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TECHNOLOGY OF ELECTRIC MELTING OF BASALT FOR OBTAINING MINERAL FIBER

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The basalt electric melting advantages in application of basalt fiber in industrialized construction and heat power engineering are shown. The results of thermodynamic calculations of the process of Kazakhstan basalt melting are given. The calculations have shown that in gaseous and condensed products of the process there are no harmful substances. Experiments on electric melting of basalt in a reactor with electromagnetic mixing of the melt were carried out. The prospects of electric melting of basalt and obtaining mineral fiber with the use of small-size module installations involving an electromagnetic reactor are shown. The specific energy consumption for obtaining a homogeneous basalt melt does not exceed 1.1 kW·h/kg, which is superior to the widely used SHF-reactors in which the specific energy consumption is several times higher.

Keywords: *basalt, electromagnetic reactor, electric melting, specific energy consumption, gas-dynamical installation, centrifuge, mineral fiber.*

Introduction. In recent years, the abbreviation MMMF (Man-Made Minerals Fiber) — artificial mineral fiber — has become very popular in the world. The world-wide production of MMMF, including slag- and glass wool, amounts to more than 5 million tons per year [1]. About 50% of the world production of MMMF account for glass fiber and glass wool that relate to potentially cancerogenic materials. The production of MMMF in Russia comes to 0.5 million tons per year (10% of the world one). According to forecasts, in recent years, the output of MMMF will increase severalfold in an effort to solve the energy saving problem and to adhere to the requirements of new construction specifications and regulations [1].

The demand for mineral wool increase rapidly in view of its use for heat insulation of buildings, in power engineering and industrial installations, and in pipelines. According to expert assessment, 85% of the entire mineral wool production is used in civil engineering and in residential and public services and 15% in power engineering. According to the information of the European Insulation Manufacturers Association, about 40% of the electric and thermal energy is consumed in the process of the maintenance of buildings, heat pipelines, and constructions in the Common Market countries. Wide application of heat insulation made from MMMF in civil engineering will make it possible to reduce emissions into the atmosphere of the main greenhouse gas — carbon dioxide (CO_2) — which will improve the ecological situation in the world.

The densities of heat insulating materials determine their efficiency: the lower the density of the material, the better its heat insulating properties are. The density of the mineral wool from basalt is 200 times lower than the density of steel, 60 times lower than that of ferroconcrete, and 45 times lower than that of brick. The low density allows mineral wool to compete with foam concretes, whereas the high heat resistance (up to 1273 K) — to compete with synthetic polymer porous fillers. Moreover, articles made from basalt MMMFs may be used for 60–80 years in corrosive media [2].

Blast cupolas and ore-smelting furnaces exhibit high capacities — up to a few tons of melt per hour. The production of mineral wool in the USA and Common Market countries is based on such furnaces. But they are mainly adapted for processing slags, the specific energy expenditures on the melting of which vary within 3–7 kW·h/kg. These furnaces are very cumbersome, require large capital outlays, costly cleaning of escaping gases, and utilization of coke residues.

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In recent years, in connection with the higher requirements on the protection of the surrounding medium and depletion of the reserves of traditional types of fossil fuels, great attention is paid to the application of ecologically pure electric energy sources for processing different kinds of mineral raw materials (basalt, gabbroic, and diabase rocks, energy slags, and other mineral wastes [3]) in electric furnaces. Electric glassmaking furnaces with daily output of less than 25 t turn out to be economically more profitable than large-capacity gas and coke furnaces [4]. If we take into account the necessity of using costly equipment to reduce pollution of the surrounding medium produced by these furnaces, the advantages of electric furnaces increase. It should be noted here that traditional electric furnaces are cumbersome structures lined by costly ceramics.

