

# MATHEMATICAL MODELING OF THERMOPHYSICAL PROCESSES IN THE BARREL OF AVIATION ARTILLERY WEAPONS AND VERIFICATION OF ITS RELIABILITY

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**Annotation.** This article considers the issue of mathematical modeling of thermophysical loading of an aircraft cannon barrel. The adequacy of the model is checked based on the Bartlett, Student and Fisher criteria, computational resources and time efficiency are evaluated. Also, the safety of the system is analyzed using probabilistic models and the permissible firing modes are based on.

**Keywords:** aviation artillery weapons, GSh 2-30, small-caliber artillery barrel, thermophysical loading, mathematical model, barrel temperature, resource efficiency, safety, probabilistic models, firing modes.

**Annatsiya.** Ushbu maqolada aviasiya to'pi stvolining termofizik yuklanishini matematik modellashtirish masalasi ko'rib chiqilgan. Modelning yetarliligi Bartlett, St'yudent va Fisher kriteriyalari asosida tekshirilgan, hisoblash resurslari va vaqt samaradorligi baholangan. Shuningdek, tizimning xavfsizligi ehtimoliy modellar orqali tahlil qilingan va ruxsat etilgan otish rejimlari asoslangan.

**Kalit so'zlar:** aviatsiya artilleriya qurollari, GSh-2-30, kichik kalibrli artilleriya stvoli, termofizik yuklanish, matematik model, stvol harorati, resurs samaradorligi, xavfsizlik, ehtimoliy modellar, otish rejimlari.

**Аннотация.** В данной статье рассматривается вопрос математического моделирования термофизической нагрузки на ствол авиационной пушки. Адекватность модели проверяется на основе критериев Барлетта, Стьюдента и Фишера, оцениваются вычислительные ресурсы и временная эффективность. Также анализируется безопасность системы с использованием вероятностных моделей, а допустимые режимы стрельбы определяются на основе.

**Ключевые слова:** авиационная артиллерия, ГШ 2-30, малокалиберный артиллерийский ствол, термофизическая нагрузка, математическая модель, температура ствола, ресурс эффективность, безопасность, вероятностные модели, режимы стрельбы.

## Introduction

The reliability and safety of aviation artillery weapons and their control systems are of great importance in modern conditions. By determining and modeling the thermophysical loading of the barrel, its resource capabilities and safe firing modes are assessed.

The reliability of the developed mathematical model of heat exchange processes in the barrel was determined by examining the spatial distribution of non-stationary values of the barrel temperature in various firing modes.

**Literature review.** Analysis of data obtained from the outputs of the thermophysical model of heat transfer in the barrel showed that the difference between the calculation results and experimental data does not exceed 10%.

The use of reliable calculated values of the studied quantities was carried out on the basis of data on specific variants of this experiment, under the conditions of changing external factors over a certain period of time, as determined in experiments at an altitude of 5000 m.

Due to the closeness of the values of the estimated quantities in the results of observations, an additional zero point was introduced. Several experiments were conducted to process barrel temperature measurements, the results of which are presented in table 1.

**Table 1**

Initial matrix of a full factorial experiment (FTE) to estimate the stem temperature by experiment [1].

Point type in the plan	$Q$	$T_2$	$t$	$T_2t$	$T^{1'}$	$T^{1''}$	$T$
FTE points	1	-	-	+	130	90	122
	2	+	-	-	185	180	212
	3	-	+	-	160	146	160
	4	+	+	+	207	194	215
Star points	5	-1.414	0	0	75	53	68
	6	+1.414	0	0	106	86	97
	7	0	-1.414	0	44	37	40
	8	0	+1.414	0	65	47	58
Starting point	9	0	0	0	89	69	80
	10	0	0	0	57	40	51
	11	0	0	0	50	39	45
	12	0	0	0	41	36	39
	13	0	0	0	40	38	38

