Smart energy coating for independent power generation in pavement and machine elements

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Abstract. Developed Smart Energy Coating is capable to generate electric power independently and to ensure a stable temperature regime for road surface, machine elements and control systems. This can provide additional reliability and safety of the structure in harsh climate. The energy production scheme is based on the Peltier principle and the insulating layer with a phase transition. Thermal conductive inclusions inside the layer with phase transition material support the stable operation of the Peltier element. In the article variants of Smart Energy Coating are proposes for the mode of operation with the highest energy generation.

1. Introduction
There are processes with emissions of waste heat in industrial and domestic sphere. This energy is lost to the environment or gives extra heat or cooling to the surrounding elements. In this case, there are unnecessary deformations that reduce the life resource of the material and negatively affect the behavior of the elements. The authors propose to study the developed material with a layer based on a phase transition material and thermoelectricity elements.

There are works on the study of such materials, in which [1] 3D modelling is carried out to study the behaviour of similar processes. A three-dimensional finite element method simulation is very important to study the temperature behavior for a better understanding of work operations. These investigations provide physical insights into switching operations and thermoelectric effects in models. The material forms, geometry and composition may influence the temperature profiles and the current behaviour, and the thermoelectric effects are related to the temperature lines and the temperature gradient. There are researches of thermoelectric cooling and heating effects [2]. It proves the possibility of the theoretical control of thermoelectric effects. Therefore this is the method of reversible control of electronic states in correlated electron materials. It is quite expensive and difficult to manufacture materials. There are superconducting materials [3] containing graphene and other additives in the composition, where thermoelectric effects allow to generate the electrical power from waste heat and the electrical control of cooling and heating.

Recent researches in thermoelectrics with nanoscaled materials [4,5] based on carbon offer prospects for solving the problem for high energy power by controlling heat and using thermoelectric effects [6-8]. A basic description of thermoelectrics usually involves two reciprocal processes: the Seebeck and Peltier effects. The Seebeck effect is the generation of a voltage due to a temperature difference and is quantified by the Seebeck coefficient or thermopower of a material. Learning material does not have a large cost and consist of simple structure.
Material can be applied in conditions of extreme temperatures, particularly in severe climatic conditions of Siberia, where temperature variations during the day can reach more than 20 degrees.

The conception of research is directed to improving the material that produces the energy closer to consumers and supplies users when it’s necessary. The coating doesn’t need heavy expenses. It takes energy from the environment and produces energy due to the properties of the coating material.

The design of small dimensions is developed for energy generation from the place of production directly and without expensive materials. This coating can be used in building construction, the transport sector and even in space industry.

The task is to save energy during excess heat. The environment produces energy due to the properties of the coating material. This is possible because of special characteristics of coating materials and its design features.

It is small size of construction for energy saving in the place of production and using without fossil fuel and expensive materials. The authors developed the coating that can be applied to various surfaces. The construction generates energy according the thermoelectric effect. This coating is capable to generate electricity independently without a fossil fuel energy sources and even the sun, wind and other sources. Heat-conducting inclusions of the inside layer with a phase transition material ensure the stable operation of the Peltier element. Along with the generation of electricity it ensures a stable temperature regime of work for any structures due to phase transition inclusions.

There are some advantages of this developed system. It is the only method for energy obtaining in a small area. There are no moving parts that makes the system highly reliable. It is not necessary to change the refrigerant because it doesn’t need there. There is no sensitivity to vibrations (important for transport). There is the possibility of a smooth and precise regulation of the temperature regime. It is an ecological compatibility. Thermoelectric devices don’t contain toxic refrigerants. It can have an arbitrary orientation in space and a gravity field. It has a small inertia, switches from cooling mode to heating mode easily.

Besides there are constructions or machines used in nonstationary temperature conditions or processes with surplus of thermal energy, lost to the environment.

2. Theoretical positions of the power generation mode
The work of the researched material is the effect of thermoelectric conversion. All thermoelectric generators have no moving parts. It may use processes of waste heat for electrical power (a form of energy recycling). The thermoelectric effect bases on phenomena of temperature difference, which creates an electric potential. In this case there are two laws.

The first and most obvious is: the higher the difference in contact temperatures, the better the electrical intensity. The second principle is: the heat conductivity (especially its phonon part) is as low as possible in the direction of current propagation.

Among the most well-known and widespread materials the variants of carbon structures in combination with phase-transition materials were considered. Carbon additives and methods for their use make it possible to obtain special properties of materials. It can be used in the operating conditions of the coating.

