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MELT-LEVEL SENSOR AND ITS APPLICATION TO INVESTIGATION OF RADIANT HEAT EXCHANGE IN AN ELECTROSLAG-REMELTING UNIT

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A light-guide transducer has been developed and experimental investigations of the distinctive features of radiant heat exchange between the smelting zone and the wall of the crystallizer of an electroslag-remelting unit have been carried out. A relation making it possible to determine the slag or metal temperature has been obtained. A method of measurement and the structure of a sensor of liquid-metal level have been developed; its operating characteristics have been investigated.

Among all the processes of special electrometallurgy, the most widespread is the technique of electroslag remelting (ESR), in view of its high economy and productivity. The essence of the technique is that the consumable electrode, manufactured from regular-production metal and connected to the current source, is dipped into a layer of molten conducting refining slag with its end. The electrode melts under the action of thermal energy released in traversal of the electric current from the electrode to the liquid slag. Liquid-electrode-metal droplets, descending to the bottom of the slag bath, form a metal bath, which, being successively hardened at the bottom in a water-cooled crystallizer, forms an ingot. Study of the regularities of heat exchange in the slag bath–crystallizer–melted ingot system is of importance for further development of the electroslag technology.

Light-Guide Transducer of the Radiative Heat Flux. To measure the specific heat flux from the liquid slag and the ingot to be melted to the crystallizer's wall one usually uses the method of an auxiliary wall installed on the path of the heat flux to be determined (this method is based on measuring the temperature difference in the wall made of a material with a known thermal conductivity). To obtain the true values of q_w one must simultaneously measure the flow rate and temperature of a cooling water and the temperature difference on the wall during the smelting [1]. The change in the smelting-zone temperature over the crystallizer's height is given in Fig. 1a.

Of greatest interest in the ESR process is the sharp increase in the specific heat flux q_w to the crystallizer's wall in the region of the "slag–metal" boundary (Fig. 1b); this increase is used for monitoring of the position of this interface [2]. A comparison of the distributions of q_w and of the electric current I_w over the height of a stationary crystallizer demonstrates that a simultaneous burst of these quantities is observed in the region of the "slag–metal" boundary. The calculated and experimental data show that the current traversing the metal bath causes no pronounced overheating in the smelting zone, i.e., cannot be responsible for the burst of the quantity q_w.

To study the distinctive features of radiant heat exchange at the "slag–metal" boundary we have developed a light-guide radiative-heat-flux (RHF) transducer incorporating a quartz light guide and an SF3-1 photoresistor with a threshold sensitivity of 10^{-11} lm. Such a resistor can be used for indication of weak fluxes, which is convenient in operation with a small-diameter optical-fiber input, and has the following characteristics: region of spectral sensitivity from 0.4 to 1.2 μm with a maximum of $\lambda_{max} = 0.7$ μm, buildup and decay lags 15 and 6 msec, and relative change in the resistance 99%. In a narrow illuminance range, we use the dependence $I_{ph} = NJ^m$, where N and m are constant coefficients in the illuminance range selected ($m = 0.5$ for high illuminances), to determine the light characteristic of the photoresistor. In the range of temperatures $\pm 50^oC$, the light resistance R_{light} changes twice and the time constants are nearly halved. The experimental energy characteristic of the photoresistance within a variation of seven orders of magnitude in the illuminance has been obtained. The data on the luminous flux have been reduced to the spectral-sensitivity maximum of SF3-1.

