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TEMPERATURE INFLUENCE ON GEOMETRIC SIZES OF CORE ELEMENTS AND THE OPTICAL CABLE RELATIVE ELONGATION

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ТЕМПЕРАТУРНИЙ ВПЛИВ НА ГЕОМЕТРИЧНІ РОЗМІРИ ЕЛЕМЕНТІВ ОСЕРДЯ ТА ВІДНОСНЕ ВИДОВЖЕННЯ ОПТИЧНОГО КАБЕЛЮ

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ТЕМПЕРАТУРНОЕ ВОЗДЕЙСТВИЕ НА ГЕОМЕТРИЧЕСКИЕ РАЗМЕРЫ ЭЛЕМЕНТОВ СЕРДЕЧНИКА И ОТНОСИТЕЛЬНОЕ УДЛИНЕНИЕ ОПТИЧЕСКОГО КАБЕЛЯ

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Abstract. The research of thermomechanical influence on geometrical sizes of core elements of an optical cable (OC) design is done in the work. It allowed improving the expression for calculating the permissible relative cable elongation by taking into account the temperature coefficients of linear expansion of the structural elements materials. The obtained temperature dependences of the change of the OC design relative elongation made it possible to establish that its value increases (decreases) with increasing (decreasing) temperature relatively to 20 °C. And also show that the usage of polycarbonate as a material of the optical module tube, where quartz optical fibers are placed, will provide smaller change of the cable relative elongation at the temperature change.
Key words: optical cable, relative elongation of a cable, optical module tube, temperature coefficient of linear expansion.

Анотація. В роботі виконано дослідження термомеханічного впливу на геометричні розміри елементів осердя конструкції оптичного кабелю (ОК). Це дозволило удосконалити вираз розрахунку допустимого відносного видовження кабелю шляхом урахування температурних коефіцієнтів лінійного розширення матеріалів конструктивних елементів. Одержані температурні залежності зміни відносного видовження конструкції ОК дозволили встановити, що його значення збільшується (зменшується) при збільшенні (зменшенні) температури відносно 20 ºС. А також вказують на те, що застосування полікарбонату як матеріалу трубки оптичного модуля, в якому розташовані кварцові оптичні волокна, забезпечить менші зміни відносного видовження кабелю при зміні температури.
Ключові слова: оптичний кабель, відносне видовження кабелю, трубка оптичного модулю, температурний коефіцієнт лінійного розширення.

Аннотация. В работе проведено исследование термомеханического воздействия на геометрические размеры элементов сердечника конструкции оптического кабеля (ОК). Это позволило усовершенствовать выражение расчета допустимого относительного удлинения кабеля путем учета температурных коэффициентов линейного расширения материалов конструктивных элементов.

Полученные температурные зависимости изменения относительного удлинения конструкции ОК позволило установить, что его значение увеличивается (уменьшается) при увеличении (уменьшении) температуры относительно 20 °С. А также указывают на то, что применение поликарбоната в качестве материала трубки оптического модуля, в котором размещены кварцевые оптические волокна, обеспечит меньшие изменения относительного удлинения кабеля при изменении температуры.

Ключевые слова: оптический кабель, относительное удлинение кабеля, трубка оптического модуля, температурный коэффициент линейного расширения.

Ensuring of the physical integrity and stability of transmission characteristics of an optical fiber (OF) is the most important task when developing and producing of optical cables (OC), constructing and technical operating of fiber-optic communication lines.

Today this has led to the development of a number of designs of optical cables, which are distinguished by a variety of design solutions, quality, parameters and materials of the elements and are able to provide the above conditions.

One of the important points of the OC design is to ensure the thermal stability of its designer characteristics under the influence of temperature change. This need is due to the fact that when the temperature changes the elastic-deformed state in the OC arises due to the difference of the temperature coefficients of linear expansion (TCLE) of the elements materials, in particular, the optical fibers and the optical module tubes (OMT), into which they are laid [1]. Such OC state can introduce the extreme tensile and compressive forces in the OF, which cause an unpredictable change of transmission parameters, premature aging or fiber breakage, and the failure of the entire fiber optic communication line.

