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Materials for Electric Heaters Used in Motor Vehicles: Existing Technologies and Development Prospects

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Abstract

Tighter environmental standards and the ban on the cold start of internal combustion engines in the northern EU countries (Sweden, Norway, Finland), the northern regions of the United States and Canada led to the development of a new industry, which involves the development and implementation of electric heating for vehicles. As a rule, such electric heating systems require an external power supply source, which, on the one hand, is a drawback, and on the other hand, it allows for the use of specialized power sources without a battery load.

For the Russian Federation, the problems of operating motor vehicles at low temperatures are quite important; however, the lack of legislative support and difficulties in understanding these issues do not lead to the massive proliferation of electric heating devices. One of the most important existing problems of the distribution of electric heating devices in the Russian Federation is the absence of components base, since the heaters and materials for their development are mainly imported from foreign countries. The import of such materials into the Russian Federation is dangerous due to their falsification. At the same time, new materials developed in the Russian Federation make it possible to manufacture new-generation of electric heaters. Moreover, such heaters have a number of new functional properties that positively affect their reliability and operational efficiency. The adaptation of such materials for the use in automotive vehicles requires a detailed analysis of the conditions in which they are planned to be used, as well as the experience of using devices close in functionality.

The article provides an overview of the existing systems and devices for electric heating, which can be used as pre-start preparation of components for motor vehicles in order to reduce the toxicity of exhaust gases when starting gasoline and diesel internal combustion engines during their operation in the winter.

Keywords

Electric heating; pre-heater; environment; carbon nanomaterials; composite; self-adjustable heater.

The environmental issues of vehicles with internal combustion engines (**ICEs**) play an important role in protecting the environment. In order to address the environmental issues of ICEs, legislation is being tightened every year, which reflects new requirements for environmental indicators. Along with the improvement of ICEs, there are other factors affecting the toxicity of exhaust gases.

For a long time, the cold start of engines was affected by such a parameter as an increase in the viscosity of lubricants at low temperatures [1–3], however, the use of synthetic oils practically solved this issue and it is not rational to connect the main difficulties with starting due to an increase in viscosity. In the era of mineral oils, a sharp increase in viscosity added another problem – an increase in the starting current of the starter, which led to a decrease in the life of the starter battery [4]. In [5], other negative factors associated with the operation of internal combustion engines were reflected: delayed start of vehicle movement, increased fuel consumption, reduced internal combustion engine life, decreased efficiency of internal combustion engines and transmissions, decreased comfort of movement onset in winter.

In [6, 7], the environmental problem of low-temperature operation of motor vehicles is highlighted, because during the operation of ICEs in conditions of negative temperatures, the concentration of toxic gases in the exhaust is of the greatest importance. In the studies presented in [8], information is provided on the effect of using a DEFA pre-heater on the amount of carbon monoxide (CO) in the exhaust of a car. The authors of the work experimentally established that at an ambient temperature of minus 20 °C the CO content in the exhaust when starting the engine using a prestart heater is reduced by 2.6 times. In [9], it was reported that when 1 kg of diesel fuel is burned, about 100 g of hazardous emissions are released into the environment. The use of pre-starting heating systems and components will reduce the toxicity of annual emissions of vehicles.

Today, there are a large number of different heating systems for both diesel and gasoline ICEs. All of them differ from each other in their design, the type of heated vehicle assembly and many other parameters. But all of them can be divided into two large groups: autonomous and non-autonomous. Autonomous heaters are mobile and can function without additional external energy sources. They have a complex structure. The principle of operation of autonomous heaters is based on the combustion of fuel, during which the heat exchanger is heated with a cooling ICE liquid. Autonomous heaters made by the German company Webasto are well known. This company began to deal with systems of autonomous heaters since 1948. Now the company produces heating systems for various types and sizes of components of motor vehicles (buses, trucks and cars, etc.). The thermal power of Webasto pre-heaters ranges from 4 to 30 kW. These heaters are capable of operating on various types of fuel: diesel, gasoline and methane.

