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PROVIDING TECHNICAL PARAMETERS OF RESISTIVE CABLES OF THE HEATING FLOOR SYSTEM WITH PRESERVATION OF THERMAL RESISTANCE OF INSULATION

Introduction. The main purpose of resistive cables is to convert the current flowing through the cable into heat. The maximum operating temperature of the conductive core should not exceed 100 °C. Power output per cable per unit length (nominal specific electrical power per 1 m of heating cable at rated line voltage per 1m cable) is the main technical parameter of these cables. The heat released by the conductivity of the core current, taking into account the change in the resistivity of the core material from temperature, is directly proportional to the square of the linear voltage drop across the core, and inversely proportional to the linear resistance of the core. Typical heat dissipation in such cables does not exceed 10 W/m, provided the cable is placed in the air. Purpose. Determination of the specific power of the cable system when varying the thickness of the insulation and the protective polymer shell, provided the thermal stability of the insulation on the basis of thermal balance between the power released in the core and the power released into the environment from the surface of the resistive heating. Methodology. The calculation of the linear heat flux is performed in two steps: when changing the radius of insulation (thickness of insulation) and the constant thickness of the protective polymer shell; at constant thickness of insulation and change of radius of the protective polymer jacket. The highest values of linear heat flux at (70-90) W/m are achieved for the optimum design of a single-conductor resistive cable from a conductive core in the range of 0,4 mm to 1,6 mm when varying the thickness of the cross-linked polyethylene insulation and protective sheath based on polyvinyl chloride plastic. The specific power of heating resistive cables, provided the thermal stability of the crosslinked polyethylene insulation is determined based on the thermal balance between the power generated in the core and the power dissipated from the surface of the cable into the air. Practical value. The thickness of the insulation and the linear voltage of the heating resistive cable, depending on the material of the core, providing thermal stability of the insulation are substantiated. The methodology of substantiation of specific power, which corresponds to thermal stability of heating resistive cables on the basis of thermal balance, can be applied to both the floor heating system and other areas of application of heating cables. References 10, tables 2, figures 4.
Key words: **resistive single conductor heating cable, specific power, linear voltage, thermal stability, polyethylene thermosetting insulation.**

Встановлено діапазон значень лінійного теплового потоку в залежності від розмірів конструктивних елементів резистивного нагрівального кабелю коаксіальної конструкції. На підставі теплового балансу потужностей, що виділяється в струмопровідній жилі та розсіюється з поверхні кабелю, визначено питома потужність нагрівальних резистивних кабелів системи теплої підлоги за умови забезпечення теплової стійкості поліетиленової термореактивної ізоляції. Обґрунтовано товщина ізоляції та лінійна напруга нагрівального резистивного кабелю в залежності від матеріалу струмопровідної жили, що забезпечують теплову стійкість ізоляції. Бібл. 10, табл. 2, рис. 4.
Ключові слова: **резистивний однопровідниковий нагрівальний кабель, питома потужність, лінійна напруга, теплова стійкість, поліетиленова термореактивна ізоляція.**

Установлен диапазон значений линейного теплового потока в зависимости от размеров конструктивных элементов резистивного нагревательного кабеля коаксиальной конструкции. На основании теплового баланса мощностей, выделяемой в токопроводящей жиле и рассеиваемой с поверхности кабеля, определена удельная мощность нагревательных резистивных кабелей системы теплого пола при условии обеспечения тепловой устойчивости полиэтиленовой термореактивной изоляции. Обоснованы толщина изоляции и линейное напряжение нагревательного резистивного кабеля в зависимости от материала токопроводящей жилы, обеспечивающие тепловую устойчивость изоляции. Библ. 10, табл. 2, рис. 4.
Ключевые слова: **резистивный однопроводниковый нагревательный кабель, удельная мощность, линейное напряжение, тепловая устойчивость, полиэтиленовая термореактивная изоляция.**

Introduction. The cable heating floor system is based on cable. The most common are resistive heating cables, which in execution are single-conductor (two-way) and two-conductor (one-way). Single-conductor cables (Table 1) are conductive core (1) with insulation (2) in the metal screen (3) and the protective polymer shell (4). here, the insulation can be either single- or double-layer. The presence of a protective screen is mandatory according to the requirements of the Rules of operation of electrical installations, and at its intersection it must be equivalent to 1.0 mm^2 of copper conductor [1, 2].