In accordance with the methodological recommendations of the source, the Bartlett statistical part was used to perform the operation of checking the equality of measurements, which includes the following calculations:

–Calculation of the arithmetic mean of the response function at the Q-point by FTE.

$$\bar{T}^1 = \frac{T^{1'} + T^{1''}}{2};$$

- FTEning Q-nuqtasida farqni baholash:

$$D_m = \sum_Q [(T^{1'} - \bar{T}^1)^2 + (T^{1''} - \bar{T}^1)^2]; \tag{1}$$

- Assessing the change in repeatability of measurements during the implementation of FTE - Assessing the change in repeatability of measurements during the implementation of FTE

$$D_b = \frac{\sum D_m}{R}. \tag{2}$$

The final form of the FTE matrix was formed by supplementing Table 1 with the results of the Bartlett statistics and summarized in Table 2. For the sake of clarity, the names of the types of design points are not given.

**Table 2**

Full FTE matrix for estimating the temperature of the trunk in the experiment

Q	T <sub>2</sub>	t	T <sub>2</sub> t	T <sup>1'</sup>	T <sup>1''</sup>	T	$\bar{T}^1$	D <sub>m</sub>	D <sub>b</sub>	( $\bar{T}^1 - T$ ) <sup>2</sup>
1	-	-	+	130	90	122	110	800	175	144
2	+	-	-	185	180	212	183	13		870
3	-	+	-	160	146	160	153	98		49
4	+	+	+	207	194	215	201	85		210
5	-1.414	0	0	75	53	68	64	242		16
6	+1.414	0	0	106	86	97	96	200		1
7	0	-1.414	0	44	37	40	41	25		0,25
8	0	+1.414	0	65	47	58	51	392		49
9	0	0	0	89	69	80	79	200		1

$Q$	$T_2$	$t$	$T_2t$	$T^{1'}$	$T^{1''}$	$T$	$\bar{T}^1$	$D_m$	$D_B$	$(\bar{T}^1 - T)^2$
10	0	0	0	57	40	51	49	145		6,25
11	0	0	0	50	39	45	45	61		0,25
12	0	0	0	41	36	39	39	13		2,25
13	0	0	0	40	36	38	38	8		0

Thus, the criterion for the uniformity of variance estimates at the Q-point of FTE is in the form of the first formula, and the variance estimates of the reproducibility of measurements in the implementation of FTE are in the form of the second formula, and the experimental value can be calculated by the following relationship:

$$B_{\text{ЭК}} = 1 / K_{\text{ЭК}} \left( Q \ln D_B - \sum_Q \ln D_m \right), \quad (3)$$

Here  $K_{\text{ЭК}}$  is the coefficient of agreement with experience depending on the number of factors  $b$  in the experimental design (approximately  $K_{\text{ЭК}} = 1.338$ ).

To check the adequacy, the FTE regression equation was estimated based on the Fisher criterion. In the calculation, the data from table 2 were used as before. The initial estimate of the variance of the inadequacy of the FTE representation of the results will look like this:

$$D_H = \frac{\sum (\bar{T}^1 - T)^2}{Q}. \quad (4)$$

The value of the experimental Fisher criterion is determined using the 4th link as follows:

$$F_{\text{ЭК}} = \frac{D_H}{D_B}. \quad (5)$$

With the previously introduced significance level, the directive value of the Fisher criterion is 3.33. Consequently, with a probability of 0.95, the hypothesis of the adequacy of the FTE regression equation is not rejected.

The data provided make it possible to model the workflow of firing and loading the barrel with an accuracy that does not reduce the previous one by a factor of at least [1].

At the same time, the assessment of the resources required to perform the specified calculations revealed some advantages of the mathematical model.

In order to compare the time efficiency of the mathematical model [2], the same modern counters were used. According to the results of direct timing and generalization of quantitative

comparisons, it was observed that the machine calculation time when using the proposed mathematical model was reduced by 1.6 times, which is quite acceptable for problems of this class.