In 1975, Webasto entered into an agreement with the Soviet government and sold a license for the production of a liquid heater for trucks of the DBW 2010 model [10]. Thus, on the basis of the Rzhevsky plant of automotive electrical equipment, Eltra-Thermo Company specializing in the production of liquid heaters for diesel engines of automotive vehicles in our time was created. Depending on the volume of the diesel engine and the overall dimensions of the car on which it is installed, pre-starting stand-alone heaters from Eltra-Thermo company are capable of generating from 5 to 30 kW of thermal power [11].

The Russian company “Advers” specializes in the production of autonomous heaters “Teplostar” designed for heating cars. In the assembly of Teplostar heaters, various components of foreign manufacturers are used (Brisk, Buhler Motor). The nominal thermal power that the heaters are capable of is 4–15 kW [12].

The German company Eberspacher specializes in the production of some of the best Hydronic brand heaters in the world for cars and vessels of all categories. Hydronic heating systems have optimal parameters and have a nominal thermal power in the range for cars: 4–5 kW, for freight vehicles: 10–35 kW [13]. One of the most popular models of heaters is “Hydronic D4 W SC” for cars with about 3 dm^3 of engine compartment volume, and the weight of 3 kg. Eberspacher also manufactures special devices that allow you to control heaters remotely, setting the desired heating parameters.

The autonomous prestarting liquid heaters “PZD” produced by the company “ShAAZ”, located in Shadrinsk, the Kurgan region are known [14]. This type of heaters carries out heating of the liquid of the cooling system of motor vehicles before starting the engine at low temperatures. The company also produces heaters, which in addition to warming up the engine allow creating favorable climatic conditions in the car with a temperature above ambient temperature. Depending on the heater model used in the car’s design, the thermal power varies from 7 to 63 kW. Such a power of the heaters is enough to install them on trucks (ZIL, GAZ, KamAZ, MAZ, Ural, KAVZ, BelAZ, NefAZ), automotive and other agricultural machinery.

In addition to the autonomous heaters that are well-known and sold in the world market there are also inventions that are protected by patent documentation. For example, in [15] an autonomous engine preheating system was described, the operation of which is based on the supply of fuel from a fuel tank independent of the vehicle to the nozzle using a fuel pump. When the nozzle solenoid valve is activated, fuel is injected into the inside of the heat exchanger where the burner is installed. The internal part of the heat exchanger communicates with the external one, inside of which there is a coolant. Using a liquid pump, the heated coolant is transported through pipelines to the engine and the battery. This invention can find its application in the conditions of the Far North. The inventions proposed in [16–18] are quite similar to the device described in [15] in the principle of operation. The invention in [16] differs from the previous one as it does not imply in its design a device designed to heat the battery.

The pre-starting system for internal combustion engine [19] is an assembly for the integrated heating of several components of the internal combustion engine: crankcase, piston group and main bearings. The coolant in the device is the heated air pumped by the fan. Air heating is due to the transfer of heat through the wall of the heat exchanger, inside which there is a pulsating combustion of fuel. For the release of excess air, a crankcase is provided in the system design.

The positive side of this development is the heating not only of the outer surface of the crankcase, but also of the internal parts and components of the internal combustion engine.

Another device is the one for pre-starting heating of a stationary internal combustion engine [20], the principle of operation of which is based on heating the heat pallets installed under the crankcase and the battery. Heating is due to the combustion of a non-freezing combustible liquid. Burners are connected to each heat chamber to which combustible liquid is transported through pipelines. Flammable liquid is ignited by electronic ignition.

A device with electronic control for steam heating of the oil sump of an internal combustion engine, gearbox and axles of a car is known [21]. The hot gas produced by the generator is fed into the flame tube, in which a nozzle is installed, which sprays non-freezing liquid, thus causing the formation of steam. The steam enters the raised pallet located under the crankcase of the car's engine through a metal duct. A significant disadvantage of this invention is the impossibility of its use on a running engine.

