A functional approach to the analysis of technological processes of using thermal radiation in the process of repairing insulation of electric locomotive equipment

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Abstract. The article provides an analysis of the interaction of the system “Emitter – Environment – Material” in the drying and hardening of the insulation of electrical equipment of electric locomotives, taking into account the intended purpose of the process. The structural-logical diagram of technological processes of using thermal radiation during repair of insulation materials of windings of power equipment of electric locomotives is presented. This structural and logical diagram indicates the need for an individual approach to the analysis of the system elements' interaction in the process of using heat radiation for the polymerization of impregnating materials for hardening. It is necessary to comply with the parameters of the maximum permissible temperature and heating rate not only for isolation of this class of heat resistance but also for an impregnating material, depending on which losses in the medium depend. A simplified approach to the analysis of the interaction process of the "System" elements in the mathematical model is proposed. The basis of this model is the relationship between the dose of irradiation of polymer insulation with thermal radiation and the expected results on the characteristics and properties of electrical insulating materials.

1. Introduction
The concept of function is one of the main concepts of modern mathematics. This concept can also be encountered both in nature and in technology, studying various phenomena and processes. Any device is considered in a set of interconnected elements. The contents of elements are revealed in the studying process of the system tasks and functions.

2. Structural and logical scheme of technological processes of repair of insulating materials
The technology and technique for hardening the insulation of electrical equipment of electric locomotives, proposed by scientists of Irkutsk State Transport University, can significantly increase the productivity of repair operations with lower costs (electricity) [1, 2, 3].

It is necessary to use mathematical modeling at the design stage to create the most efficient resource-saving industrial plants. As part of the fulfillment of the state task of the research and development work on the topic "Improving the reliability of power equipment of traction rolling stock" (№АААА-А19-119010990009-3), work is currently underway to compile a set of mathematical models of technological processes for the use of thermal radiation in the repair process...
of electrical equipment of electric locomotives. In this regard, first of all, it is necessary to analyze the system "Emitter-environment-material" (after this – the "System"). In the case of analyzing the interaction of the system during the re-installation of insulation of the electric equipment of electric locomotives, first of all, it is necessary to take into account the purpose of the technological process of heating the insulating material with heat radiation in general.

In this regard, a structural-logical diagram of technological processes for the use of thermal radiation in the repair of insulation materials of windings of power equipment of electric locomotives was compiled (Figure 1).

![Figure 1. The structural and logical diagram of the technological processes of using thermal radiation in the repair of insulation materials of windings of power equipment of electric locomotives](image-url)
Thus, the use of thermal radiation in the repair process of insulating structures can be divided into four technological processes:

– removal of moisture from the insulation;
– drying after painting;
– accelerated heating;
– hardening of insulation.

With the further introduction of thermal radiation in the technology of repairing equipment of electric locomotives, the number of processes for the target feature increase.

The process of heating moistened insulation to dry it is associated not only with the removal of moisture (it is a thermophysical process) but also associated with the need to preserve the structure of polymer insulation as much as possible [4].

Exceeding the maximum permissible temperature and heating rate for a given class of insulation can lead to a violation of the operational characteristics of the equipment. Moreover, this process is technological.

When heating the insulation after painting with enamel, primer or varnish at low temperatures, only a thermophysical process takes place, proceeding with the obligatory observance of the necessary temperature regimes of heating and exposure time.

The use of thermal radiation for accelerated heating of parts of power equipment with high thermal inertia is due to the significant highly concentrated heating of steel parts of power equipment. Heated steel parts may be close to insulating structures. It is necessary to take into account the mutual emission factors of the system surfaces under consideration, as well as the edge effect during the operation of the emitters. In this case, only the thermophysical phenomena of the process are analyzed.

It is entirely different from approaching the analysis of the interaction of the "System" in the process of using heat radiation for the polymerization of impregnating materials to strengthen. In this work, the term "hardening" used in a process in which liquid polymers (varnishes and compounds) are transformed into solid polymers (curing, gelatinization, polymerization) under the influence of thermal radiation in the manufacturing and restoration technologies of insulating structures of electrical equipment for various industries, agriculture and transport [5, 6, 7]. Besides, the term "hardening" laid down the main characteristics and properties of electrical insulating materials: electrical and mechanical strength, heat resistance, cold resistance, moisture and water resistance, flexibility and elasticity, chemical resistance, roughness, cracking resistance and other are critics and properties. As experimental laboratory studies have shown, the complex of these characteristics and properties is directly correlated with the surface roughness of the cured polymer on the insulating structure of electrical equipment — the lower the roughness, the stronger the electrical insulation. However, to ensure these characteristics and properties, it is necessary to remember that the energy characteristics of coherent and incoherent thermal radiation and the physicochemical properties of liquid polymers are the basis for ensuring the modification of polymers with a given roughness functional characteristic in the technological process.