Modeling was carried out for variants of a layer containing a nanocomposite material with nanocrystals Bi$_2$Te$_3$, coating by layer of molecules C$_{60}$. The fullerene molecules determine the properties of nanocomposite material. At different concentrations, the thermo-emf of the composite material increases with a decreasing of a thermal conductivity [9].

As an example is used in the laboratory we can see the Smart Energy Coating, it is a polyimide substrate that can be measured 54×20×0.1 mm with the precipitation of thermoelectric material Bi$_2$Te$_3$. Molecules of fullerenes are good electron acceptors. Due to this, fullerene molecules are able to capture electrons, easily intercalate, forming fulerides.

In addition to usual electrical and thermal conductive properties of the module, the surface layer has properties of radiation absorption in the medium- and long-wave spectrum [10]. Such spectrum
corresponds to the wavelength of solar radiation at the earth’s surface. According to data, optical and infrared absorption spectrum of deposited layers of clusters $C_{60}$ with different thicknesses, which are applied to a substrate, is significant. The reflecting component is relatively small and depends on a degree of substrate reflection. The effect of apparent negative absorption is due to the reflection of the radiation of the substrate. This effect can be used in obtaining of solar heat in solar installations. There, the absorption and reflection coefficients of the outer structure layers are one of the main functional components.

We’re able to use the temperature difference to transform a current by Seebeck effect. While all materials have a nonzero thermoelectric effect, in most materials it is small. But low-cost materials that have a sufficiently strong thermoelectric effect (and other required properties) could be used in applications including power generation and refrigeration. A commonly used thermoelectric material in such applications is bismuth telluride.

The main characteristic describing the efficiency of work can be calculated [11] from the formula:

$$ Z = \frac{S^2}{\kappa} $$

where $S$ is the Seebeck coefficient, $\sigma$ is the conductivity coefficient, $\kappa$ is the thermal conductivity coefficient, and $Z$ is called the thermoelectric figure of merit.

$Q$-factor is often understood as $ZT$. The principle of work in SmartEnergyCoating can be described as following. Hot contact of coating takes from the environment heat, equal to the sum of Peltier heat $QP$ and heat of equipment $QT$, related to thermal conductivity through the thermoelement, and returns the part of Joule heat evolved in the thermoelement. Heat Peltier, taken away by hot junction, is:

$$ Q_P = S_1 \cdot T_1 \cdot I $$

where $I$ is the current flowing through the thermoelement.

In this case thermal conductivity takes place. Thermal conductivity transfers heat:

$$ QT = K(T_1 - T_2) $$

where $K = kF/l$ is the heat transfer coefficient, $F$ and $l$ are the cross-sectional area and length of the conductive elements. The length is sufficiently small to reduce the resistance of the conductor.

The electrical power supplied to the external load is:

$$ W = I^2 R $$

where $I$ is the current, $R$ is the load resistance.

Current strength is:

$$ I = \frac{S(T_1 - T_2)}{R + r} $$

where $r$ – internal resistance of a thermoelement which is equal:

$$ r = \frac{l}{(F \sigma)} $$

The Seebeck coefficient $S$ is equal to the sum of $S_1$ and $S_2$ of the pair of elements:

$$ S = \frac{1}{2}(S_1 + S_2) $$

The Joule heat is:

$$ Q_r = I^2 R $$

It is assumed that half of the Joule heat is removed through the cold contact, and half is returned to the hot contact. Thomson's heat is neglected. As a result, it is equal to the sum:

$$ Q_1 = Q_P + QT - 1/2Q_r $$

The heat removed from the cold surface is:

$$ Q_2 = Q_1 - W $$

The efficiency of thermoelement is:
\[ \eta = \frac{W}{Q_1} = \frac{S^2(T_1 - T_2)^2 R}{(R + r)^2} \frac{1}{ST \frac{S(T_1 - T_2)}{R + r} + K(T_1 - T_2) - \frac{S^2(T_1 - T_2)^2 r}{2(R + r)^2}} \]  

(11)

where \( Q_1 \) – Heat supplied to the hot surface of the thermoelement

The maximum power in the thermoelement, as well as in other current sources, is allocated under the condition \( R = r \), that is, for \( m = 1 \). In this case, the efficiency is:

\[ \eta = \frac{T_1 - T_2}{T_1} \frac{1}{1 + \frac{2}{ZT} - \frac{1}{4} \frac{T_1 - T_2}{T_1}} \approx \frac{T_1 - T_2}{T_1} \frac{1}{1 + \frac{2}{ZT}} \]

(12)

The researching of expression (12) on the extremum shows that the maximum efficiency corresponds to the ratio:

\[ m_{\text{max}} = M = \sqrt{\frac{T_2}{T_1} + \frac{1}{2} ZT} \]

(13)

We can see from expression (11), the thermoelectric material must have simultaneously a high electrical conductivity, large thermo-emf and low thermal conductivity.