In the Russian Federation, increasing use has been made of electric high-frequency installations for melting mineral raw material, including basalt. The main developers and manufacturers of these installations are two firms: the Federal State Unitary Enterprise "Federal Scientific-Production Center Altai" (the city of Biisk) and Limited Liability Corporation "The Firm Ros′" (the city of Barnaul of the Altai region of RF) [5]. The major part of these installations is a water-cooled graphite or ceramic crucible located in a copper inductor whose electric feeding is provided by a high-frequency generator with a frequency from 0.44 to 1.76 MHz. The installations are compact, easily mounted and serviced, and allow one to obtain a well homogenized melt due to its overheating (above 2073 K) with subsequent cooling to the required temperatures (of the order of 1823 K) and discharge of the melt in the upper part of the crucible. The induction heating and overheating of the melt lead to increased energy expenditures from 2 to 4.5 kW·h/kg per kg of melt. Moreover, there are limitations on the output not exceeding 100 kg/h.

Taking into account the foregoing, it seems worthwhile to conduct melting of mineral raw material with subsequent obtaining basalt wool in an electromagnetic reactor (EMR) with higher ecological-economic characteristics as compared to the above-considered fuel and electric furnaces. In this article, we present the results of a thermodynamic analysis and of experimental investigation of the process of melting basalt in a three-phase reactor with bulk electromagnetic mixing of melt [6–8] with its subsequent distention into a basalt fiber.

The most important property of the basalt fiber is that it melts at a temperature of 1423 K, which is much higher than for the glass fiber and is close to the melting point of ceramic fiber. At the same time, basalt fiber is much cheaper than the ceramic one. The temperature of application of basalt fiber varies from 13 to 973 K whereas glass fiber is applied in the temperature range from 223 to 653 K. Basalt fibers have a high chemical resistance to the influence of moisture, solutions of salts, chemical and alkaline media. Basalt-fibrous materials are noncombustible, and at high temperatures they do not emit harmful gases. The thermal conductivity coefficient of basalt wool is of the order of 0.05 $W \cdot m^{-1} \cdot K^{-1}$ [5].

Basalt continuous fiber finds wide application in composite construction materials as an additive to concrete, tile, pedestrian-way tiles and asphalt, and railroad ties. Chemical treatment of the surface makes it possible to provide direct connection of basalt with epoxy regions and other polymeric systems. This is especially efficient in the production of basalt-plastic fittings, various construction profiles, pipes, and nets [9].

Pierced mats from basalt fiber without fillers and binding components have excellent heat- and soundproofing properties, but they do not rot and are noncombustible. Therefore pierced mats are used for raising fire-resistance of metal structures and boxes of the systems of ventilation and removal of flue gases. For example, application of rolled basalt fire-proof material of Public Corporation "Tizol" (the city of Nizhnyaya Tura, Sverdlovsk region, Russia) in Russia and Kazakhstan provides protection from fire for more than 3 mln m^2 of building structures and engineering supply lines per year [10].

Thermodynamic Calculations of Heating and Melting of Basalt. To determine the optimal parameters of the technology of melting mineral substance, thermodynamic calculations of heating and melting in an electromagnetic reactor were carried out. The electromagnetic reactor is a thermally insulated system, the function of the lining in which is played by a natural layer of slag lining deposited in the process of reactor operation from the melt layer that contacts with the water-cooled walls. Thus, the process of melting in such a reactor is close to adiabatic one, and for calculating such a process it is possible to use the methods of numerical analysis for isolated thermodynamic systems.

Calculations of high-temperature processes of melting and processing of mineral raw material were carried out with the aid of a universal program of thermodynamic calculation of multicomponent heterogeneous systems TERRA [11]. Table 1 presents the chemical composition of the main types of Kazakhstan basalts used for calculations. The calculations of heating and melting of basalt were made in the temperature interval 400–2000 K at a pressure of 1 atm. Account was made of the erosion of graphite electrodes by adding 2% of carbon to basalt.

TABLE 1. Chemical Composition of Basalt Rocks of Kazakhstan

Deposit	Content, wt.%									
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5
Aktyubinsk	47.29	12.93	13.56	1.25	7.91	13.98	2.95	0.13	–	–
Arkharly	51.14	16.44	10.96	1.87	4.07	10.4	2.84	1.46	0.15	0.67
Malaisary	49.93	19.30	11.41	0.98	5.12	9.55	2.67	0.66	0.18	0.20

