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Моделирование конвективных процессов теплообмена между неоднородными газовыми смесями и поверхностями малокалиберного артиллерийского ствола

И. А. Подкопаев, А. В. Подкопаев*, В. И. Должиков

Военный учебно-научный центр Военно-воздушных сил
«Военно-воздушная академия имени профессора Н. Е. Жуковского и Ю. А. Гагарина» (г. Воронеж)
Российская Федерация, 394064, г. Воронеж, ул. Старых большевиков, 54а
*E-mail: aleksanpodkopaev@mail.ru

Современные образцы авиационного артиллерийского оружия (ААО) представляют собой импульсные тепловые машины, преобразующие энергию порохового заряда в энергию сильно сжатых и нагретых пороховых газов (далее – газы), совершающих при своем расширении работу по сообщению снаряду кинетической энергии. В контекстах артиллерийской науки, ААО и боеприпасы структурируются в виде системы, которая вступает во взаимодействие с источниками нагрева и окружающей средой, последовательно совершая термодинамические циклы. Основным элементом, наиболее интенсивно подвергающимся теплофизическим нагрузкам и оказывающим значительное влияние на боевые качества и стоимость ААО, является малокалиберный артиллерийский ствол (далее – ствол). Вследствие этого проблема определения температурного поля ствола является одной из центральных проблем проектирования ААО и оптимизации режимов стрельбы. Успешное решение этой проблемы во многом зависит от точности моделирования процессов теплоотдачи к каналу и от внешней стенки ствола при выстреле. Вместе с тем адекватный синтез и расчет соотношений, описывающих явление конвекции, сопровождающее выстрел, затруднены, что связано с наличием фазовых превращений в состоянии газов, одновременным присутствием в областях решений сверхзвуковых и дозвуковых зон, существованием ламинарных, турбулентных течений и других нелинейных образований. Целью работы поставлена разработка относительно простой и приемлемой для инженерной практики математической модели теплообмена внутри и окрестностях ствола при околостенных течениях теплоносителей (далее – модель). Достижение цели работы осуществляется сосредоточенным выбором критериальных уравнений аппарата термодинамического подобия, соответствующих геометрическим и физическим условиям однозначности процессов нагружения ствола. Введение функций, учитывающих зависимость теплофизических свойств газов от температуры, позволило повысить точность определения параметров теплоотдачи при выстреле на 19 % в сравнении с известными результатами. Разработанная модель может быть использована при проведении прикладных расчетов, связанных с определением теплового состояния ствола. Специализация объекта исследования не исключает возможности доработки модели в целях математического представления тепловых эффектов в термонапряженных конструкциях сложной формы.

Ключевые слова: коэффициент теплоотдачи, критериальное уравнение теории термодинамического подобия, теплофизический параметр газов, адекватность.

Modelling convective heat transfer processes between inhomogeneous gas mixtures and surfaces of a small-caliber artillery barrel

I. A. Podkopaev, A. V. Podkopaev*, V. I. Dolzhikov

Air Force Military educational and scientific center "Air Force academy
named after professor N. E. Zhukovsky and Y. A. Gagarin"
54a, Starykh bol'shevikov St., Voronezh, 394064, Russian Federation
*E-mail: aleksanpodkopaev@mail.ru

