Energy saving of high-temperature processes by intensive melt degassing

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Abstract. The paper considers the possibility of energy saving high-temperature processes for producing melt. Reducing energy consumption is ensured by a set of measures aimed at intensifying the process of degassing of the melt and increasing its efficiency. Presented are modern methods of degassing melts. The main parameters that determine the nature of the movement of gas bubbles in the melt are the Reynolds criterion and the dynamic viscosity of the melt. The viscosity of the basalt melt decreases with increasing temperature. The creation of vacuum conditions in the degassing chamber provides a multiple increase in the rate of degassing of the melt and a decrease in heat loss to the environment.

Key words: intensification, degassing, melt, basalt, energy saving, vacuum.

1. Introduction
Today, the urgent issue is the lack of energy resources, energy saving and environmental friendliness of production [1]. Reducing specific fuel consumption in production is one of the main trends in modern industry [2]. This can have a special economic effect in energy-intensive industries related to ferrous metallurgy and the composite industry. So, the composite materials market in Russia today includes more than 150 major players and amounts to 700 $ million. In this direction, growth is expected to be no less than 20% per year due to the introduction of new technologies, automation, and an increase in production [3]. The volume of the Russian market of ferrous metallurgy is more than 124 $ billion [4]. The industry is mature and growing at a slower pace, but due to the large volume, the introduction of new technologies can have a significant economic effect.

Reducing the energy consumption for heating can be achieved by intensifying technological processes at all stages of obtaining the melt, this reduces the requirements for overheating of the melt and reduces specific fuel consumption. One of such technological processes is degassing of the melt. To obtain a high-quality product from the melt, it is necessary to remove gas bubbles and dissolved non-metallic inclusions.

2. Modern methods of degassing

2.1. Degassing at atmospheric pressure
After heating, the melt passes in a thin layer through special bathtubs of a large area. To achieve the necessary degassing rate, the melt must have a large contact surface with the atmosphere. This leads to
large heat losses to the environment due to heat conduction and radiation. This method is technologically the simplest, not requiring the cost of additional equipment, is the most inefficient and energy-consuming, but it is common in the production of basalt composites, continuous composite fibers [5]. The advantage of this method is the possibility of application in continuous production.

### 2.2. DH vacuum process

This method is used in the metallurgical industry. Up to 12% of the total metal volume from the ladle is sucked into the vacuum chamber through the nozzle. In the chamber, degassing of the melt takes place. Due to the use of vacuum and a small volume of the melt, the process proceeds intensively for 15–30 s [6]. Then the melt returns to the bucket, mixes and a new portion enters the vacuum chamber. This method requires a large number of repetitions of cycles to achieve the required degree of degassing of the entire volume of the melt. Batch evacuation cannot be used in continuous production.

### 2.3. RH vacuum process

The vacuum chamber has two nozzles. In the first case, the melt flows from the bucket into the chamber, in the second, back into the bucket. Due to the constant circulation of the melt through the vacuum chamber, the efficiency of the process increases in comparison with portioned evacuation [7]. To date, this method is often used in large metallurgical plants.

### 2.4. VD vacuum process

The melt bucket is completely placed in a vacuum chamber. The method requires the creation of vacuum in a large volume, while the degassing surface remains quite small compared to the thickness of the melt layer [8]. Because of this, the process takes longer than with circulation evacuation. Ladle evacuation cannot be used in continuous production.

Thus, there is a need to develop an intensive degassing method available for use in the continuous production of composites and metallurgy.

### 3. Review of existing method

The circulating evacuation method RH is basically the closest to the developed one. Circulation evacuation was first successfully applied in 1957 by the German company RUHRSTAHL HENRICHSHUTTE.

The RH facility on figure 1 includes: a vacuum chamber with a vacuum wire, vacuum pumps, a mechanism for moving the vacuum chamber, a dosing and additive system. The vacuum chamber is mounted on a transport trolley to move between the working position and the stand-by position for

**Figure 1.** Scheme of the circulation vacuum degasser RH - TOP. 1 - steel pouring ladle; 2 - a vacuum chamber; 3 - inlet pipe; 4 - drain pipe; 5 - a device for feeding bulk in a vacuum; 6 - burner; 7 - exhaust gas.
vacuum processing. The case of the vacuum chamber is cylindrical, up to 10 meters high, with two nozzles in the lower part. The inner surface of the housing in contact with the melt has a lining with special refractory bricks. The circulation pipes have an additional lining on the outside. The inlet pipe is equipped with a nozzle system for supplying an inert argon gas. The vacuum chamber has a system of gateway devices for introducing additives [9].

The widespread use of the RH-TOP type is due to the possibility of more complete and faster decarburization of the steel melt, which is reflected in a reduction in processing time (by 7–10 min), a decrease in temperature losses, and a lower carbon concentration in comparison with VD / VOD. In addition, the lack of intense interaction with the refining slag of a steel-pouring ladle is useful in the smelting of steel grades IF, which are especially pure in carbon content [10].