The design of such cables is similar to radio frequencies ones intended, for example, for the transmission of television signals. The conductive core is copper, galvanized steel, or high resistance alloys. Polyethylene (thermally reactive insulation) crosslinked by chemical or physical method; organosilicon rubber, heat-resistant polyvinyl chloride plastic are used as insulation [3]. The insulation resistance must be at least 100 TΩ·m. The protective shell is made of polyvinyl chloride plastic or light stabilized polyethylene.

The main purpose of resistive cables is to convert the current flowing through the cable into heat. The maximum operating temperature of the conductive core should not exceed 100 °C [4, 5]. Power output per cable per unit length (nominal specific electrical power per 1 m

of heating cable at rated line voltage per 1 m of cable) is the main technical parameter of these cables. Characteristic heat dissipation in such cables does not exceed 10 W/m, provided that the cable is placed in the air (Table 1) [4, 5].

Table 1
Typical characteristics of a single-conductor heating resistive cable for heating floor system

Parameter	Value
Maximum temperature of the core, °C	100
Maximum allowable temperature without load, °C	100
Maximum linear heat dissipation, W/m	10
Minimum installation temperature, °C	–10
Rated frequency of 50 Hz, V	220
Maximum load current, A	16
Minimum bending radius at operation and storage, mm	150
Minimum allowed radius of single bending, mm	30

Problem definition. The heat P_v released by the current flow along the core, taking into account the change in the resistivity of the conductor material from the temperature [6, 7] $\rho_{gt} = \rho_{T_0} \cdot (1 + \alpha_\rho \cdot (T_g - T_0))$, is directly proportional to the square of the linear drop in the voltage U_p on the core and inversely proportional to the linear resistance $R_{gt} = \dfrac{\rho_{gt}}{\pi \cdot r_1^2}$ of the conductive core with radius r_1

$$P_v = U_p^2 / R_{gt} = \frac{U_p^2}{\rho_{gt}} \cdot \pi \cdot r_1^2, \text{ [W/m]}, \qquad (1)$$

where α_ρ is the temperature coefficient of resistivity ($\alpha_\rho = 0.004$ K^{-1} for copper, $\alpha_\rho = (0.0001–0.00025)$ K^{-1} for nichrome); T_g, T_0 are the temperature of the conductive core in the heated state due to the flow of the rated current and in the initial state (20 °C), respectively.

In resistive cables, the conductive core has a high internal resistance and, when connected to the mains, is uniformly heated throughout. This property makes it strictly follow the temperature of the operating cable: at deterioration of heat dissipation in a separate area overheat and burn of the cable are possible. Therefore, as a rule, these cables are connected via heating temperature controllers. Fixed cable resistivity imposes a limit on the overall length: reducing it relatively to the recommended values leads to an increase in the specific power, which reduces the durability of the cable. Conversely, increasing the length reduces the specific power and, accordingly, the heating efficiency.

The set of structural features and materials used in the design of cables for heating floor systems must provide a set of electrical, thermal and mechanical characteristics in accordance with the operating conditions at the optimum dimensions.

In [6], the problem of optimizing the power cable of a coaxial structure is formulated to ensure the maximum heat flux dissipated from the cable surface at a fixed thickness of polymer insulation. The target optimization function is the linear density of the heat flux dissipated from the cable surface, depending on the thickness of the protective polymer shell. In low-voltage heating resistive cables, ensuring maximum linear heat flux density is possible by varying both the thickness of the protective polymer shell and the thickness of the insulation. The basic condition for optimizing cable design is to provide thermal insulation resistance, which limits, firstly, the long-term operating temperature of the conductive core, and secondly, the temperature on the cable surface, which must not exceed 60 °C according to the requirements for an electrical cable heating system [2].