The above conditions are achieved by providing the smallest contact of the OF (or many OF) and the inner surface of the OMT wall and in practice, as a rule, is realized at the OC production temperature by free placement of optical fibers inside the tube of the optical module (Fig. 1).

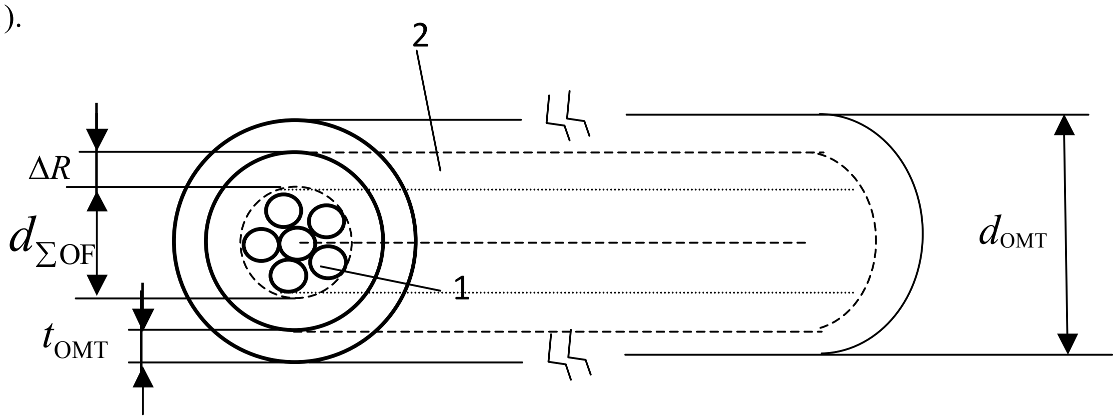

Figure 1 – Bunch of optical fibers, freely enclosed in the optical module tube:
1 – optical fiber; 2 – optical module tube

Thus, under the influence of temperature, the longitudinal and transverse dimensions of the core elements of the OC (in particular OF, OMT, central strength element) are changed in accordance to the TCLE values of their materials.

In addition, in a number of sources, for example [1-3], it is noted that the important aspect in designing of OC is the right selection of the OMT diameter, the radial thickness of its walls and the number of optical fibers located therein, with providing the necessary space within the module for free movement of OF in it under the action of the mechanical loads on the cable.

The mentioned geometric dimensions of the elements allow to determine the relative elongation of the OC design, which is the criterion for calculating the cable's maximum permissible tensile load F_{mp}, which is regulated in product technical conditions and must be provided throughout the normative term [1]

$$F_{mp} = \sum_{i=1}^{n} E_i \varepsilon_c S_i \,, \quad (1)$$

where n – number of elements providing the mechanical strength of the cable; E_i – Young's module of the material of the i-th OC element, N/mm^2; ε_c – permissible relative elongation of the OC; S_i – cross section area of the i-th element, mm^2.

The outlined situation indicates the need to perform the research of the temperature influence on the geometric parameters of the OC elements, since at present in the technical literature there is no complete data on the result of the temperature influence on the geometric dimensions of the elements and the parameters of the OC design.

The purpose of this work is to study the results of the temperature influence on the geometric dimensions of the elements and relative elongation of the optic cable with modular design.

The design of the OC should be constructed taking into account the provision of OF materials and other elements minimal interaction in the manufacture and operation, as well as when their size changing under of the environmental influence with different temperatures [1].

The presence in the OC design the elements, made of materials with different TCLE, causes different changes of their geometric sizes. In this case, due to the difference of the TCLE of OF and OMT materials, their lengths under the temperature change differently, which results to the appearance of compression or stretching forces of the optical fiber located inside the optical module tube [4].