A device with electronic control for steam heating of the oil sump of an internal combustion engine, gearbox and axles of a car is known [21]. The hot gas produced by the generator is fed into the flame tube, in which a nozzle is installed, which sprays non-freezing liquid, which leads to the formation of steam. The steam enters a "false pallet" located under the crankcase of the car engine through a metal duct. A significant disadvantage of this invention is the impossibility of its use on a running engine.

There are also the results of intellectual activity aimed at solving the problem of autonomous engine start-up preparation at low temperatures, which are not protected by patent documentation. In [22], a device was proposed that involves the use of a heat storage element. When the engine is running, the heat accumulator stores the heat of the hot engine oil and ensures its storage until the next start of the engine. Thermal batteries are designed to accumulate thermal energy during operation of the internal combustion engine and are often used in conjunction with a liquid preheating system. In [23], experimental studies were carried out to evaluate the efficiency of use of the developed pre-start system for the thermal preparation of internal combustion engines, which combines a conventional system based on a heater operating on diesel fuel and a heat storage system. According to the experimental data, the internal combustion engine preheating time at an air temperature of –40 °C when using the developed heating system is reduced by 5 minutes compared to the standard internal combustion engine pre-treatment system. In [24], pre-start heaters were proposed in the form of various designs of heat exchangers, where gas burners widely used in everyday life act as a source of thermal energy. The tests were carried out on the engines of agricultural tractors MTZ-80 and DT-75NB and demonstrated the heating rate of the coolant of 2.5–4 °C/min.

In [25], a rational diagram of the connection point of an autonomous heater in the heating system providing more uniform heating of the cylinder-piston group parts is studied. The system significantly reduces the engine warm-up time to the optimum temperature.

Heating tools [26], having a number of indisputable advantages, at the same time, have significant disadvantages, namely, a complex design and low reliability, which is associated with the use of liquid fuel to ensure their performance.

We consider the electric heating tools in terms of their performance and design features.

Electric heating systems can be attributed to the tools of improving environmental safety during the operation of motor vehicles, specified in the requirements of many countries as compulsory for their application [27–29].

A device for heating engine oil inside the engine crankcase is known [30]. The device has a housing, inside of which there is a conductive tape, to which an electric current is connected using two electrodes. The device has an intra-crater arrangement. This device was tested on a VAZ-3413 diesel engine to reduce oil viscosity. The power of the device with a supply voltage of 24 V was 280 W.

An automobile heating cover [31], which consists of heating wires made of dacron threads with electrically conductive spraying based on metal oxides is known. Heating wires are fixed to aluminum foil. The heating temperature of the heating cover depends on the rating supplied to the heating wire voltage. The device is designed to maintain the temperature inside the engine compartment at low temperatures and to ensure pre-start preparation of the engine in the winter. The maximum heating temperature was 60 °C.

A device is known for maintaining crankcase oil of an internal combustion engine in a heated prestart condition [32]. The temperature is maintained by flexible heating elements mounted on the outer walls of the crankcase. Temperature adjustment is carried out using the control unit, which is connected with an oil temperature sensor installed in the crankcase, an ambient temperature sensor, and temperature sensors of flexible heating elements.

The main advantage of autonomous liquid heaters is that in addition to reducing the warm-up time of the internal combustion engine, there is also a reduction in the amount of time spent warming up the interior of the vehicle. Their work is based on the combustion of fuel, which feeds the general system of a vehicle and on the electricity of the battery.

