the measured discrete values of $I(\lambda_i)$ with those calculated for the same wavelengths. Naturally, for better stipulation of the problem, one can employ additional conditions, for example the value of the thickness $x = \delta$ where the temperature equals the melting point (δ is determined by measuring the thickness of the solidified layer of the melt after an experiment), or known data on the relation $k(\lambda,T)$, but obtained for lower temperatures, or both simultaneously. The experiment, however, consists in registering the spectrum of radiation of an optically infinite layer of the melt. Such an experiment can be run with different values of the flux q of heating CO_2 laser radiation. Here, as indicated above, at the same surface temperature, the temperature distribution in the melt will vary. It is only necessary to ensure an optically infinite thickness of the melt. A criterion of its existence is the equality of the reflectivity to that of an optically infinite layer (with normal incidence of the radiation, $\rho = (n-1)^2/(n+1)^2$). In the short-wave region of the spectrum, this condition must be realized for the longest wavelength of the range being considered, while in the long-wave infrared, for the shortest. Since the absorption coefficients of melts of refractory oxides are very high, an optically infinite layer is realized in many cases at a geometric thickness not exceeding a few tenths of a millimeter.

Useful additional information can be obtained by measuring the wavelength dependence of the reflectivity of a melt in the process of its cooling after the heating laser radiation has been switched off.

Figure 5 shows a typical section of the time dependence of the temperature for an oxide sample cooling process. Super cooling

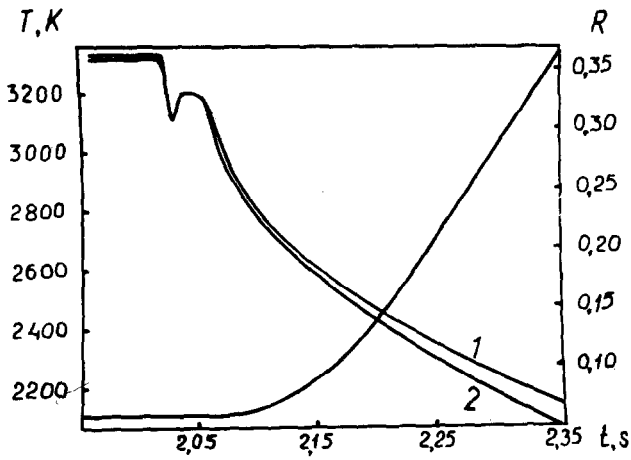

Fig. 5. Cooling section in experiment for studying the temperature dependence of the reflectivity of magnesium oxide at wavelength of 0.63 μm: 1 - T_{1ef}; 2 - T_{2ef}; 3 - R.

is followed by a plateau of crystallization whose duration depends on the thickness of the melt layer. Calculations show the temperature distribution over the entire melt layer and two-phase zones during crystallization to be close to isothermal. This is confirmed by the equality of the two effective temperatures T_{1ef} and T_{2ef} for the different wavelength $\lambda = 0.55$ μm and $\lambda = 0.72$ μm measured by pyrometer. The difference in the magnitudes of the refractive index for melts and nucleating crystals is usually not great and scattering in the two-phase region may be disregarded. This enables us to determine the value of the absorption coefficient $k = f(\lambda_1, T_m)$ at the solidification (melting) point T_m from the measured reflection spectrum according to the vanishing of the optically infinite layer for a wavelength λ.

INFLUENCE OF VAPOR CONDENSATION NEAR A SAMPLE ON THE RESULTS OF STUDYING THE THERMAL RADIATION CHARACTERISTICS

Studying of the thermal radiation characteristics of refractory oxides at the extreme temperatures is hindered by evaporation of the oxides. When the latter are heated by CO_2 laser radiation in the air, the evaporation products condensate near the surface being heated. Condensation causes nuclei to appear that grow, and the droplets are then carried off by convective flows. The concentration of the droplets and their size change within the confines of the plume of evaporation products emerging from the oxide surface being heated.

A number of the theoretical investigations (Biberman *et al.*,

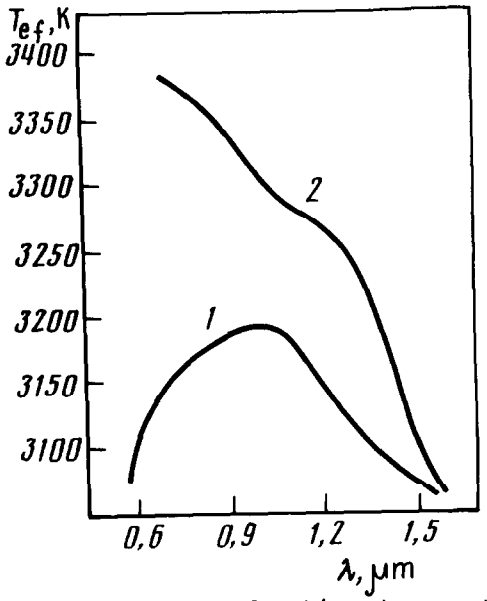

Fig. 6. Dependence of the effective temperature T_{1ef} of magnesia ceramic on the wavelength when heating in air with a flux density of 2000 W/cm^2 :1 - without blowing air over sample; 2 - with blowing.