4. Suggested model
At the National Research University “MPEI” at the Department of High-Temperature Technology Energy, methods for the continuous melting of various materials are being developed. The use of continuous processes allows us to simplify their automation, reduce equipment downtime, increase product yield and improve its quality. A schematic diagram of a reactor for producing basalt melt [11, 12] is shown in figure 2.

![Figure 2](image-url)

Figure 2. Scheme of the reactor for continuous melting of basalt. 1 - heating zone; 2 - a hopper with a batcher and a basalt loader; 3 - heat exchanger; 4 - furnace arch; 5 - heating burners; 6 - spinneret feeders; 7 - lubricant application mechanisms; 8 - mechanisms for winding fiber onto bobbins; 9 - conveyor; 10 - melting zone; 11 - perforation for gas supply; 12 - pump; 13, 18 - partitions of the degassing chamber; 14 - degassing chamber; 15 - a vacuum pump; 16 - cooling system; 17 - under; 19 - exhaust gas.

A feature of such systems is the impossibility of using traditional methods of degassing the melt. At the Department of High-Temperature Technology Energy at the National Research University MPEI, the system is being developed and physically modeled for intensive degassing of the melt. The main feature of the developed model is the ability to work in continuous mode with a constant flow of the melt through the degassing chamber. In contrast to the method of circulating evacuation, the degassing of the melt in the proposed installation occurs in one stage. At the moment, one of the important development tasks is to optimize the installation for use with melts of different viscosities (steel, basalt, etc.) in various industries. It is necessary to take into account viscosity, melt temperature, the costs of degassing systems and heat loss.

The main parameter determining the efficiency of the installation for degassing the melt is the rate of rise of gas bubbles. The nature of the movement of gas bubbles in a liquid is determined by the Reynolds criterion, which is determined by the formula [13]:

\[
\text{Re} = \frac{\rho v D}{\mu}
\]
Re = \frac{Dw\rho}{\mu} \quad (1)

where D is the diameter of the bubble; w is the velocity of the bubble; \rho is the fluid density; \mu is the viscosity of the fluid.

For values of Re \leq 1, the laminar nature of the movement is observed, the speed of which is calculated by the following formula [14]:

\begin{equation}
\omega = g \frac{D^2(\rho - \rho_a)}{18\mu} \quad (2)
\end{equation}

where g is the acceleration of gravity; \rho_a is the gas density.

The values 1 < Re < 10 correspond to the transition regime, after which the turbulent nature of the movement is established at Re > 10 [15]. The speed in this mode is determined by the formula:

\begin{equation}
\omega = \sqrt{\frac{2\sigma}{D^2(\rho - \rho_a)}} \quad (3)
\end{equation}

where \sigma is the surface tension.

Basalt is characterized by a significant decrease in viscosity with increasing temperature [16]. A number of methods for calculating the viscosity of basaltic melts are proposed. The regression equation [17] has the following form:

\begin{equation}
\mu = A \times (T - 1100)^{-2.58} \quad (4)
\end{equation}

where A is a coefficient depending on the chemical composition of basalt rock, t is the melt temperature.

As a result of experimental work to determine the high-temperature viscosity of rock melts on a viscometer, carried out at the Department of Glass and Ceramics Technology, BSTU [18], it was found that the mathematical model given in equation (4) ensures good convergence of the calculated and experimental data. Thus, assuming the basalt melt viscosity \mu = 18.0 at a temperature T = 1300 °C [19], it is possible to calculate the viscosity for temperatures of 1400 °C, 1500 °C, 1600 °C, and 1700 °C. The obtained values of the dynamic viscosity of the basalt melt are shown in table 1.

Given the features of the nature of the movement of gas bubbles in the liquid and the properties of the basalt melt at various temperatures, it is possible to construct graphs on figure 3 showing the dependence of the speed of movement of bubbles in the melt on their diameter. In the graphs presented on figure 3, the extremum corresponds to a change in the regime of motion of the bubble. It is seen that the rate of ascent of a gas bubble in the laminar regime increases along a parabola with an increase in its diameter. Moreover, the lower the melt viscosity, the steeper the parabola. In transition mode, the velocity decreases according to the hyperbolic law. The nature of the movement of bubbles of larger diameter is not of interest, since their diameter will exceed the height of the melt layer in the degassing chamber, which is up to 50 mm.

In the production of basalt composites, in particular basalt superthin fibers (BSTF) and basalt continuous fibers (BCF), the absence of even minimal, on the order of 1 \mu m [20], gas inclusions and voids in the melt fed to the bottling is especially important. Based on the graphs on figure 3, the speed of movement of such bubbles is extremely small. This is due to the low density and high viscosity of the basalt melt. By creating a vacuum in the degassing chamber, it is possible to increase the diameter of the gas bubbles contained in the melt and increase their speed. n is the ratio of the rate of ascent of bubbles in the degassing chamber when created in her discharge to speed at atmospheric pressure. The dependence of n on the discharge \Delta P in the degassing chamber is shown in the graph on figure 4. Dependence has the form of a steep hyperbole. Thus, with an increase in rarefaction and approaching vacuum, the intensity of degassing of the melt increases significantly. When a low vacuum degassing is created in the chamber, the process speed increases by 22 times, in conditions of medium vacuum - by 102 times. On this basis, the creation of a large vacuum in the degassing chamber of a basalt melt using vacuum pumps is promising.
Figure 3. Graphs of the dependence of the rate of ascent of a gas bubble \( w \) on its diameter \( D \) for basalt melts of different temperatures, respectively: I - 1300 °C; II - 1400 °C; III - 1500 °C; IV - 1600 °C; V - 1700 °C.