Along with autonomous pre-starting heaters, non-autonomous heaters are actively used. The operability of such heaters is ensured by their power supply from an external AC source with a voltage of 220 V. The power of non-autonomous pre-starting heaters is in the range from 500 W to 5 kW. Basically, their work is based on heating the coolant with a heating element and its circulation through the ICE cooling system. This type of heaters has been known since 1949. Often these are heating elements that are installed in various components of the internal combustion engine and most often in the internal combustion engine block. The heating elements “Start MINI”, which can be installed in the cylinder block of the internal combustion engine of such brands of cars as “Toyota”, “Hyundai”, etc. is known. The rated power is 0.6 kW [33] (Fig. 1).

There are also devices of various designs from the company “DEFA” (Fig. 2). The power of these heaters varies from 0.3 to 1.5 kW.

There are similar in structure pre-starting heating elements “Calix RE 167”, “Calix RE 163” and “Calix RE 153” made by the company “Weber” (Saint Petersburg) [34]. Their power is 550 W. They are installed on various cars, incl. “Fiat”, “Ford”, “Iveco”, “Mitsubishi”, etc.

In addition to the standard electric heaters described above, there are heating plates made in the form of rectangles of various sizes. They are widely used in various places where it is necessary to evenly and efficiently heat surfaces. Their heating occurs due to the supply of electric current to the heating element, which is enclosed in silicone. Installation of such heaters consists in gluing them to the outer surface of the ICE crankcase using double-sided tape or installation using cold welding. Such large firms as Keenovo and Hotstart are engaged in their production.

Keenovo heating plates (Fig. 3) are produced with different capacities from 100 to 1350 W. The supply voltage can be carried out both from the vehicle’s on-board network with a nominal voltage of 12–24 V, and from an alternating current network with a voltage of 220 V. When applying electric voltage to them, they maintain a temperature on their surface from +90 to + 180 °C [35].

Hotstart heating plates (Fig. 4) are similar to the above-described plates and have a similar appearance and technological design. The heaters of the Hotpads AF40024VDC model, designed for 24 V DC, have a power of 400 W [36]. Keenovo has a maximum power of heating plates powered by the on-board network of a truck is 250 W.

Fig. 1. Pre-starting heaters from the Start-MINI firm

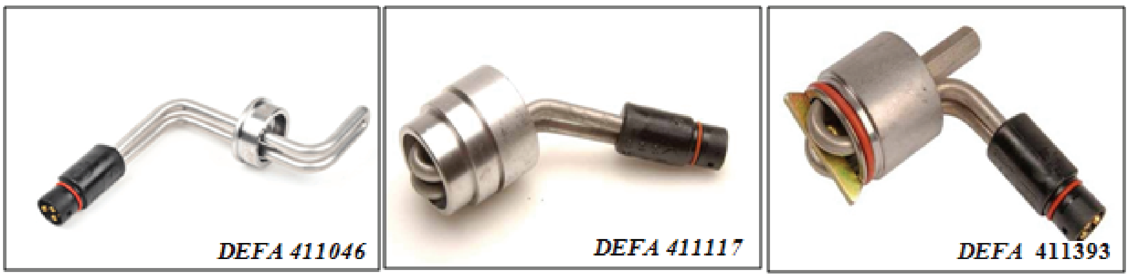

Fig. 2. ICE heaters from the company “DEFA”

