Experimental and statistical models for determining the critical values of external action parameters on optical elements in extreme conditions of their operation

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Abstract: *The study has been carried out and experimental and statistical models have been developed to determine the critical values of external extreme action parameters (intense heat flows, times of their action, increased external pressures) on optical elements made of glass and ceramics, the excess of which leads to their surface destruction (the appearance of cracks, chips and other defects) and, ultimately, to the failure of optoelectronic devices.*
***KEYWORDS**: OPTOELECTRONIC DEVICES, ELECTRON BEAM, OPTICAL GLASS AND CERAMICS*

1. Introduction

Modern optoelectronic devices (pulsed laser rangefinders of sight complexes, laser medical devices, IR devices, etc.) with optical elements made of glass (optical glass K6, K108, K208, etc.) and ceramics (optical ceramics KO1, KO2, KO3, etc.) (Fig. 1) during their storage, transportation and use are subjected to extreme external actions (intense heating flows and external pressures, shockthermal actions in the conditions of shot and flight, etc.) [1 – 7]. At the same time, under these conditions, the surface destruction of the above mentioned elements occurs (cracks, chips, depressions and other defects appear), which ultimately leads to a significant deterioration in the technical and operational characteristics of the devices and their failure.

Therefore, the preliminary determination of the critical values in the main parameters of external actions (external heat flows, times of their action, external pressures, etc.) on the surface of optical elements is of significant importance. Determination of these critical parameters at the stage of design and bench testing will allow to prevent their possible failures in the extreme operating conditions (Fig. 2).

Nowadays, external actions on the surface of optic elements haven't been investigated sufficiently: there are only separate calculation results of the maximum permissible values of thermoelastic stresses in optical elements leading to their destruction [8 – 11]; experimental studies on determining the considered parameters of external actions on elements for different conditions of their operation are absent.

Therefore, the **objective** of this paper is to conduct experimental studies and develop experimental and statistical models to determine the dependences of critical values of the external heat flow q_n^* from the critical values of its impact t^* at normal and increased external pressures.

2. Research results and their analysis

Plates with thickness of H = 2…6·10^{-2} m were used to study parametrical impact of external thermal actions (heat flow q_n and time of its action t)) on the working surfaces of optical glass elements (K8, K108, K208, БК10, ТФ110) and ceramics KO1, KO2, KO3, KO5, KO12), the main physical and mechanical characteristics can be found in the studies [12 – 15].

For modeling exterior thermal actions on optical elements at normal conditions (P = 10^5 Pa, T = 273 K), controlled IR heating with quartz lamps of КГМ-220-1000-1 type was used with РИФ-101 thermal sensors to control temperature on the surface of elements in the range of 300... 1900 K and external heat flows in the range of 1,5·10^5…2,3·10^6 W/m^2 [1, 3].

Modeling of the increased heating temperature effects (up to 1500 K) and external pressures (up to 10^7 Pa), as well as supersonic speeds of air flow (up to 2·10^3 m/s) and angular rotation speeds (up to 4·10^3 rad/s) at semispherical optical elements (operating conditions of supersonic equipment) were carried out on standard testing facilities [1, 3]. Installations are made of a unit with three test chambers, which house optical elements, volumetric electric heaters and modules for controlling the heating process; multiplierto increase pressure in the chambers; chambers with heated air; replaceable nozzle; states with fixed element; rotation node; control panel.