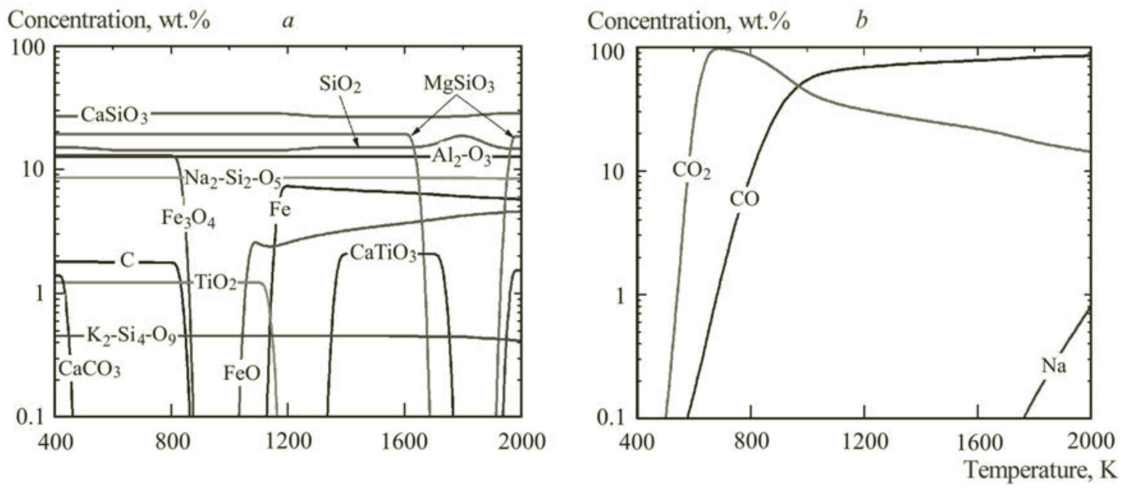

Fig. 1. Temperature dependence of the compositions of Aktyubinsk basalt melt (a) and of the gas phase (b) with account for 2% carbon addition.

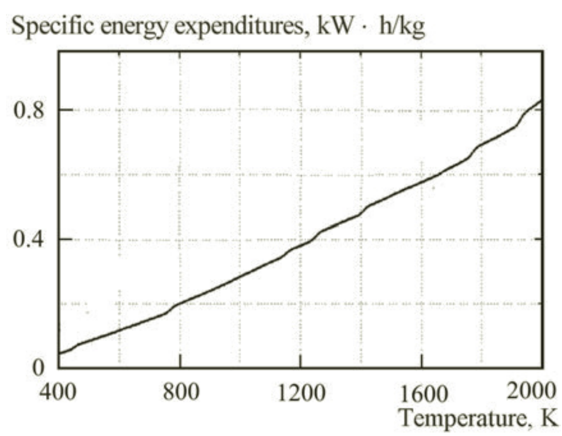

Fig. 2. Temperature dependence of specific energy expenditures on heating and melting of Aktyubinsk basalt.

Figure 1 presents equilibrium compositions of condensed and gaseous phases. In the entire temperature range the melt is composed of calcium monosilicate ($CaSiO_3$), silica (SiO_2), aluminum oxide (Al_2O_3), sodium disilicate ($Na_2Si_2O_5$), and potassium tetrasilicate ($K_2Si_4O_9$). Magnesium monosilicate ($MgSiO_3$) is present in the temperature range up to 1700 K, or above 1900 K. In the temperature range 1350–1750 K there is also calcium titanate ($CaTiO_3$). At a temperature above 1200 K one can observe iron (Fe) and its oxide (FeO). As to the gaseous phase, it consists mainly of carbon oxides (CO and CO_2) and sodium vapors (Na). Note that at a temperature exceeding 1000 K, the gaseous medium is reducing.

Figure 2 presents the temperature dependence of specific energy consumption of heating and melting of Aktyubinsk basalt. At a melting temperature of basalt in the range 1500–1600 K the specific energy consumption on the process varies in the range 0.56–0.58 kW·h/kg.

