HEAT EXCHANGE IN MOLTEN POOL IN LIQUID-PHASE MELTING OF ORE-COAL PELLETS

V.N. KOSTYAKOV[2], **E.B. POLETAEV**[2], **G.M. GRIGORENKO**[1], **S.N. MEDVED**[2], **E.A. SHEVCHUK**[2],
A.A. YASINSKY[2] and **O.A. YAKOVISHIN**[2]
[1]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine
[2]Physical-and-Technological Institute of Metals and Alloy, NASU, Kiev, Ukraine

Results of the heat exchange investigation in a pool in liquid-phase melting of the ore-coal pellets are presented. Dependence of heat-transfer coefficient from the slag to a pellet upon intensity of the slag mixing in the furnace pool is established.

Keywords: pellet, slag, reducer, heat-transfer coefficient, speed, mixing, melting, metal

Melting of the ore-coal pellets in the arc furnace is characterized by diversity of heat and mass transfer processes, stipulated by action of both heat engineering and combination of physical-chemical factors, which accompany decarburization of the pool, slag formation, oxidation of the metal by oxygen of the furnace atmosphere, etc.

Combination of all processes, occurring in the furnace, represents for the time being irresolvable task and can not be described mathematically.

For real conditions and mathematical description construction of the model is simplified, if one takes into account a number of issues, characteristic of melting of metallized pellets in the arc furnace at different types of charging.

One may assume that for melting with application of the metallized pellets process of their dissolution in the molten pool is of a subordinate character in comparison with melting, because temperature of the molten metal is higher than melting point of the pellets. Among all questions of interest is determination of peculiarities of the process, stipulated by thermal physics characteristics of the material, because they are different in the pellets and the scrap.

The assigned task may be solved first of all by the model of heat exchange between a pellet being heated and the molten metal (the slag). Kinetics of heating and melting of a pellet may be considered on basis of the model of heat transfer by heat conductivity in the body of spherical shape under boundary conditions of third kind, i.e. at constant temperature of the metal (the slag).

Duration of the pellet melting, heated in the course of the convection heat transfer, depends upon thermal physics properties of the material and coefficient of heat exchange at the interface between the body and the medium. Heat exchange between the body and the medium, characterized by heat exchange coefficient α, may vary under real conditions within much wider range than physical properties. In the arc furnace heating and melting of the metallized pellets occurs both in the slag and at the slag–metal interface.

The investigations showed that values of coefficient of heat exchange between the metal and the melting in it scrap or a metallized pellet change within a narrow range. So, in melting of slag in a converter values of the heat exchange coefficient achieve α = 58–62 J / (m^2·s·°C) [1].

Investigation of melting of cylindrical steel specimens and metallized pellets in the induction furnace showed that heat exchange coefficient at a relatively low intensity of mixing equaled 13 J / (m^2·s·°C); at maximum power (intensive mixing) its values were within 139–220 J / (m^2·s·°C).

Taking into account somewhat overstated latter values, one may assume that the heat exchange coefficient in melting of a pellet in the molten metal may constitute 11–146 J / (m^2·s·°C) [2]. Because of a lower heat conductivity, density and increased viscosity of the slag in comparison with the molten metal, its heat exchange coefficient may be by several orders lower than in the molten metal–pellet system.

As a rule, heating and melting of the metallized pellets is accompanied by release of gases, stipulated by reaction between carbon and iron oxides. It is found [2] that noticeable release of gases (mainly CO) starts at 800 °C. As rate of a pellet heating increases, maximum of gas release shifts in direction of high temperatures. Recalculation of intensity of the CO release into rate of decarburization at heating rate 250 °C / min will give intensity 0.2 % C per minute, and share of carbon, which entered into reaction, — more than 1 %. High level of the gas release intensity from surface of a pellet in heating in slag or at the slag–metal boundary stipulates significant intensity of mixing of the melt layers, which directly contact with the pellet and, as a result, increased heat exchange.