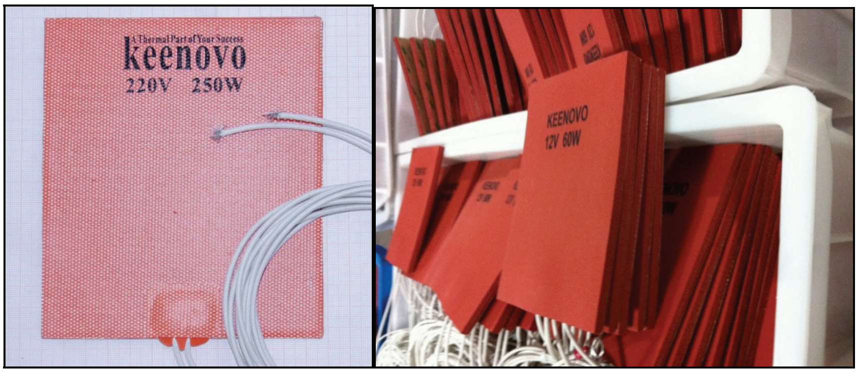

Fig. 3. Keenovo heating plates

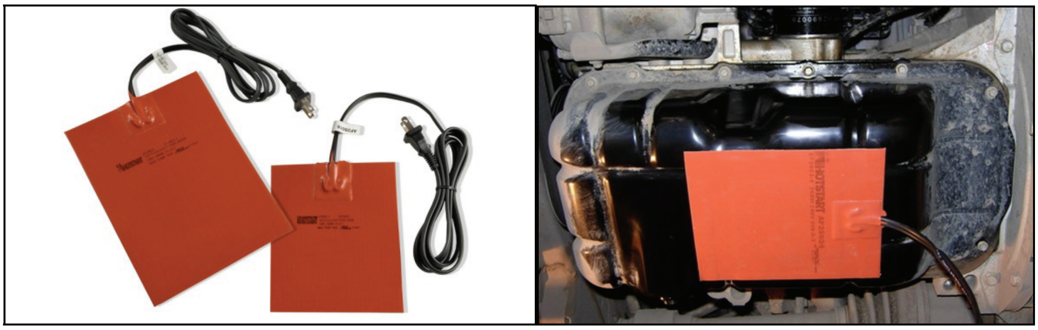

Fig. 4. Hotstart flexible heating mats

Recently, heating elements with the effect of temperature self-regulation have been of great interest. Heating elements whose operation is based on the heat release of posistors (thermistors) are known [37]. The fact is that posistors increase the value of their resistance with increasing temperature, and, accordingly, self-regulate heat release on their surface. This phenomenon is called a positive temperature coefficient [38, 39]. Based on posistor ceramics, scientists made a device that is designed for pre-starting heating of engine oil in the crankcase of an internal combustion engine. To do this, posistors are installed in the case. The surface of the body was attached to the engine block [40]. The heating of the posistors occurs when an electrical voltage is applied.

A device facilitating the starting of an internal combustion engine, in which posistors are used as heating elements is known [41]. A significant disadvantage of posistors is their fragility, which was a deterrent to their use on the elements of ICEs.

The advent of domestic carbon nanomaterials allows import substitution and can mark the beginning of the development of a new generation of electric heaters [42].

A composite is a multicomponent composition, which most often consists of a base and modifier fillers. Scientists use various polymers as the basis of composites: epoxies, abs plastic, polyurethane, polyethylene [43–46], and etc. As a modifier, various materials can be used. Micro-sized and nanoscale metal powders, various chemical compounds, etc. But the use of carbon nanostructures as a filler of composite materials is of particular importance. The role of carbon nanostructures in the composition of polymers is different. This can be hardening of the initial polymer, for example, in [47], scientists increased the strength of epoxy resin by modifying it with functionalized fluorine carbon nanotubes, increase hydrophobicity, and in [48] hybrid functional polymeric materials (**HFPMs**) based on epoxy binders were obtained, which contained functionalized carbon nanotubes and Sulfon tetrafluoroethylene telomere.

The basis of electric heating systems is most often an electrically conductive composite. In this regard, one of the promising areas of science is the development of electrically conductive composite materials modified with carbon nanostructures. Carbon nanomaterials (**CNMs**) are popular among studies aimed at creating electronic devices for various purposes. This is due to the excellent conductive properties of the CNMs. As CNMs, carbon nanotubes (CNTs) [49], graphene [50], and various composites based on them [51, 52] can be used.

