Foam Glass Based on Russian Far East Raw Materials and its Use in Mechanical Engineering

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Abstract. The necessity of developing a technology for the synthesis of foam glass based on Russian Far East local raw materials is substantiated for its use as thermal insulation of oil pipelines. A powder technology using the hydrate method was developed for the production of foam glass based on diatomite from the Chernoyarskoe deposit. The results of experimental studies of the synthesized foam glass properties were presented. The effectiveness of its use as thermal insulation of oil pipelines in harsh climatic conditions of the Russian Far East was proved.

1. Introduction

Foam glass today is one of the most advanced heat and sound insulation materials used in construction. This is due to the set of its properties: low density and coefficient of thermal conductivity, durability, high compressive strength, frost resistance, environmental friendliness, incombustibility, moisture resistance, etc. That is why foam glass can be used in almost any conditions. Therefore, the unconventional use of foam glass in mechanical engineering as thermal insulation of oil and gas pipelines in harsh climatic conditions is quite logical.

Oil and gas engineering in Russia is one of the most important sectors of the fuel and energy industry, which is developing every day. The most active development here is currently underway in the Far Eastern region of our country. One of the main problems encountered during the transportation of oil in this region is its thickening due to harsh weather conditions. About eight months a year, the air temperature in the Russian Far East does not rise above 0 °C, the average temperature of a short summer is +10 °C, and humidity reaches 70 %. Therefore, when using sufficiently long oil pipelines, they are not only insulated, but intermediate stations are also installed to heat the pipeline and reduce the viscosity of oil. Traditionally, for thermal insulation of oil pipelines, polyurethane foam up to 100 mm thick is used, which is placed in a galvanized thin-sheeted shell to protect it from mechanical damage and external influences. However, steel and polyurethane foam lose their protective and thermal insulation properties over time, due to a weather influence. In this regard, a developed material should not lose its properties under such harsh atmospheric conditions over time. Foam glass is such a material, however, due to its rather high production and logistics costs, it is advisable to produce foam glass near the immediate places of oil production and transportation. However, in the Far East there are no deposits of traditional raw materials used for the manufacture of foam glass (sand, soda, potash, etc.) [1-15]. In this connection, it is urgent to develop a technology for the synthesis of foam glass based on the raw materials of this region.
2. Experimental studies
In the study of natural and industrial raw materials of the Far East, it was found that the most promising raw materials for the synthesis of foam glass are the diatomite of the Chernoyarskoe deposit, the opoka of the Botchinsky deposit and quartz sand of the Chalganskoe deposit. As a result of applying a set of physicochemical research methods: determination of elemental and particle size distribution, microscopic analysis, X-ray phase analysis, synchronous thermal analysis, it was found that diatomite of the Chernoyarskoe deposit is the preferred raw material for the synthesis of foam glass [16]. This is due to the presence of amorphous silica in the diatomite composition, which contributes to faster chemical reactions at lower temperatures than when using quartz sand. Compared to the opoka, diatomite contains a smaller amount of refractory alumina, which also favorably affects the reduction of energy consumption in the synthesis of foam glass.

It was also discovered as a result of studies [17] that the compositions of foam glass with a solution of sodium hydroxide as a foaming agent have the best indicators of density, thermal conductivity, and strength at a low synthesis temperature. Thus, a technology for producing foam glass by the hydrate method based on diatomite from the Chernoyarskoe deposit in the Far East was developed.

2.1. Preparation of raw materials and molding of semi-finished products for the synthesis of foam glass
In the synthesis of highly porous heat-insulating foam glass, the fractional composition of the main raw material is of great importance [18], therefore, before molding the semi-finished products, diatomite was preliminarily dried and ground to a specific surface of 3000 cm²/g. The preparation of the foaming agent was to obtain a 50% aqueous solution by mixing sodium hydroxide powder with distilled water. The resulting solution is added to the milled diatomite in the ratio “diatomite:sodium hydroxide” = 80:20 and stirred for 30 minutes, then kept at 50 °C for 1 hour [17]. Extracting the mixture in a warm environment is necessary to intensify the interaction of the mixture components with each other and the formation of a gel-like sodium hydrosilicates, which serves as an activator of sintering and the formation of a liquid phase at low firing temperatures. The next stage of preparation of the raw mixture included the addition of glycerol in an amount of 5 wt. % over 100, which acts as an intensifier for pore formation. For its uniform distribution, the resulting composition was mixed for 30 minutes. Next, the resulting raw material mixture is weighed 10 g each and molded in the form of a cube (20x20x20 mm) by uniaxial pressing of 5 MPa.

