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MICROWAVE TECHNOLOGY OF THERMAL INSULATION MATERIALS BASED ON LIQUID GLASS AS AN ALTERNATIVE TO FOAM GLASS

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An energy-saving and environmentally friendly microwave technology is proposed for producing composite thermal insulation materials based on liquid glass, which are not inferior to foam glass in terms of their properties. It is shown that the use of microwave radiation allows fabricating volumetrically grouted materials by simultaneous porization of the granules and the binder. In such a way, a monolithic structure of products is formed, where the space between the granules is filled with the swollen binder limited by a denser surface layer. It has been proven that the use of microwave radiation allows achieving heating and softening of the entire mass of the liquid-glass composition due to the internal acceleration of the movement of water molecules, their friction, and release of thermal energy, and not due to high temperature from the outside. This has made it possible to carry out swelling at a lower temperature and during a much shorter heat treatment time than at the traditional convective heating, because the sample layer is heated almost instantly under microwave exposure and the liquid glass composition reaches a pyroplastic state in a few seconds. It has been determined that a part of the energy of electromagnetic radiation is transformed into heat, which contributes to intensive porization with the volumetric expansion of the liquid-glass composition. The other part of the energy is directed to structural changes in the material leading to the improvement of its properties, which is associated with the «non-thermal» microwave radiation action.

Keywords: thermal insulation material, foam glass, microwave radiation, liquid glass composition, convective heating, technology.

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Introduction

The main type of construction thermal insulation material in industrialized countries (EU, USA, Canada, etc.) is light concrete with porous aggregates. Aerated concrete and silicates are used as thermal insulation materials and products with an average density of 300–500 kg/m^3. Depending on the type of the used pore former and the binder in these materials, they are divided into aerated concrete, aerated silicate, foamed concrete, and foamed silicate. These concretes can be mixed with a pore former and they are called aerated foamed concretes, aerated foamed silicates, and the like [1]. Their disadvantages include high values of water absorption and hygroscopicity, as well as very low bending strength, since this material does not have elasticity and the application of small bending forces leads to its cracking.

Foam glass possesses a set of performance properties that meets the highest regulatory requirements. It is a rigid, highly porous thermal insulation material with a closed, porous structure, which is a solidified glass foam with a size of polyhedral and rounded cells of 0.5–3 mm. It should be noted that foam glass is recognized in the European Union as one of the most effective thermal insulation construction materials. The parameters of construction foam glass are stipulated in the all-European special regulatory and technical document EN 13167 Thermal insulation for buildings – Factory-made cellular glass products. Foam glass in the EU does not have any restrictions and is a universally recognized as a construction thermal insulation material. Foam glass is the strongest of all effective thermal insulation materials. The compressive strength of foam glass is several times higher than that of fibrous materials and foamed plastics.

The following methods are used to fabricate foam glass: 1) sintering the glass powder in a mixture with gas generators followed by annealing; 2) swelling the molten glass mass by blowing with air or gases; 3) foaming the crushed glass with foam-forming substances before cold sintering and fixing the resulting porous structure with stabilizers; 4) foaming the softened glass under vacuum; and 5) adding the finely divided additives swollen in the temperature range of the molten mass to silicate melts in a liquid or plastic-viscous state [2].

The disadvantages of foam glass include its sensitivity to vibration-induced damage. In addition, the costs of installing foam glass are quite high due to its fragility. The cost of this type of insulation is high as compared with other insulants with similar properties. The production of foam glass requires modern equipment, which has a high cost, so only a large enterprise can afford it.

Thus, the urgent task is to develop the technology and a composition of thermal insulation materials (TIM), which would allow achieving the satisfactory level of properties of foam glass while reducing production costs. Thus, an alternative to foam glass can be thermal insulation materials based on liquid glass (LG). Such materials are characterized by a long service life (50 years or more) and operating temperature from -200 to $+650^0$C. These materials are fire-safe (they melt and do not emit combustion products when heated above $+600^0$C), they are non-combustible because they do not contain organic binders; and they are not susceptible to the action of acids. In addition, these materials are biologically stable (do not rot and not attract the attention of rodents), and environmentally friendly.