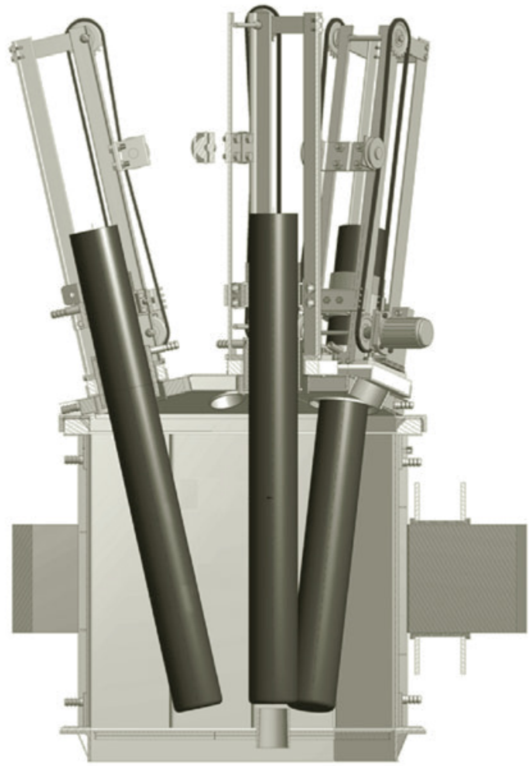

Fig. 3. General view of EMR with a neutral central electrode and force electrodes located at a certain angle relative to the chamber axis.

Testing the Basalt Melting Process in an Electromagnetic Reactor. Experiments on heating and melting of basalt were carried out in an electromagnetic reactor with three immersion electrodes with the use of the principle of noncontact electromagnetic displacement of the melt. The electromagnetic reactor is a melting chamber made of vertical water-cooled isolated sections from sheets of stainless nonmagnetic steel. From above the chamber is limited by a water-cooled lid on which there are devices for insertion of three force electrodes and of one central neutral electrode and for charge supply as well as a branch pipe for effluent gases, and below there is the cooled bottom (hearth) with a lap-hole for discharging the melt (Fig. 3).

Figure 4 presents the schematic diagram of the electromagnetic reactor. From the outside the chamber is surrounded by a three-phase electromagnet of a transverse magnetic field with windings connected successively into the circuit of electrodes. The electric power supply to the reactor is provided by a three-phase controlled thyristor regulator connected into the circuit through an isolation transformer. The reactor is started by faulting electrodes on the track of graphite powder or with the aid of additional heat source, for example, a plasmatron torch. After obtaining a melting lens of basalt, further heating of the raw material occurs at the expense of the conductivity currents in the melt between force electrodes. As a result of the interaction of these currents with the magnetic field that encloses the melting zone of the three-phase electromagnet, forces appear that act on the melt and ensure its electromagnetic mixing and, as a consequence, accelerate the heating of the basalt melt, improve the homogenization of the melt, and increase the efficiency of the electromagnetic reactor.

The neutral electrode acts as a gate of the tap-hole and favors additional heating of the melt in the lower part of the reaction chamber in the region of the tap-hole. At the reactor output of up to 200 kg/h the diameter of the outlet of the tap-hole is 8 mm.

The reaction chamber in section has a hexagonal shape. This shape was chosen from the conditions of strengthening the magnetic field, which is achieved by bringing closer together the poles of the electromagnet preserving a large enough distance between the electrodes. This leads to an increase in the working voltage and to a decrease in the value of the working current at the given reactor power. Note that the reduction of the value of the working current leads to a decrease in the current density on the electrodes, and consequently, to a decrease in their wear. Since in the initial period, up to the formation of the lens of melting, the process of basalt melting is hampered, the spacing between the electrodes was set to be minimal.