Under real production conditions at continuous loading of pellets into the pool conditions of heat exchange between the medium and a pellet in the process of heating and melting change in direction of the heat exchange increase. This is explained by change of mean density of the pellets (due to which they move from the slag lower to the slag–metal interface) and development of the decarburization reaction in the pellet, which intensifies heat exchange owing to increased degree of turbulence of the slag or the molten metal flows, which wash the pellet.

At correctly organized pellet melting technology heat exchange in the slag and at the slag–metal boundary is characterized by values α_{sl} = 3.6 J / (m^2·s·°C) and α_{sl-m} = 36–73 J / (m^2·s·°C) [2].

At the heat exchange coefficient value less than 3.6 J / (m^2·s·°C) and typical for the pellets size of the sphere, values of the Biot criterion constitute 0.5–2.0. At this ratio of internal and external heat flows heating of a pellet occurs in such way that by the time of the melting point achievement, temperature gradient on its surface gets insignificant over its radius.

In Physical-and-Technological Institute of Metals and Alloys (FTIMS) of the NAS of Ukraine heat exchange in melting of the ore-coal pellets in motionless and boiling slag were investigated.

Goal of this work was investigation of heat exchange in the pool in liquid-phase melting of the ore-coal pellets. The investigations were carried on experimental installation (Figure 1), the design of which included Tamman furnace, a frequency converter (FR-5520-0.4K), an electric motor, and a graphite crucible. By rotation of the crucible with slag intensity of the slag boiling in melting of the ore-coal pellets was simulated.

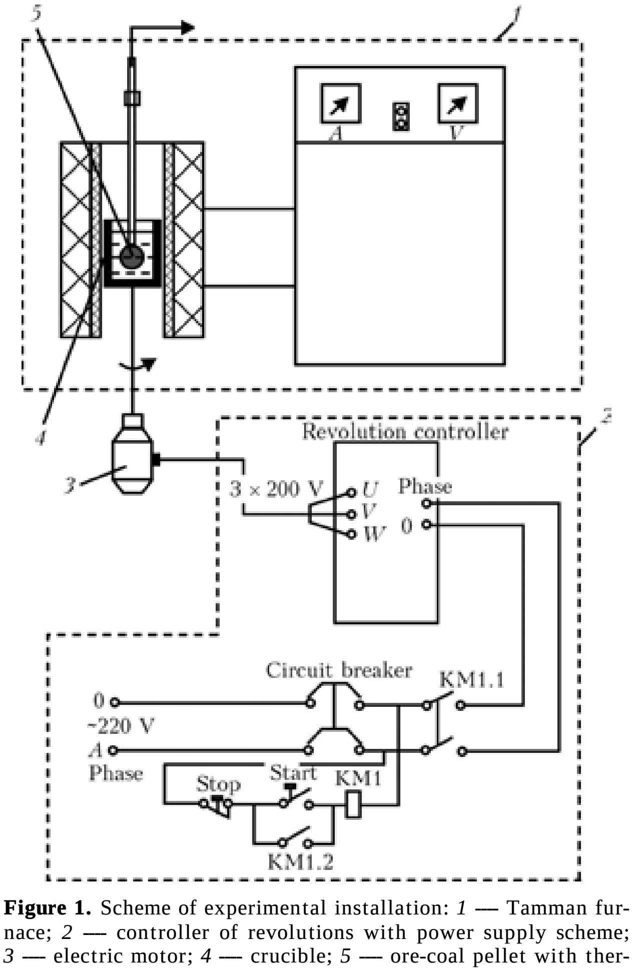

Figure 1. Scheme of experimental installation: *1* — Tamman furnace; *2* — controller of revolutions with power supply scheme; *3* — electric motor; *4* — crucible; *5* — ore-coal pellet with thermocouple

In the experiments lime-silica slag (55.5 % CaO, 44.5 % SiO_2) was used with melting point 1475 °C. Mass of the slag in all experiments was constant — 0.3 kg.