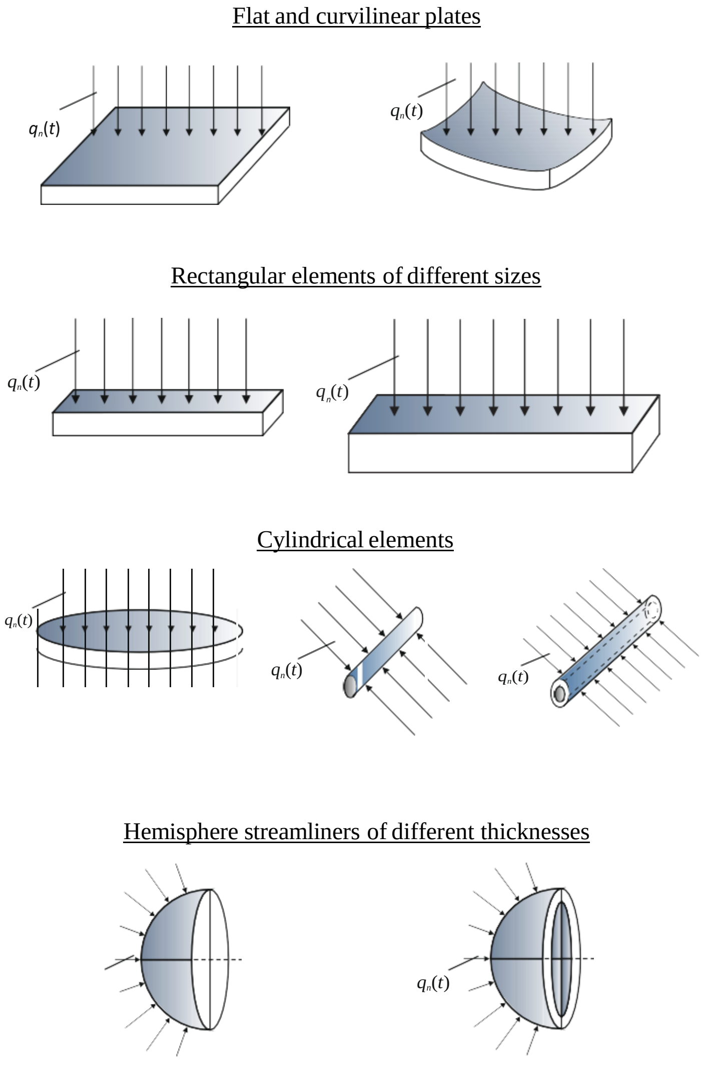
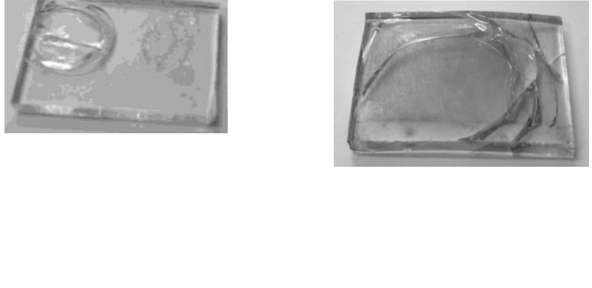


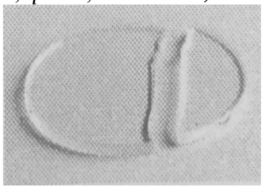
Fig. 1. *General appearance of optical elements of devices exposed to extreme external actions during their operation.*

Cracks, chips

K8, q_n^* = 3·10^5 W/m^2, t^* > 10 s K8, q_n^* = 1,5·10^5 W/m^2, t^* > 14 s



KO2, $q_n^*= 1,2\cdot10^6$ W/m², $t^* > 25$ s



Influxes, undulating surfaces

K108, $q_n^*= 6\cdot10^5$ W/m², $t^* > 6$ s

Areas of rapid boiling

K8, $q_n^*= 10^6$ W/m², $t^* > 4$ s

Fig. 2. *Observed destructions of the elements from optical glass (K8, K108) and ceramics KO2 by exceeding the parameters of external actions of their critical values (q_n^*, t^*).*

The influence of external heat flows and the time of their action on the surface of optical plates during their uneven heating. The dependences of the critical values of the external heat flow q_n^* on the critical values of the impact t^* at normal and increased external pressures (fig. 3 - 6), when the surface layers of optical elements are destroyed, has been established as a result of experimental studies (relative error did not exceed 5... 7%).

Elements made of optical glass. From the data presented in fig. 4, 5, it can be seen that when t^* is increased from 4 s to 24 s, the value q_n^* decreases by 5... 6 times; at the same time, an increase in external pressure from $P = 10^5$ Pa to $P = 10^7$ Pa leads at the given t^* to the decrease in q_n^* by 1,2…1,7 times, and at the given q_n^* – to the decrease of t^* by 1,3…1,5 times.

