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Features of the Extraction of Metals from Waste in a Solar Furnace

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Abstract—This paper analyzes the potential for using solar plants based on mirror-concentrating systems in technological processes for processing inorganic materials, in particular, processing materials in a stream of concentrated high-density solar radiation. To solve the problem of waste disposal of the mining and metallurgical process, it is proposed to use mobile, compact solar devices that allow the processing of mining and metallurgical waste directly in the immediate vicinity of dumps with the extraction of metals. The geometric and optical-energy parameters of the concentrator for processing in order to extract metals from mining wastes are calculated. It is shown that a system of mirrors that consists of a heliostat (100 m^2) and a paraboloid-shaped concentrator with a diameter of 10 m can focus a solar radiation flux with a density, which is sufficient to melt metallurgical waste from the Almalyk Mining and Metallurgical Plant. It has been revealed that when the material is heated in a carbon medium the process of metal reduction from their oxide states proceeds according to the reaction MeO + C = Me + CO. Some metals oxidize when cooled in air according to their chemical affinity for oxygen. It has been revealed that the continuous supply of material to the melting unit will make it possible to melt the material in the amount of 2400 kg per 1 sunny day. This indicates that in 1 year one solar furnace can process 500 tons of industrial waste with the extraction of 110 tons of iron and 16 tons of copper. It is shown that ultrasonic treatment of waste materials stimulates an increase in the amount of reduced copper in the melt by 8 times compared to the initial state of the material.

Keywords: solar concentrators, mirror concentrating systems, high flux densities, material processing, metal recovery

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INTRODUCTION

The use of technical means (lasers, plasmatrons, cathode-beam, or arc lamps) that create fluxes of quanta and/or high-density particles for surface modification and material processing make it possible to create non-equilibrium microstructures that can be used to manufacture materials with higher resistance to corrosion, high-temperature oxidation, and wear. Solar plants based on mirror concentrating systems have unique capabilities for processing metal materials (welding and surfacing, surface treatment, coatings and surface hardening, as well as powder metallurgy) and nonmetal materials (ceramics, fullerenes, carbon nanotubes) [1, 2].

A number of researchers [3–8] have considered the possibility of using a stream of concentrated solar energy instead of hydrocarbon energy at high temperatures. The results obtained by scientists from Uzbekistan, Turkmenistan, Ukraine, and Russia in the field of theory and practice of using solar furnaces for carrying out various high-temperature processes show the promise of their use for carrying out technological operations to obtain various kinds of refractory materials [9–14].

At present, the search for new energy sources is being intensively conducted along with the efficient use of existing sources. Especially great attention is paid to renewable energy sources because of their ability to be regenerated by natural processes. In this regard, solar energy is one of the most promising renewable energy sources [15, 16]. Various designs of melting units installed in the focal area of solar plants make it possible to implement technologies for energy-intensive processes in the ceramic, glass, and metallurgical industries. For example, in [17], use was made of a melting aggregate containing a graphite cavity, which absorbs the energy of concentrated high-density solar radiation and becomes a heat source. Due to the high thermal conductivity of graphite, the material in the reaction chamber is heated and melted. However, it seems to us that the efficiency of such a design of the melting unit will not be high in terms of the amount of melted material per unit of time, as well as the full melting of the loaded material.

The goal of this study was to develop a solar plant and a melting unit for processing waste from metallur-

Table 1. The chemical composition of waste from metallurgical production of the AMMP

Element	SiO_2	Fe_2O_3	CaO	K_2O	ZnO	MgO	CuO	PbO	MnO	MoO_3
Content, wt %	52.24	38.57	3.25	2.57	1.07	1.13	0.40	0.24	0.22	0.22

gical production to extract metal alloys from them. The paper will also study the effect of ultrasonic treatment of waste from the metallurgical production of the Almalyk Mining and Metallurgical Plant on the processes of extracting metal alloys from them in a solar furnace.

METHODICAL APPROACH

At the first stage, the chemical composition of wastes from the metallurgical production of the Almalyk Mining and Metallurgical Plant (AMMP) was analyzed (Table 1).

As follows from Table 1, silicon and iron oxides are the predominant components in technogenic waste.

The analysis has shown that such a composition of AMMP wastes is characterized by a low melting point, which was $T = 1750$ K with a material dispersion of not more than 100 μm.

At the second stage of the study, the flux density of concentrated solar radiation was calculated based on the Stefan–Boltzmann equation, which describes the radiation of heated bodies,

$$Q = \sigma\varepsilon T^4,$$

where ε is the emissivity of the material, $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4 is the Stefan–Boltzmann constant, T is the body temperature (K). When the value of the emissivity of rock materials is 0.85, the required flux density for melting waste from the metallurgical production of the AMMP ($T = 1750$K) is $Q = 50$ W/cm^2.