For manufacturing of the ore-coal pellets an iron-ore concentrate, a carbon-containing reducer and the grade 400 cement, which functioned as a binder in formation of the pellets, were used. Content of the cement constituted 15 % of total mass of the ore concentrate and the reducer.

Electrode scrap, containing 86 % C, was used as the reducer. Consumption of the reducer exceeded by 30 % its quantity, theoretically necessary for full reduction of iron in a pellet. Weight share of components in the mixture was as follows, %: ore concentrate — 66.7; reducer — 19.0; cement — 14.3.

The pellets were produced by ramming the mixture in a specially made mould. In center of the pellet the VR-20 / 5 tungstenrhenium thermocouple was placed. For protection of the thermocouple junction against direct contact with iron and its oxides protective electrocorundum coating was applied on the surface. The pellets were subjected to hardening drying at room temperature within 7 days and then to low-temperature (300 °C) drying in the drying chamber.

Mass of a pellet was 0.009 kg, density — 2150 kg / m^3. Chemical composition of the ore-coal pellets was as follows, wt.%: 1.33 FeO; 58.6 Fe_2O_3; 7.34 SiO_2; 0.82 Al_2O_3; 10.92 CaO; 0.6 MgO; 0.02 TiO_2; 16.34 C; 0.34 K_2O; 0.06 P_2O_5; 0.63 S.

At the beginning of the experiment the crucible with slag was installed in isothermal zone of the furnace, the furnace was turned on, and the slag was melted. The slag temperature was measured by the tungstenrhenium thermocouple, junction of which was protected by a quartz tip. Readings of the thermocouple were registered by the M1108 portable millivolt-ammeter.

After melting of the slag and its overheating up to (1550 ± 5) °C the crucible with the slag was imparted rotational movement at a preset speed, and the pellet was immersed into the slag. In process of the experiments speed of the crucible rotation equaled 0; 0.01; 0.02 and 0.04 m / s.

Temperature of the pellet center from the instant of its immersion into the slag was registered by the UPIT portable universal instrument, developed by FTIMS of the NAS of Ukraine and designed for periodic measurements of temperatures by means of the converters. Error of the temperature measurement equaled ± 1 °C. Time interval between previous and subsequent measurements of the pellet center temperature was constant and equaled 5 s. Time of the pellet heating was registered by a stop-watch.

Duration of a pellet heating was determined by its stability. Failure of the specimen being heated was detected at high temperatures; it was stipulated by intensive gas release of the iron reduction reaction products in internal layers of a pellet and swelling and loss of strength of a pellet because of phase and structural transformations during heating [3].

Change of the pelt surface temperature and coefficient of convective heat exchange between the pellet surface and the slag depending upon intensity of the slag boiling and time of heating were determined using data presented in Figures 2 and 3. These graphs are built according to calculated values of the Fourier criterion and analytical solution results of differential equation of heat conductivity in case of heating of bodies of spherical shape under non-stationary conditions in the constant temperature environment [4]. They are applicable for this case because mass of the slag is 30 times higher than that of the pellet.

The graphs are drawn in the form of the following equation:

$$\theta = f\left(\mathrm{Bi},\ \mathrm{Fo},\ \frac{r}{R}\right)$$

or

$$\theta = f\left(\frac{\alpha R}{\lambda},\ \frac{a\tau}{R^2},\ \frac{r}{R}\right),$$

where θ is the dimensionless variable temperature; Bi is the Biot criterion, which determines character of temperature distribution within volume of the pellet being heated; Fo is the dimensionless time; r / R is the dimensionless coordinate; r is the current value of the pellet radius, m; R is the pellet radius; λ is the pellet heat conductivity, J / (m^2·s·°C); a is the pellet heat diffusivity coefficient, characterized by its heat inertia properties, m^2 / s.

Heat diffusivity coefficient is determined from the expression

$$\alpha = \frac{\lambda}{c\rho},$$

where c is the pellet heat capacity, J / (kg·°C); ρ is the pellet density, kg / m^3.