The current models of aviation artillery weapons (AAW) are the pulsed heat engines that convert the energy of a powder charge into the energy of highly compressed and heated powder gases (hereinafter referred to as gases), which, when expanding, perform work on communicating kinetic energy to the projectile. In the context of artillery science, aviation artillery weapons and ammunition are structured as a system that interacts with heat sources and the environment, sequentially completing thermodynamic cycles. The main element that is most intensively subjected to thermophysical loads and has a significant impact on the combat qualities and cost of aviation artillery weapons is a small-caliber artillery barrel (hereinafter referred to as the barrel). As a result, the problem of determining the temperature field of the barrel is one of the central problems of designing aviation artillery weapons and optimizing firing modes. The successful solution of this problem largely depends on the accuracy of modeling the processes of heat transfer to the channel and from the outer wall of the barrel during firing. At the same time, an adequate synthesis and calculation of the relations describing the phenomenon of convection accompanying the shot is difficult, which is due to the presence of phase transformations in the state of gases; the simultaneous presence of supersonic and subsonic zones in the solution regions; the existence of laminar, turbulent flows and other non-linear formations. The aim of the work is to develop a relatively simple and acceptable for engineering practice mathematical model of heat transfer inside and around the barrel with near-wall coolant flows (hereinafter referred to as the model). Achieving the goal of the work is carried out by a concentrated choice of criterion equations of the apparatus of thermodynamic similarity, corresponding to the geometric and physical conditions for the uniqueness of the processes of loading the barrel. The introduction of functions that take into account the dependence of the thermophysical properties of gases on temperature made it possible to increase the accuracy of determining the parameters of heat transfer during a shot by 19% in comparison with the known results. The developed model can be used in applied calculations related to determining the thermal state of the barrel. The specialization of the object of study does not exclude the possibility of refining the model for the purpose of mathematical representation of thermal effects in thermally stressed structures of complex shape.

Keywords: heat transfer coefficient, criterion equation of the theory of thermodynamic similarity, thermophysical parameter of gases, adequacy.

Introduction

The phenomenon of a shot, the duration of which is measured in thousandths of a second, is inevitably associated with the action of high temperature gases on the bore and heat removal from the outer wall of the barrel. While studying the functioning of AAW in a thermal setting, as a rule, the boundary layer theory known in thermodynamics is used [1; 2], according to which the temperature loads on the object under study depend only on the instantaneous values of the coolant temperature, determined from the energy characteristics of the heat source. This hypothesis of a brief history does not consider the change in the thermophysical characteristics of individual gas components during a shot (thermal conductivity coefficients λ_1, dynamic viscosity η_1, specific heat capacity c_1) and it does not take into account the unsteady effects associated with the dependence of the physical parameters of the gas mixture on the current temperature of the gases T_1. One of the ways to consider changes in the physical coefficients of the gas mixture as combustion and charge advances is to use provisions on the non-stationary parameters of gas flow [3; 4].

There is also heat transfer from the heated sections of the barrel to the environment (air) during a shot. In general, heat exchange between gases and the barrel, the outer surface of the barrel and air can occur through forced convection and radiation. Comparing to long thin-walled barrels for tank and anti-tank guns, solar radiation has a significantly smaller effect on the temperature field of AAW barrels than convection [5]. The influence of radiation on the formation of the barrel temperature T is not studied by this research.

Therefore, the entire complexity of studying the physical essence of the transformation of gunpowder energy into the energy of directed transfer in time and space of a projectile, accompanied by factors affecting the barrel, is connected with the determination of the value of the total heat transfer coefficient α_I, I = 1,2, taking into account heat transfer processes from gases to the barrel (I = 1) and from the outer surface of the barrel to the air (I = 2).

Calculating the state parameters of gas and air flows is a very complex gas-dynamic problem. The previously published article [6] presents the mathematical reproduction of heat transfer on the walls of the barrel as an independent problem. The investigations show [2; 7], that the intensity of heat exchange between the surface of the body and the coolants in one way or another functionally depends on many parameters: the geometric shape and size of the body; physical properties, direction and speed of coolant flow; temperature conditions of interaction between body and substance, and others. As a result, the research highlights as priorities the issues of justifying a method of formalizing the processes of heat transfer from a turbulent gas flow to the channel wall and from the outer wall of the barrel into the atmosphere, acceptable for engineering calculations.