In this regard, research is aimed at creating heating elements. This type of heating element often consists of a nanomodified electrically conductive polymer and current-conducting electrodes. Various materials can be

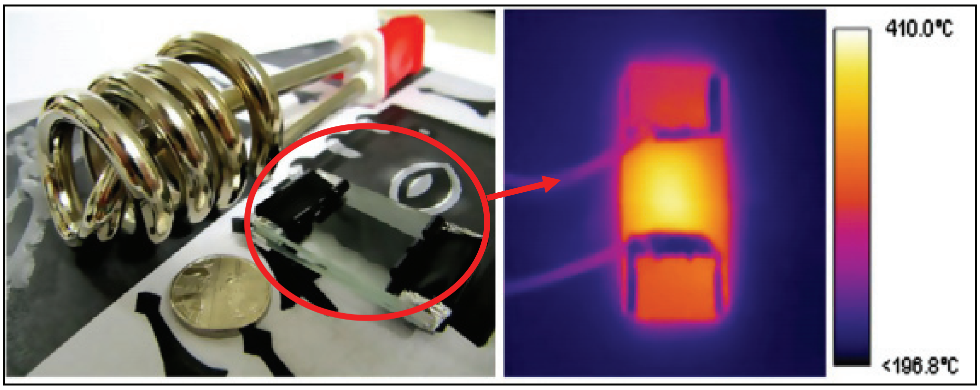

Fig. 5. CNT-based flexible heater [57]

used as the basis of nanomodified polymers for heaters [53–55].

In [56], a method for manufacturing a heating element based on a fluoroplastic modified with 20 and 35 wt. % of paste containing graphene-like material was described. Electricity was applied to the opposite surfaces of the fluoroplastic / graphene-like composite. On one surface, the composite was coated with graphite emulsion; on the second surface, it was plated with nickel. The resulting heater layout was isolated with a polyethylene sheath. The researchers found that when the resulting heater was connected to an AC source with a voltage of 220 V, its power increased and stabilized over time. Thus, for a heater with 35 and 20 wt. % of graphene-like material in the fluoroplastic, the power was 121 and 110 W, respectively.

In [57], the researchers made a flexible heater, in which CNTs were used as the electrically conductive phase (Fig. 5).

A heating film was obtained during the synthesis of CNTs. On a rotating shaft made of polycarbonate, CNTs were deposited. After that, the resulting wound material was removed from the shaft and cut to a size of 210×297 mm. The material turned out to be very light in comparison with existing heaters based on nichrome or aluminum [58]. When the measuring electrodes were located along the CNT distribution in the heater, the specific volume resistance was 2×10^{-4} Ω×m, and when the measuring electrodes were located across the CNT distribution, it was 7×10^{-4} Ω×m. The researchers showed an example of the practical application of CNT-based heaters. To do this, the developed heater was fixed to the wing of the aircraft model, and ice was fixed from above. For comparison, on the same wing, aircraft models fixed ice on the surface of the wing, which did not have a heating element. When voltage was applied, the ice that was on the heater began to melt rapidly, while on the surface of the wing of the aircraft, not equipped with a heater, the ice kept its shape and did not melt. This type of heaters can be used as anti-de-icing devices of aircraft.

In [59], CNT-based composites were made, which were reinforced with fiberglass and insulated with epoxy resin (Fig. 6).

A meso/microporous CNT composite was used as the electrically conductive phase initiating electric heating of the polymer. The heater composite was made by dispersing a suspension of CNTs in deionized water with a Triton X-100 surfactant using a three-roll mill and ultrasonic treatment. The composite was formed by filtering the resulting suspension of CNTs through a filter. The pore size of the filter is 1 μm. After filtration, the composite was subjected to heat treatment at 90 °C for 5 h. Copper electrodes were used to supply electric voltage to the composite. The electrical conductivity of the developed composite was 64.9 S/cm. The average surface temperature of the heater when applying a voltage of 12 V DC was 120 °C.