The main restraining factor in the production of swollen materials based on LG is the difficulty in obtaining thermal insulation products in the form of blocks, plates, and half-cylinders due to the difficulty of uniform heating of the inner layers of large samples. Therefore, the technology of hot swelling mainly involves obtaining materials in the form of granules with a diameter of 3–10 mm. Composite materials are usually prepared by contact grouting of swollen liquid glass granules with the binder [3]. However, the strength of adhesion of the granules with the binder is not high enough, therefore such materials break at the contact points of granules even with small applied forces. This problem can be solved by application of microwave technology, which allows fabricating volumetrically grouted materials by simultaneous porization of the granules and the binder. This is due to the fact that an important feature of the microwave field action is the volume and not only the surface (as it happens in the case of common thermal action) nature of heating of the exposed samples. In this way, a monolithic structure of products is formed, in which the space between the granules is filled with the swollen binder limited by a denser surface layer [4–6].

The prospects for conducting foaming processes under the influence of microwave radiation have been demonstrated when preparing various inorganic-based foam materials [7–10]. As compared with traditional methods, there is a reduction in the duration of the technological process, a decrease in temperature, an increase in energy efficiency and product quality. It is also noted that there is the possibility of foaming without the introduction of blowing agents, but with the interaction of a microwave field with water, and the creation of well-expanded, finely porous, and homogeneous foam materials.

Theory

The use of microwave radiation for technological purposes began about 70 years ago. However, we rarely hear about the use of microwave radiation for industrial purposes and technological processes. Active implementation of microwave technology is restrained by technological (complexity of equipment, lack of design experience, and lack of qualified specialists), economic (high cost of microwave dielectric heating systems), and psychological factors (which are based on some statements about the harmfulness of the electromagnetic field for humans). It is believed that the main restraining factor in the development of microwave electrical technology is the economic one. So far, the efficiency of magnetrons (the main source of microwave radiation) does not exceed 75%. However, theoretical studies of designers of generating sets makes it possible to claim that this value can be increased up to 95%, thereby significantly increasing the economic efficiency of microwave systems. In addition, it is increasingly possible to find a klystrode as a source of microwave radiation, the efficiency of which is higher than that of a magnetron [11]. Therefore, the use of microwave systems for industrial purposes is a promising research direction.

Microwave radiation on the scale of electromagnetic radiation is between the regions of IR radiation and radio waves, and it corresponds to wavelengths (λ) from ~1 m to ~1 cm. Based on an international agreement for laboratory and household microwave ovens, there are allocated frequencies of 2.45 GHz ($\lambda \approx 12.2$ cm) and 915 MHz ($\lambda \approx 32.7$ cm) [11].

The absorption of microwave radiation is due to two factors. First, the movement of dipoles (polar molecules or other isolated groups of atoms) acquires a certain orientation related to the nature of the applied field. When the radiation intensity decreases, this orientation disappears and the chaotic rotational (and oscillating) movement of molecules is renewed, while heat energy is released. At a frequency of 2.45 GHz, the orientation of the dipoles of molecules and their rearrangement can occur several billion times per 1 second, which leads to rapid heating of the sample. The second factor, which is particularly important for heat release in aqueous solutions, is due to the directed migration of ions present in the solution under the influence of an external field. This migration of ions is an electric current that flows through the solution with force I. The current flow through a conductor with resistance R leads to the release of heat proportional to IR^2. Since resistance R increases with temperature, and the current carried by ions I increases with their concentration, both of these factors significantly affect the loss tangent of microwave radiation in solutions [12].