Thermal conductivity \( k \) includes electron \( k_e \) and lattice (phonon) \( k_L \) components:

\[ k = k_e + k_L \]

(14)

Modern materials with addition \( C_{60} \) allow to reduce the values of thermal conductivity. Addition \( C_{60} \) allows to increase under certain conditions thermo-emf. This is because the material with the additive is a nanocomposite. The presence of fullerene on the surface affects the nanodispersity of the sample and leads to an additional scattering of phonons at the boundaries [14-17]. Increase of electrical conductivity by additional doping is a promising direction.

3. Modelling

Computer simulation was experimented to determine the distribution options for thermal conductive inclusions. In this case, the scale of dimensions is chosen conditionally to determine the places of heat-conducting and heat-accumulating additives on the plane. Then it will be simulate in volume.

Depending on the external boundary conditions and operating conditions [18,19], we can calculate the location of the thermal inclusions for the optimum performance of the structure.

Figure 1 shows the simulation of the total heat flux and the location of the phase-transition inclusions.

**Figure 1.** The location of the phase-transfer layer is shown in blue. Brown color - parts of heat-conducting inserts for Peltier elements.
Figure 2. Phase-transition layer with thermal conductive inclusions.

Figure 4 presents heat-conducting inclusions in constructions of complex forms. In this simulation, a spherical shape is embedded. It is the similar circular form for the most uniform distribution of thermal lines in graphite conductors with density. In addition, an alternation of the phase-transition layer and the conducting layer allows to use the functional completely.

Thus, the phase-transition layer with heat-conducting inclusions makes it possible to distribute the temperature field through heat-conducting inclusions. The required value of the temperature difference arises in places with Peltier elements directly. The remaining areas are protected from excessive heat flux reliable.

At the figures we can identify the optimal distance of the phase-transition in the thickness of the coating and the places of heat-conducting elements. Elements with a specified conductivity at temperature level within the required limits and with a minimum temperature difference are determined. This makes it possible to obtain a given temperature difference for generating electricity.

4. Implementation
After simulation results, the SmartEnergyCoating prototype was created. The phase transition composition was selected in such a way that its melting point was equal to the work temperature (ambient) and compensated for all linear extensions of the structure, thus preventing destruction. The phase material is a synthetic substance has paraffin physical properties.

The generated electricity can be used for pipelines with automation elements, so well the coating is both a heat-insulating composite material and can generate electricity. Effect of thermal insulation and independent energy production by the coating presents.

Most of the mass of the phase-transition material is located on the outer surface. This allows to ensure the damping of temperature deformations and allows independent power supply to remote elements.

It allows to increase the plasticity of roads and building structures where necessary. Flexible electrically conductive connections constantly support the work of the phase-transition material and allow to work with a sufficient level of quality.

Fixed parameters: with a difference in surface temperatures of about 40 °C reached 1.5 A, 4 V for 12 h with small interruptions. Specific thermal resistance of the thermal insulation layer was 1.6 W/sq.m °C. In this case, no linear extensions of the main material occurred and the coating worked as a heat-insulating layer.

5. Conclusions
According to the results of thermal modelling and several natural experiments we can draw conclusions. The coating can be used to generate energy in remote areas with severe climatic conditions. It is possible to obtain energy at any temperature difference in systems with solar energy due to design features.

The developed heat-insulating layer containing in the structure a phase-transition material with heat-conducting inclusions allows distributing a temperature field through heat-conducting inclusions. In this case, the value of the temperature difference arises directly in places with Peltier elements. The remaining areas are reliably protected from excessive heat flux. Such a coating can be used in building structures, in pipeline systems of hot water supply and heating. At this regime, the drop in temperature
for thermal power generation will be insignificant, but the output voltage is sufficient for the operation of equipment, lighting, instrumentation.

The layer of heat-accumulating composite material can be used in solar installations and recuperation. It allows to reduce heat losses by technology of "Smart Wall" without the electricity systems and any energy. In addition, it allows to avoid the "dew point" in structures. It will increase the hygienic and exploitative properties of buildings and structures.

Also it may use in life-support systems. The design of small dimensions is developed for energy generation and using in the immediate region and without expensive materials. This coating can be used in building construction, the transport sector and even in space industry. It takes energy from the environment and produces energy due to the properties of the coating material. This is possible because it has the properties of materials and design features.

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