Flat electric heaters with the effect of self-regulation based on nanomodified polymer composite

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Abstract. The present paper considers the effect of multi-walled carbon nanotubes (acting as a part of a silicon-organic composite) on the properties of a self-regulating electric heater. Flat electric heaters were manufactured with a heat exchange area of 1600 m². The heater operating parameters were studied in the temperature range from -60°C to +70°C. The dynamics of the electric current consumed was investigated under self-regulation in the same temperature range. It was revealed that when cutting the self-regulating heater into separate parts, the properties of self-regulation and power are maintained in proportion to the size.

1. Introduction
The improvement of electric heating devices is aimed at developing “smart” materials that cause the reduction of energy costs with the possibility of the formation of new functional properties. Currently, there has been a rapid transition from the known technologies based on the principles of electric heating associated with the use of metal conductors [1,2]. The latter are widely used in anti-slip devices [3], flexible heaters for space technology [4], local heaters, and pre-start heaters of motor vehicle components [5]. The transition to new materials allows the development of electric heaters which have a controlled heating rate at different values of the supply voltage of both direct and alternating current. Carbon nanotubes (CNTs) can be attributed to this type of materials [6,7]. They are used to form coatings on flexible substrates [8] or as a component which, in turn, can be made on the basis of various polymer matrices [9-11].

The use of CNTs as a modifier in composites makes it possible to develop novel electrically conductive polymers, the characteristics of which can be altered depending on external influencing factors (mechanical, climatic, etc) [12,13]. Many nanomodified polymer compositions have a positive temperature coefficient (PTC) [14]. Materials with the PTC properties can change the value of electrical resistance depending on its temperature. Such materials can be applicable for heating elements with the effect of temperature self-regulation [15].

Today on the world market there are a huge number of companies (e.g., Eltrace, Ceilhit, Lavita) in the world market engaged in the production of heating cables with the effect of self-regulation. However, heating large surfaces using such cables leads to installation difficulties, which is economically disadvantageous. In this regard, the aim of the present research was to develop samples of flat heaters (SFH) with the effect of self-regulation, having a heating area larger than that of heating cables.
2. Materials and methods

2.1. Materials
As the basis for SFHs, a Silagerm 8030 silicone compound (Tekhnologiya-Plast LLC, Lyubertsy, Russia) was used. It consists of two components – a base and a hardener. This compound is used for manufacturing elastic forms. For the elastomer production, the base and the hardener must be mixed in a ratio of 1/1. Full cure occurs within 12 h. Taunit MWCNTs (NanoTechCenter LLC, Tambov, Russia) were employed as an electrically conductive filler for the base. This nanomaterial have an average outer diameter of 35±15 nm, an average inner diameter of 15±5 nm, and a length of about 2 μm [16]. It was synthesized through the CVD method.

2.2. Manufacturing a nanomodified elastomer
To prepare 960 g of an elastomeric composite containing 3 wt.% MWCNTs, 28.8 g of the MWCNTs were added to a 2-L beaker. 465.6 g of the silicone compound base were added to the MWCNTs sample and mixed using an HT-120 DX vertical rotary agitator (DAIHAN Scientific, Seoul, South Korea) at a rotation speed of 1000 rpm 1 h. Then, 465.6 g of the hardener was added to the MWCNTs-base mixture and the stirring procedure was repeated for 10 min.

The resulting composite was applied to a plate made of aluminium foil (GRIFF, Moscow, Russia) with a thickness of 100 μm, which was previously mechanically pre-treated using emery paper with a grain size of 100 μm. This made it possible to impart artificial surface roughness to the aluminum foil, thereby improving the adhesion of the composite to it. After uniform application of the composite, an identical aluminium plate was installed on it. The resulting assembly was molded between two flat surfaces. After polymerization at a temperature of + 80 °C for 4 h, the electric heater sample was removed from the assembly, cut to the required size, and isolated using a fluoroplastic-based polymer shell based. From the front part, the electrical leads were left to connect supply voltage. Using this technology, the sample shown in figure 1 was made.