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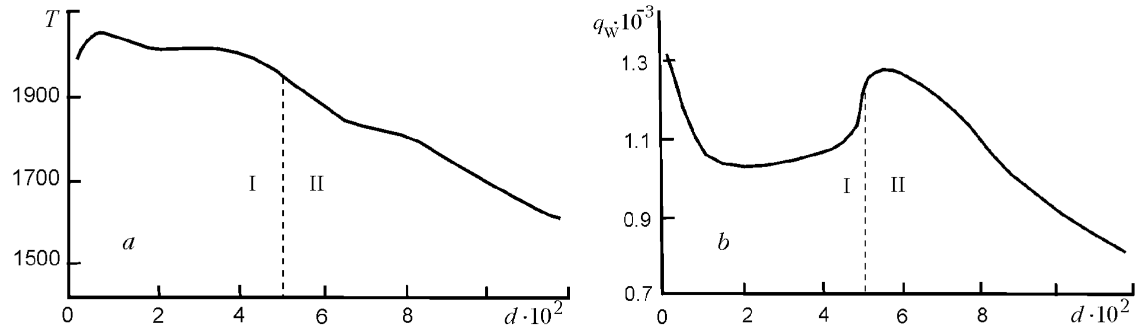

Fig. 1. Distribution of the temperature T (a) and the conductive heat flux q_w to the wall (b) over the height d of the crystallizer's smelting zone [1]: I, slag; II, metal. T, K; d, m; q_w, kW/m^2.

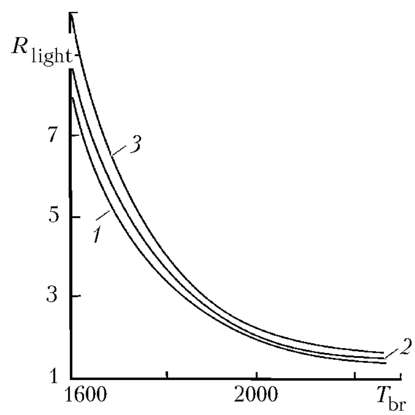

Fig. 2. Photoresistance R_{light} of the light-guide sensor vs. brightness temperature of an SI 10-300: 1, 2, and 3) photoresistor Nos. R_{light}, kΩ; T_{br}, K.

To select photodetectors with similar energy characteristics we alternately illuminated them with an SI10-300 ribbon-filament lamp through a quartz light guide of diameter 1 mm. The value of the brightness temperature of the ribbon was monitored by a pyrometer. We selected several SF3-1 products with a small spread (≤1.5%) in characteristics (Fig. 2).

To calibrate the radiant-heat-flux transducer we used a "Uran" radiative heater. Its electric circuit of control of the filament current of the xenon lamp made it possible to maintain a prescribed level of the radiant-heat-flux temperature with an error of 10%. Since the light-guide hot end in the crystallizer must be arranged immediately adjacent to the skull surface, the light-guide aperture is equal to zero, in practice. Therefore, in calculations, the end of the transducer's "forepart" was covered with a glass-reinforced-plastic plate with a hole equal to the light-guide diameter, which made it possible to record mainly normally incident beams. According to the calibration results, the values q_r = 170, 200, 250, 300, and 350 kW/m^2 correspond to R_{light} = 6.3, 4.1, 2.1, 0.83, and 0.22 kΩ.

To evaluate the intrinsic thermal radiation of the light-guide end we carried out mechanical modulation (using a rotating shield) of the radiant heat flux supplied. The measurement results showed that this radiation is about half the value of the radiant heat flux supplied.

The structure of an RHF transducer was finally selected in the process of experimental trial on the ESR unit of the E. O. Paton Institute of Electric Welding. The selected structure of the RHF transducer was as follows: quartz as the light-guide material, light-guide diameter 1.0 mm, and diameter of the hole for installation of the light guides in the "forepart" of the transducer 1.1 mm. To eliminate mechanical failure of the light-guide hot end we "buried" it to a depth of 0.7 mm. The "forepart" of the transducer was manufactured from copper, and its casing was made of stainless steel (Fig. 3). The "forepart" was attached to the crystallizer's casing using a threaded connection. The pho-