2.2. Firing of semi-finished products and the formation of the foam glass porous structure
In the synthesis of foam glass using powder technology, the loading of semi-finished products must be carried out at a temperature of 600 °C, which eliminates premature volatilization of pore-forming gases. When semi-finished products were loaded into the high temperature zone, the processes of solid-phase and liquid-phase sintering begin first on the surface and then in the entire mass of samples, which prevents the evaporation of the gas phase. Due to the presence of gel-like sodium silicate in the mixture composition, liquid-phase sintering is shifted to the zone of lower temperatures, while the viscosity of the mass is significantly reduced. The released vapors of chemically bound water and the gases from decomposition and interaction of the material components are retained by a viscous mass, and pores begin to nucleate. With increasing temperature, lowering viscosity and surface tension, the formation of a porous structure continues. At this time, the number and size of pores increases. However, the resulting porous structure must be fixed in time by rapid cooling and annealing. If the temperature continues to increase, the viscosity decreases and pores reach their maximum size and begin to coagulate or collapse due to increased internal pressure created by gaseous substances that expand under the temperature influence. The temperature-time made required for obtaining a uniform porous structure of heat-insulating foam glass was discovered experimentally; and it is presented in Figure 1.
Figure 1. Foam glass synthesis mode:
1 – heating, 2 – foaming, 3 – structure stabilization, 4 – slow cooling (annealing)

Thus, the synthesis of foam glass is carried out by loading samples into a furnace at 600 °C, followed by heating to 850 °C and holding at this temperature for 30 minutes, rapid cooling to 600 °C for 20 minutes and following structure stabilization and slow cooling (annealing) to eliminate internal stresses and increase strength.

2.3. Foam glass properties
The synthesized foam glass samples based on the diatomite of the Chernoyarskoe deposit were tested for compressive strength, density, porosity and thermal conductivity. The properties are shown in the Table 1.

Table 1. Properties of the synthesized foam glass.

| №  | Property                  | Unit of measurement | Numerical indicator |
|----|--------------------------|---------------------|--------------------|
| 1  | Density                  | kg/m³               | 280-300            |
| 2  | Porosity                 | %                   | 80-90              |
| 3  | Thermal conductivity     | W/(m·K)             | 0.07-0.08          |
| 4  | Compressive strength     | MPa                 | 1.5-1.7            |

3. Justification of the effectiveness of synthesized foam glass
A thermal calculation of the oil pipeline was carried out to confirm the effectiveness of the developed foam glass as a thermal insulation for oil pipelines in harsh climatic conditions of the Russian Far East, [20, 21]. Initial data:
- inlet temperature t₁ = 90 °C;
- outlet temperature t₂ = 70 °C;
- ambient temperature t_{amb} = -30 °C;
- oil consumption (volumetric) V = 0.378 m³/s;
- pipeline length L = 4000 m;
- pipeline outer diameter D = 1240 mm = 1.24 m;
- insulation thickness δ_{ins} = 100 mm = 0.1 m;
- наружный диаметр слоя изоляции D_{ns} = D + 2δ_{ns} = 1.44 m.

In accordance with Russian State Standard No. 31447-2012, pipelines are made of 09G2S grade steel with wall thickness δ_{w} = 14 mm = 0.014 m. The calculation results are presented in Table 2 and in the form of a graphical dependence of the oil product stream final temperature on the thickness of the insulation layer – in Figure 2.
Figure 2. Dependence of the final temperature of the oil flow in the pipeline on the insulation layer thickness

Table 2. Estimated values of the oil product final temperature for various heat transfer coefficients and thickness of the thermal insulation layer

| Insulation layer thickness δ, mm | Heat transfer coefficient K, W/(m²·K) | Outlet temperature t_{out}, ºC |
|---------------------------------|--------------------------------------|-------------------------------|
| 0                               | 31,615                               | 26,28                         |
| 5                               | 7,712                                | 70,55                         |
| 10                              | 4,392                                | 78,52                         |
| 20                              | 2,360                                | 83,69                         |
| 30                              | 1,613                                | 85,65                         |
| 40                              | 1,226                                | 86,68                         |
| 50                              | 0,988                                | 87,32                         |
| 60                              | 0,828                                | 87,75                         |
| 70                              | 0,712                                | 88,06                         |
| 80                              | 0,625                                | 88,29                         |
| 90                              | 0,557                                | 88,48                         |
| 100                             | 0,502                                | 88,72                         |
| 110                             | 0,457                                | 88,75                         |
| 120                             | 0,419                                | 88,85                         |
| 130                             | 0,387                                | 88,94                         |
| 140                             | 0,360                                | 89,01                         |
| 150                             | 0,336                                | 89,08                         |
| 160                             | 0,316                                | 89,13                         |
| 170                             | 0,297                                | 89,18                         |
| 180                             | 0,281                                | 89,23                         |
| 190                             | 0,266                                | 89,27                         |
| 200                             | 0,253                                | 89,31                         |
| 210                             | 0,241                                | 89,34                         |
| 220                             | 0,230                                | 89,37                         |
| 230                             | 0,220                                | 89,39                         |
| 240                             | 0,211                                | 89,42                         |
| 250                             | 0,203                                | 89,44                         |
| 260                             | 0,195                                | 89,46                         |
| 270                             | 0,188                                | 89,48                         |
| 280                             | 0,181                                | 89,50                         |
| 290                             | 0,175                                | 89,52                         |
| 300                             | 0,169                                | 89,54                         |
4. Summary
The presented data on the properties of the synthesized foam glass based on the diatomite of the Chernoyarskoe deposit clearly confirm its effectiveness in thermal insulation of pipelines transporting oil over long distances in harsh climatic conditions of the Russian Far East. The developed technology allows to obtain high-quality heat-insulating material based on local raw materials, which reduces its cost, excluding the costs of transporting the finished foam glass or the necessary raw materials.

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