To increase the efficiency of practical use of these data when designing and manufacturing various devices based on optical elements using well-known methods of mathematical statistics [16] the following experimental and statistical models have been obtained (relative error of 3... 5 %):

$$q_n^*(t^*,P) = (a_0 + a_1\cdot P + a_2\cdot P^2)\cdot(t^*)^{b_0+b_1\cdot P+b_2\cdot P^2} \quad (1)$$

where q_n^* – in W/m²; t^* – in s; P – in Pa; a_0, a_1, a_2, b_0, b_1, b_2 - empirical constants, the values of which depend on the nature of optical glass (Table 1).

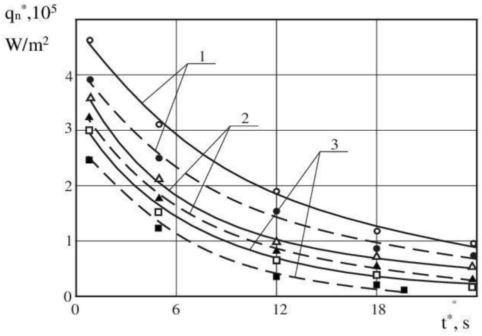


Fig.3 *Dependences $q_n^*(t^*)$ for elements from optical glass K8 (1), K208 (2) and K108 (3), untreated by the electron beam (the width of the sample is $H = 4\cdot10^{-3}$ m): ——— – $P = 10^5$ Pa; – – – – $P = 10^7$ Pa; ●, ○, Δ, ▲, □, ■ – experimental data.*

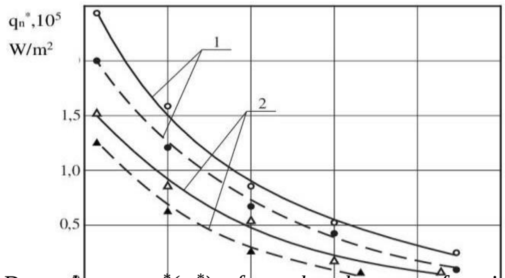


Fig.4. *Dependences $q_n^*(t^*)$ from the elements of optical glass TФ110 (1) and БK10 (2), untreated by electron beam (the width of the sample $H = 4\cdot10^{-3}$ m): ——— – $P = 10^5$ Pa; – – – – $P = 10^7$ Pa; ●, ○, Δ, ▲ – experimental data.*

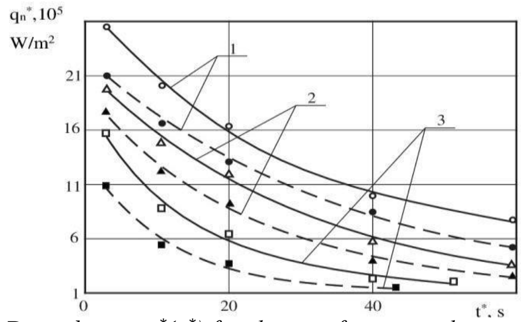


Fig.5. *Dependences $q_n^*(t^*)$ for elements from optical ceramics KO5 (1), KO1 (2) and KO12 (3), untreated by electron beam (the width of the sample is $H = 6\cdot10^{-3}$ m):——— – $P = 10^5$ Pa; – – – – $P = 10^7$ Pa; ●, ○, Δ, ▲, □, ■ – experimental data.*

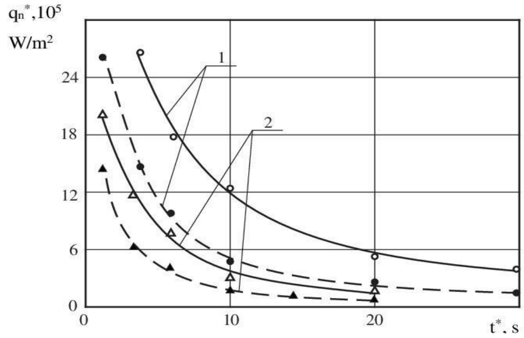


Fig. 6. *Dependences $q_n^*(t^*)$ for the elements from optical ceramics KO2 (1) and KO3 (2), untreated by electron beam (the width of the sample is $H = 6\cdot10^{-3}$ m): ——— – $P = 10^5$ Pa; – – – – $P = 10^7$ Pa; ●, ○, Δ, ▲ – experimental data.*