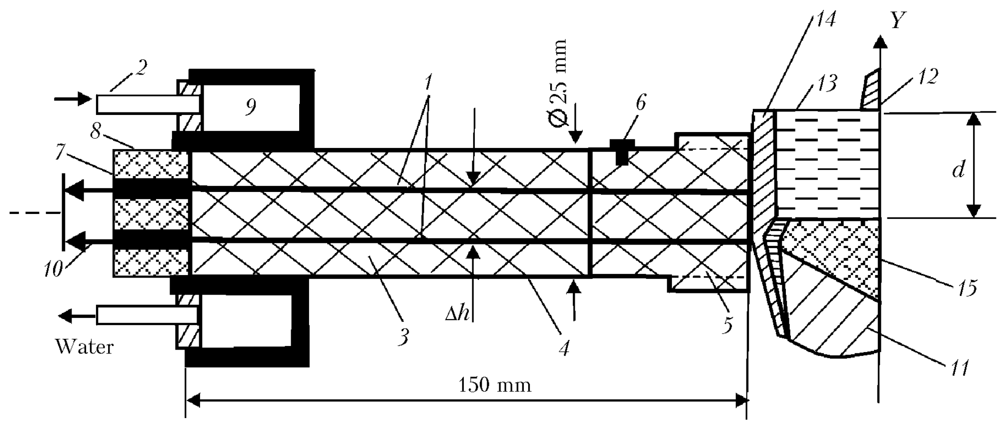

Fig. 3. Structure of the light-guide melt-level sensor: 1) light guide; 2) union; 3 and 8) textolite bushings; 4) steel casing; 5) forepart; 6) screw; 7) photodetector; 9) vessel; 10) photodetector outputs; 11) ingot; 12) electrode; 13) liquid slag; 14) skull; 15) liquid metal; Δh, distance between the light guides, mm; d, m.

todetector was placed in a textolite bushing manufactured from two cylinders. An external water heat exchanger was located on the transducer cold end.

Results of Investigation of the RHF in a Moving Crystallizer of the ESR Unit. The capacity of a thin (several millimeters thick) layer of liquid slag for transmitting optical radiation sufficient for filming and photographing of the ESR process through a quartz "window" was experimentally established in [3]. The results of the structural analysis of the composition of the skull showed the presence of ~30% of transparent components (glass, corundum, spinel, etc.) and of pores. This points to the semitransparency of the skull made of an ANF-29 fluxing agent and allows experimental investigations of radiative heat exchange. Using the optical transducer developed, the distribution of the radiant-heat flux $q_{w,r}$ over the crystallizer's height has experimentally been established for the first time (Fig. 4).

An indirect check of the correctness of the RHF-transducer readings can be the calculation results [1], according to which the power input attains ~4000 kW/m^2 in the crystallizer; the fraction of the radiation loss by the slag mirror amounts to about 6%, which corresponds to 240 kW/m^2. The light-guide transducer showed $q_{w,r}$ = 255 kW/m^2, i.e., a value similar to the calculated one, near the slag-mirror surface.

When the light-guide end is dipped into the liquid slag, a skull film appears between them; the blocking action of the film leads to a sharp decrease in the radiant flux to the crystallizer's wall (Fig. 4, zone 1). The upper layer of the slag traversed by most of the electric current is the hottest; therefore, the signal of the transducer changes here only slightly (zone 2). With distance from the slag-bath mirror, this signal smoothly decreases (zone 3) to a distance of ~3 cm from the "air–slag" boundary, which corresponds to a monotone reduction in the slag temperature. As the metal-bath mirror is approached, the signal of the transducer increases and attains its maximum in the region of the "slag–metal" boundary (zone 4). Upon the traversal of the cylindrical part of the metal bath (zone 5), the signal sharply decreases due to the formation of an air gap between the ingot and the crystallizer's wall (zone 6).

Since the phase-transition temperature on the exterior surface of the skull is constant and the smelting-zone temperature decreases along the crystallizer's wall (see Fig. 1a), the maximum of the radiant flux at the "slag–metal" boundary in the case of a semitransparent skull can appear either due to the burst of the release of the electric power at the "slag–metal" boundary or because of the thinning of the skull film in the region of the metal-bath meniscus.