Presented in Figures 2 and 3 dependences are drawn for two values of the dimensionless coordinate: $r / R = 0$ and $r / R = 1$, which correspond to the pellet center and its surface.

Heat exchange coefficient α and the pellet surface temperature were determined according to the calculated Fourier criterion and dimensionless temperature of the pellet center for each instant of the time, at which temperature of the pellet center was measured. In calculation of the heat diffusivity coefficient heat capacity and heat conductivity of the pellet material were assumed to be constant and represent mean values of mentioned thermal physics properties within temperature range of 0–1200 °C.

Necessary for calculation of the heat capacity and heat conductivity values were taken from [5].

Dimensionless temperature of the pellet center θ_c was determined from the expression

$$\theta_c = \frac{T_c - T_0}{T_{sl} - T_0},$$

where T_c is the measured temperature of the pellet center, °C; T_0 is the pellet temperature prior to its immersion into the slag, °C; T_{sl} is the slag temperature, °C.

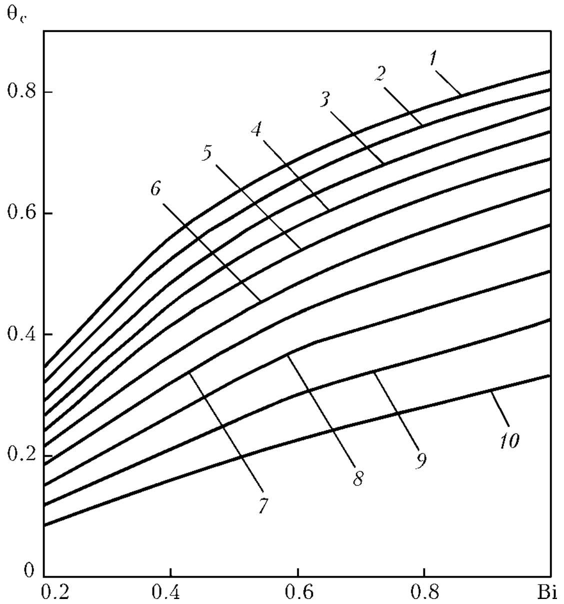

Figure 2. Curves for determination of Biot criterion by known values of Fourier criterion and dimensionless temperature of sphere center at Fo: *1* — 0.840; *2* — 0.770; *3* — 0.700; *4* — 0.640; *5* — 0.580; *6* — 0.515; *7* — 0.450; *8* — 0.386; *9* — 0.320; *10* — 0.257

Using found values of dimensionless temperature of the pellet center and the Fourier criterion value, the Biot criterion was found with application of the data, presented in Figure 2.

Heat exchange coefficient α was determined from the expression

$$\alpha = \frac{\mathrm{Bi}\lambda}{R}\ \text{[J / (m·s·°Ñ)]}.$$

Dimensionless temperature of the pellet surface was determined using data of Figure 3.

Temperature of the pellet surface T_s was determined from the expression

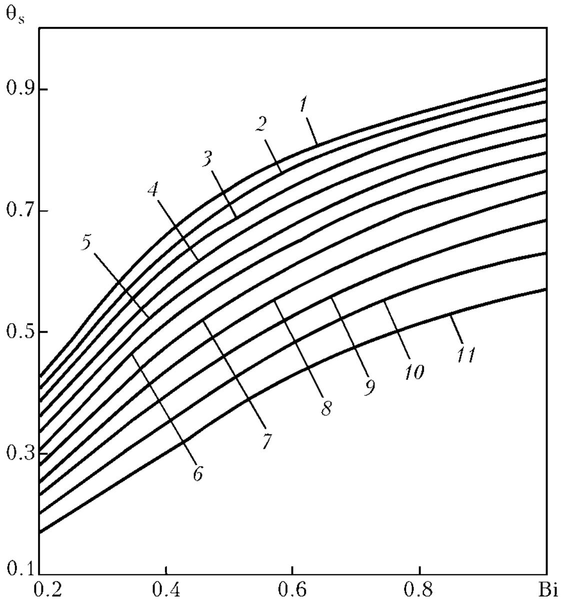

Figure 3. Curves for determination of dimensionless temperature of sphere surface by known values of Fourier and Biot criteria at Fo: *1* — 0.900; *2* — 0.840; *3* — 0.770; *4* — 0.700; *5* — 0.640; *6* — 0.580; *7* — 0.515; *8* — 0.450; *9* — 0.386; *10* — 0.320; *11* — 0.257