In analytical studies, the heat transfer process is described by a system of differential equations that takes into account both thermal and hydrodynamic phenomena and includes the equations of heat transfer, heat transfer, motion, and continuity [8–10]. It is difficult to obtain an exact solution to the problem in analytical or numerical form, even with high-performance computers, since the longitudinal flow around a pipe of circular cross-section is characterized by both strong unevenness of gas state parameters and turbulence, and a very complex geometry of the computational domain. Therefore, to calculate such flows, the approaches related to averaging the equations of motion and further consideration of the flow in the form of a continuous flow have become relatively widespread. An example of this approach is, for example, the paper [11], where calculating the flow is based on a mathematical model of a porous isotropic body. As this approximate approach is developed, various options to derive the averaged transport equations used are proposed, and various ways to take into account flow turbulence and other flow features are considered. A slightly different approximate method for solving the problem is also known [12], when the real flow through the pipe is replaced by a continuous "homogeneous" flow without involving a mathematical model of a porous body. In principle, both the first and second approaches allow to obtain information about the dynamic and thermal characteristics of the phenomenon averaged over the volume of the body. In this case, using empirical initial data and assumptions have to be used, they are in a relatively good agreement with the real structure of the flow. It is explained, first of all, by the fact that the data necessary to solve the problem can be found only approximately and in some cases with a large error. This approximate assessment of the initial data is caused by the lack of uniform dynamic dependencies.

The presented above approaches should be noted not to have lost their relevance yet. Therefore, the publication [13] argues a unique version of the thermal model developed on the basis of the apparatus of probability theory; the articles [14; 15] propose schemes for experimental studies and methods for processing output data that provide increased accuracy in determining body temperature; the investigation [16] determines the temperature fields of finned walls of various configurations with numerical solutions of the multidimensional heat conduction problem; the research [17] proposes tools for modelling the temperature field in gas turbine assemblies, taking into account as much as possible the set of parameters in multifactor boundary conditions of the boundary layer. The publications [18–22] present the examples of exploration on similar topics in the field of aviation artillery science.

The methods developed in these areas are completely objective and can serve as the basis for calculating the heat transfer characteristics on the surface of a pipe of complex geometric shape.

Justification and specification of the criterion equations for heat transfer of the phenomenon of a shot from AAW

A feature of heat transfer from hot gases to the barrel bore and from the outer surface of the barrel to the air is that the medium where heat spreads moves. The movement results in transferring heat along with the gas mass. It is obvious that the nature of heat transfer is determined by the shape of the region and the properties of interaction flows - velocity distribution, flow regime, and others.

Based on the above, the approach of calculating the total heat transfer coefficient α_{I}, I = 1,2, using statistical formulas where there are the criterion dependencies of the similarity theory - Reynolds number Re, Nusselt number Nu, Prandtl number Pr [3; 4; 8; 9].

Since the desired value α_{I}, I = 1,2, is total or effective, the amount of heat transferred will be the sum of two independent terms of heat transferred by forced convection from the gases to the barrel bore and from the outer wall of the barrel to the air. Both of these terms can be calculated separately and then added together.

Then

$$\alpha_{\mathrm{I}} = \frac{\mathrm{Nu}_{\mathrm{I}}\,\lambda_{\mathrm{I}}}{l},\ \mathrm{I} = 1,2\,. \tag{1}$$

To calculate by formula (1) the number Nu_{I}, I = 1,2 – a dimensionless quantity characterizing the intensity of heat exchange along the length of the barrel l at its internal (I = 1) and external (I = 2) boundaries, the researchers used the dependencies where the similarity criteria were constructed according to the defining dimensions of the space where heat transfer occurred, and the flow temperature along the length of the barrel l was chosen as the determining one: gas temperature T_1 inside, air temperature T_2 outside the barrel. The gas temperature T_1 is calculated by solving the main problem of internal ballistics [23]. An array of air temperature values T_2 as a function of the altitude of AAW application is specified based on the standard atmosphere SA-81 [24]. The designations of the thermal conductivity coefficients λ_{I}, I = 1,2, similar to the designation of the classifier of heat transfer boundaries in the barrel, have the meaning of the thermal conductivity of gases λ_1 (I = 1) and air λ_2 (I = 2).

When modelling the movement of a coolant in the barrel and air during longitudinal flow around the outer surface of the barrel at Mach number M > 1, a turbulent boundary layer is observed, that is a turbulent flow regime is realized ($\mathrm{Re}_1\ 10^4$), and with the ratio of the defining dimensions (length l and diameter d) of the barrel bore $l/d \approx 50$, heat transfer can be calculated using formulae for characteristics of the coolant flow regimes.

