Energy-efficient furnace for basalt fiber production

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Annotation. In recent years, the production of products made of composite materials based on carbon fiber, glass fiber, and basalt fiber has been developing. Composite products based on continuous basalt fiber are becoming more and more widespread, since basalt is practically an inexhaustible raw material and is actually prepared by nature for use. This article suggests the design of a melting furnace, since the melting process is the most energy-intensive in the production of fiber. The article provides a list of heat engineering principles necessary for creating an energy-efficient furnace, such as the maximum heating of basalt by waste gases, Gorenje fuel directly in the basalt melt and the organization of the melt barbatage, heating of the gas-air mixture and the use of vacuum in the melt clarification zone. This paper presents the results of a demonstration study on physical models showing the operation of the bubbling layer, the saturation of the melt with gas bubbles, and the process of removing visible gas inclusions. The final part of the article presents the results of evaluating the performance and energy costs in the developed furnace.

1. Introduction

Recently, new products based on composite materials are increasingly appearing, this is due to the fact that such materials are highly efficient and durable. The authors [1] argue that the prospects for progress are associated with the development and widespread use of composite materials (composites). Products made of composite materials in the civil sphere, as a rule, replace products made of steel [2]. Iron as the main component of steel products is a fairly common element on earth, but the production of steel requires additional materials, such as coking coals, alloying elements, etc., as well as elements for extracting it from iron-containing ores, multi-stage processing and finishing to the required quality in the production of steels.

Meanwhile, special attention is paid to such material as basalt. In a sense, the volume of basalt is inexhaustible. Together with granite, basalt forms the solid shell of the Earth. It is an erupted igneous rock with a SiO₂ content of 42÷52% [3], according to an earlier source [4] the chemical composition is presented in table 1.

| Component | %     | Component | %     |
|-----------|-------|-----------|-------|
| SiO₂      | 50.66-47.46 | Na₂O      | 2.92-2.59 |
| Al₂O₃     | 13.89-12.60 | K₂O       | 1.29-0.72 |
| Fe₂O₃     | 4.78-2.37  | H₂O       | 2.28-0   |
| FeO       | 11.60-7.25 | TiO₂      | 2.87-1.3 |
| MgO       | 9.50-4.73  | P₂O₅      | 0.78-0.37 |
| CaO       | 9.83-8.2   | MnO₂      | 0.31-0.12 |

It is important to note that basalt is a multicomponent structure with various crystalline and partially amorphous mineral phases [5].

Production of basalt fiber is about 50 thousand tons per year [6], the annual growth in production and consumption of basalt continuous fiber under the source data [7] is 10÷14%.
At the moment, there is a huge variety of different technologies for the production of composite products [8], some of them [9]: manual laying, automated laying, spraying, vacuum forming, pressure impregnation, winding forming, pultrusion, etc.

2. Existing technology and its features
The General structural scheme for the production of continuous basalt fiber includes the extraction of rock in a quarry (usually by explosive method), crushing, screening, washing, dewatering, and then into a melting reactor where at temperatures of 1 400÷1 600°C is the melting of basalt. The basalt melt enters the furnace feeder and passes through the holes of the die feeder. Elementary basalt threads with a diameter of 8÷14 microns from the die feeder are fed to the oiling device, the winding machine winds continuous fibers on bobbins. After that, the primary thread from the bobbins of the harnessing machine is rewound to the roving bays. In the nitisbornik, elementary fibers are folded into a single bundle (roving) and wound on a bobbin by a winding machine on its spindle.

The briefly presented technology shows that the most important from the point of view of applied heat engineering is the creation of an energy-efficient furnace for basalt melting, since this is the most high-temperature process.

Optimization of reactor operation is usually an increase in the energy efficiency of fuel use, which can be achieved in three ways [10]:
1. reduction of thermal waste of the installation (here and losses through masonry, process openings, with flue gases, outgoing product flows, etc.);
2. regeneration of heat waste (air heating, charge heating, etc.);
3. external use of heat flows (water heating, steam production, electricity, etc.).

Furnaces that partially use the heat of exhaust gases include a furnace for melting basalt [11] structurally, the installation has a longitudinal flame propagation. Basalt melting occurs when the furnace temperature is maintained at 1 450 ± 50 °C as a result of burning a gas-air mixture, due to the low thermal transparency of the melt and the increased crystallization temperature, its thickness of the active melting layer does not exceed 150 mm.