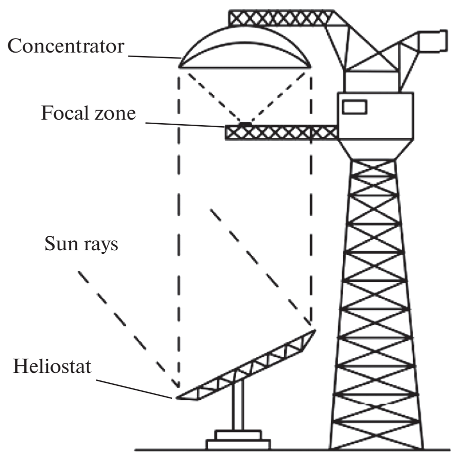

Fig. 1. Scheme of the solar plant that will be used for the recycling of materials.

The analysis of the results of studies on the processing of ores shows that the density at the focus of the solar furnace $E = 100$ W/cm^2 will be more than sufficient to melt technogenic waste with the extraction of metal alloys from them. In this case, it is obvious that the larger the focal spot size, the greater the amount of processed waste, i.e., the efficiency of this process.

Let us estimate what optical-geometric (dimensional) parameters a solar concentrator must have in order to provide the required technological modes. Calculations of the optical-geometric parameters of a bi-mirror (heliostat–concentrator) solar plant were carried out according to [18]. The following data were used for calculations: the flux density of concentrated solar radiation $E = 100$ W/cm^2, preferably with a flat distribution over spot diameter $d = 30$ cm. For this purpose, we will first determine what power will be in the circle with a diameter of 30 cm at a uniform density of 100 W/cm^2 in the focal zone:

$$W_f = \frac{E_f \pi d^2}{4} = \frac{100 \times 3 \times 0.3^2}{4} = 70\,650 \text{ W}.$$

On the other hand, such power must be provided by the concentrator midsection area. The estimates consider a round concentrator. If we denote the diameter of the concentrator midsection as D_c, then

$$\frac{E_0 R_g E_c \pi D^2}{4} = W_f,$$

where R_g and R_c are the reflection coefficients of the heliostat and concentrator mirrors and E_0 is direct solar radiation. Then,

$$\frac{E_f \pi d^2}{4} = \frac{E_o R_g R_c \pi D_c^2}{4}.$$

From here, for the concentrator midsection, we obtain

$$D_c = d_f \sqrt{\frac{E_f}{E_o R_c R_g}}.$$

This equation makes it possible to calculate the diameter of the concentrator corresponding to the given values of optical and energy parameters, taking into account the conditions of technological processes.

The proposed scheme of the solar plant, which will be used to process materials, is shown in Fig.1.

As can be seen from Fig. 1, the solar furnace is designed according to the bi-mirror scheme of mirror concentrating systems of the heliostat–concentrator

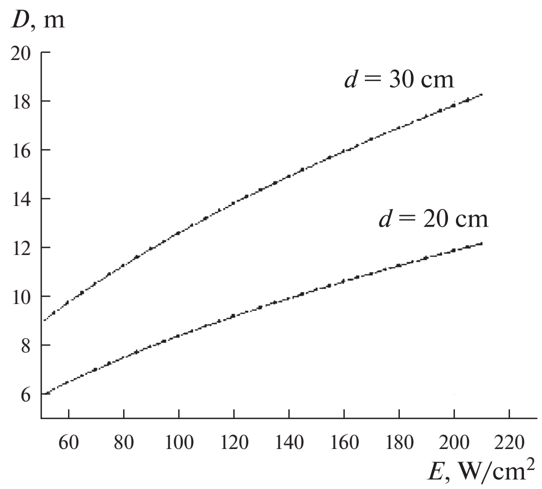

Fig. 2. Dependence of the concentrator diameter on the required radiation density.

type. Such a scheme of mutual arrangement of reflecting elements, mirrors allows concentrating solar radiation into a focal region with a vertical flux vector, which is convenient for technological purposes of processing materials in the focal plane.

At the third stage of the experiments, in order to identify the effect of preliminary ultrasonic exposure on the material, technogenic wastes were irradiated with pulses of ultrasonic vibrations in an ultrasonic bath of the DSA50-Ski-1.8L brand (manufactured in China).

RESULTS AND DISCUSSION

Assuming the radiation density to be 0.07 W/cm^2 and the reflection coefficient of the mirrors to be 0.9 (the same for the concentrator and heliostat), we obtain $D_c = 17.81$ m ≈ 18 m. This value of the concentrator diameter is quite large. Therefore, it is necessary to clarify experimentally the smallest value of the concentrated flow density, which is sufficient to melt the material processed.