Therefore, **the goal of the paper** is to determine the specific power of the cable system when varying the thickness of the insulation and the protective polymer shell, provided the thermal stability of the insulation on the basis of thermal balance between the power released in the conductive core and the power released to the environment surface of resistive heating cable.

A model for determining linear heat flux. The linear heat flux q_l dissipated in the resistive cable of the coaxial structure (Fig. 1) during the flow of rated current through the core is defined as [6]

$$q_l = \frac{\pi (T_g - T_{OS})}{R_\Sigma}, \text{ [W/m]}, \qquad (2)$$

where T_{OS} is the ambient (air) temperature, K; R_Σ is the total thermal resistance of cable elements and the environment, (K·m)/W.

The calculation of the linear heat flux is performed in two stages: the first is at the radius along the insulation r_{2var} (thickness of insulation) is changed and at the constant thickness of the protective polymer shell; the second one − on the contrary: at a constant thickness of insulation and change of radius r_{4var} of the protective polymer shell.

In both cases, the total thermal resistance R_Σ [6-10]

$$R_\Sigma = R_2 + R_4 + R_{OS}, \qquad (3)$$

is a function of the design dimensions of the cable.

The thermal resistances of the conductive metal core and the metal screen are assumed to be zero (the thermal conductivities of metals are 20-100 times greater than the thermal conductivity of insulating materials [7, 9]), that is, $R_1 = R_3 \approx 0$.

Components of thermal resistance: thermal insulation resistance (for the first stage of calculation when changing r_{2var}):

$$R_{2var} = \frac{1}{2\pi\lambda_2} \cdot \ln\left(\frac{2r_{2var}}{2r_1}\right), \qquad (4)$$

thermal resistance of the protective polymer shell (for the second stage of calculation when changing r_{4var}):

$$R_{4var} = \frac{1}{2\pi\lambda_4} \cdot \ln\left(\frac{2r_{4var}}{2r_3}\right), \qquad (5)$$
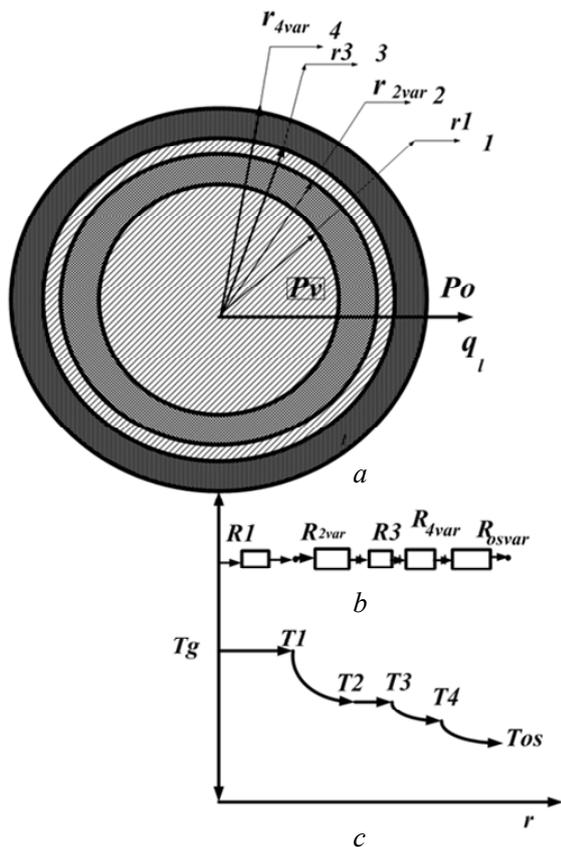
Fig. 1. Typical design (*a*), thermal substitution circuit (*b*) and schematic representation of temperature distribution (*c*) by thickness of resistive coaxial heating cable (1 – conductive core, 2 – insulation, 3 – metal screen over insulation, 4 – protective polymer shell)

thermal resistance of the environment (air) (in both cases, changing each component of the thermal resistance leads to a change in the cooling surface S_{os} of the cable):

$$R_{os\,var} = \frac{1}{\alpha_{ef} \cdot S_{os\,var}}. \qquad (6)$$

In the formulas (4), (5) presented: λ_2, λ_4 are the thermal conductivities of insulation and protective polymer shell, respectively; α_{ef} is the effective coefficient of heat transfer to the environment due to convection and radiation, $2r_1$ is the diameter of the core, $2r_{2var}$ is the diameter of the insulated wire, $2r_3$ is the diameter of the metal screen, $2r_{4var}$ is the diameter along the polymeric protective shell.