It is obvious that convective heat exchange in the barrel is of an unstabilized nature of a turbulent flow regime, since the flow of gases occurs in a small volume. Some stabilization of the flow is observed in case when the moving boundary of interaction (the bottom of the projectile) moves towards the muzzle. The general form of the criterion equation for gases during coolant flow in channels of annular cross-section under the specified conditions ($\mathrm{Re}_1 > 10^4$) has got the form:

$$\mathrm{Nu}_1 = \mathrm{A}\,\mathrm{Re}_1^{\kappa}\,\mathrm{Pr}_1^{\upsilon}\,k_z\,, \tag{2}$$

where A, κ, υ – coefficients determined by experiments; k_z – correction factor taking into account the change in the heat transfer coefficient from gases to the barrel bore α_1 in the flow stabilization section.

Due to generalizing the existing data [3; 25–28], the following relationship is established to determine the number Nu_1 in expression (2) for forced convection of gases in a finned channel with an annular cross-section:

$$\mathrm{Nu}_1 = 0{,}023\,\mathrm{Re}_1^{0{,}8}\,\mathrm{Pr}_1^{0{,}43}\,. \tag{3}$$

Formula (3) obtains the coefficient $k_z = 1$ with $l \geq 15d$.

Heat will be removed from the outer surface of the barrel by an air flow with high blowing speeds. Since the air flow occurs in a much larger volume, convective heat exchange at the outer wall of the barrel is subject to the transitional flow regime and it is characterized by greater stabilization of the flow.

During a transitional ($2100 < \mathrm{Re}_2\ 10^4$) stabilized air flow, the following relationship could determine the Nu_2 number:

$$\mathrm{Nu}_2 = \mathrm{A}\,\mathrm{Re}_2^{\kappa}. \tag{4}$$

By processing the most accurate data, several authors have obtained an expression to determine the number Nu_2 when air flows along the surface of a cylinder of variable cross-section [9; 25; 29; 30]. Processing of experimental data has showed that the values of the number Nu_2 in expression (4) are proportional to the number $\mathrm{Re}_2^{0,8}$:

$$\mathrm{Nu}_2 = 0{,}034\,\mathrm{Re}_2^{0,8}. \tag{5}$$

Formula (5) is valid when the ratio of the internal and external radii of the cylinder does not exceed 0.2. Due to the researchers' report, the experimental data are in good agreement within 10–12%.

The numbers Re_I, I = 1,2, in formulae (2), (4), characterizing the ratio of inertial forces to molecular friction forces, are determined according to the following expressions:

– Re_1 number in formula (2) for gases flowing in the barrel channel could be placed in the functional connection with the velocity of the gases during the shot v_1, which is also calculated by solving the main problem of internal ballistics [23] and the reference value of the coefficient of dynamic viscosity of gases η1 [3; 4]:

$$\mathrm{Re}_1 = \frac{v_1 l}{\eta_1}; \tag{6}$$

– Re_2 number in formula (4) for air flowing along the surface of the barrel will be calculated based on the value of the speed of the oncoming air flow during firing v_2, which, with a comfortable (intra-fuselage) placement of the AAW, is identified with the speed of the aircraft and also the nominal value of the coefficient of air kinematic viscosity μ_2 [25]:

$$\mathrm{Re}_2 = \frac{v_2 l}{\mu_2}.$$

The number Pr1 in formula (2) characterizes the similarity of speed and temperature fields in the gas flow, it is determined by the formula

$$\mathrm{Pr}_1 = \frac{v_1}{a_1} = \frac{\eta_1 c_1}{\lambda_1}, \tag{7}$$

where a_1 – temperature conductivity coefficient of gases.

In gas-pulse systems, which include AAW samples, large specific heat fluxes are often transmitted. Intensive heat exchange of gases with the surfaces of the barrel is achieved at significant temperature gradients of the heat exchanger along the barrel bore radius, that is at large temperature differences $[T_1 - T]$, $[T - T_2]$. The thermophysical properties of coolants depend, first of all, on the instantaneous values of the gas temperature T_1, and to calculate the physical characteristics of gases, it is necessary to know the physical characteristics of their components at high temperatures. Therefore, to calculate the values of the defining criteria of similarity and heat transfer coefficient, it is necessary to calculate the values of the physical parameters of gases that are a gas mixture.