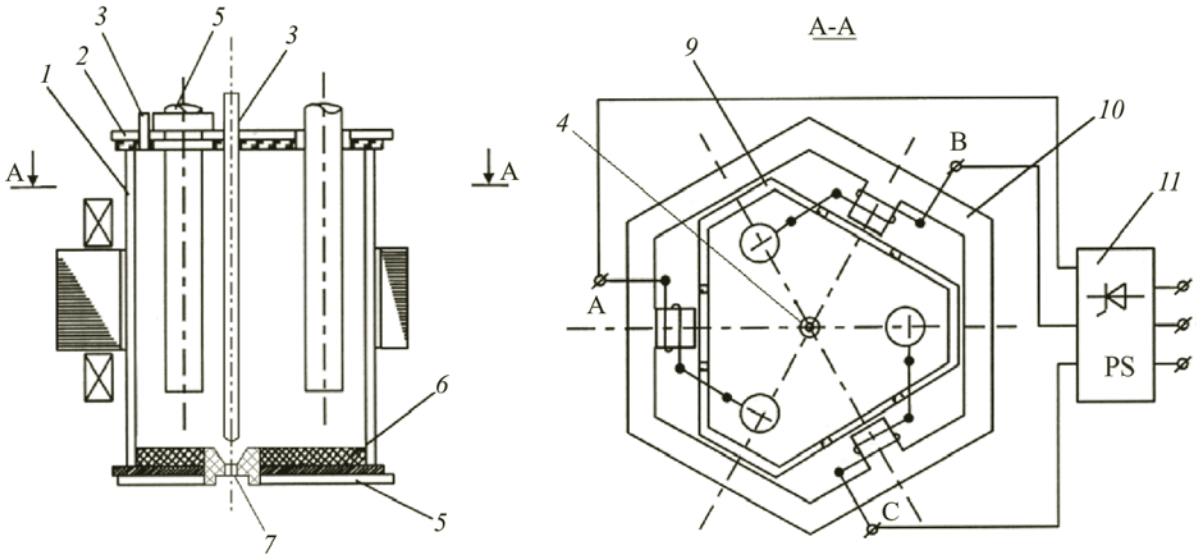

Fig. 4. Schematic diagram of three-phase EMR with three immersion force electrodes: 1) melting chamber; 2) lid of the reactor; 3) pipe for supplying basalt crumbs; 4) central graphite electrode; 5) force graphite electrodes; 6) bottom of the reactor; 7) refractory lining of the reactor bottom; 8) tap-hole for discharging melt jet; 9) sections of the reactor chamber; 10) three-phase electromagnet; 11) power supply source.

In the working regime of the melting of basalt, the force electrodes were removed from each other to a certain distance to ensure the needed electric power and increase the voltage between them. To provide this procedure, the force electrodes, together with the mechanisms that supply them, are fitted on the lid of the reactor in a slanted position, which allows one to bring the electrodes to the center when descending them. In addition to the three force electrodes there is also a central neutral electrode mounted on the chamber axis which is also equipped with a mechanism for displacement that provides periodic regulated discharge of the basalt melt.

The melt from the electromagnetic reactor is discharged with the stream temperature at the exit equal to 1813–1923 K and, as tests have shown, it turned out to be extremely aggressive in relation to various ceramic materials used for fabrication of the tap-hole. Thus the surfaces of the tap-holes made of quartz, zirconium dioxide, and titanium nitride were destroyed (dissolved by the melt jet). The best results were obtained for water-cooled tap-holes made from siliconized graphite. An insert from siliconized graphite is pressed into a graphite cap which in turn with the aid of the lower flange is fixed in a water cooled conical sleeve. The entire system is fixed in the sleeve of the bottom part of the reactor. To thermally insulate the internal surface of the melting chamber use was made of chamotte brick of thickness of up to 65 mm. A mixture of crushed chamotte and quartz glass on liquid glass (silicate glue) was used as a binder.

During the operation of the electromagnetic reactor the lining on the surface was partially eaten up by the melt, the surface was covered with slag, and subsequently a stable bath of the melting chamber was formed. The thickness of the slag layer attained 30–35 mm in the lower part and 8–12 mm in the upper part. Figure 5 shows the photographs of the electromagnetic reactor in operation (Fig. 5a) and of the escaping jet of the basalt melt (Fig. 5b).

In the experiments, use was made of two methods of obtaining mineral fiber from a melt: gas-dynamical inflation and mechanical one (with the use of a centrifuge). For the gas-dynamical inflation of the basalt melt jet into fiber use was made of a gas-dynamical head adapted for a flow rate of up to 250 kg/h of the melt. Table 2 presents the results of balance melts of basalt after the electromagnetic reactor attained the working regime in discharging the melt jet and continuous supplying the raw material through the branch pipe for inserting basalt crumb.

It follows form Table 2 that the total heat losses through the water cooled sections of phase "A" are 16.54 kW, of phase "B" 14.62 kW, and of phase "C" 16.21 kW. The total heat losses of the electromagnetic reactor attain 79.61 kW, which provides the thermal efficiency of the reactor equal to 53.2%.