This concept determines the high efficiency of microwave radiation in producing swollen materials based on LG, since substances that can be heated using microwave radiation must either have a high value of the dielectric loss factor (i.e. they must contain mobile dipoles with a sufficiently large dipole moment) or high electron, hole, or ion conductivity at the temperature of the experiment [13]. Obviously, dipole fragments with a zero effective charge have the greatest mobility in the crystal structure. Among inorganic substances, water, which makes up ~50% of liquid glass, greatly meets these requirements (high mobility of molecules and a large value of the dipole moment). The microwaves affect the water molecules in liquid glass making them rotate at a frequency of millions of times per second creating molecular friction and heat that heats the material resulting in a rapid increase in the vapor temperature and the creation of a pressure gradient that causes significant structural changes in the liquid-glass composition (LGC) that leads to its swelling. That is, the use of microwave radiation allows achieving heating and softening of the entire mass of the LGC due to the internal acceleration of the movement of water molecules, their friction, and release of thermal energy, but not due to the supply of high temperature from the outside. This makes it possible to carry out swelling of the LGC at a lower temperature and during a significantly shorter heat treatment time than at traditional convective heating, because the sample layer heats almost instantly under microwave radiation, and the LGC reaches a pyroplastic state in a few seconds.

In the case of microwave radiation of aqueous suspensions of solid materials, there is a rapid temperature rise throughout the material volume not only due to this rise but also due to increased convection currents in the solution as well as the action of some other factors. For example, some works suggest that the «non-thermal» effect of microwave radiation, namely, an increase in the rate of processes in the microwave field, are related to the Maxwell-Wanger effect. It is in the fact that in heterogeneous systems consisting of phases with different dielectric properties, when an electromagnetic field is applied, it is possible for charges to appear at the boundaries of the phase interface, i.e., surface polarization [13]. This effect can be traced by studying the swelling process of the LGC under the influence of microwave radiation and comparing the obtained data with materials obtained by traditional convective heating.

Experimental

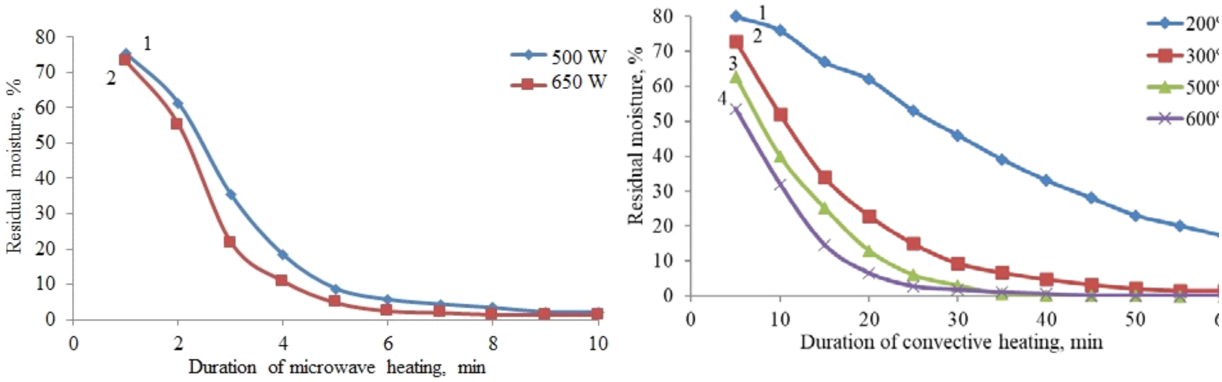
In this work, we studied the processes of bulging of LGC during the production of heat-insulating materials under the action of microwave radiation and with traditional convective heating. The research has been carried out in a laboratory microwave installation, which allows measuring the temperature of samples, with a standard operating frequency of 2.45 GHz, an output power of 300, 500, and 650 W, which corresponds to the sample temperatures of 55–60, 100–110, and 115–120^{0}C and in a muffle furnace at the temperatures of 100, 200, 300, 500, and 600^{0}C.

The liquid glass composition used for manufacturing composite thermal insulation materials contains sodium liquid glass as the main component, zinc oxide and hemihydrate gypsum as modifiers of coagulation and crystallization, hydrogen peroxide as a foaming agent, and ethoxylated alkylphenol as a foam stabilizer. Non-swollen granules based on liquid glass and zinc oxide are used as granular fillers. The manufacturing of thermal insulation materials has been carried out according to the technology described elsewhere [4–6].

Results and discussion

To study the swelling process, the dependences of the change in the residual humidity and the swelling coefficient of the composite TIM on the microwave parameters and convective heating were plotted (Figs. 1 and 2).