In this case, it is necessary to observe the parameters of the maximum permissible temperature and heating rate not only for this class of insulation but also for the impregnating material. Moreover, the process of hardening is significantly affected by the formation of "gray gas" in the medium [8], in which energy losses occur. Thus, it is necessary to take into account the impregnating material, depending on which losses in the environment depend. So when using varnish-based impregnating materials, losses in the "gray gas" environment are maximal, since a significant part of the solvent evaporates in the form of vapors during the polymerization. And when using impregnating materials based on compounds, these losses are minimal due to different physics of the polymerization process with virtually no use of solvents. The hardening process is also associated with chemical changes in the liquid polymer and subsequent phase transitions as a result of heating by thermal radiation. This process indicates difficulties and difficulties in the analysis of processes for hardening, precisely polymer insulation. Moreover, the variety of modern types of impregnating materials further complicates this task. However, with a simplified approach to the analysis of the process of interaction...
of the elements of the system under consideration, a particular analogy can be drawn in mathematical modeling.

3. Mathematical modeling of the process of polymer insulation hardening by thermal radiation

A mathematical model is necessary to improve the process of hardening of polymer insulation by thermal radiation. A mathematical model establishes the relationship between the dose of exposure of polymer insulation to thermal radiation and the expected final results. This model needs to be tested experimentally for adequacy.

\[
\frac{dt}{d\tau} = \nu \cdot t
\]  (1)

\(t\) – the heating temperature of polymer insulation, °C;

\(\nu\) – the specific heating rate of polymer insulation by thermal radiation, °C.

Formally, this equation is similar to the equation of the rate of a chemical reaction of the first kind. However, in polymer hardening processes, the specific heating rate depends on the power concentration

\[
\nu = f(p)
\]  (2)

By analogy with the Mono equation

\[
\nu = \frac{\nu_{max} p}{K_c + p}
\]  (3)

\(p\) – power concentration;

\(K_c\) – constant, defining the purpose of the process.

The basis for each considered technological process of insulation repair is its heating by thermal radiation. The insulation material is heated not by sequentially redistributing one type of energy according to the standard scheme "heat" → "heat", as occurs when using contact or convective heat exchange, but by converting electric energy into heat according to the complicated scheme "electric energy"→"heat"→"electromagnetic radiation"→"heat". At the first stages of the process of hardening polymer insulation in the infrared emitter, thermal radiation energy generates due to the influence of electric current on the radiator heating body. The filament most often acts as a heating body. Further, the energy is transferred to the learning surface of the insulation in the electromagnetic waves form and again turns into heat, which subsequently performs one or another technological process, as mentioned above. The indicated stages can be represented in the form of a structural-logical model showing the relationship between input and output parameters.

The structural-logical model shows the energy relationship along the entire path of converting electrical energy in a particular process with its intended purposes. Moreover, it allows you to visually choose mathematical models to justify the technological process of drying and hardening of polymer insulation by thermal radiation. The mathematical model should reproduce the dynamics of the effect of thermal radiation on the insulating structures of the windings of power equipment. In this case, the mathematical model must take into account the spectral characteristics of the emitters, the geometric structural features of the windings, the type of insulation, and the optical properties of the impregnating composition.

In each specific case of mathematical modeling, the purpose of the technological process significantly affects the "System" composition in terms of its expansion and addition of new elements. These entail significant changes in the mathematical model final form is expressed in modifications of the equation in terms of the members' number and the appearance of new coefficients.

IR radiation upon reaching the material is converted into thermal energy as a result of the absorption capacity of the material. In this case, the temperature of the irradiated body reaches a limit
value, since part of the energy received is returned to the environment. The more significant difference between the material temperature and the ambient temperature, the higher the heat loss. In paragraph 4.7 of this work, experimental studies show determination and analysis are the quantities on which the value of the limiting heating temperature of the irradiated surface depends.

Such parameters are the energy illuminance of the surface of the irradiated material, the absorption and reflectivity of the irradiated surface. It can be expected that these values affect the limiting temperature to the same extent so that with increasing energy illumination and absorption capacity, the limiting temperature also rises. The performed experimental studies prove the correctness of this assumption.

The relationship between these quantities can be expressed by the formula proposed by Tiller and Garber, which has the following form

\[ T_{\text{max}} = T_0 + \frac{A_\lambda \cdot E}{\alpha \cdot F} \]

where:
- \( T_0 \) – the ambient temperature;
- \( A_\lambda \) – absorption capacity;
- \( \alpha \) – convection heat transfer coefficient;
- \( F \) – surface area involved in the heat exchange between raw materials and air.