TABLE 2. Technical Characteristics and Thermal Balance of EMR

Parts of EMR	No. of unit	Water flow rate, kg/s	Water temperature at exit, K	Temperature drop in surrounding water, deg	Heat losses, kW
Sections of phase "A"	1	0.1	297	6	2.51
	2	0.1	299	8	3.35
	3	0.1	299	8	3.35
	4	0.09	308	17	7.33
Sections of phase "B"	1	0.09	300	9	3.98
	2	0.1	292	1	0.42
	3	0.09	297	6	2.26
	4	0.1	310	19	7.96
Sections of phase "C"	1	0.1	302	11	4.61
	2	0.1	296	5	2.1
	3	0.09	298	7	2.8
	4	0.1	307	16	6.7
Electrodes	A	0.075	297	6	1.89
	B	0.06	296	5	1.26
	C	0.075	298	7	2.2
	CGE	0.075	297	6	1.89
Coil	A	0.05	300	9	1.88
	B	0.05	308	17	3.56
	C	0.05	309	18	3.77
Lid		0.13	310	19	10.35
Bottom		0.13	301	10	5.44

Based on the bringing the material and thermal accounts to a balance for the process of basalt melting, the following integral characteristics of the process have been obtained:

1) electric power of EMR 170.1 kW (current 295 A, voltage 333.3 V);
2) basalt flow rate 192 kg/h;
3) specific energy expenditures 0.9 kW·h/kg;
4) heat loss of EMR 79.61 kW;
5) EMR efficiency 53.2%;
6) wear of a force electrode 0.085 kg/h.

As a result of the tests of the electromagnetic reactor with the volume of the melting zone of 0.2 m^3 the following technical characteristics have been obtained:

1) power 170–200 kW;
2) basalt melt output 180–200 kg/h;
3) temperature of the outflowing melt jet 1813–1923 K;
4) specific expenditures on basalt melting 0.9–1.1 kW·h/kg;
5) time of attainment of the working regime 60 min;
6) thickness of the slag lining in the upper part of the EMR 8–12 mm;
7) thickness of the slag lining in the lower part of the EMR 30–35 mm;
8) air consumption by a gas-dynamical head 1080 m^3/h (compressor power 75 kW).