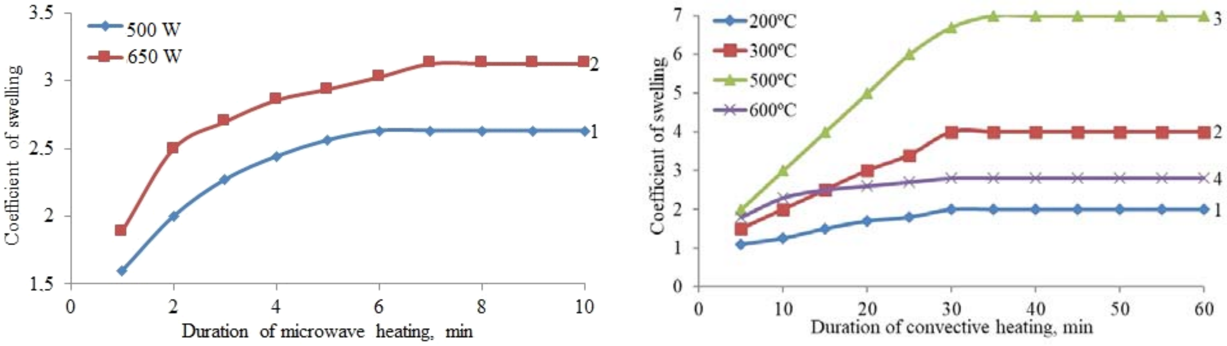
The given data show that at a power of microwave radiation of 500 W, which corresponds to a temperature of 100–110^{0}C, swelling proceeds quite intensively in contrast to convective heating, where swelling practically does not occur at all. In this case, the swelling coefficient is equal to 2.63, and the residual moisture is reduced to 2.15%. During convective heating, swelling of the LGC is observed only at a temperature



a

b

Fig. 1. Dependence of residual moisture on microwave (a) and convective (b) heating parameters



a

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Fig. 2. Dependence of swelling coefficient on microwave (a) and convective (b) heating parameters

of 200^{0}C, but mainly due to swelling of the binder. Swelling of the granules practically does not occur since prolonged heating causes the loss of molecularly bound water; therefore, the porization ability of the granular LGC is significantly reduced.

With an increase in the microwave radiation power and the convective heating temperature, the removal of water occurs faster and the swelling coefficient increases excluding swelling at a temperature of 600^{0}C. Thus, at this temperature, the swelling ratio of the composite material is lower than at the temperatures of 200–500^{0}C, which is explained by crystallization of sodium silicate. In addition, such material has the appearance of separated granules glued together with the binder, and not a monolithic block. Under the influence of microwave radiation, swelling and removal of water occur much faster due to the increase in the speed of oscillation and friction of water molecules contained in the LG, and a constant mass value is reached faster. Thus, at the maximum radiation power of 650 W (which corresponds to a temperature of 115–120^{0}C), the process ends in 8 minutes, the swelling coefficient is ~3, and the residual moisture is 1.42% (at the initial moisture of the LGC ~80%). The material obtained by convective heating at a temperature of 300^{0}C is closest to this material in terms of the swelling coefficient and residual moisture. However, the LGC reaches this swelling coefficient after 20–30 minutes of heating, while the maximum value of the swelling coefficient, which is 4, is reached by the LGC after 40 minutes. It should be noted that due to thermomechanical stresses during swelling, the material cracks, especially its upper layers. Swelling occurs most intensively at a convective heating temperature of 500^{0}C. The swelling coefficient reaches 7, but the material also cracks in the process of swelling, which leads to a decrease in its strength. In addition, all processes that take place during convective heating should be carried out for ~1 hour in order for the material to reach a constant mass.

Thus, the use of microwave radiation in swelling of composite materials allows not only reducing the process duration and temperature in comparison with traditional convective heating, but also preparing materials with better performance properties, since there is a modification of the liquid glass matrix under the influence of microwave radiation in this technology, which is due to the «non-thermal» effect. Therefore, a part of the electromagnetic radiation energy is transformed into heat, which contributes to intensive porization with the volumetric expansion of the LGC, and the other part is directed to structural changes in the material leading to the improvement of its properties, which is connected with the «non-thermal» effect of microwave radiation.