In [1], it is shown that for the case of the equality of the TCLE of OF and OMT materials, the diameter of the optical module tube d_{OMT} can be taken as the sum of the diameters of the OF (or many fibers) and the double radial thickness of the OMT wall

$$d_{\text{OMT}} = d_{\text{OF}} + 2t_{\text{OMT}}\,, \quad (2)$$

where d_{OMT} – diameter of the optical module tube, mm; d_{OF} – diameter of an OF (or bunch of fibers), mm; t_{OMT} – radial thickness of the OMT wall, mm.

Then, the minimum diameter of the optical module tube, taking into account the interaction between the OF and the inner surface of the OMT wall, as well as the changing of the radial dimensions of these elements at temperature change, can be determined [1]

$$d_{\text{OMT}} = \frac{2t_{\text{OMT}}\left[1+\text{ТКЛР}_{\text{OMT}}\left(t-20\right)\right] + d_{\text{OF}}\left[1+\text{TCLE}_{\text{OF}}\left(t-20\right)\right]}{1-\sqrt{1+\dfrac{ctg^2 \pi/n}{\sin^2\theta}\cdot\dfrac{\Delta\text{TCLE}\cdot(t-20)}{2\cos^2\theta}}}, \quad (3)$$

where TCLE_{OMT}, TCLE_{OF} – materials TCLE of OMT and OF accordingly, K^{-1}; t – temperature, ºC; n – number of the cable core elements, enclosed around the central strength element (CSE); θ – angle of the spiral layering of the elements in the cable core, rad.

However, in practice, in real OC designs when using the existing polymeric materials, the equality of TCLE of OMT and OF can not be achieved, therefore, the optic module's tube diameter is chosen higher than the value $d_{\text{OF}} + 2t_{\text{OMT}}$. That is why, the distance (gap filled by the hydrophobic filler) is supposed between the OF and the inner surface of the OMT wall to ensure the free movement of the fibers within the tube of the module.

Based on Fig. 1 it is known that the distance between the OF and the inner surface of the OMT wall with the axial arrangement of fibers inside the module equals [3]

$$\Delta R = \frac{d_{\text{OMT}} - 2t_{\text{OMT}} - d_{\text{OF}}}{2}\,. \quad (4)$$

At temperature change, this distance varies due to the change of the radial dimensions of the OMT and OF on the additional value $\Delta R_{add}(t)$ [1]

$$\Delta R_{add}(t)=\left[\left(d_{\mathrm{OMT20}}-2t_{\mathrm{OMT20}}\right)\mathrm{TCLE}_{\mathrm{OMT}}-d_{\mathrm{OF20}}\mathrm{TCLE}_{\mathrm{OF}}\right]\frac{(t-20)}{2}, \quad (5)$$

where d_{OMT20}, t_{OMT20}, d_{OF20} – diameter of the OMT, its radial thickness and OF diameter (bunch of fibers) at temperature 20 ºC, mm.

General expression for determining the distance ΔR at temperature change

$$\Delta R(t)=\Delta R+\Delta R_{add}(t)=$$
$$=\frac{1}{2}\left[\left(d_{\mathrm{OMT20}}-2t_{\mathrm{OMT20}}\right)\left[1+\mathrm{TCLE}_{\mathrm{OMT}}(t-20)\right]-d_{\mathrm{OF20}}\left[1+\mathrm{TCLE}_{\mathrm{OF}}(t-20)\right]\right]. \quad (6)$$

Changing of the free space inside the OMT leads to a decreasing of the fibers ability to move when introducing the applied, first of all, longitudinal forces to the cable. This causes to reducing of the cable relative elongation, and thus limiting its mechanical strength.

The relative elongation of the OC design ε_c at temperature 20 °C can be determined by expression [2, 3, 5]

$$\varepsilon_c=-1+\sqrt{1+\frac{4\pi^2R^2}{h^2}\left(\frac{2\Delta R}{R}-\frac{\Delta R^2}{R^2}\right)}, \quad (7)$$

where ε_c – relative elongation of the OC design; R – radius of the spiral stacking of elements in the layer, mm; ΔR – distance between the OF and the internal surface of the OMT wall, mm.