1985; Biberman and Erukhimovich, 1987; Erukhimovich, 1989) present a model of the condensation and growth of the droplets in the field of intensive electromagnetic radiation. This model shows that the condensate droplets can have a limited values of radii, while under some conditions, notwithstanding the presence of supersaturation, condensation may not occur at all. But the proposed model cannot be employed for specific numerical calculations for refractory oxides because, first, information on the thermophysical properties of the oxides at the 3000-4000 K required for these calculations is not available, and, second, it is difficult to appraise the degree of supersaturation at different distances from the surface being heated. Petrov and Chernyshev (1987) were the first to note the possible influence of the formation of an appreciable amount of condensate particles near the surface of oxide ceramics when heated by a flux of high-density laser radiation on the results of measuring the radiation characteristics at the extreme temperatures. This phenomenon has been studied in greater detail by Vorobyev *et al.* (1991).

Figure 6 shows the results of two experiments involving the measurement of the intensity of radiation of a vertically positioned magnesium oxide ceramic sample when its central part was heated by the flux q. The radiation spectra were registered in a quasi-steady temperature state and were recalculated to the effective temperature of a blackbody with the same radiation intensity. The only difference was that in the second experiment, a stream of the ambient air was blown over the heated section of the sample. It can be seen that in the last case higher values of the measured effective temperatures and a qualitatively different nature of their spectral dependence were obtained. In the first experiment in the visible region, T_{ef} also decreased with

decreasing λ because of scattering, which grew with the decreasing λ. This does not correlate with the nature of the change in the absorption coefficient of magnesium oxide because near the electron edge of absorption it should grow with decreasing λ. Blowing away of the condensate particles by a stream of air yielded a more plausible relation $T_{ef} = f(\lambda)$.

A mathematical description of the process of formation, growth, and migration of the condensate droplets is associated with appreciable difficulties because of it being impossible to consider all the processes including: inflow of the mass of oxide vapor from the evaporating surface; carrying off the vapor and condensate particles by the stream of free convection of the air; cooling of the vapor by heat conduction in the air; interdiffusion of the air and vapor; nucleus formation from the undercooled vapor; growth of the nuclei and droplets by coalescence and coagulation; heating of the particles by CO_2 laser radiation and by radiation of the sample surface itself; and cooling of the particles by radiation and heat conduction into the surrounding gas.

The space in which condensation occurs and in which the formed droplets migrate depends on the formation of convective streams near the sample. The amount of formed vapor depends on the temperature of the surface and the time. The size of the particles also depends on the flux of the CO_2 laser radiation because the droplets are heated by the radiation, and the latter limits their growth. For example, when heating a vertical flat magnesium oxide sample using a flux of about 2000 W/cm^2 and with an irradiation spot 3 mm in diameter, the size of the condensate particles with a change in the distance to the surface from 0.5 to 2.5 mm changed from hundredths of a micrometer to about 0.25 μm. There were no particles at a distance over 3.5 mm. It is exactly such a particle size that underlied the dependence of the effective temperature on the wavelength shown in Fig. 6 because it resulted in a sharp reduction in scattering, increasing in the visible region of the spectrum while shrinking almost to zero at the beginning of the infrared region at λ =1.5 μm.

When silicon dioxide ceramic samples were heated under similar conditions in the quasi-steady state near the heated spot in the beam of the CO_2 laser, no particles formed at all. But at a lower flux, approximately 500 W/cm^2, quite intensive scattering on the condensate droplets was observed. In the first case, the mass of the carried off SiO_2 was greater, but no scattering was observed in the near-surface layer because of the restricted growth of the particles as a result of their being heated by the CO_2 laser radiation.

The difference between the behavior of SiO_2 and MgO is apparently due to the difference in the magnitude of the absorption index $\kappa = k\lambda/4\pi$ at the wavelength of 10.6 μm, which according to Plass (1964) is 0.025 for MgO, and to Petrov *et al.* (1982) is 0.33 for SiO_2. Blowing away of the condensate particles enables one to obtain more correct information on the radiation characteristics and optical properties of the melt, but it is not always possible. Running of experiments in good vacuum would eliminate the errors associated with the influence of the condensate, but the heating of oxides in vacuum often leads to a change in their optical properties because of incongruent

evaporation.

What has been said above indicates that the formation of condensate particles near a material being studied may very greatly distort the results of measuring the thermal radiation characteristics at the temperatures where intensive evaporation occurs, and this must be given serious attention.

CONCLUSION

The use of CO_2 laser for heating oxides in the air has removed virtually all restrictions on the maximum temperatures that can be reached to study thermal radiation characteristics. Since the specific nature of intensive surface heating may affect the accuracy of the results obtained very greatly, an individual approach must be used for every substance being studied, and the heating and measurement conditions must be selected correctly. Notwithstanding the difficulties noted herein, the use of laser heating substantially improves the accuracy of measuring the optical properties of oxide melts in comparison with the customary methods of studying them by measuring the thermal radiation characteristics of flames and plasma containing molten oxide particles.