Method for taking into account the dependence of the physical parameters of a gas mixture on the current gas temperature

In the planned specifications in modeling convective processes of near-wall flows, we will follow the fact that the gunpowders used to equip unitary cartridges for AAW, in terms of their chemical elemental composition, are compounds of carbon, hydrogen, oxygen, nitrogen with an intramolecular oxygen content sufficient for the complete conversion of combustible elements into gas. Therefore, their burning results mainly in obtaining gaseous products, and only in some cases a small amount of solids is formed.

Research shows [4; 31], that the main combustion products of gunpowder are carbon dioxide CO_2, carbon monoxide CO, nitrogen N_2, hydrogen H_2 and water vapor H_2O. In some cases, the transformation products may contain CH_4 methane, but under normal combustion conditions these products are contained in very small quantities.

The composition of the transformation products depends on the nature of the gunpowder and the conditions under which the gunpowder of a given nature burns. The greater the oxygen balance of gunpowder, the more combustion products contain carbon dioxide CO_2 and water H_2O, that is, products of complete oxidation. The lower the oxygen balance of gunpowder, the more products of incomplete combustion – carbon monoxide CO and hydrogen H_2. The ratio between the main products is determined by the equilibrium of the water gas reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2.$$

The qualitative and quantitative composition of combustion products may vary somewhat depending on the gas pressure during the shot and the cooling conditions of the products, since when gunpowder burns in a closed volume, the gas pressure during the shot is determined by the loading conditions of the AAW. Increasing loading conditions and increasing gas pressure during firing, the content of carbon dioxide CO_2 and methane CH_4 increases slightly, and the content of carbon monoxide CO and hydrogen H_2 decreases. This is explained, on the one hand, by the course of secondary reactions, and on the other, by a different direction of explosive transformation reactions. The appearance of nitrogen oxides NO in the combustion products of gunpowder is due to the fact that combustion occurs in several stages, described by the Serebryakov – Zeldovich – Belyaev temperature profile [1; 4; 31]. Nitrogen oxides NO are intermediate products and in the last stage of gunpowder combustion they interact with the products of incomplete combustion according to the reactions:

$$2CO + 2NO \leftrightarrow 2CO_2 + N_2 + q;$$

$$2H_2 + 2NO \leftrightarrow 2H_2O + N_2 + q,$$

where q – heat from gas combustion reaction.

The theoretical analysis of the chemical composition, percentage contents and energy characteristics of gunpowders used to equip unitary cartridges for AAW demonstrated that to determine the coefficients of thermal conductivity, dynamic viscosity and heat capacity of the ι-th component of the gas mixture ($\lambda_{1_\iota}, \eta_{1_\iota}, c_{1_\iota}, \iota = \overline{1,5}$), approximating analytical dependencies can be used [1; 25], the dependencies specify formulae (6), (7).

For gas CO_2 ($\iota = 1$):

$$\lambda_{1_1} = (5,89832 + 0,0963058\, T_1 - 0,000757319\, T_1^{3/2}) \cdot 10^{-3}\,; \tag{8}$$

$$\eta_{1_1} = (5,60846 + 0,043375\, T_1 - 0,0007347768\, T_1^{3/2}) \cdot 10^{-3}\,; \tag{9}$$

$$c_{1_1} = 21,6966 + 0,090772\, T_1 - 0,00243224\, T_1^{3/2} + 0,0000187612\, T_1^{2}\,. \tag{10}$$

For gas CO ($\iota = 2$):

$$\lambda_{1_2} = (4,01627 + 0,0861\, T_1 - 0,000614918\, T_1^{3/2}) \cdot 10^{-3}\,; \tag{11}$$

$$\eta_{1_2} = (\,8{,}19784 + 0{,}043251 T_1 - 0{,}000325791 T_1^{3/2}\,)\cdot 10^{-3}\ ; \tag{12}$$

$$c_{1_2} = 24{,}4476 + 0{,}0181285\, T_1 - 0{,}000357338 T_1^{3/2} - 1{,}89466\cdot 10^{-6} T_1^{2}\ ; \tag{13}$$