In terms of its properties, the developed thermal insulation material is close to foam glass since both the obtained material and the foam glass consist of gas-filled cells separated by the thinnest partitions. These partitions are not loose and porous, unlike foamed and aerated concrete, but solid, smooth, and fire-polished. Comparison of some properties of this material with foam glass and the material obtained by convective heating is given in Table.

The developed material is somewhat inferior to foam glass only in terms of water absorption and hygroscopicity, therefore it is limited in water resistance and is not recommended for use in structures and buildings operating in conditions of high humidity.

The technology of composite TIM based on LG includes the following stages: 1) preparation of the LGC according to the selected composition of granules; 2) granulation of the LGC in calcium chloride solution; 3) keeping the granules in the solution for 30–40 minutes at a temperature of 25–30°C; 4) drying the obtained granules in the air for 24 hours, or in a dryer at a temperature of 50–60°C for 1 hour, or in a microwave system at a radiation power of 300 W for 10 minutes until the material reaches a residual moisture content of ~50%; 5) preparation of the LG binder according to the selected formula of the composite material; 6) mixing the LG binder and unswollen granular semi-finished product in a 1:1 ratio; 7) formation of the product and its swelling in a microwave system at a power of 650 W, which corresponds to a temperature of 115–120°C for 8–10 minutes; and 8) removing the product from the mold.

In comparison with the existing methods of producing TIM based on liquid glass, the technology of composite materials has been simplified due to the combination of the stages of swelling the granular filler and the binder. The developed production scheme consists in simultaneous porization with the volumetric expansion of granules and the binder under the influence of microwave radiation, which allows eliminating the stage of separate swelling of granules reducing the binder consumption by 2–3 times, the process duration by 5–6 times, and the temperature by 2–3 times.

Compared with the foam glass production technology, the proposed microwave swelling technology is characterized by the advantages shown in Fig. 3.

There are positive examples of using microwave systems in the production of foam glass. Thus, the use of microwave radiation as a heating source for producing foam glass was reported [14]. Glass is foamed during processing, which leads to the formation of more than 50 volume percent spherical pores, the materials being characterized by a uniform distribution of pores and low density. Study [15] showed the possibility of processing domestic and industrial broken glass into highly effective thermal insulation materials using microwave activation thus reducing the duration of the foam glass formation. However, the process of preparation of foam glass remains the same, only the heat treatment time of the finished product is shortened.

Comparison of some properties of TIM

Property	TIM, subtraction during convective heating	TIM, subtraction during microwave heating	Foam glass
average density, kg/m^3	200–220	220–240	120–220
water absorption, %	65–67	28–32	1–10
hygroscopicity, %	14–15	4–5	vapor-tight
bending strength, MPa	0.5–0.6	0.8–0.9	–
compression strength, MPa	0.4–0.5	0.6–0.7	0.5–2.0
thermal conductivity coefficient, W/m·K	0.07–0.08	0.05–0.055	0.05–0.09
maximum exploitation temperature, ^{0}C	600	650	460