In [60], it was proposed to use the resistive film as heaters for anti-icing systems. Graphite was used as the basis, from which graphene nanoplates were made by intercalation. The resistive film was made from a homogenized suspension of ethanol with deionized water and graphene nanoplates. A resistive film was applied to a laminating substrate of polyethylene terephthalate (**PET**) and a copolymer of ethylene vinyl

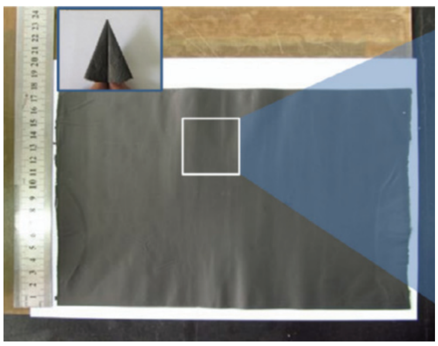

Fig. 6. CNT-based material for electrical heater [59]

acetate (**EVA**). To organize the supply of electric current to the resistive film, electrodes made of copper foil were used. After applying a resistive film and electrodes, EVA and PET were applied on top. The resulting assembly was sintered at 110 °C in an oven. Thus, a flexible heating element based on graphene nanoplates was obtained (Fig. 7).

The researchers demonstrated that the heater maintained a constant temperature field on its surface regardless of bending deformations. The thickness of the heater was 0.19 mm. When powered by a direct current source with a nominal voltage of 3.7 V, the power of the heating element was 0.89 V/cm^2. The temperature on the surface of the heater at an ambient temperature of –6 °C was 12.5 °C.

The synthetic electric heating coatings for protection against icing are known [61]. Acrylic varnish with an elastomer was used as the basis of electric heaters. To impart conductive properties to the base, it was modified by 2–18 wt. % of multi-walled carbon nanotubes (**MWCNTs**). In order for the electric heating coatings to be hydrophobic, the electrically conductive composites consisting of a base and MWCNTs were coated with a suspension of acetone with SiO_2 nanoparticles. After temperature effects, fluoroalkylsilane was formed on the coating surface [62]. It was found that the optimal mass content of MWCNTs in the composite is 12.5 wt. %, since the strength characteristics of the film electric heater deteriorate at high concentrations of MWCNTs. The specific surface electric resistance of the heater decreased with decreasing thickness of the film heater. As an example of the practical use of the invention, it was used to cover one of the fan blades placed in low-temperature conditions (Fig. 8).

The film heater was connected to a direct current source. Over the 300 seconds of testing, the film heater heated the fan blade, rotating around its axis at a speed of 100 rpm to 45 °C.

In [63] the coatings that can be used as heating elements based on composites, epoxy resins modified with graphene nanoplatelets (GNP) (8–12 wt. %) were described (Fig. 9).

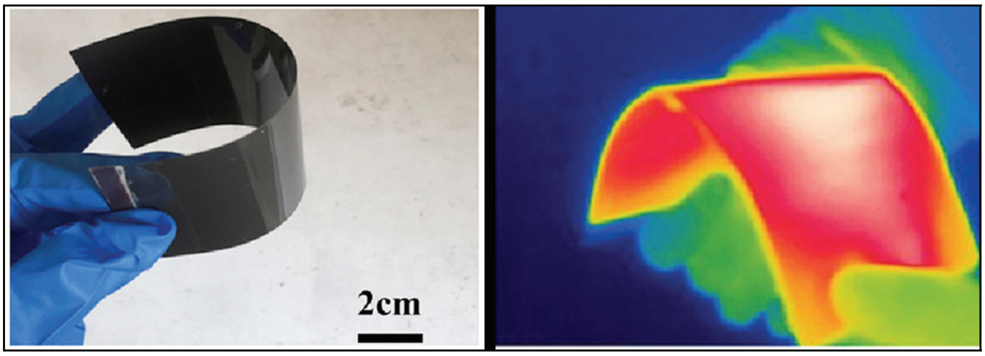

Fig. 7. Flexible heating element based on graphene nanoplates [60]