For gas H_2O ($\iota = 3$):

$$\lambda_{1_3} = (\,-\,20{,}3507 + 0{,}17663\, T_1 - 0{,}00057079 T_1^{3/2}\,)\cdot 10^{-3}\ ; \tag{14}$$

$$\eta_{1_3} = (\,-\,0{,}0346853 + 0{,}55828 T_1 - 0{,}000452251 T_1^{3/2}\,)\cdot 10^{-6}\ ; \tag{15}$$

$$c_{1_3} = 28{,}90216 + 0{,}0105406\, T_1 + 0{,}000198288 T_1^{3/2} - 4{,}36359\cdot 10^{-6} T_1^{2}\ . \tag{16}$$

For gas H_2 ($\iota = 4$):

$$\lambda_{1_4} = (\,80{,}3534 + 0{,}375747\, T_1 - 0{,}000917275 T_1^{3/2}\,)\cdot 10^{-3}\ ; \tag{17}$$

$$\eta_{1_4} = (\,4{,}28174 + 0{,}019866 T_1 - 0{,}000146665 T_1^{3/2}\,)\cdot 10^{-6}\ ; \tag{18}$$

$$c_{1_4} = 30{,}9404 - 0{,}0147268\, T_1 + 0{,}000637427 T_1^{3/2} - 6{,}05625\cdot 10^{-6} T_1^{2}\ . \tag{19}$$

For gas N_2 ($\iota = 5$):

$$\lambda_{1_5} = (\,5{,}1584 + 0{,}0784756\, T_1 - 0{,}000534648 T_1^{3/2}\,)\cdot 10^{-3}\ ; \tag{20}$$

$$\eta_{1_5} = (\,8{,}47204 + 0{,}0401594 T_1 - 0{,}000297397 T_1^{3/2}\,)\cdot 10^{-3}\ ; \tag{21}$$

$$c_{1_5} = 25{,}2938 + 0{,}0128032\, T_1 - 0{,}000180876 T_1^{3/2} + 3{,}33147\cdot 10^{-7} T_1^{2}\ . \tag{22}$$

Formulae (8)–(22) are applicable at gas temperatures of $400\ \text{K} \le T_1 \le 3000\ \text{K}$.

Calculating the physical characteristics of a mixture from the values for individual gas components can use methods developed for studying objects in related subject areas and systematized in the source [25].

To calculate the thermal conductivity coefficient of a mixture of gases, the dependence is applicable

$$\lambda_1 = \frac{\sum_{\iota}^{5} \varepsilon_\iota \cdot m_\iota \cdot \lambda_{1_\iota}}{m_{\text{см}}}\ , \tag{23}$$

where ε_ι – mole fraction of the ι-th component of a gas mixture; m_ι – mole mass of the ι-th component of a gas mixture; m_{sm} – mole mass of a gas mixture.

The values of mole fractions ε_ι and molar masses m_ι of ι-ths components of a mixture of gases ($\iota = \overline{1,5}$) are available in reference books, problem books or applications to the textbooks, for example, [3; 4; 25]. To calculate the molar mass of a mixture of gases in expression (23), the formula known in thermophysics is used:

$$m_{\text{см}} = \sum_{\iota}^{5} \varepsilon_\iota \cdot m_\iota\ .$$

To calculate the coefficient of dynamic viscosity of a gas mixture, there is formulation

$$\eta_1 = \left(\sum_{\iota}^{5} \frac{\varepsilon_\iota}{\eta_{1_\iota}} \right)^{-1}\ .$$

Calculating the coefficient of heat capacity of a mixture of gases is carried out according to the expression

$$c_1 = \sum_{\iota}^{5} \varepsilon_{\iota} \cdot c_{1_{\iota}}.$$

It should be noted that the given criterion equations, which serve to determine the total heat transfer coefficient from gases to the barrel bore and from the outer surface of the barrel to the air α_I, I = 1,2, are not universal dependencies and they are given for very specific conditions, characterized by the shape of the cross-section of the barrel, thermophysical properties of gases and barrel steel material, as well as unsteadiness of gas flow.