Taking into account all temperature-dependent parameters, the expression (7) will take the form

$$\varepsilon_c(t)=-1+\sqrt{1+\frac{4\pi^2R(t)^2}{h(t)^2}\left(\frac{2\Delta R(t)}{R(t)}-\frac{\Delta R(t)^2}{R(t)^2}\right)}. \quad (8)$$

As known, the radius of the spiral stacking of the elements in the core of the cable is defined as (Fig. 2) [3]

$$R=\frac{d_{\mathrm{CSE}}+d_{\mathrm{OMT}}}{2}, \quad (9)$$

where d_{CSE}, d_{OMT} – CSE and OMT diameters respectively, mm.

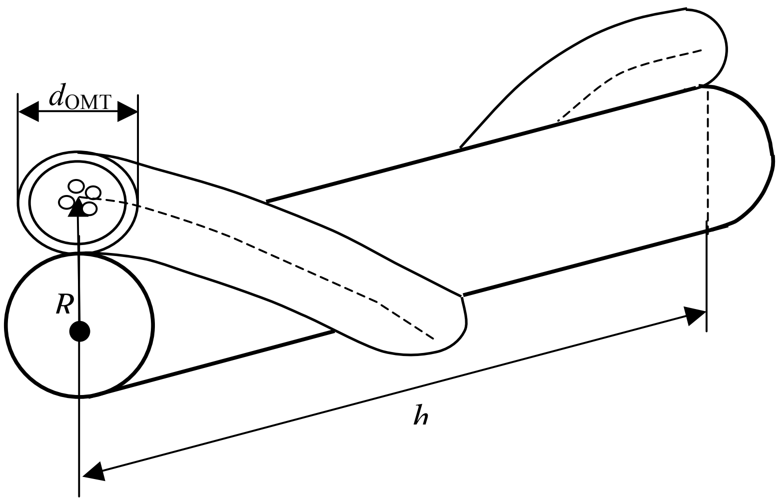

Figure 2 – Spiral stacking of the optical module tube around the CSE

Between the diameters of OMT and CSE there is a connection defined in [4, 5], which is characterized by the coefficient *k*, which is determined by the number of elements in the cable layer

$$d_{\mathrm{CSE}} = d_{\mathrm{OMT}} k . \qquad (10)$$

However, in the case of the temperature change of the OC relative elongation, using the expressions (7) and (8), the simplified expression (10) is incorrect, since the connection with the TCLE of the CSE material is lost.

Changing the diameters of OMT $d_{\mathrm{OMT}}(t)$ and CSE $d_{\mathrm{CSE}}(t)$ under the influence of temperature change can be defined as

$$d_{\mathrm{OMT}}(t) = d_{\mathrm{OMT20}}\left[1+\mathrm{TCLE}_{\mathrm{OMT}}(t-20)\right],$$
$$d_{\mathrm{CSE}}(t) = d_{\mathrm{CSE20}}\left[1+\mathrm{TCLE}_{\mathrm{CSE}}(t-20)\right], \qquad (11)$$

where $d_{\mathrm{OMT20}}, d_{\mathrm{CSE20}}$ – diameters of OMT and CSE at temperature 20 ºC, mm; $\mathrm{TCLE}_{\mathrm{OMT}}$, $\mathrm{TCLE}_{\mathrm{CSE}}$ – TCLE of OMT and CSE materials accordingly, K^{-1}.

The change of the spiral stacking step of the elements must be determined from the ratio to the axial length of the element

$$\Delta h = \frac{h \cdot \Delta l_{\mathrm{OMT}}}{l_{\mathrm{OMT}}}, \qquad (12)$$

where l_{OMT}, h – the initial length of the OMT and stacking step at temperature 20 ºC, mm; $l_{\mathrm{OMT}} = \sqrt{h^2 + (2\pi R)^2}$; Δl_{OMT} – change of the OMT length due to temperature, mm; $\Delta l_{\mathrm{OMT}} = l_{\mathrm{OMT}} \mathrm{TCLE}_{\mathrm{OMT}}(t-20)$.