Table 1. Values of absolute and dimensionless temperatures of pellet center and surface, and Fourier and Biot criteria in case of pellet heating in immovable slag

τ, s	T_c, °Ñ	θ_c	Fo	Bi	θ_s	T_s, °Ñ
5	81	0.040	0.064	–	–	–
10	116	0.063	0.129	0.550	0.217	353
15	173	0.100	0.193	0.405	0.246	396
20	248	0.149	0.257	0.385	0.277	444
25	322	0.197	0.320	0.370	0.325	517
30	395	0.245	0.386	0.360	0.368	583
35	465	0.290	0.450	0.355	0.405	640
40	530	0.333	0.515	0.355	0.445	701
45	597	0.377	0.580	0.355	0.483	759
50	664	0.421	0.640	0.365	0.515	808
55	726	0.460	0.700	0.370	0.544	852
60	784	0.500	0.770	0.373	0.575	900
65	843	0.538	0.840	0.375	0.595	930
70	894	0.571	0.900	0.380	0.627	979
75	941	0.602	0.965	0.387	–	–

Note. Here in all cases $\mathrm{Bi}_{av} = 0.366$, $\alpha_{av} = 73.26$ J / (m^2·s·°Ñ).

$$T_s = \theta_s(T_{sl} - T_0) + T_0 \ [°Ñ],$$

where θ_s is the dimensionless temperature of the pellet surface.

Experimental and calculated values of parameters of the pellet heating process in molten slag are presented in Tables 1–4.

It follows from the presented data that initial period of heating of the pellets is characterized by increased values of the Biot criterion. At this period change of temperature field significantly differs from initial thermal state of the body. That’s why character of mentioned process is not determined unambiguously by conditions of heating and properties of the pellet. Later at Fo ≥ 0.3, value of the Biot criterion remains practically constant. This proves establishment of regular heating conditions, at which distribution of temperatures over volume of the pellet does not depend upon initial conditions and is determined by conditions of heating and thermal physics properties of the pellet material.

Presented data also show that character of temperature distribution within the pellet volume is determined by the Biot criterion, i.e. conditions of external heat exchange, when intensity of internal heat exchange or internal heat resistance of the pellet does not change in the process of heating. As speed of the slag rotation increases, i.e. as intensity of the slag boiling gets higher, intensity of heat exchange between surface of the pellet and molten slag increases. So, when speed of the slag rotation increases from 0 to 0.04 m / s, the Biot criterion increases from 0.366 to 0.715 and coefficient of heat exchange from 73 to 143 J / (m^2·s·°C) (Figure 4).

As intensity of heat exchange in the pool increases, rate of the pellet heating gets higher (Table 5).

Data, presented in Table 5, prove that heating of a pellet in the rotating slag reduces time, necessary

Table 2. Value of absolute and dimensionless temperatures of pellet center and surface, and Fourier and Biot criteria in case of pellet heating in rotating slag (speed of rotation $v_{sl} = 0.01$ m / s)

τ, s	T_c, °Ñ	θ_c	Fo	Bi	θ_s	T_s, °Ñ
5	81	0.040	0.064	–	–	–
10	110	0.059	0.129	0.520	0.219	355
15	211	0.125	0.193	0.510	0.276	442
20	290	0.176	0.257	0.455	0.315	502
25	375	0.232	0.320	0.445	0.367	582
30	456	0.285	0.386	0.435	0.413	652
35	532	0.330	0.450	0.415	0.455	717
40	604	0.380	0.515	0.420	0.495	777
45	669	0.424	0.580	0.415	0.535	839
50	728	0.462	0.640	0.415	0.565	884
55	784	0.500	0.700	0.420	0.595	930
60	836	0.533	0.770	0.410	0.625	976
65	890	0.568	0.840	0.410	0.653	1019

Note. Here in all cases $\mathrm{Bi}_{av} = 0.425$; $\alpha_{av} = 85$ J / (m^2·s·°Ñ).