When using AAW, determining the state of coolants is reduced to repeated calculation of the criterion equation (3) using formulae (6), (7) and constructing the functions:

$\lambda_{1_{\iota}}(T_1), \iota = \overline{1,5}$ of type (8), (11), (14), (17), (20); $\eta_{1_{\iota}}(T_1), \iota = \overline{1,5}$ of type (9), (12), (15), (18), (21); $c_{1_{\iota}}(T_1), \iota = \overline{1,5}$ of type (10), (13), (16), (19), (22). Programme requests for gas temperature values T_1 are carried out for each step of integration of the system of internal ballistics equations grouped in [23].

The calculation of criterion equation (5) is constant at constant values of the specified speed of the aircraft v_2 and the reference value of the coefficient of kinematic viscosity of air μ2.

The completed form of modelling the processes of near-wall flows of gases and air during a small-caliber artillery shot was a computer program that allows to calculate heat transfer parameters from the values of the physical parameters of the gas mixture. The computer program was created and debugged using the Microsoft Developer Studio software product, the Fortran Power Station 4.0 environment and the Fortran-90 algorithmic language.

Due to the required level of abstraction and due to the inevitable loss of some information, the presented model does not provide a complete picture characterizing the researched physical processes. Justification of particular formulations and further discussions of the consequences seem possible after checking the adequacy of the model to real processes of heat exchange between the barrel and surrounding coolants.

Verification of the model adequacy

Establishing a set of properties of a model that reveals its suitability for solving a given problem is possible by comparing the results of mathematical modeling with data from natural experiments and previously obtained results of theoretical work. This approach can significantly increase the objectivity of conclusions.

Fig. 1 presents comparative graphs of the results of mathematical modeling of the heat transfer process during a shot with previously obtained illogical theoretical solutions and borrowed experimental data [32]. The adequacy of the model was verified based on mandatory compliance with the conditions of thermal and geometric similarity stated above.

Analysis of the results of calculating the intensity of the influence of coolants on the barrel demonstrated an increase in accuracy in the convergence of theoretical results of determining the parameters of heat transfer during a shot to the experiment results by 19 %. Consequently, applying the proposed tool, it is possible to more accurately determine the amount of heat entering the bore and removed from the outer wall of the barrel under various conditions of firing from the AAW.

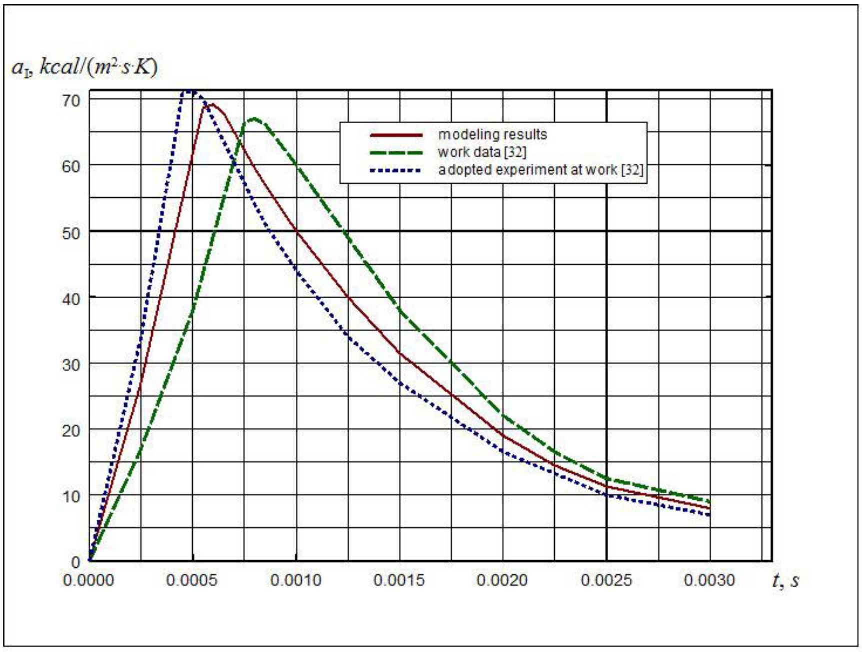

Рис. 1. Зависимость полного коэффициента теплоотдачи от времени при малокалиберном артиллерийском выстреле