Table 1. Dynamic viscosity of basalt melt at various temperatures

| Temperature \( T \) (°C) | Dynamic viscosity \( \mu \) (Pa*s) |
|--------------------------|----------------------------------|
| 1300                     | 18.0                             |
| 1400                     | 6.3                              |
| 1500                     | 3.0                              |
| 1600                     | 1.7                              |
| 1700                     | 1.1                              |

Figure 4. A graph of the velocity ratio \( n \) and the discharge in the degassing chamber \( \Delta P \).
5. Conclusion
Optimization of technological processes in industry is an important task of modern science. In the context of a decrease in natural fuel reserves and an increase in consumption, its importance increases many times over. One of the areas providing energy saving opportunities is the intensification of melt production processes. At the Department of High-Temperature Technology Energy of the National Research University MPEI, physical modeling of degassing processes is being carried out to verify theoretical calculations and assumptions. In the developed unit, various measures have been taken to reduce the energy consumption of high-temperature processes. Creating a vacuum in the degassing chamber leads to an increase in the rate of degassing of the melt by 20-100 times, which allows to reduce the dimensions of the installation. Thus, thermal losses to the environment are reduced, and the requirements for the room in which the unit is installed are reduced. The continuous operation of the degassing unit provides a constant temperature regime, in which there is no need to heat the unit to maintain the temperature between cycles.

From the point of view of degassing processes, the highest temperature of the melt is optimal, since under such conditions a low viscosity is ensured. With a decrease in viscosity, the speed of movement of the melt in the furnace increases, the efficiency of the degassing unit, and the degree of homogenization of the melt. Thus, the comprehensive optimization and intensification of high-temperature processes according to the methods described in this work suggests the possibility of a significant reduction in energy consumption in melting furnaces.

References
[1] Federal law of 23.11.2009 N 261-FZ On energy saving and on improving energy efficiency and on amendments to certain legislative acts of the Russian Federation (ATP Consultant Plus)
[2] Ushakov V Y 2011 The main problems of energy and possible ways to solve them Bulletin of the Tomsk Polytechnic University 4 513
[3] The Ministry of Industry and Trade of Russia 2017 available at http://minpromtorg.gov.ru/press-centre/news/#rossiyskiy_rynok_kompozitov_pokazyvает_ezhegodnyy_rost_na_20 (Accessed 5 May 2020)
[4] Metallurgy of Russia available at https://www.urm-company.ru/about-us/blog/151-metallurgiya-rossii/ (Accessed 5 May 2020)
[5] Dzhigiris D D and Makhova M F 2002 Basics of the production of basalt fibers and products (Moscow: Teploenergetik) p 412
[6] Knuppel G 1984 Deoxidation and vacuum treatment of steel (Moscow: Metallurgy) p 416
[7] Zborshik A M 2010 Modern steel refining processes (Donetsk: Donetsk: State Higher Educational Institution “DNTU”) p 165
[8] Smirnov A N 2002 Continuous casting of steel (Donetsk: Donetsk: State Higher Educational Institution “DNTU”) p 536
[9] Morozov A N 1974 Out-of-furnace degassing of steel (Moscow: Metallurgy) p 288
[10] Pivtsaev V V 2009 Comparative efficiency of steel degassing during evacuation at RH and VD (Minsk: Technology) p 360
[11] Strogonov K V and Nazarov M N 2019 Device for the manufacture of continuous basalt fibers (Moscow: Patent № 2695188 RU)
[12] Strogonov K V 2020 Development and physical modeling of a basalt melting reactor Vestnik MPEI 4 2530
[13] Loitsyansky L G 2003 Mechanics of fluid and gas (Moscow: Drofa) p 840
[14] Chantsev V U 2017 Determination of the parameters of air-bubble bubbling in water Problems of the Arctic and the Antarctic 1 3945

[15] Malenkov I G 2017 About the motion of large gas bubbles emerging in a liquid Applied Mechanics and Technical Physics 6 130134

[16] Osnos S P 2018 Research and selection of basaltic rocks for the production of continuous fibers Composite World 1 5662

[17] Tatarintseva O S 2011 The dependence of the viscosity of basaltic melts on the chemical composition of the initial mineral raw materials Glass and Ceramics 10 1114

[18] Voronkovich E L 2017 Technological properties of basaltic melts Young scientists 9 2427

[19] Dubrovsky V A 1971 Properties of melts of the main igneous rocks of Ukraine and fibers based on them (Kiev: Technique) p 278

[20] Osnos S P 2010 About the characteristics of basalt fibers and their applications Composite World 3 2428