Figure 2 shows the effect of the thickness of the polyethylene insulation ($\lambda_2 = 0.25$ W/(m·K)) and the polyvinyl chloride protective shell ($\lambda_4 = 0.35$ W/(m·K)) on the linear heat flux of the resistive heating cable of the coaxial structure. The calculation is made for three diameters of conductive core:

• $2r_1 = 0.4$ mm – curves 1 and 1';
• $2r_1 = 0.8$ mm – curves 2 and 2';
• $2r_1 = 1.6$ mm – curves 3 and 3' when varying the radius of insulation (r_{2var} / r_1) – curves 1, 2 and 3, and when varying the radius of the polymeric protective shell (r_{4var} / r_1) – curves 1', 2' and 3', respectively.

The effective heat transfer coefficient is 10 W/(m² K). The thickness of the polymer shell is 0.5 mm for curves 1,

2 and 3. Insulation thickness is 0.8; 1.6 and 3.3 mm for curves 1', 2' and 3', respectively.
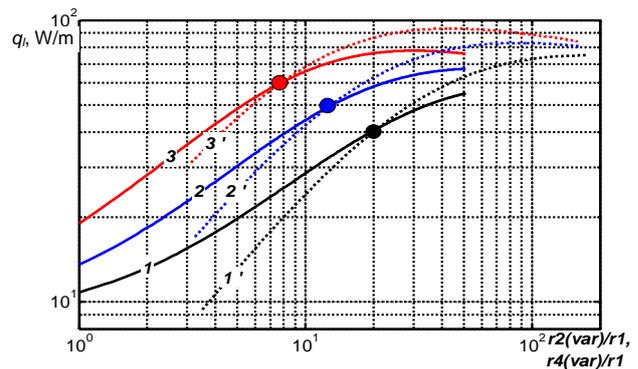

Fig. 2. Determination of expected values of linear heat flux depending on the size of structural elements of a resistive heating cable of a coaxial structure

As the calculation results prove (see Fig. 2), the maximum values of linear heat flux that can be dissipated from the cable surface are in the range of 70 to 90 W/m (curves 1 and 3). Such values correspond to a significant 40-100 times larger diameter along insulation and protective shell relative to the diameter of the conductive core. The values of the linear heat flux in the range (40-50) W/m are provided at smaller ratios of geometric dimensions (shown by points on curves 1, 2, 3 in Fig. 2).

Specific power of heating resistive cables, provided thermal insulation resistance. The value of the linear heat flux in the range (40-50) W/m (Fig. 3, curve 5) is provided by the cable design, conductive core of which is made on the basis of 0.8 mm diameter nichrome, with cross-linked polyethylene insulation 4.8 mm thick and polyvinyl chloride protective shell 0.5 mm thick.
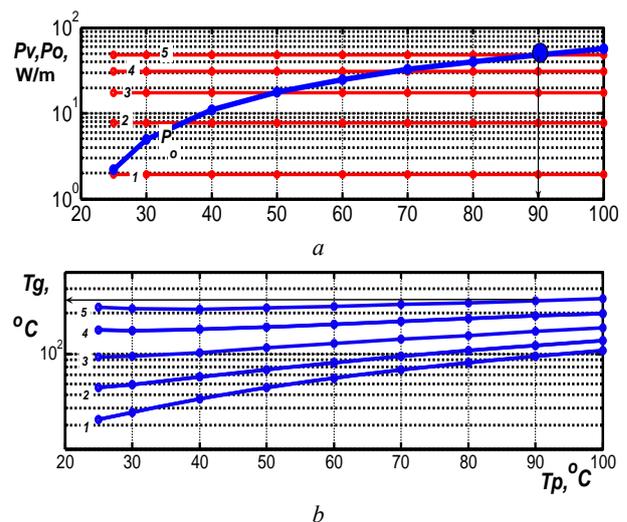