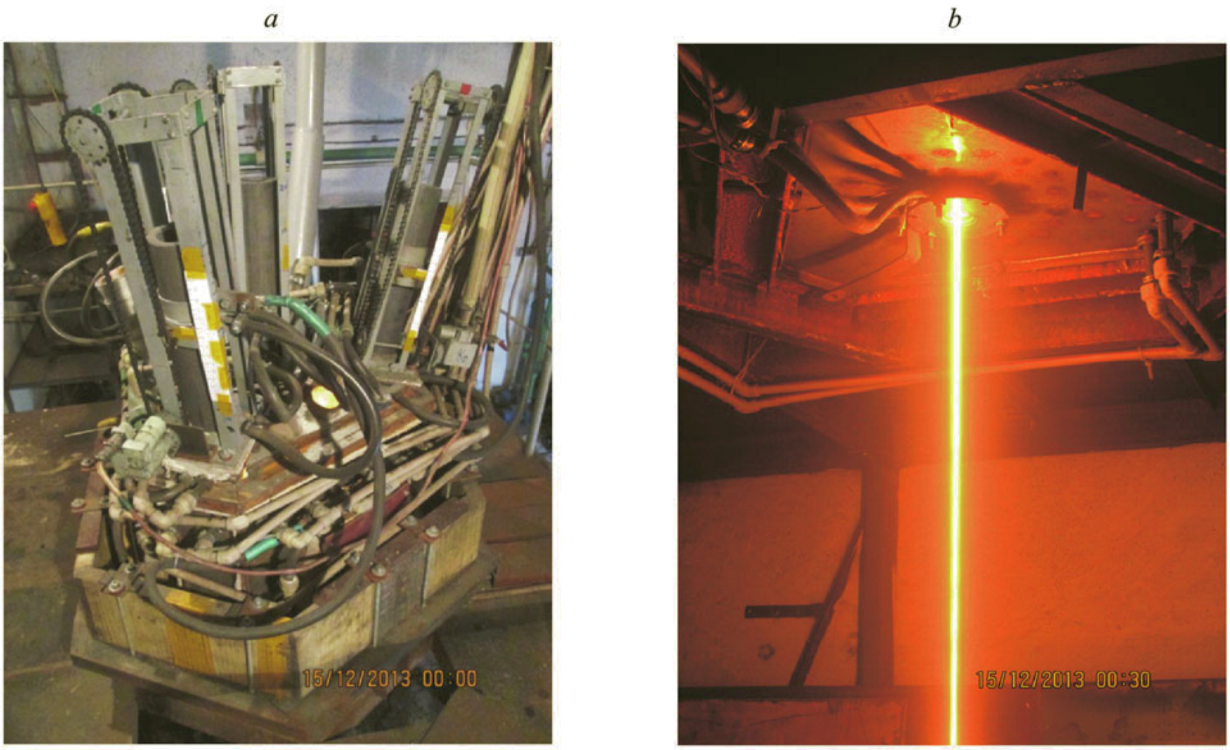

Fig. 5. Experimental EMR (a) and basalt melt jet (b) (temperature 1873 K).

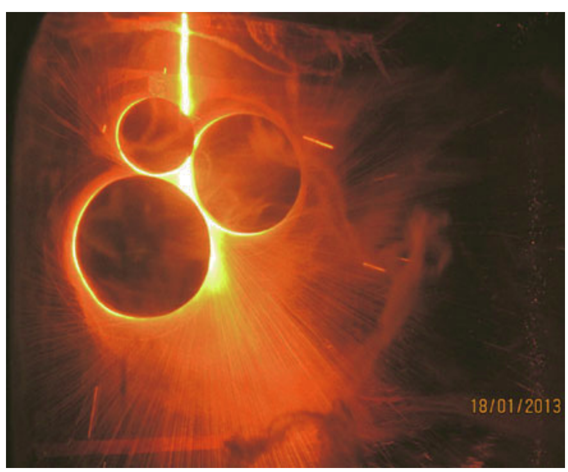

Fig. 6. Inflation of the basalt melt jet into fiber with the aid of a three-roll centrifuge.

Thermodynamical calculations have shown that specific energy expenditures on the processes of heating and melting of basalt in an electromagnetic reactor amount to 1 kW·h/kg. Thus, the discrepancy between the experiment and prediction does not exceed 20%, which is a good result that allows one to use the program TERRA for calculating the processes of heating and melting of basalt in an electromagnetic reactor. Note that the measured low energy expenditures profitably distinguish this technology from the SHF-technology, with the use of which the energy expenditures are 3–4 times higher. The efficiency of the electromagnetic reactor is 2.5 times higher than the efficiency on mineral wool cupola (a shaft vertical furnace) [12].

For centrifugal inflation of a basalt jet outflowing from the tap-hole of the reactor, use was made of a three-roll centrifuge with a settling chamber and a flow fan (Fig. 6). After the settling chamber the basalt fiber in the form of a soft mat was put on a conveyer. The centrifugal inflation of the basalt jet into a fiber has shown a greater energy efficiency in comparison with gas-dynamical inflation. This is explained by the decrease in the used power of the blow fan to 30 kW in comparison with the power used by the air compressor, i.e., 75 kW.

Conclusions. Thermodynamic calculations were performed for the process of heating and melting of basalt in wide temperature range (300–2000 K). The calculations have shown that the specific energy expenditures of heating and melting of basalt amount to 0.8 kW·h/kg.

The tests have demonstrated that the average energy expenditures on obtaining basalt melt in an electromagnetic reactor come to 1 kW·h/kg. The discrepancy between the experiment and prediction does not exceed 20%, which allows one to use the program TERRA for calculating the processes of heating and melting of basalt in an electromagnetic reactor and determining the initial data for designing it. The investigations carried out have shown the high efficiency of basalt melting in an electromagnetic reactor. The low specific energy expenditures on melting and obtaining a melt jet profitably distinguish the EMR technology from the well-known technologies of melting mineral materials, including basalt.

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