According to the source [12], the total cost of production of basalt fibers is 1.5 cubic meters of gas and 4 kWh of electricity per 1 kg of product, which in terms of 57,630 MJ/t.

At this stage, it is important to understand the theoretical minimum energy consumption for the basalt melting process. when calculating the theoretical minimum energy consumption for basalt melting, the heat capacity was taken in accordance with the reference book [4], presented in the table. 2.

| №  | Temperature range, °C | Specific heat capacity, kJ/(kg·°C) |
|----|----------------------|-----------------------------------|
| 1. | 20 – 470             | 0.199                             |
| 2. | 470 – 750            | 0.243                             |
| 3. | 750 – 880            | 0.626                             |
| 4. | 880 – 1 190          | 0.323                             |
| 5. | 1 250 – 1 500        | 1.675                             |
The results of calculations are a temperature-thermal graph of basalt heating and melting (figure 1), which allowed us to determine the theoretical minimum cost of 1,244 kJ/kg required for heating, melting, and overheating of basalt to a temperature of 1,450°C (the most common in operating furnaces).

A characteristic feature of rock melts is a significant change in viscosity in a narrow temperature range. The source [11] illustrates that the optimal temperature for the minimum breakage value of a continuous fiber is a temperature of 1,220°C.

3. Developed version of an energy-efficient furnace

The greatest contribution to improving the energy efficiency of the thermal engineering process of basalt melting is made by the thermal engineering principle of the submerged torch, which is one of the ways to carry out heat and mass transfer between two media, one of which is a liquid (melt), the other a gas.

The principle of a submerged torch involves the interaction of gas and liquid, but the main difference between this principle is the powerful mechanical interaction of gas and liquid. This is achieved by passing the burning gas through the entire volume of the liquid, which leads to a significant development of the gas – liquid surface, strengthening the convective component of heat and mass transfer, thus intensifying heat exchange.

High-temperature bubbling Gorenje inside the melt creates a complex structure, including solid particles, liquid, and gas. In the melt bath, a large heat exchange surface is formed between the combustion products and the material melt. Intensive mixing of the melt will lead to an increase in the melting rate, as well as to the uniformity of the process product.

An important advantage of submersible combustion devices is the combination of several functions in one device: a heat energy generator and a motion stimulator, mixing of the liquid [13, 14]. Gorenje is a unique device. Bubbling the melt reduces the overall temperature in the furnace space above the melt.

The next and key process is the clarification of the melt. Methods of clarification or degassing of melts are known [15], the main ones can be distinguished:
- at atmospheric pressure with increasing melt temperature;
- by reducing the height of the melt;
- vacuum treatment of the melt.

The thermal engineering principles and technical solutions presented above allowed us to propose the design of the reactor (figure 2) for the method of operation of which a patent was obtained [16].

In accordance with figure 2, the perspective furnace should consist of a device 1 for preheating the basalt charge, made in the form of a mine, the design is protected by a patent [16]. The task of this device is to heat the incoming basalt in a countercurrent scheme with gases leaving the melting zone of the reactor to a temperature close to the melting temperature (1,000°–1,150°C), which pass through the perforated cones.

Descending, the perforated plate of the lower tier delivers a portion of heated basalt to the melting zone. The main part of the melting zone is the bubbling of the melt 2 organized by dispersed purging of the melt through a perforated tray. The base is tilted to allow natural movement of the melt and molten basalt pieces. Additional heat sources 3 are provided to maintain the required temperature.
The melting part of the furnace ends with a partition, the task of which is to minimize the impact of melt vibrations from the melting zone on the melt entering the lifting pipe of the melt clarification chamber. Due to the larger getstartline compared to the gas content in the surge pipe camera lightening 4, as well as by creating a vacuum in the chamber of clarification, the melt rises in the chamber lightening moving in a thin layer of melt is the removal of visible bubbles. The discharge in the clarification chamber is carried out through a technological opening. Partition 5 is designed to separate the clarified melt from the downpipe from the UN-clarified melt entering the lifting pipe. The clarified and homogenized melt 6 is fed to the die feeders, where, as in existing furnaces, it is formed into continuous fibers, which are covered with a special substance using an oiler and fed to the device 7 that winds the fibers into bobbins.