This formula shows that the limiting temperature can be achieved with lower energy illumination of the infrared emitter if the absorption capacity of the insulating material is sufficiently high. This circumstance can be observed in the example of baking thermosetting synthetic resin varnish.

Thus, the operating surface and insulation temperature depends on the of the entire “System” elements characteristics as a whole, not only on the optical properties of the material from is made. In this connection, it is necessary to analyze the influence of each element of the “system” to identify those elements that have the most significant impact on the hardening process.

Figure 2 shows the structural diagram of the “System”. The main characteristics of the “System” structure element evaluate their relationship and their impact on the process as a whole.

As can be seen from the figure, the “System” is conventionally divided into eight elements, each of which is one way or another affects the operability of the subsequent one.

To supply the “System,” a single-phase two-wire network with a voltage of 220 V is often used, however, to improve energy efficiency in the development of thermal radiation generators, it is better to use a three-phase system.

To control the operating modes of the emitters in the “System” may be provided with a converter. The converter can be a conventional transformer, as well as a power regulator, which allows control of the heating temperature by changing the spectral composition of the emitters.

Irradiators are combinations of an emitter and a reflector. Currently, there are a massive number of infrared emitters. Their market is continually evolving, and the scope of their use is expanding. This research work has a continuation. Soon, it is necessary to analyze emitters for technological processes of using infrared radiation in the process of repairing insulation, taking into account their spectral characteristics. Ceramic emitters are most widely used in the drying of paints and varnishes. It is in the irradiator that the main flow of thermal radiation is formed. The choice of material and shape of the reflector significantly affects the loss of radiation during operation – often curved aluminum plates with a polished surface used as reflectors. The most common in terms of efficiency and reliability are electric infrared emitters.
The medium between the irradiator and the heated object is significantly different for each of those processes. In the case of strengthening polymer insulation over the entire period, the medium itself also changes. At the initial time, the medium will mainly represent air. Further, in the process of heating a liquid polymer (polymer material), solvent vapors intensively begin to be released from its surface. In this case, the intensity of the vapor evolution substantially depends on the impregnating material. So for materials based on varnishes, consisting of 90% solvent, the evaporation rate is maximum, and for compounds – the minimum evaporation rate. Thus, the type of liquid polymer significantly affects the chemical composition of the medium, which in turn affects the loss of thermal radiation.

The process of hardening insulation is characterized by the presence of a liquid polymer, which can be varnishes, resins, compounds, or other impregnating materials. Depending on the type of electrical equipment, various types of insulating materials with different numbers of layers are used. At the same time, the optical characteristics of materials differ significantly, having different indicators of reflection, transmission, and absorption.

4. Conclusion
The main provisions of the analysis of the interaction of the "System" with a functional approach are as follows:

1) The original "System" is considered not as a single whole and indivisible, but as a specific structure consisting of separate parts – subsystems connected and having interconnections.

2) The main structural elements of the "System" are emitters and insulating materials. In this regard, it is necessary to consider the main characteristics of these elements of the system under...
consideration. For an insulating material, the main characteristics are geometric, thermophysical, optical, and thermal radiation. For emitters – energy and spectral.

3) The number of factors that insignificantly affect the "System" is limited in this case, which allows us to consider such a system as an object of shallow dimension, reduced to simple mathematical methods.

4) For the mathematical description of the dynamic behavior of the "System," as a first approximation, one can use the differential equation of the energy balance, which also allows one to obtain a dynamic thermal model (chapter 3).

5) The criterion of optimality in the study of the relationship of the elements of the "System" should be considered the maximum allowable temperature, power density, and heating rate for a particular process under study.

The methodological sequence in the analysis of the interaction of the "System" in the case of using thermal radiation in the repair of insulation can be represented by the following points:

1) The structural scheme of the "System" must be clarified for each technological process individually to draw up adequate mathematical models.

2) It is necessary to have the requirements of the process for the maximum allowable temperature or heating rate of the material.

3) When analyzing the stages, it is necessary to take into account the influence of other stages on them as initial and boundary conditions.

As a result, because the mathematical model should adequately reproduce the kinetics and dynamics of heating by thermal radiation of polymers in an appropriate manner [9, 10]. Before developing a mathematical model, it is necessary to carry out a set of experimental laboratory work to study the hardening processes of elements of insulating structures of electrical equipment. Based on these studies, it is necessary to develop a set of mathematical models for calculating the infrared energy supply modes in the manufacturing and repair technologies of insulating structures of electrical equipment of electric locomotives.

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