As the results obtained show, a change within ±5% in the electric-power input during the smelting does not affect the reading of the RHF fiber-optical transducer located in the region of the "slag–metal" boundary (probably due to the low transparency of the slag). The burst of the radiant heat flux at this boundary attains 50%. In the experiments carried out in the ESR furnace, the slug-film thickness on the ingot surface was δ_{sk2} = 0.6 mm. According to [4], it can approximately be taken that, above the "slag–metal" boundary, we have $\delta_{sk1} \sim 1.5$ mm (the thickness of the slag interlayer below the boundary is ~1 mm). The results given in Fig. 4 make it possible to calculate the values of the transmission coefficients of the skull film: τ_{sk1} = 0.35 and τ_{sk2} = 0.66. Then, from the relation τ_{sk1} = exp

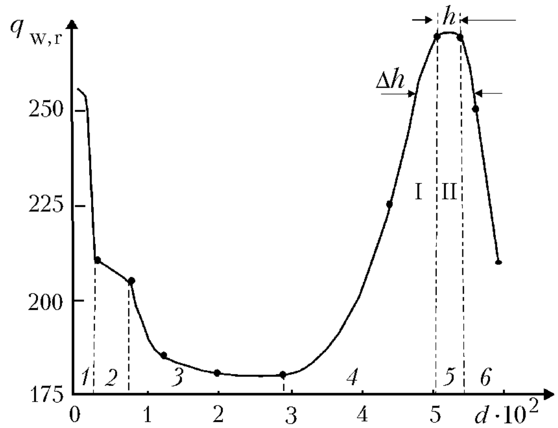

Fig. 4. Density distribution of the radiative heat flux $q_{w,r}$ over the height d of the smelting zone: 1 and 2) upper layers of the slag; 3 and 4) central and lower layers of the slag; 5) liquid-metal zone; 6) ingot zone. I, slag; II, metal. $q_{w,r}$, kW/m^2; d, m.

$(-k_{sk1}\delta_{sk1})$, we have $k_{sk1} = -\ln \tau_{sk1}/\delta_{sk1} = 0.72$ mm^{-1} for the absorption coefficient. The k_{sk1} value obtained is about 15 times higher than that for quartz at $\lambda = 0.78$ μm and $T = 1683$ K [5].

It is not impossible that the sharp increase in $q_{w,r}$ in the region of the "slag–metal" boundary is due to the thinning of the skull. Since the skull is a plane multilayer structure of semitransparent parallel layers (decrystallized glass, corundum and spinel crystals, and fluorite) having different refractive indices, we can represent the skull film as a plane light guide. In this case the gradual growth in q_w, as the light-guide end approaches the "slag–metal" boundary, can be a consequence of the input of radiation from the liquid metal into the cross section of the skull film at the site of its thinning (radiation end input). This hypothesis must additionally be checked. A possible reason for the burst of the radiant heat flux at the "slag–metal" boundary can also be the accumulation of heat in the surface layer of the material suffering failure [6].

The results obtained on the distribution of the radiant heat flux in the smelting zone of the crystallizer make it possible to develop a liquid-metal-level sensor for a system of control of the crystallizer motion.

Sensor of the Liquid-Metal Level and Its Operating Characteristics. In connection with the development of the electroslag technology, in a number of cases one must move the crystallizer upward, strictly maintaining a prescribed level of a liquid metal bath. Otherwise, the liquid metal can either flow out from under the low flange of the crystallizer or ascend to the broadening part of the crystallizer, which will make it difficult to raise the latter. This brought the special sensors of the light-metal level and devices for automatic control of the ESR process into being. The use of the above sensors in moving-crystallizer furnaces allows determination of the linear and mass flow rates of melting of an ingot, i.e., construction of a system of automatic control by the basic technological parameter of the ESR process. It is difficult to determine the metal-bath level relative to the crystallizer using the existing (contact, ultrasonic) level sensors, since the metal bath is covered with a molten-slag boundary and, furthermore, the "slag–metal" melt boundary possesses a high aggressiveness. A noncontact inductive sensor operating on the principle of induction of eddy currents in a conducting nonmagnetic medium whose level must be monitored has been developed at the E. O. Paton Institute of Electric Welding [7]. The sensitivity of this sensor depends on the electrical conductivity of the medium under study and the skull-film thickness. Since the casing wall that is in direct contact with the slag and metal baths is water-cooled, there is the possibility of the water arriving at the crystallizer in the case of burning-out of the wall.