Thus, the resulting expression to determination of the relative elongation of OC, taking into account the temperature influence on the geometric dimensions of all the elements of the cable, has the following view

$$\varepsilon_c(t) = -1 + \sqrt{1 + \frac{4\pi^2}{(h_{20}+\Delta h)^2}\left(d_{\mathrm{OMT20}}\begin{pmatrix}\left[1+\mathrm{TCLE}_{\mathrm{OMT}}(t-20)\right]+ \\ (k+1)\left[1+\mathrm{TCLE}_{\mathrm{CSE}}(t-20)\right]\end{pmatrix}\Delta R(t) - \Delta R(t)^2\right)}, \qquad (13)$$

where d_{OMT20} – diameter of OMT at temperature 20 ºC, mm; h_{20} – stacking step of core elements at temperature 20 ºC, mm; Δh – change of the stacking step according to equation (12), mm; $\mathrm{TCLE}_{\mathrm{OMT}}$, $\mathrm{TCLE}_{\mathrm{CSE}}$ – TCLE of OMT and CSE accordingly, K^{-1}; *t* – operating temperature, ºC; *k* – coefficient that takes into account the number of elements in the cable core, enclosed around the central strength element; $\Delta R(t)$ – temperature-dependent distance between the OF bunch and the internal surface of the OMT wall, mm.

Using the improved expression (13), the temperature dependence of the relative elongation of the cable design is determined on condition: initial stacking step at *t* = 20 ºC h = 100 mm, TCLE of elements materials of the OC according to Table 1, diameter of OMT d_{OMT20} within (2…3) mm, coefficient *k* = 1, that corresponds to 6-elements cable design, radial l thickness of the OMT wall t_{OMT20} equals 20 % of the d_{OMT20}, diameter of bunch of the 12 OF d_{OF20}=1,06 mm [3]. The calculations results of the temperature dependence of the cable relative elongation at different diameters of OMT, made of polybutylene terephthalate, polyamide, polycarbonate, are shown on Fig. 3. Fig. 4 shows the temperature dependence of the relative elongation of OC with OMT diameter 2.3 mm and OMT materials according to Table 1.

In this paper, the study was done using the following assumptions:

1. As materials of the optical module tube accepted only polybutylene terephthalate, polyamide, polycarbonate, and optical fiber accepted quartz glass.

2. The lengths of OMT and OF at temperature of 20 °C are equal to each other, that is, the optical fiber length (or the fiber bunch) is equal to the length of the axial line of the optical module.

3. The influence of materials of filling elements, aramid yarn, protective coverings, etc. were not taken into account.

Table 1 – Value of temperature coefficients of linear expansion of materials of OC elements

№	Element of OC	Material of element	Value of TCLE of material, K^{-1}
1	Central strength element	fiberglass rod	$6{,}6\cdot10^{-6}$
2	Optical module tube	polybutylene terephthalate	$1{,}5\cdot10^{-4}$
		polyamide	$7{,}8\cdot10^{-5}$
		polycarbonate	$6{,}5\cdot10^{-5}$

Table 2 – The values of the relative elongation of the OC at temperature *t* within range (-40…+70) ºC

№	Material of element	The values of the relative elongation of the OC at temperature *t*, ºC				
		-40	0	+20	+40	+70
1	Polybutylene terephthalate	0,134	0,138	0,140	0,142	0,145
2	Polyamide	0,137	0,139	0,140	0,141	0,143
3	Polycarbonate	0,138	0,139	0,140	0,140	0,142