Fig. 3. On determination of the specific power provided thermal resistance of the insulation of the heating resistive cables (curve 1 – linear voltage 2 V/m; curve 2 – 4 V/m; curve 3 – 6 V/m; curve 4 – 8 V/m; curve 5 – 10 V/m)

The total cable diameter is 11.6 mm with aluminum screen thickness of 0.1 mm. Such values are observed at

linear voltage of 10 V/m, which corresponds to the thermal balance between the power released in the core P_v and the power dissipated from the surface of the cable P_0 into the air (see Fig. 1,*a*; curve 5 in Fig. 3,*a*).

The temperature on the cable surface ($T_p = T_4$) is 90 °C, of the conductive core – $T_g = 250$ °C (curve 5 in Fig. 3,*b*). At these temperatures, the thermal stability of the cross-linked polyethylene insulation is disrupted, which makes it impossible for the heating cable to work in the floor heating system. The cross-linked polyethylene insulation temperature should not exceed 90 °C [3, 9]. The use of more heat-resistant polytetrafluoroethylene or mineral insulation ensures the creation of high-temperature cables for heating oil pipelines and process equipment [5].

Reducing the line voltage to 6 V/m (Fig. 3, curve 3) provides a thermal balance ($P_v = P_0$) at the level of 18 W/m at a cable surface temperature of 50 °C. In this case, the temperature of the conductive core exceeds the maximum permissible value of 100 °C and is 115 °C (see curve 3 in Fig. 3,*b*).

Reducing the thickness of the insulation to 1 mm ensures a thermal balance at the cable surface temperature 53 °C and the core temperature 86 °C at nominal linear voltage of 4 V/m (Fig. 4,*a*, curve 2). The expected value of the specific power is 8.8 W/m (Fig. 4,*a*, curve 2 in the upper figure).

When using a copper core of the same design, the value of the specific power is 7 W/m (Fig. 4,*b*, curve 2 in the upper figure) at linear voltage of 0.5 V/m. The surface temperature of the cable surface is 47 °C, the temperature of the core is 80 °C (Fig. 4,*b*, curve 2). The cable diameter is 4 mm.

Comparison of two identical by dimensions cable structures with different conductive core material proves that: at supply voltage of 220 V, the length of the cable section with a nichrome core is 55 m with total power of 484 W; the length of copper section cable is 440 m with total power of 3080 W. Eight sections based on the cable with nichrome core total length of 440 m provide power of 3872 W.

When placing the cable directly in the floor (cement-sand mortar), the thermal resistance of the environment [7]

$$R_{OS_t} = \frac{1}{2\pi\lambda_{OS} \cdot L} \ln\left(\frac{h}{d} + \sqrt{\left(\frac{h}{d}\right)^2 - 1} \right),$$

where $\lambda_{OS} = 0.6$ W/(m·K) is the thermal conductivity of cement-sand mortar; $L = 1$ m is the cable length, d is the cable diameter, h is the depth of cable location.

Table 2 shows a comparative analysis of thermal resistances at the location of the cable in the air and cement-sand mortar at a distance of 50 mm from the floor surface.