Fig. 1. The dependence of the total heat transfer coefficient on time for a small-caliber artillery shot

Prospects for further dissemination of solutions for AAW research

The practical application of the developed tools for assessing the intensity of thermal loading of the barrel contributes to the improvement of quantitative approaches to solving problems indirectly or directly related to the thermophysical aspects of modernization of structural schemes and algorithms for using AAW. Including the proposed model in the formalizations of a higher level of the hierarchy eliminates the need to operate with rather voluminous constructs to express the connections formed in the case of an absolutely perfect formulation of the studied problem.

The primary importance of the identified quantitative parameters, which have a major impact on the heating and cooling of the barrel, is justified by the presence of additional opportunities when working out the requirements for AAW innovations (modernizations) various automation schemes.

However, as before, there are still some questions:

– removal of a number of assumptions when calculating the gas temperature T_1, the values of which are included in the form of variables in the approximating analytical dependencies (8)–(22), which form the criterion equation (3) through expressions (6) and (7);

– impossibility of fully taking into account the dependence of the thermophysical parameters of air on the altitude of the use of AAW in the criterion equation (5) due to the theoretical complexity and significant resource intensity of dynamic mathematical models of the atmosphere.

Conclusion

Using the methods and techniques of the theory of thermodynamic similarity, one of the possible variants of the model has been synthesized, which makes it possible to fairly objectively identify fast processes of heat transfer during the movement of gases in the barrel bore and air near the outer wall of the barrel. It should be expected that further accumulation of knowledge of the theory of heat transfer will follow the path of a deeper study of the phenomena and a more accurate mathematical description of AAW in a thermodynamic formulation. Based on these positions, directions to improve the recommended approach are justified.

The introduction of the proposed model into the practice of designing and testing AAW will allow to obtain objective assessments of the quality of AAW operation while minimizing the plans of full-scale experiments, reducing the time and material resources for research and development.

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Подкопаев Илья Александрович – адъюнкт; Военный учебно-научный центр Военно-воздушных сил «Военно-воздушная академия имени профессора Н. Е. Жуковского и Ю. А. Гагарина». E-mail: ilya.podkopaev.96@bk.ru.

Подкопаев Александр Владимирович – кандидат технических наук, доцент, профессор кафедры эксплуатации комплексов авиационного вооружения (и прицельных систем); Военный учебно-научный центр Военно-воздушных сил «Военно-воздушная академия имени профессора Н. Е. Жуковского и Ю. А. Гагарина». E-mail: aleksanpodkopaev@mail.ru.

Должиков Василий Иванович – кандидат технических наук, доцент, начальник кафедры эксплуатации комплексов авиационного вооружения (и прицельных систем); Военный учебно-научный центр Военно-воздушных сил «Военно-воздушная академия имени профессора Н. Е. Жуковского и Ю. А. Гагарина». E-mail: Link707@mail.ru.

Podkopaev Ilya Aleksandrovich – adjunct; Air Force Military educational and scientific center “Air Force academy named after professor N. E. Zhukovsky and Y. A. Gagarin”. E-mail: ilya.podkopaev.96@bk.ru.

Podkopaev Aleksandr Vladimirovich – Cand. Sc., associate professor, professor of the department operation of aircraft weapon systems (and sighting systems); Air Force Military educational and scientific center “Air Force academy named after professor N. E. Zhukovsky and Y. A. Gagarin”. E-mail: aleksanpodkopaev@mail.ru.

Dolzhikov Vasily Ivanovich – Cand. Sc., associate professor, head of the department operation of aircraft weapon systems (and sighting systems); Air Force Military educational and scientific center “Air Force academy named after professor N. E. Zhukovsky and Y. A. Gagarin”. E-mail: Link707@mail.ru.