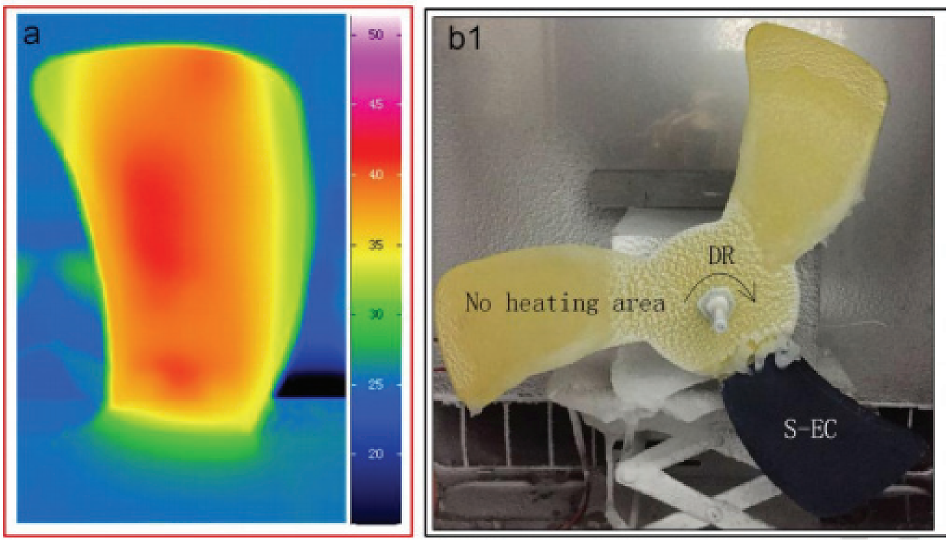

Fig. 8. Heating of the rotating blade [61]

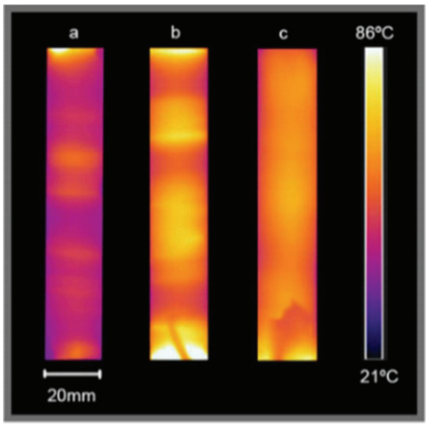

Fig. 9. The temperature field on the surface of the heaters:
a – 8 mass % GNPs; *b* – 10 mass % GNPs; *c* – 12 mass % GNPs [63]

Coatings were applied to a laminated glass fiber substrate. With an increase in GNPs, the electrical conductivity of the coatings increased from 0.001 to 0.01 S/m. The heating rate at a supply voltage of 800 V increased with increasing mass content of GNPs in the nanomodified composite and was 7.2; 10.3 and 13.6 °s/min for composites modified with 8, 10 and 12 wt. % GNPs, respectively. All composites exhibited uneven surface heating.

The information analysis showed that the solution of low-temperature operation is an important task. The existing technologies related to pre-start heating of motor vehicle units are divided into several types, namely, autonomous and non-autonomous electric heaters. The operation of autonomous systems of electric heaters depends on their power supply from the on-board network of a vehicle with a nominal voltage of 12–24 V of direct electric current, which makes them mobile and ensures their operation in places remote from external sources of electric current. Non-autonomous electric heaters, on the contrary, require an AC power source with a nominal voltage of 110–220 V, which causes inconvenience when operating vehicles in the field. However, heating systems for motor vehicles based on non-autonomous electric heaters, unlike autonomous electric heater systems, can save the vehicle's battery life. Despite the abundance of new inventions in the Russian Federation, of all existing electric heaters non-stand-alone heaters have been widely used. This is due to the insufficient level of research and development of new materials that could be used as the basis for the manufacture of new autonomous electric heaters for internal combustion engines and other components of automotive vehicles that require heat treatment before the initial bunch of vehicles at low temperatures.

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