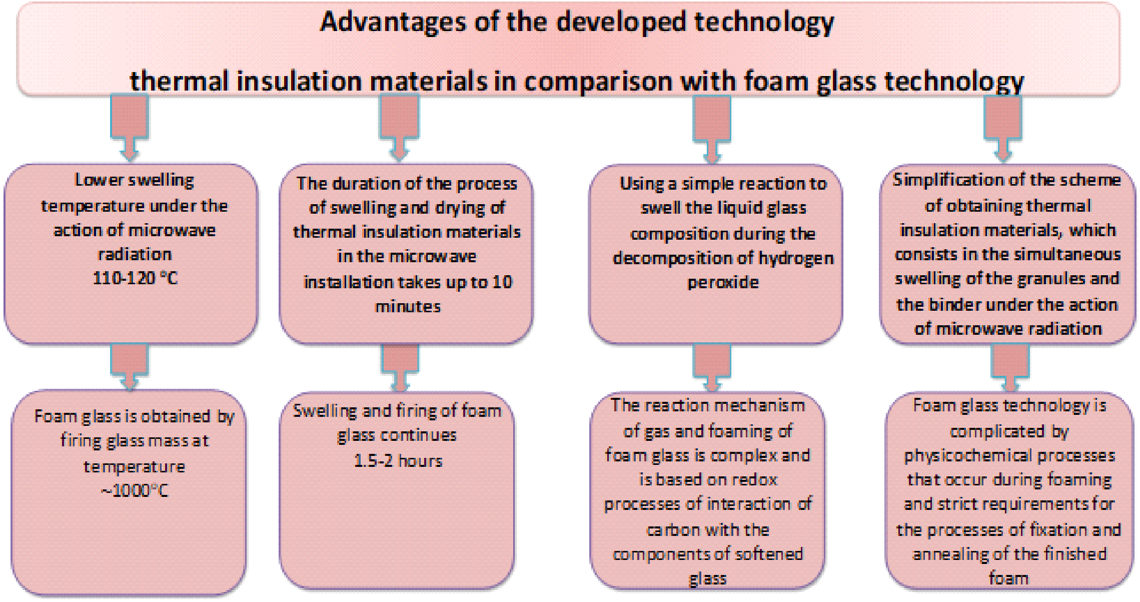

Fig. 3. Advantages microwave technology of TIM based on LG in comparison with foam glass technology

Conclusions

Thus, due to the developed microwave technology and the formula of obtaining composite TIMs based on liquid glass, it is possible to approach the level of properties of foam glass while reducing production costs. The obtained TIMs are distinguished by a competitive price, low thermal conductivity, high mechanical strength, convenience, and ease of installation with a guarantee of medium density over the entire mounting surface. The material holds its shape perfectly, has constant geometric dimensions and does not compact when exposed to moisture and oil; after drying, the shape and all thermophysical parameters of the material are preserved. Microwave technologies, equipment as well as the product obtained with their use are environmentally friendly because there are almost no emissions of harmful substances into the atmosphere. The microwave system creates comfortable conditions for service personnel and does not harm the environment.

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МІКРОХВИЛЬОВА ТЕХНОЛОГІЯ ТЕПЛОІЗОЛЯЦІЙНИХ МАТЕРІАЛІВ НА ОСНОВІ РІДИННОГО СКЛА ЯК АЛЬТЕРНАТИВА ПІНОСКЛУ

Т.Е. Римар

Запропонована енергоощадна та екологічно безпечна мікрохвильова технологія виробництва композиційних теплоізоляційних матеріалів на основі рідинного скла, які за своїми властивостями не поступаються піноскл. Показано, що застосування мікрохвильового випромінювання дозволяє одержувати об'ємно омонолічені матеріали шляхом одночасної поризації гранул та зв'язуючого, при цьому формується монолітна структура виробів, в якій простір між гранулами заповнено спученим зв'язуючим, обмеженим більш щільним поверхневим шаром. Доведено, що використання мікрохвильового випромінювання дозволяє досягти розігріву і розм'якшення всієї маси рідинноскляної композиції за рахунок внутрішніх процесів прискорення руху молекул води, їх тертя та виділення теплової енергії, а не за рахунок підводу високих температур ззовні. Це дало можливість проводити процес спучення при більш низьких температурах та впродовж значно меншого часу термообробки, в порівнянні з традиційним конвективним нагрівом, оскільки при мікрохвильовому впливі шар зразка прогрівається майже миттєво, а піропластичного стану рідинноскляна композиції досягає за декілька секунд. Визначено, що частка енергії електромагнітного випромінювання перетворюється на теплоту, що сприяє інтенсивній поризації з об'ємним розширенням рідинноскляної композиції, а інша частка енергії направлена на структурні зміни в матеріалі, які приводять до поліпшення його властивостей, що пов'язано з ефектом «нетеплової» дії мікрохвильового випромінювання.

Ключові слова: теплоізоляційний матеріал, піноскло, мікрохвильове випромінювання, рідинноскляна композиція, конвективний нагрів, технологія.

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