$n = 1$ piece.	28 s	
$n = 25$ piece.	406 s	
$n = 25$ piece, $\Delta t = 3$ s	407 s	

**Picture-1.** Calculation cycle diagram of previously developed mathematical models for modeling thermophysical loading of the AAW barrel.

$n = 1$ piece	17 s	
$n = 25$ piece	254 s	
$n = 25$ piece, $\Delta t = 3$ s	255 s	

**Picture-2.** Calculation cycle diagram of the developed mathematical model of thermophysical loading of the AAWD barrel.

**Solution.** Thus, the presented methods for calculating the non-stationary temperature field of a shaft with different walls allow to significantly increase the time of collection of statistical data of the reliability states of the system.

The proposed methodology allows to ensure the interdependence and consistency of the use of a set of non-homogeneous mathematical dependencies, to formalize the safety of the application and to provide unified methods for assessing the technical potential of the AQS.

In essence, the quantitative value of the probability of failure-free operation of the system  $P[T_{np} > T(t, N, n)]$  plays the role of an indicator characterizing the conditions of loading the system from the inside and from the influence of the external environment.

$$P[T_{np} > T(t, N, n)] = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\eta_n} e^{-\frac{\eta^2}{2}} d\eta. \quad (6)$$

From a mathematical point of view, it follows that calculations according to the above equation do not go beyond the limits of elementary probability theory, since the distribution function of the probability of a random variable taking a value less than or equal to  $\eta$  is the integral of the probability density function in the interval from  $-\infty$  to  $\eta$ . The problem of solving the above equation is reduced to constructing an expression for calculating the integral exponent  $\eta$ , the numerator of which is  $\eta$  and the upper non-negative limit of integration  $\eta_n$ .

Analyzing the AAW as a pulsed heat engine for military purposes, identifying the system as a non-stationary one with random parameters [3], it is possible to provide evidence

of the reliability of the probability estimates of the emergency  $T_{np}$  and the determining T system state parameters.

$$\eta = \frac{M[T_{np}] - M[T(t'_{N,n})]}{\sqrt{\sigma_{T_{np}}^2 + \sigma_{T(t'_{N,n})}^2}}, \quad (7)$$

where  $M[T_{np}]$  and - respectively, the mathematical expectation and the mean square deviation of the "strength",  $M[T(t'_{N,n})]$  and  $\sigma_{T(t'_{N,n})}$  - respectively, the mathematical expectation and the mean square deviation of the "load".

The exact and rigorous implementation of the proposed approach is complicated and leads to very difficult equations. On the other hand, in the case of calculating the limit model modes for thermal resistance, the assumption of the values of "strength"  $T_{np}$  and "load"  $T(t'_{N,n})$  equal to their mathematical expectations  $M[T_{np}]$  and  $M[T(t'_{N,n})]$  naturally leads to a decrease in the degree of objectivity of the probabilistic assessment of the deterministic thermal state of the shaft.

The proposed approach is not without drawbacks, but, from a practical point of view, this is not as important as its advantages, which include relative simplicity and absolute clarity. Therefore, the mathematical model in the form of the above equations is well suited for substantiating methods for determining the maximum technical potential of an automatic control system by conducting numerical experiments that reproduce the set of knowledge about the probability of the system operating without failures for various combinations of the number of shots N and the number of shots n.

To determine the numerical characteristics of any random event associated with the transition of the system to a limit state under certain conditions, an indirect method of probability theory is used, the meaning and content of which is that these events allow for many repetitions of the independent implementation in which they occur.