The presence of a sharp maximum of the specific RHF to the crystallizer's wall at the "slag–metal" interface made it possible to develop the structure of a light-guide melt-level sensor. Two identical RHF transducers sharing the casing are installed over the crystallizer's height (Fig. 3). The vertical distance between the light-guide axes (h = 1.8 mm) must be somewhat larger than the length of the $q_{w,r}(d)$-curve portion on which the radiant flux preserves its maximum value (Fig. 4). Since the error of calibration of a single RHF transducer on the "Uran" unit is ~10%, the

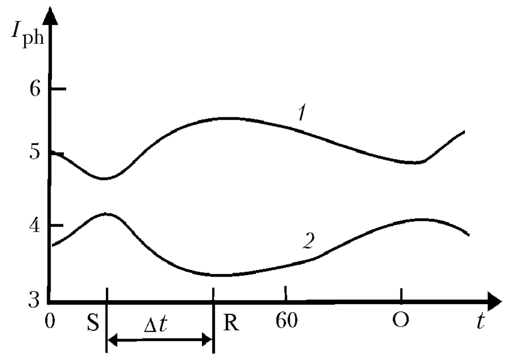

Fig. 5. Dynamic characteristic of the light-guide melt-level sensor: 1 and 2) upper and lower transducers; S and R, stop and rise of the crystallizer in smelting with an ANF-29 fluxing agent. t, sec; I_{ph}, mA.

distance between the axes of two light guides must be such as to ensure the ratio $(q_{w,r1} - q_{w,r2})/q_{w,r2} \geq 20\%$ on each portion of the plot $q_{w,r}$ (d). This condition is satisfied by $\Delta h \sim 8$ mm.

Representing the condition of zero disbalance of the upper and lower single transducers as $q_{w,r1} - q_{w,r2} = 0$, we obtain

$$\frac{T_{m2}^4 - T_{ph.t}^4}{T_{sl1}^4 - T_{ph.t}^4} = \frac{\varepsilon_{sl1}}{\varepsilon_{m2}} \frac{\tau_{sk1}}{\tau_{sk2}} .$$

The light transmission of the light guides of length 150 mm has been taken to be 100%. Substitution of the data from [1] into this relation shows that it holds accurate to ~88%. This confirms the possibility of using the melt-level sensor to evaluate T_{m2} or T_{sl1} at the instant the crystallizer stops. The problem of control of the melt level is reduced to maintaining the zero difference of the signals from the upper and lower transducers. Such a method of monitoring of the level is invariant, in practice, to the skull-film thickness.

The dynamic characteristic of the sensor was experimentally investigated in a copper crystallizer of diameter 200 mm with the use of ANF-29 and ANF-32 fluxing agents in the smelting regime for $I_{op} = 1.2$ kA and $U_{op} = 40$ V. The position of the level was monitored visually using cuts made on the crystallizer's wall every 10 mm. The rate of melting of the ingot, determined visually, was 10 mm/min on the average. Figure 5 gives a change in the signals of the photocurrent of two transducers. At the instant the crystallizer stops (it is denoted as S), the signal from the lower transducer is maximum, whereas the signal from the upper transducer is minimum. The instant of the beginning of the rise of the crystallizer (denoted by the letter R) corresponds to the inverse relation. The time interval S–R corresponds to the melting of the ingot with a stationary crystallizer. After the period Δt, the lower transducer goes below the "slag–metal" boundary and its signal decreases, whereas the upper transducer approaches this boundary and its signal increases. In multiple traversal of the "slag–metal" level from top to bottom (with a stationary crystallizer) and from bottom to top (with the rise of the crystallizer) by the sensor, the behavior of the curves was constant. Using the data of the given plot, we can determine the average rate of melting of the ingot; it is equal to ~12 mm/min and coincides with the results of visual monitoring within the experimental error. According to Fig. 4, when the distance between the axes of two light guides is equal to 8 mm, the zero disbalance of the bridge circuit corresponds to a position of the S–R axis of the sensor 1–2 mm below the "slag–metal" boundary. This is responsible for the fact that a certain difference in the values of the photoresistances of the upper and lower transducers is characteristic of the instant of stop (point S, Fig. 5) in visual monitoring and control of the crystallizer motion.