Elements made of optical ceramics. The data presented in fig. 5, 6, demonstrate that both for the optical elements processed by the electronic beam and for the untreated ones, with a decrease of q_n^* from $2,5\cdot10^6$ W/m² to $1,5\cdot10^5$ W/m², the value of t^* increases by 6... 8 times. At the same time, the decrease in external pressure from $P = 10^7$ Pa to $P = 10^5$ Pa leads at the given q_n^* to an increase of t^* by 2…2,5 times, and with the given t^* – to an increase of q_n^* by 3... 4 times.

Table 1: *Empirical constant values in experimental and statistical models (1) for optical glass elements*

Brand of glass / Constant	K8	K108	K208	БK10	TФ110
a_0	$1,76\cdot10^6$	$1,53\cdot10^6$	$1,67\cdot10^6$	$9,02\cdot10^5$	$1,28\cdot10^6$
a_1	-10^{-2}	0,31	0,16	0,13	$3,6\cdot10^{-2}$

a_2	$4{,}7\cdot$ $\cdot10^{-10}$	$-2{,}5\cdot$ $\cdot10^{-13}$	$-2{,}4\cdot$ $\cdot10^{-9}$	-10^{-13}	$-6{,}2\cdot$ $\cdot10^{-14}$
b_0	-0,94	-1,07	- 1,24	- 1,21	- 1,11

b_1	$-7{,}9\cdot10^{-9}$	$-9\cdot10^{-8}$	$5{,}8\cdot10^{-8}$	$-8{,}3\cdot10^{-8}$	$-3{,}7\cdot10^{-8}$
b_2	$9{,}5\cdot10^{-17}$	$6{,}7\cdot10^{-15}$	$-1{,}4\cdot10^{-15}$	$5{,}1\cdot10^{-15}$	$3{,}8\cdot10^{-15}$

To increase the efficiency of practical use of the obtained results, as well as for elements from optical ceramics, the following experimental and statistical models have been developed (relative error of 5...7 %):

$$q_n^*(t^*,P)=(c_0+c_1\cdot P+c_2\cdot P^2)\cdot(t^*)^{d_0+d_1\cdot P+d_2\cdot P^2} \quad (2)$$

where q_n^* – in W/m^2; t^* – in s; P– in Pa; c_0, c_1, c_2, d_0, d_1, d_2 - empirical constants, the values of which depend on the nature of optical ceramics (Table 2).

Table 2: *Empirical constant values in experimental and statistical models (2) for optical ceramic elements*

Ceramic / Constant	KO1	KO2	KO3	KO5	KO12
c_0	$7{,}84\cdot10^6$	$5{,}91\cdot10^6$	$5{,}17\cdot10^6$	$5{,}68\cdot10^6$	$5{,}47\cdot10^6$
c_1	0,32	$-8{,}3\cdot10^{-2}$	$-0{,}12$	$-4{,}21\cdot10^{-2}$	0,242
c_2	$-3{,}8\cdot10^{-8}$	$6{,}6\cdot10^{-10}$	$3{,}2\cdot10^{-11}$	$-1{,}3\cdot10^{-14}$	$9{,}1\cdot10^{-9}$
d_0	$-0{,}72$	$-0{,}79$	$-1{,}13$	0,48	$-0{,}76$
d_1	$-3{,}2\cdot10^{-8}$	$-1{,}6\cdot10^{-8}$	$-7{,}9\cdot10^{-9}$	$2{,}5\cdot10^{-8}$	$-0{,}24$
d_2	$1{,}2\cdot10^{-15}$	$1{,}3\cdot10^{-16}$	$-2{,}3\cdot10^{-16}$	$1{,}5\cdot10^{-15}$	$-1{,}6\cdot10^{-17}$