4. Demonstration models of the developed furnace

In the Mathematical model of the basalt preheating device (figure 3), the movement of gases through the device is simulated. Figure 3A shows a section of the two upper tiers of the installation showing how the installation can look like in principle, figure 3b shows the distribution of flue gas pressure across the tiers of the installation (without basalt), the total pressure loss is insignificant and according to the simulation results was 5 Pa.

The real picture of the melt bubbling is complicated by many factors, including bubbles interacting with each other, which can lead to changes in their shape and trajectory, as well as to fusion and fragmentation. In connection with this fundamentally important is the demonstration of the physical model.

The purpose of the demonstration models is to clearly show the processes taking place, so when creating a physical model and to provide visibility of the design, organic glass was chosen, and glycerol was chosen as the liquid modeling the basalt melt, since at a temperature of 5÷10°C it has a
viscosity close to that of basalt at a temperature of 1 400°C. According to the source [18], the viscosity of glycerol at 10°C is 3.95 Pa·s, the viscosity of basalt melts according to the source [19] can be 3 Pa·s at a temperature of 1 450°C.

The model provides a perforated tray (figure 4), which will be used in industrial furnaces to intensify the basalt melting process and homogenize the melt. In addition, a part of the reactor designed for glycerol clarification is provided behind the partition, which will significantly reduce the size of the unit due to high-speed clarification of the melt.

5. Performance Evaluation and heat balance of an energy-efficient furnace

At this stage of development of a promising reactor, it seems correct to rely on the known [11] data obtained experimentally, according to which the use of bubbling mode increases the productivity of melting furnaces by almost two times from 1 000÷1 500 kg/(m²·day) in conventional flame furnaces to 2 500÷2 600 kg/(m²·day) in furnaces where compressed air is purged with a flow rate of 17 Nm³/(m²·day). According to the results of experiments and published in the source [11], the use of a combustible gas-air mixture as an energy carrier during bubbling significantly increased the melt temperature, which allowed reducing the temperature of the flame space from 1 450°C to 1 400°C, increasing the service life of the oven.

In furnaces with a radiating torch, the heat transfer coefficient is 700÷1 200 W/(m²·K), and when organizing a torch immersed in the melt during heat exchange of a solid particle with a mineral melt reaches 3 000÷4 000 W/(m²·K) [20], which suggests a twofold increase in the heat exchange rate, and hence the melting rate.

Another factor that allows increasing the melting rate is the use of basalt of a smaller fraction. To date, basalt is served in the furnace with a size of 20÷25 mm, the use of a fraction of 10±5 mm will reduce the melting time by another 2 times.

The next key difference of the new furnace is the heating of the charge to a temperature of 1 000÷1 150°C, i.e. to a temperature extremely close to the beginning of melting. Assuming that a kilogram of continuous basalt fiber requires 1.18 kg of the original basalt, then heating to 1 150°C will allow you to supply material containing 390 kJ, which is 27% of the required amount of heat (1 438 kJ per 1.18 kg of basalt). Thus, the heating period to the melting point has actually been extended beyond the perimeter of the melt bath, which means that the productivity will increase by approximately 27%. All of the above will reduce the melting time by 5÷6 times. The possibility of such a significant increase in productivity has been proven in practice in the ferrous metallurgy. In particular, in open-hearth furnaces, the standard melting time is 5÷6 hours. In the Converter process, the total duration of melting in 100÷350 ton converters is from 40 to 50 minutes [21].

The above arguments allow us to estimate the expected performance of a promising basalt melting reactor at 6 250÷7 500 kg/(m²·day).

6. Conclusions

The growing demand for continuous basalt fiber and competition in the market require the creation of energy-efficient basalt melting furnaces. The creation of such furnaces is possible with an integrated approach that reduces heat losses, including by heating up to 1 000÷1 150°C the basalt entering the
furnace with flue gases, as well as the supply of a gas-air mixture heated to 1 000°C to the furnace. Organization of bubbling of the melt and clarification of the melt by creating a vacuum. The conducted demonstration studies allowed us to determine some dimensions of the basalt melting furnace under development, for example, the height of the arch relative to the melt in the melting part should be 250 mm, and the melt clarification zone should be about 400 mm. When developing and implementing an industrial basalt melting furnace, the existing energy costs of 57 630 MJ/t [12] can be reduced to the estimated 2 629.26 MJ/t. Thus, the energy effect can be up to 55 000 MJ/t.

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