The static characteristic of the sensor was experimentally investigated with the use of a bridge recording circuit. The nominals of the resistances and the supply voltage of the circuit were selected with allowance for the experimental dependence $R_{light}(T_{br})$ obtained (Fig. 2). The disbalance current was supplied to the input of a metal-level controller which incorporates an M1531 switch-board narrow-profile device with light-beam indication on the milliammeter scale and a unit of three-position signaling and control. The rise (descent) of the crystallizer leads to a movement of the sensor from the liquid-metal level until the disbalance signal disappears. The static characteristic is shown

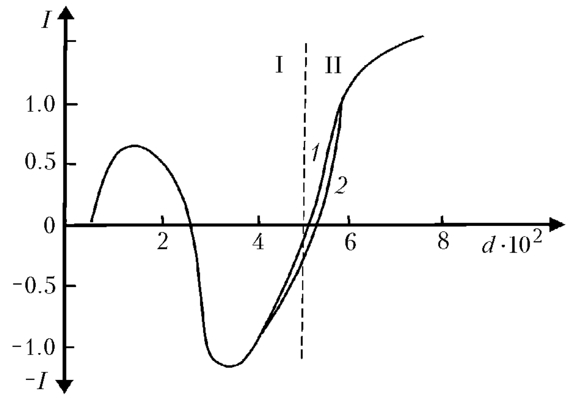

Fig. 6. Static characteristic of the light-guide melt-level sensor: 1 and 2) ANF-29 and ANF-32 fluxing agents; I, slag; II, metal. I_{ph}, mA; d, m.

in Fig. 6. A displacement of the metal level by no more than ±5 mm from the horizontal axis of the sensor corresponded to the values of the current I on the milliammeter scale equal to ±0.45 and ±0.60 mA for the ANF-29 and ANF-32 fluxing agents respectively. The slight difference between the static characteristics is, apparently, attributed to different absorption coefficients of the skull for the ANF-29 and ANF-32 fluxing agents (since the rate of growth in $q_{w,r}$ (d) in the region of the "slag–metal" boundary can somewhat change).

As compared to an inductive sensor, a light-guide sensor, in addition to its high sensitivity, is much easier to manufacture, less expensive, and safer to operate (since it excludes the possibility of the cooling water arriving at the smelting zone). Also, we have developed the structure of a light-guide melt-level sensor in which removable quartz "windows" in combination with constant fiber-optical channels are used.

Smeltings in which a light-guide sensor was used to control the crystallizer motion by the level of a metal bath accurate to ±5 mm in melting of ingots 200 mm in diameter (U_{op} = 62 V, I_{op} = 4.5 kA, fluxing agent ANF-29, rate of melting of an ingot 34 mm/min, and skull thickness 1.5 mm) were carried out on the ESR unit of the "Scientific-Technical Center of Artillery and Small Arms" (Kiev).

CONCLUSIONS

1. Using a quartz light-guide radiative-heat-flux transducer, we have obtained, for the first time, experimental data on the distribution of the specific radiative heat flux to the wall of the crystallizer of an electroslag-remelting furnace and have established the existence of the flux maximum in the region of the "slag–metal" boundary. Based on the transmission coefficients determined experimentally, we have found a computational relation for evaluation of the metal (T_{m2}) or slag (T_{sl1}) temperature for the zero signal of a differential melt-level sensor.

2. We have obtained a parametric relation describing the algorithm of measurement of the melt level by a differential light-guide sensor. The structure of the sensor and the electronic circuit of control of the crystallizer motion have been developed.