Table 3. Value of absolute and dimensionless temperatures of pellet center and surface, and Fourier and Biot criteria in case of pellet heating in rotating slag (speed of rotation v_{sl} = 0.02 m / s)

τ, s	T_c, °Ñ	θ_c	Fo	Bi	θ_s	T_s, °Ñ
5	81	0.040	0.064	--	--	--
10	133	0.074	0.129	0.655	0.250	402
15	226	0.140	0.193	0.565	0.315	502
20	327	0.207	0.257	0.545	0.375	594
25	427	0.266	0.320	0.515	0.425	670
30	519	0.326	0.386	0.500	0.470	739
35	604	0.380	0.450	0.500	0.515	808
40	688	0.436	0.515	0.510	0.555	869
45	762	0.485	0.580	0.510	0.593	927
50	828	0.528	0.640	0.505	0.625	976
55	884	0.565	0.700	0.510	0.655	1022
60	930	0.595	0.770	0.500	0.697	1086

Note. Here in all cases Bi_{av} = 0.51; α_{av} = 102 J / (m^2·s·°Ñ).

Table 4. Value of absolute and dimensionless temperatures of pellet center and surface, and Fourier and Biot criteria in case of pellet heating in rotating slag (speed of rotation v_{sl} = 0.04 m / s)

τ, s	T_c, °Ñ	θ_c	Fo	Bi	θ_s	T_s, °Ñ
5	75	0.036	0.064	--	--	--
10	169	0.097	0.129	0.870	0.321	511
15	298	0.180	0.193	0.725	0.402	635
20	430	0.268	0.257	0.760	0.483	759
25	550	0.346	0.320	0.750	0.548	858
30	650	0.410	0.386	0.695	0.583	912
35	741	0.470	0.450	0.685	0.630	984
40	825	0.526	0.515	0.685	0.670	1045
45	922	0.590	0.580	0.715	0.705	1099

Note. Here in all cases Bi_{av} = 0.715; α_{av} = 143 J / (m^2·s·°Ñ).

Table 5. Influence of slag rotation speed on rate of pellet heating

v_{sl}, m / s	Time of heating (s) at T in center of pellet, °C				
	500	600	700	800	900
0	36.5	45.0	53.0	61.5	70.5
0.01	33.0	40.0	47.5	56.5	66.0
0.02	29.0	35.0	41.0	47.5	56.5
0.04	23.0	27.5	33.0	38.5	44.0

for achievement of the preset temperature of the pellet center. So, at speed of the slag rotation 0.01 m / s time, necessary for achieving by center of the pellet of temperature 900 °C, reduces in comparison with immobile slag by 6.8 %, and if speed of the slag rotation increases up to 0.04 m / s it reduces by 60 %.

So, results of the investigations allowed establishing dependence of the heat-transfer coefficient upon intensity of the slag mixing.

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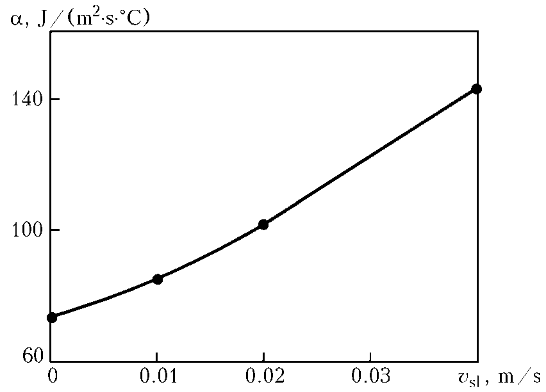

Figure 4. Influence of speed of slag rotation on intensity of heat exchange between slag and surface of pellet

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