curve 1 – linear voltage 3.75 V/m;
curve 2 – 4 V/m; curve 3 – 4.25 V/m

curve 1 – linear voltage 0.4 V/m;
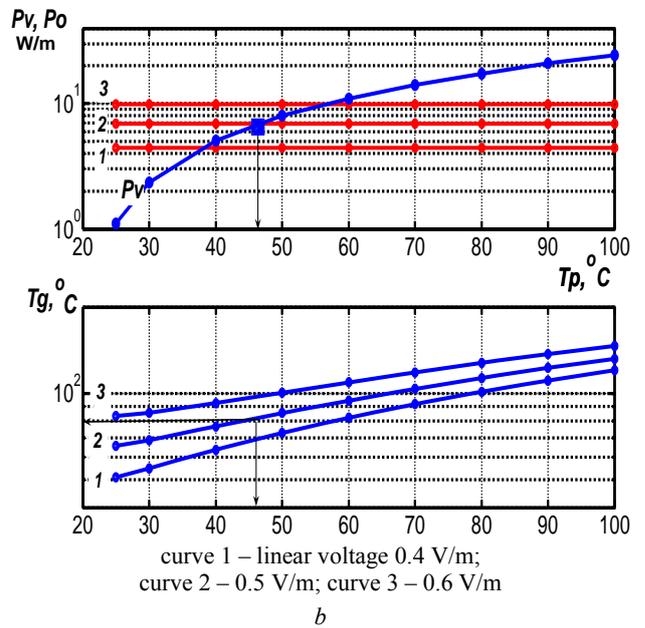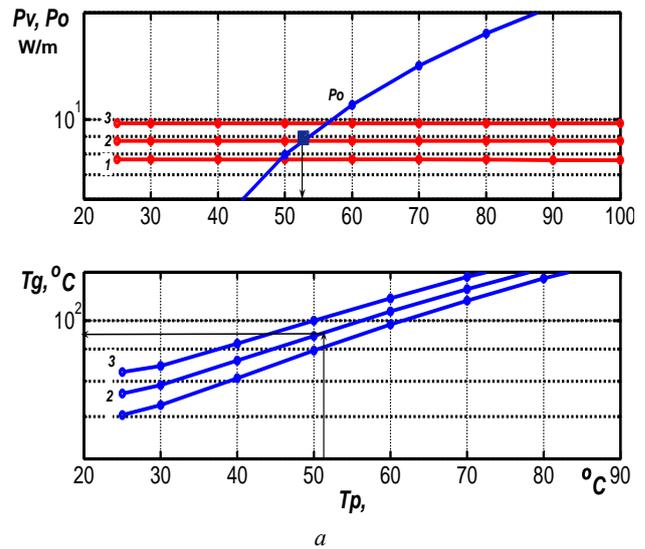curve 2 – 0.5 V/m; curve 3 – 0.6 V/m

b

Fig. 4. Effect of insulation thickness and line voltage of the heating resistive cable on thermal resistance of the thermosetting polyethylene insulation

Table 2
Impact of the environment surrounding the cable with diameter of 4 mm on the total thermal resistance

Cable thermal resistance: $R_2 + R_4$, K·m/W	When the cable is placed in the air		When the cable is placed in cement-sand mortar	
	Air thermal resistance: R_{OS}, K·m/W	Total thermal resistance R_Σ, K·m/W	Thermal resistance of the environment surrounding the cable: R_{OS}, K·m/W	Total thermal resistance R_Σ, K·m/W
1.3507	3.2811	4.6318	1.0376	2.3883

The location of the cable in the cement-sand mortar reduces the total resistance by 1.94 times compared to the location in the air, which ensures the effectiveness of the heating resistive cable.

Conclusions.

1. It is established that the highest values of linear heat flux at the level of (70-90) W/m are achieved for the

optimum design of a single-conductor resistive cable with conductive core in the range from 0.4 mm to 1.6 mm when varying the thickness of the cross-linked polyethylene insulation and protective shell based on polyvinyl chloride plastic.

2. Based on the heat balance of the power released in the conductive core and dissipated from the cable surface, the specific power of the heating resistive cables of the floor heating system is determined to ensure the thermal stability of the polyethylene thermosetting insulation. It is proved that for two identical cable designs with different conductive core material, the use of nichrome compared to copper is more efficient: the specific power is greater by 1.26 times, the linear voltage – by 8.5 times, respectively. In both cases, the thermal stability of the cross-linked polyethylene insulation is ensured.

3. The considered technique of substantiation of the specific power, which corresponds to the thermal stability of the heating resistive cables on the basis of thermal balance, can be applied to both the floor heating system and other areas of application of heating cables.

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