Determination of dangerous areas on the surface of hemispherical fairings in IR devices exposed to maximum heating and destruction in the conditions of supersonic blowing by air flow and axisymmetric rotation. The tests have revealed that at a blowing speed of up $8\cdot10^2…1{,}2\cdot10^3$ m/s 30…40 % the tested fairings are destroyed, while at blowing speeds of $1{,}5\cdot10^3…2\cdot10^3$ m/s more than 90% of the tested fairings are subjected to destructions. The increase in the angular speed of the axisymmetric rotation of the fairings (up to $4\cdot10^3$ rad/s) practically does not affect the formation of thermo effects of the gas flow on the surface of the fairings and their destruction. In addition, according to the results of schlieren-photographic studies of gas flow structure and directly according to the final results of the tests, it has been established that the main contribution to the destruction of the fairings is provided by turbulent supersonic blowing of the air flow, which leads to significantly uneven heating of their surface and the formation of zones of elevated thermal actions, where local overheating of streamliners occurs, that leads to their destruction.

At the same time, the locations of these zones for laminar wrapping mode are located in the vicinity of the front critical points for all the studied airflow speed ranges V, and in the case of turbulent mode – significantly shifted along the surface of the fairings. As a result of the conducted studies for the turbulent wrapping mode of the hemispheric fairing the following dependence was obtained $\theta(V)$ (θ – the angular coordinate along the surface of the fairing from the front critical point ($\theta = \theta_{max}^* = 0$) to the place, where both the maximum heating of the fairing and its destruction occur ($\theta = \theta_{max}^*$) (Fig. 7). From the results presented in Fig. 7 it follows that with an increase in the speed of blowing of the air flow, the locations of the fairing surface destruction zones practically do not change: with an increase of V from $7\cdot10^2$ m/s to $2\cdot10^3$ m/s, the values θ_{max}^* lie within 21...23^0.

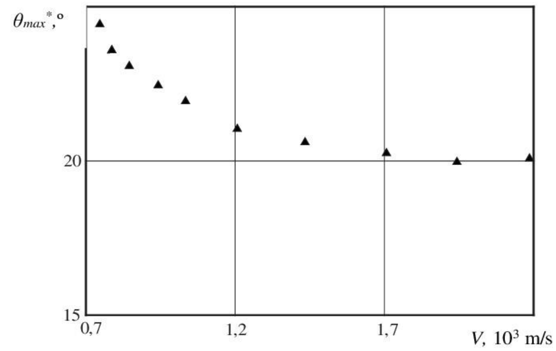


Fig. 7. *Dependence $\theta_{max}^*(V)$ for turbulent blowing of the fairing with supersonic air flow: ▲ – results of experimental studies.*

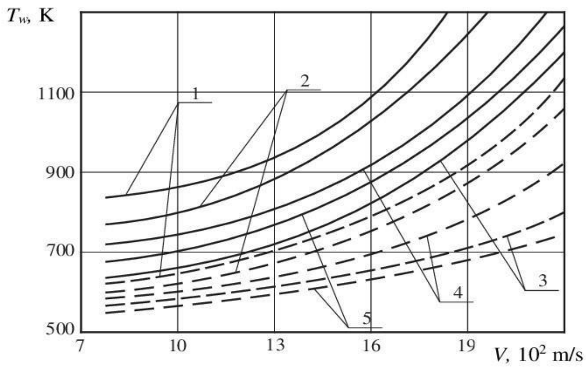


Fig. 8. *Dependence of the temperature T_w in different surface points of fairings from optical ceramics KO1 (1), KO2 (2), KO12 (3), KO3 (4) and KO5 (5) on the speed of the external supersonic gas flow: ——————— temperature in maximum thermal impact zones, which are located along the surface of the fairing from its front critical point ($\theta \neq 0^0$); – – – – – temperature at the front critical point of the fairing ($\theta = 0^0$).*