3. It has been established that the influence of the grade of a fluxing agent on the static characteristic of the light-guide level sensor is insignificant. It has been shown that the dynamics of change in the signals from the upper and lower single transducers in multiple traversal of the "slag–metal" boundary is stable.

4. The light-guide melt-level sensor developed is inexpensive and safe to operate. Since the temperature of the crystallizer hot wall is much lower than the crystallization temperature of quartz, the optical characteristics of the light guide do not change.

NOTATION

d, distance from the "slag–metal" boundary, m; h, length of the portion of the smelting zone with a maximum value of $q_{w,r}$, m; I, bridge-circuit current, mA; I_{op}, current through the electrode, kA; I_w, electric current traversing the slag from the electrode to the crystallizer's wall, kA; I_{ph}, photocurrent, mA; J, illuminance, W/cm^2; k_{sk}, absorption coefficient of the skull, mm^{-1}; m and N, dimensionless coefficients; q_w, density of the conductive heat flux to the crystallizer's wall, kW/m^2; $q_{w,r}$, density of the radiative heat flux to the crystallizer's wall, kW/m^2; q_r, density of the normally incident radiative heat flux, kW/m^2; R_{light}, light photoresistance, kΩ; T, temperature of the smelting zone, K; T_{m2}, temperature of the metal surface for $Y = -5.2$ mm, K; $T_{ph.t}$, slag–skull phase-transition temperature, K; T_{sl1}, slag temperature for $Y = 2.8$ mm, K; T_{br}, brightness temperature of the lamp, K; t, smelting time, sec; U_{op}, voltage in the crystallizer, V; Y, distance of the light-guide axis from the "slag–metal" boundary ($Y = 2.8$ mm for the upper light guide and $Y = -5.8$ mm for the lower light guide when $I = 0$), mm; Δh, distance between the light-guide axes, m; Δt, melting time of the ingot, sec; δ_{sk}, skull thickness, m; ε_m, emissivity factor of the metal surface; ε_{sl}, emissivity factor of the slag; λ, radiation wavelength, μm; τ_{sk}, transmission coefficient of the skull film. Subscripts: sk, skull; sk1, skull on the light-guide upper end; sk2, skull on the light-guide lower end; m, metal; op, operating; light, light; w, wall; ph, photoelectric; ph.t, phase transition; sl, slag; br, brightness; r, radiative; 1, upper light guide; 2, lower light guide; max, maximum.

REFERENCES

1. B. I. Medovar (Ed.), *Thermal Processes in Electroslag Remelting* [in Russian], Naukova Dumka, Kiev (1978).
2. B. E. Paton and B. I. Medovar (Eds.), *Electroslag Furnaces* [in Russian], Naukova Dumka, Kiev (1976).
3. D. A. Dudko, G. Z. Voloshkevich, I. I. Sushchuk-Slyusarenko, and I. I. Lychko, Study of the electroslag process using filming and photographing through a transparent medium, *Avtomatich. Svarka*, No. 2 (215), 15–19 (1971).
4. A. A. Sharapov and S. E. Volkov, Calculation of the thickness of the liquid layer of the slag crust in remelting under the slag layer, *Teoriya Metallurgich. Protsessov*, Issue 2, 193–195 (1974).
5. A. V. Vanyushin, G. Yu. Levenfel'd, and V. A. Petrov, Spectral coefficient of absorption of quartz glasses KV and KGS at temperatures of 1300–1700 K in the spectrum range 0.25–1.25 μm, *Teplofiz. Vys. Temp.*, No. 6, 1215–1218 (1978).
6. G. A. Frolov, The constant of thermal destruction and its role in the processes of heating and entrainment of mass of a material, *Inzh.-Fiz. Zh.*, **77**, No. 3, 19–46 (2004).
7. É. I. Shmakov, B. I. Medovar, A. I. Chvertko, et al., *Inductive Noncontact Liquid-Metal-Level Sensor*, Inventor's Certificate 4946 USSR; *Byull. Izobr.*, No. 45 (1975).