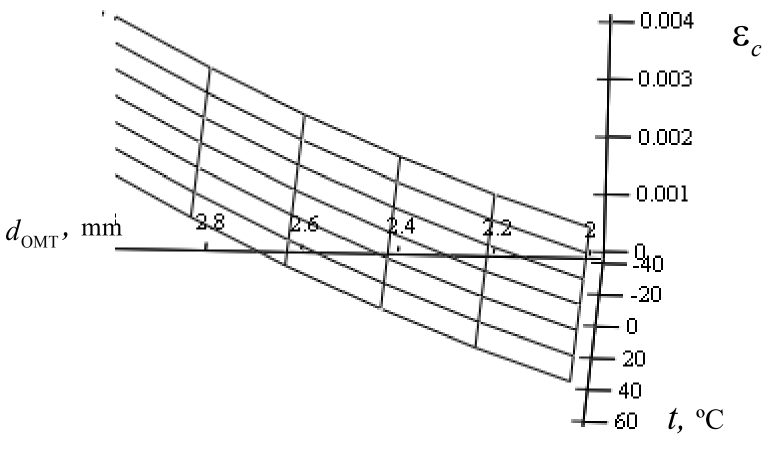

Figure 3 – Temperature dependence of relative elongation of the OC at different diameters of OMT

The obtained dependences of the relative elongation of OC ε_c show that when the temperature is changed within range (-40...+70) ºC the choice of OMT material causes the change of the geometric dimensions of the module tube and the freedom of movement of the OF inside it. On the Fig. 4 dependence analysis showed that the usage of polycarbonate as a material of OMT will provide less variation of the cable relative elongation, and therefore the total magnitude of the permissible longitudinal mechanical strength of the cable.

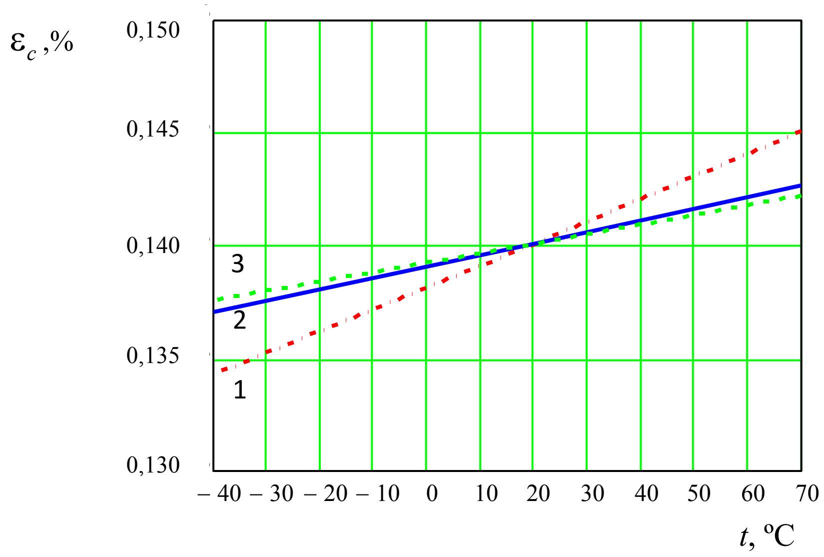

Figure 4 – Temperature dependence of relative elongation of OC for various materials of OMT: 1 – polybutylene terephthalate; 2 – polyamide; 3 – polycarbonate

Conclusions:

1. The research of thermomechanical influence on geometrical sizes of core elements of an optical cable (OC) design is done in the work. It allowed improving the expression for calculating the permissible relative elongation of the cable by taking into account the temperature coefficients of linear expansion of the structural elements materials.

2. The obtained temperature dependences of the changing of the OC design relative elongation made it possible to establish that its value increases (decreases) with increasing (decreasing) temperature relatively to 20 °C. And also show that the usage of polycarbonate as a material of the optical module tube where quartz optical fibers are placed will provide smaller changing of the cable relative elongation at the temperature change.

3. In order to take into account when the OC designing the changing of the longitudinal mechanical strength of the OC and the correct selection of materials, in particular OMT, CSE and OF, it is necessary to take into account the temperature influence on the geometric dimensions of the cable core elements and its permissible relative elongation.

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Bondarenko O.V., Stepanov D.M.

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