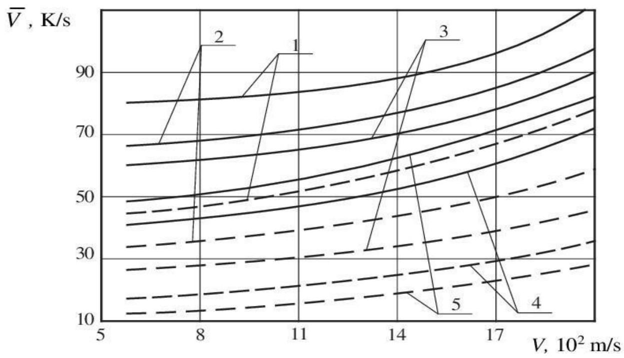


Fig. 9. *Dependence of the average heating speed $\overline{V}$ of the fairing from optical ceramics KO1 (1), KO2 (2), KO12 (3), KO3 (4) and KO5 (5) in different zones, exposed to external supersonic airflow: ———— – zones with maximum thermal effects, that are located along the surface of the fairing from its frontcritical point ($\theta \neq 0^0$); – – – – – zone with elevated temperature, that corresponds to the front critical point of the fairing ($\theta = 0^0$).*

The obtained test results of fairings made of optical ceramics in conditions of supersonic blowing of air flow are due, as shown by numerical calculations of kinetic heating of the fairing surface [1, 3], by very high temperatures in the areas of the surface of the fairing, that are exposed to destructions during operation: an increase of V to $V = 2\cdot10^3$ m/s leads to an increase in the temperature in stated zones to 1400...1500 K, and at the front critical point – up to 1000...1100 K (Fig. 8). In addition, the estimate of the average heating speed $\overline{V}$ ($\overline{V}$ has been estimated as the average integral characteristic during the action of IR devices with fairings) of the fairing surface in these zones shows its significant values and significant dependence from V (Fig. 9): raising V to $V = 2\cdot10^3$ м/с m/s leads to an increase in the average heating speed of the product surface in these zones up to 100...120 K/s, and at the front critical point – up to 70...80 K/s.

Increased temperature values and heating speeds of fairing surfaces in the above-mentioned hazardous zones lead to the emergence of significant thermal strains in these zones, which exceed their critical values, that for the considered optical ceramics are the reason of the destruction in the surface layers ofthe fairings.

3. Conclusions

1. For the first time, the following influence patterns of external thermal effects on optical elements have been established:

– with the steady heating of the elements, the increased heating temperatures (up to 1500 K) and external pressures (up to 10^7 Pa), observed when using devices with these elements, do not lead to noticeable violations in the integrity of the surface layers of elements (the appearance of cracks, chips, etc.);

– with uneven heating of the elements the increase in the external heat flow q_n (from $5·10^5$ W/m²до $2·10^6$ W/m²) and the time of its action t (from 24 s to 60 s) leads to the destruction of elements made of optical glass and ceramics; at the same time, an increase in external pressure from 10^5 Pa до 10^7 Pa reduces their critical values by 1,2…2,5 times;

– for the specified ranges of changes in parameters q_n and t with external influence on optical elements, experimental and statistical models have been developed to determine the dependencies of their critical values $q_n^*(t^*, P)$ (relative error 3...7%), that allows at the stage of design and manufacture of devices to determine possible critical modes of their heating at high external pressures, the excess of which leads to the destruction of optical elements and failure of devices.

2. For the first time, IR device testing with hemispherical fairings made of optical ceramics in the conditions of their blowing with supersonic air flow allowed to establish:

– at a blowing speed of up to $5·10^2…10^3$ m/s 30…40 % of the tested fairings are subjected to destruction, and at blowing speeds of $1,5·10^3…2·10^3$ m/s more than 70% of the fairings are subjected to destructions;

– for laminar mode of wrapping the destruction of fairings is observed next to their critical points $\theta = 0^0$ (θ – spherical coordinate), and in the case of turbulent wrapping mode, the area of destruction shifts along the surface of the fairings from the front critical point at a distance corresponding to $\theta = 21…23^0$, that allows by adjusting the speed and direction of launching products with the considered IR devices by 1,5…2 times to reduce the number of destructions of their fairings in stated hazardous areas and increase their reliability when operating in the conditions of shot and flight.

4. References

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