ABSTRACT

A mathematical model of hypervelocity electrical arc heated light gas gun has been developed that enables to predict all the major gas dynamics parameters of AHLGG vs time and coordinate and also the components of energy conversion during the launching process. The laws of electric energy delivery and arc current are used as the initial data. The model is based upon a set of equations of 1-D non-steady motion of compressible gas, combined with empirical relations, describing losses of energy during arc heating process and ingress of the metal vapor into the light gas due to the electrode erosion. The working gas is considered as a binary one, which composition and properties depend on electric parameters of discharge and type of the electrodes material. The empirical data used were obtained at the arc current up to 1.5 MA and the hydrogen density of 10—30 kg/m³. The system of equations was solved numerically by means of the Godunov’s method. The model and the software had been verified by the series of 43 tests and the quantitative parameters of deviations had been obtained.

NOMENCLATURE

AHLGG Arc Heated Light Gas Gun
\( g \) Pure Gas Subscript
\( m \) Metal Vapor Subscript
\( \gamma \) Mass Fraction
\( \omega \) Mass of Gas Component
\( M \) Molecular Mass
\( C \) Specific Heat
\( k \) Specific Heats Ratio

\( \alpha \) Covolume
\( \rho \) Density
\( P \) Pressure
\( R \) Gas Constant
\( T \) Gas Temperature
\( \Omega \) Electric Charge
\( C_e \) Erosion Law Constant
\( t \) Time
\( I \) Arc Current
\( U \) Arc Potential, Averaged Over Time
\( W \) Closed Vessel Volume
\( E_e \) Arc Electric Energy, \( E_e=\Omega U \)
\( E_{in} \) Internal Energy Increment
\( H \) Electrodes Enthalpy of Destruction
\( \eta \) Arc Heating Efficiency
\( V \) Muzzle Velocity
\( V_o \) Muzzle Velocity at Zero Metal Vapor Injection Conditions

INTRODUCTION

Inspite of the AHLGG had been described more than 30 years ago,\(^1\) reports on numerical models of electrothermal launchers have appeared only in recent time. Probably, that is caused by relatively recent appearance of effective methods of gas dynamics equations solution and experimental data on features of the interior ballistics of the AHLGG. The major feature is, first of all, electrode erosion, that consumes a lot of electric energy (20—70% as usual) and causes metal vapor ingress into the
light gas. This causes formation of the mixture of the light gas and erosion products, which properties differ much from that of the pure gas. These processes have a considerable effect on the AHLGG performance. That is why attempts to use quite perfect gas dynamics models without erosion consideration lead to remarkable disagreement of computational and experimental results, which grows with the velocity increase. As the experimental investigation of arc burning at gun pressure and megaampere current is extremely difficult, there are no sufficient data for creation of the theoretical model of light gas arc heating. Therefore one has to use empirical relations, describing arc heating, which are obtained in dedicated experiments. These relations, being combined with the gas dynamics system of equations for the pure gas and erosion products mixture, give the entire mathematical model of interior ballistics of the AHLGG. In general, such a model is similar to modern classical gun models, where empirical relations for the powder burning are currently in use.

**EMPIRICAL RELATIONS**

Dedicated experiments were carried out by means of the closed vessel technique. Experiments with heavy projectiles were used as well, because their conditions are pretty close to that of the constant volume. In each experiment electrodes weighing was carried out, that enabled to establish the relation between the eroded mass and electric charge:

\[ \omega_m = C_e \Omega \]

The relation is obtained for various metals and tests conditions. For tungsten the value of \( C_e \) is found to be about 40 mg/C.

The arc heating efficiency was studied by means of the closed vessel only. The experimental conditions are described in. Assume that all the energy loss is consumed by an ablation of the electrodes metal and there is a linear function between the lost energy and eroded metal mass, then the
process in the vessel can be described by the following equations of mass and energy conservation:

\[ W \frac{d\rho_m}{dt} = IC_e \]  \hspace{1cm} (1)

\[ W \frac{dP}{dt} = \frac{dE_e}{dt} - HW \frac{d\rho_m}{dt} \] \hspace{1cm} (2)

Substituting Eq.(1) in Eq.(2) and integrating the resulting equation over the burning time, we get the expression for the energy loss:

\[ E_e - E_{in} = HC_e \Omega \]

Defining \( h = E_{in}/E_e \) as the arc heating efficiency we obtain:

\[ \eta = 1 - \frac{HC_e}{U} \] \hspace{1cm} (3)

The validity of the assumed proportionality between the energy loss and the eroded mass is confirmed by the experimental data (see Fig.1). The estimated value of the enthalpy of destruction for tungsten is close to 20 MJ/kg. Note, that, according to the arc efficiency definition, the product in the fraction numerator in Eq.(3) is the electrode potential drop. For tungsten this value is about 750 V. On the basis of Eq.(3) we can make an important remark: for the efficiency increase the total arc potential should be increased. This equation enables to estimate practically attainable arc heating efficiency. If the value of \( U \) is 8-10 kV, which corresponds to the capacitor bank maximum voltage of 20-25 kV, then \( \eta \) should be greater than 0.9.

**MODEL DESCRIPTION**

The assumption had been made, that the pure gas and erosion products form a homogenous, thermally equilibrium mixture, behaving as a binary gas. Taking into account real properties of metals and gases and also reasonable pure gas mass fraction, the following binary gas parameters were derived: \( M = M/\gamma_g \), \( C = C/\gamma_g \), \( k = kg \). The isentropic exponent was treated as a function of temperature and pressure up to \( 10^4 \) K and 10 kbar.

The state equation was adopted in a Dupre form \( P(1/p-\alpha\gamma_g) = RT \), and the covolume \( a \) was considered as the function of the pressure up to 10 kbar.

0-D equations of continuity and energy for the chamber included terms, describing metal vapor ingress and energy loss, related to the electrode erosion.

The barrel process was described by two continuity equations (for each mixture component); momentum equation, including the gas skin friction; energy equation, including convective heat transfer to walls of the barrel. The skin friction and the heat transfer were evaluated for the conditions of the gas flow in the tube behind the accelerating piston. The dependence of the gas viscosity and thermal conductivity on temperature was represented by exponential approximations.

The projectile motion equation included the projectile friction force and the ambient back pressure. The piston friction was evaluated using the experimentally found friction coefficient.

**SOLUTION OF THE PROBLEM**

The problem was solved by means of Godunov's discontinuity decay on a moving grid technique.\(^4\) The chamber was treated as a single mesh. Mass fluxes of the two components were computed separately by the uniform procedure. Probably it was the Godunov's approach that prevented the troubles of negative mass fractions.\(^5\) The program had been written down in VAX-FORTRAN language. The runtime was within 10-70 minutes depending on the bore and velocity. The output data were presented in table and graphic form.

Besides ordinary projectile and gas motion parameters, the program puts out the metal vapor density as the function of the time and coordinate (Fig. 2). The graph is plotted for the example with the burning time exceeding 1/2 of the total launching time and the muzzle velocity of 4.2 km/s. The program also puts out the instantaneous energy balance table for any moment of the launching which is pretty useful for estimation of the role of separate processes in the entire launching process.
CONCLUSIONS

The phenomenological approach in arc burning process representation proved to be valid for application in the AHLGG simulation. The simulation model of the AHLGG based on empirical relations for arc burning predicts satisfactorily the major gun parameters.

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