![Figure 1. Appearance of SFHs based on a nanomodified elastomer.](image)

![Figure 2. SFH with holes: a) sample of a nano-modified heater, b) punch.](image)

2.3. Imparting artificially localized damages to the SFHs
To carry out this work, in accordance with the previously described technology, an SFH was made with dimensions of 200 × 300 mm (figure 2a). Holes were made in the center of the obtained sample using a piercer made of a cylindrical tube with a wall thickness of 0.5 mm and an outer diameter of 9 mm. The lower part of the piercer was ground in order to obtain a sharp edge (figure 2b). Wires were soldered to the electrodes.
2.4. Studying the electrophysical parameters of the SFHs based on the nanomodified elastomers.

The studies were performed on a measuring bench that consisted of a “LATR TDGC2-3” laboratory autotransformer (LATR) (Resanta, Moscow, Russia), with which the alternating electric current voltage from 0 to 220V was applied to the sample. For temperature measurements, electric current and power, two multimeters UNI-T UT61E and UNI-T UT71E (Uni Trend Group, Dongguan, China) were used; they were synchronized via USB interfaces with a personal computer (PC) based on “Intel Xeon E5450” processor (Intel, Santa Clara, USA).

Climatic tests of SFHs were carried out using a “KTH-1000” certified heat and cold chamber (NPF Tekhnologia, St. Petersburg, Russia) in the temperature range from -60 to +70 °C. Temperature field distribution measurements on the SFHs surface were carried out using a Testo-875 thermal imager (Testo, Lenzkirch, Germany).

3. Results and discussion

The studies showed that the SFH possess the effect of temperature self-regulation, since when the ambient temperature changes, the power consumption also changes. This power change occurs in proportion to the energy required to stabilize the temperature on the SFH surface (figure 3). For the SFH with dimensions of 40 × 40 mm, the specific power was found to be 800±10% W/m² at a chamber temperature of +10 °C. When the temperature in the chamber was reduced to -40 °C in order to maintain the required thermal conditions on the surface, the specific power of the SFH was 1500 ± 20 % W/m².

![Figure 3. Changes in the SFH power at different temperatures.](image)

![Figure 4. A dependence of the change in the current of the SFHs connected to an AC source with a voltage of 220 V when it is cooled.](image)

Based on the data obtained, it was established that with a decrease in the temperature from -10 down to -70 °C, the value of the current flow in the SFHs with dimensions of 40 × 40 cm increases from 2.6 up to 3.65 A (figure 4).

The technology for manufacturing functional nanomodified materials for the SFH, as well as their electrophysical properties, made it possible to change the properties of self-regulation - namely, the possibility of changing the degree of increase in power with decreasing ambient temperature.

It has been shown that the operational and technical characteristics of the SFH are preserved after cutting it into separate parts of arbitrary shape and cutting holes in it (3 holes with a diameter of 9 mm), which is confirmed by photographs taken using a thermal imager (figure 5).
The heat release of the SFH with holes of arbitrary shape made in it does not change its performance, and the material does not deteriorate, which follows from the uniformity of the temperature field and the absence of any obvious temperature deviations in the boundary zone of the holes (figure 5).

The SFH cutting leads to the fact that the single parts obtained also have the property of self-regulation, when the power is proportional to the cutting area (figure 6).

The temperature field is uniform over the entire SFH surface. It was found that the temperature difference on the SFH surface between any two points is not more than 10 °C, which can be confirmed using a thermal imaging photograph (figure 7a) and a histogram of temperature values at randomly selected points (figure 7b). The experimental studies showed that the best mode of heat generation on the SFH surface was observed at an AC supply voltage of 220 V.

Compared to ceramic heaters (figure 8) presented in [19], the ones developed herein are distinguished by their flexibility, since they are made on the basis of elastomers. The dimensions of ceramic electric heaters are strictly limited, so the production of a heater with a large heat transfer area is difficult. Self-regulating cables [20] differ from ceramic heaters in flexibility, which is similar to the developed heaters. However, the heating of large areas leads to installation difficulties and a large length of self-regulating cable, which is not economically viable.
4. Conclusion

A technique was developed to manufacture a nanomodified elastomer used as a basis for the SFH production. A large SFH, possessing the effect of power self-regulation, was produced using this technique. The SFH allows heating surfaces with a large area in contrast to the existing self-regulating cables. So, when doing this using self-regulating cables, it is required to carry out complex installation, establish heat-conducting contact with the heated surface, etc.

In the present work, it is proved that the SFH remains operational when damaged. This makes it possible to manufacture technological holes in the SFH, which are intended for mounting it on the heated surface.

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