When processing the material on probabilistic methods for evaluating random variables, the expression was chosen as the maximum permissible lower limit of the probability of system failure, which stochastically describes the processes of using AAW in the form of a product of the probabilities of a number of different events associated with the safe operation of the system in various firing modes:

$$P_{\min}^{(N)} [T_{np} > T(t'_{N,n})] = \prod_N P_{\min}^{(N)} [T_{np} > T(t'_{N,n})]. \quad (8)$$

The fact that the number of turns N and the number of subsequent shots n in the firing modes are not the same imposes strict requirements on the sequence of calculations according to formulas 6-8 at the stage of calculating the probability of system malfunctions, while there are no objective reasons for the frequent occurrence of each of them.

1. Direct determination of the minimum possible value of the probability of system failure when firing ammunition in the N-m-th firing mode for each  $P_{\min}^{(N)} [T_{np} > T(t'_{N,n})]$  N-th firing mode.

2. Calculation based on formula (8) and taking as a base value the permissible lower limit of the probability of system failure-free operation under conditions  $P_{\min_{\Pi}}^{(N)} [T_{\text{np}} > T(t'_{N,n})]$  of a limited number of experiments  $N$ .

As a structural, but independent part of the proposed methodology, the loading coefficient of the AAW when firing in the  $N$ - $m$  -mode is included. When specifying the requirements for the previously established technical efficiency indicator, the output data on the results of the use of the AAC are subordinated to a set of isolated loading parameters of the system. The expression for the AAW loading coefficient in  $N$ - $\mu$ -mode firing, based on the analogy of a number of formulations, is proposed in the form of an irreducible fraction, which shows the ratio between the AAW cycle time  $\tau_{\Pi}$  and the time set  $t'_{N,n}$ .

$$k_{3_N} = B \frac{t_{\Pi}}{t'_{N,n}}. \quad (9)$$

The assignment of numerical experiments was carried out taking into account:

- the boundary, close to extreme, conditions of operation of the system, associated with minimizing the height of the AAW application [4];
- the air flow velocity  $v_2$ , taken as an average value within the operational speeds of the UA;
- the permissible firing modes predetermined by the standard automation of the weapons control systems of the multi-purpose "Su" type aircraft [5].

Due to some design features and aspects inherent in the algorithmic support of the multi-purpose AAW "Su" type QBT, the permissible firing modes used in the performance of the tasks of attacking ground (sea) and air targets are summarized in unified schemes, which are adopted as follows.

I. The fixed combat firing mode defines 4 bursts of 25 shots each and ensures the continuation of firing and the absence of a system transition to a limit state, when the interval between shots between 4 bursts is 3 seconds or more, in the range of all firing operating conditions of the AAW.

II. The fixed combat firing mode is  $N = 4$  units,  $n = 25$  units  $\wedge$   $N = 5$  units,  $n = 10$  units and the time  $\Delta t = 3$  s. Here  $\wedge$  is the logical multiplication sign of events. The combined mode defines 4 bursts of 25 shots each and 5 bursts of 10 shots each and guarantees that the system will not go to the limit state, when the break between shots is 3 seconds or more between 8 bursts, in the range of all firing conditions of the AAW.

III. The fixed training firing mode ( $N = 15$  units,  $n = 10$  units,  $\Delta t = 3$  s) defines 15 bursts of 10 shots each and guarantees that the system will not go to the limit state, when the break between shots is 3 seconds or more between 14 bursts, in the range of all firing conditions of the AAW.

Such methods of determining the limit modes of firing are considered the most effective, based on the organizational and methodological principles of a systematic approach and helping to expand the range of safe conditions for the use of AAW.

**Conclusion.** Thus, the proposed methodology allows for the integration of deterministic parameters and restrictions determined by the design and conditions of use of



AAW, as well as the formation of probabilistic estimates when substantiating the limit safe modes of the system in terms of heat resistance.

Studies show that the proposed mathematical model allows for reliable modeling of the thermophysical loading of the AAW barrel. The resource efficiency of the model is high, and objective results were achieved through the use of probabilistic methods in assessing safety. Allowed firing modes serve to expand the technical and tactical capabilities of AAW.

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