Figure 2 shows the dependence of the concentrator diameter on the concentrated radiation flux density. The calculations were performed for two values of the focal spot diameter, 30 cm and 20 cm.

Figure 2 shows that if the concentrator diameter is 10 m, then it must provide a spot with a diameter of 30 cm; therefore, an average radiation flux density of 65 W/cm^2 can be obtained in the focal zone of such a concentrator.

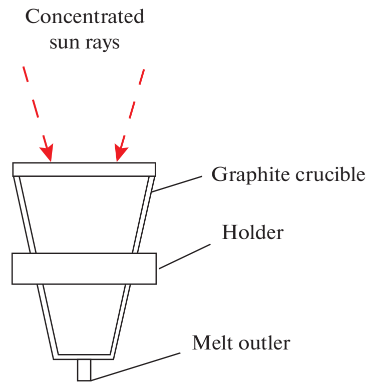

Fig. 3. Graphite melting furnace.

For the purpose of processing materials in the focal region, we have developed a special design of a graphite melting unit in the form of a truncated cone (Fig. 3).

The process of processing metallurgical waste from the AMMP in a solar furnace consisted of melting the material and quenching the melted material in water. Analysis of the chemical composition of the melted material showed the presence of substances of metallic (approximately 22 wt % FeCu alloy) and ceramic (approximately 71 wt % $CaMaSi_2O_6$) compositions separately.

In a carbon medium, the process of metal reduction from their oxide states proceeded by the reaction MeO + C = Me + CO. However, before the melt drops enter the water, the metals in the drop have time to oxidize in the air atmosphere, according to their chemical affinity for oxygen. For example, at a temperature of 1600°C, the chemical affinity of elements for oxygen decreases in the series Be, Ca, Zr, Mg, Al, Ti, C, Si, V, B, Mn, Cr, Sb, Zn, Fe, W, Mo, Co, Ni, Cu, and As. Due to the fact that the elements located in this row to the left of iron have a higher chemical affinity for oxygen in comparison with it, they quickly oxidize, which is observed in the experiment.

The chemical composition of the melt of the AMMP technogenic waste material subjected to ultrasonic exposure is given in Table 2.

An analysis of the composition of the metal part of the technogenic waste melted in a solar furnace showed that their preliminary ultrasonic treatment led to an eightfold increase in the amount of reduced copper compared to the initial state of the material. In this case, we observe an increase in the yield of metals up to 25 wt %, which is the maximum indicator for the studied compositions of the masses. This may be due

Table 2. The chemical composition of the metal part of the melted technogenic AMMP waste subjected to ultrasonic treatment

Element	Fe	Cu	Mo	SiO_2	CaO	Sb_2O_3	MgO	MnO	PbO	ZnO
Content, wt %	88.01	3.28	0.63	2.81	3.32	0.12	1.13	0.22	0.24	0.21

to the acceleration of technological processes based on the absorption of the energy of high-intensity ultrasonic frequency mechanical vibrations by the particles of the substance. In particular, as noted in [19], the use of high-intensity ultrasonic vibrations accelerates processes by a thousand times and increases the yield of useful products, as well as makes it possible to obtain a material with new properties.

The analysis shows that the capacity of the melting unit is 2 kg of material. Such an amount of substance can melt in 3 s of irradiation in the focal area of the solar plant. So, if a continuous supply of material to the melting unit is provided, then it is possible to melt the material in the amount of 2400 kg for an 8-h sunny day. Based on the fact that the minimum number of sunny days in Uzbekistan is 220, then 500 tons of technogenic waste can be processed in a working year. In this case, the yield of iron and copper will be 110 tons and about 16 tons, respectively.

CONCLUSIONS

Thus, the system of mirrors consisting of the heliostat (100 m^2) and the paraboloid-shaped concentrator with a diameter of 10 m can focus the solar radiation flux with a density that is sufficient to melt the metallurgical waste of the AMMP. It has been revealed that when the material is heated in a carbon medium the process of metal reduction from their oxide states proceeds according to the reaction MeO + C = Me + CO. Some metals oxidize when cooled in air according to their chemical affinity for oxygen. It has been revealed that the continuous supply of material to the melting unit will make it possible to melt the material in the amount of 2400 kg per 1 sunny day. This indicates that in 1 year it will be possible to process 500 tons of industrial waste with the extraction of 110 tons of iron, 16 tons of copper on one solar furnace. Solar radiation can become an alternative source of energy in metallurgical processes. It is shown that preliminary ultrasonic treatment of waste materials stimulates an eightfold increase in the amount of reduced copper in the melt compared to the initial state of the material.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest. The authors declare that they do not have a conflict of interest.

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