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REFERENCES

Bakhir, L.P., Levashenko, G.I., and Tamanovich, V.V., 1977. Opredeleniye mnimoi chasti kompleksnogo pokazatelya prelomleniya djidkoi okisi alyuminiya. *Zh. Prikl. Spektroskopii,* 26:514-520 (in Russian).

Biberman, L.M., and Erukhimovich, I.L., 1987. K teorii kondensatsii peresytshennogo para. *Teplofizika Vysokikh Temperatur*, 25:292-295 (in Russian).

Biberman, L.M., Brykin, M.V., and Khrapak, A.G., 1985. Gomogennaya kondensatsiya v pole elektromagnnitnogo izlucheniya. *Teplofizika Vysokikh Temperatur*, 23:446-455 (in Russian).

Bober, M., Karow, H.U., 1977. Measurement of spectral emissivity of UO_2 above the melting point. In: A. Cezairliyan (Editor), *Proc. 7th Symp. on Thermophysical Properties*, ASME, New York, pp. 344-350.

Bober, M., Karow, H.U., and Muller, K., 1980. Study of the spectral reflectivity and emissivity of liquid ceramics. *High Temperatures - High Pressures*, 12:161-168.

Cabannes, F. and Billard, D., 1987. Measurement of infrared absorption of some oxides in connection with the radiative transfer in porous and fibrous materials, *Int. J. Thermophysics*, 8:97-118.

Crosbie, A.L., 1980. Emittance of a finite scattering medium with

refractive index greater then unity. *AIAA Journal*, 18:730-732.
Erukhimovich, I.L., 1989. K teorii ravnovesiya peresitshennogo para i djidkosti v elektromagnitnom pole. *Teplofizika Vysokikh Temperatur*, 27:1229-1232 (in Russian).
Galaktionov, A.V., Petrov, V.A., and Stepanov, S.V., 1988a. Radiatsionno-konduktivny perenos energii v silno rasseivayuschikh materialakh. In: *Teplomassoobmen - MMF*, Problem papers at Minsk International Forum, Sections 1, 2, ITMO im. A.V. Lykova, Minsk, pp. 208-222, (in Russian).
Galaktionov, A.V., Kobzev, G.A., Petrov, V.A., and Stepanov, S.V., 1988b. Vzaimodeystvie opticheskogo izlucheniya s poluprozrachnymi poristymi keremikami. In: *Tezisy dokladov VII Vsesoyuznoi konferentsii po vzaimodeistviyu opticheskogo izlucheniya s veshchestvom*. GOI, Leningrad, pp. 473-474, (in Russian).
Lingart, Yu.K., Petrov, V.A., and Tikhonova N.A., 1982. Opticheskie svoystva leikosapfira pri vysokikh temperaturakh. I. Oblast poluprozrachnosti. *Teplofizika Vysokikh Temperatur*, 20:872-880; II. Svoystva monokristalla v oblasti neprozrachnosti i svoystva rasplava. Ibid, 20:1085-1092 (in Russian).
Mularz, E.J., and Yuen M.C., 1972. An experimental investigation of radiative properties of aluminium oxide particles. *J. Quant. Spectrosc. Radiat. Transfer*, 12:1553-1568.
Musatov, M.I., Sidorova, E.A., and Ivanov, B.G., 1977. Opticheskaya prozrachnost krupnykh kristallov leikosapfira. *Optico-Mekhanicheskaya Promyshlennost*, 2:39 (in Russian).
Petrov, V.A., and Chernyshev, A.P., 1987. Eksperimentalnoye issledovanie poverkhnostnogo nagreva keramiki iz oksida migniya lazernym izlucheniem. *Teplofizika Vysokikh Temperatur*, 25:361-368 (in Russian).
Petrov, V.A., Stepanov, S.V., and Mukhamedyarov, K.S., 1982. Tablitsy standartnykh spravochnykh dannykh GSSSD 26-81: Opticheskie konstanty i radiatsionnye kharakteristiki kvartzevykh stekol pri temperaturakh 295, 473, 673, 873, 1073, 1273, 1473 K, spektralnyi diapazon 3.7-11.7 μm. Gosstandart, Moscow pp. 1-20, (in Russian).
Plass, G.N., 1964. Mie scattering and absorption cross sections for aluminium oxide and magnesium oxide. *Applied Optics*, 3:867-872.
Vorobyev, A.Yu., Petrov, V.A., Titov, V.E., and Chernyshev, A.P., 1991. Eksperimentalnoye issledovanie kondensatsii parov tugoplavkikh oksidov pri poverkhnostnom nagreve misheni v vozdukhe lazernym izlucheniem. *Teplofizika Vysokikh Temperatur*, 29:981-987, (in Russian).