JOURNAL OF PROPULSION AND POWER
Vol. 11, No. 4, July–August 1995

Fresh Approach to Solid Rocket Motor Design

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The possibility of improving the performance of commercial carrier rockets launched from water (surface) through the use of water as the working medium in booster solid-propellant rocket motors (SRMs) is considered. Two ways are suggested: 1) before blasting off, the free inner volumes of the rocket motor are filled with water that is displaced in launching, and 2) water is supplied while the motor is running. This article reports the results of experiments carried out with solid propellant samples and model setups. The results prove the validity of the proposed methods and allow the refinement of calculation techniques for the prediction of SRM performance characteristics. The serviceability of the solid propellant charges working in combination with water is demonstrated. A mathematical model is proposed for the operation of a hydrocombined propellant motor with water and powdered additives applied to the combustion chamber.

Nomenclature

c_p = specific heat of gas at constant pressure
d = particle diameter
G = flow rate of steam from particles
I_{vac} = specific impulse in vacuum
L = charge channel length
M = Mach number
Nu = Nusselt number
P = pressure
Pr = Prandtl number
q = specific heat flux from particles to gas
R = gas constant
Re = Reynolds number
r = current radius of particle
T = temperature
t = time
u_i = linear velocity of particle evaporation front
v = linear velocity of gas
v_i = linear velocity of particles of the ith fraction
w = chamber volume
x = coordinate
α = heat exchange coefficient
γ = adiabate index
λ = gas thermal conductivity
μ = dynamic viscosity of gas
ρ = gas density
ρ_c = particle density
ρ_i = "particle gas" density

Subscript
i = particle fraction number

Introduction

THE engineers of the National Rocket Center "The Makeev Design Office" are working on designing commercial carrier rockets launched from a water surface. The design is based on technologies used for submarine ballistic missiles. The special conditions of employment of such rockets, when the environment is seawater, open up new possibilities of improving motor performance.

Of most interest are two methods of utilizing water. The first method implies filling free inner volumes of the motor with water before launching. The other approach suggests supplying water into the running motor. Let us consider the two methods in succession.

Filling Free Inner Volumes of Motor with Water

This method makes it possible to avoid the effect of the excessive external pressure that appears in dipping the rocket into water, and vertical adjustment. It is most reasonable to fill the first-stage solid rocket motor (SRM), which experiences the largest loadings since its submergence is maximum. Water is removed from the motor on starting. After initiation of the igniter, the charge surface not covered with water is ignited. As pressure in the combustion zone increases, water is driven out of the motor and additional parts of the charge freed of water begin to burn. Thus, filling the motor with water allows one not only to reduce external loading on the carrier rocket, but also to smoothly increase the thrust on starting (instead of the classical "gun" starting).

To check the validity of the method and refine calculation techniques for the main parameters of the interior ballistics of the motor filled with water before it is started, a series of experiments has been carried out in propellant samples and subscale motors. Cyclotetramethylene tetranitramine (HMX)-containing, ammonium perchlorate (AP)-based, and other propellant formulations were used. The following results have been obtained. Holding a composite solid propellant in seawater changes the propellant surface structure. The character of the change depends on the formulation of a particular propellant. The most significant surface changes were observed in propellants in which AP was the only oxidizer. The longer the propellant samples are held in seawater and the higher the environmental temperature and pressure, the stronger the structural changes in the propellant surface layer. It has been established that the ignition characteristics of the samples depend essentially on an exposure time up to 0.5 h. When the samples are submerged in water for a longer period of time, the propellant parameters stabilize. The structural changes of the surface layer are due to the dissolving surface oxidizer particles. The resulting caverns, as well as the micropores of the surface layer, are filled with water that forms a sort of film that changes heat transfer conditions on ignition.

The results and conclusions obtained have been supported qualitatively by testing a subscale motor shown schematically in Fig. 1. The motor is charged with a composite solid propellant containing ammonium perchlorate as an oxidizer. The 500-mm-long charge has a central channel which, in the head

Received Nov. 28, 1994; revision received Feb. 10, 1995; accepted for publication Feb. 10, 1995.

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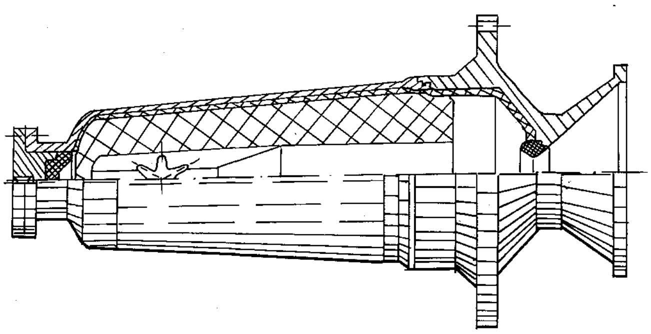

Fig. 1 Experimental subscale motor.

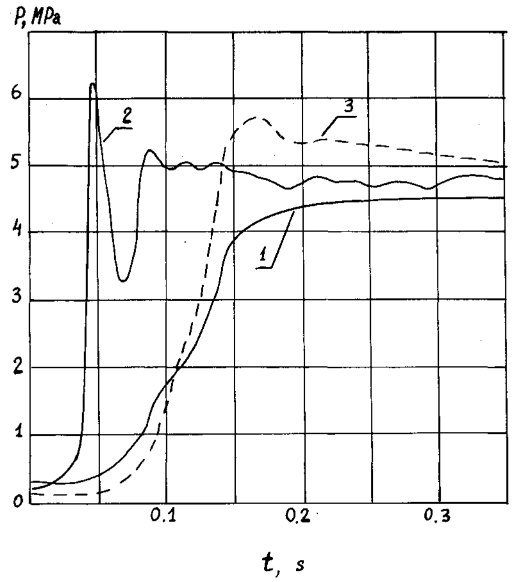

Fig. 2 Effect of water-covered area of original charge surface on diagram of motor start (percentage of water-free original charge surface: 1) 3.5, 2) 30 and 3) 100%).

end, transforms to a hexagonal star of variable cross section. The charge, ignited by means of coarse-grained black powder contained in a percale bag, is initiated with an electric fuse. The overall original burning surface of the propellant charge is 0.2235 m^2. The maximum safe pressure in the motor is 13 MPa. The tested motor was dipped into the water in an upright position. The level of filling the channel with water, the time of holding the propellant in water, the igniter weight, and the nozzle throat diameter were varied. The test has shown that if the propellant is submerged in water for 30 min, the ignition time increases by 0.04 s; after 1 h in water the ignition time increases by 0.05–0.06 s; and after 5 h in water, the ignition time is 0.07 s longer than that for motor initiation in air. This confirms the results previously obtained for experimental samples of propellant (the insignificant increase in ignition time when the propellant is held in water longer than 30 min).

The larger the open (water-free) surface of the propellant the higher the pressure at the initial time. In this case, the water is driven from the charge more quickly, and the starting procedure is close to that in air. Figure 2 presents starting diagrams for motors with different free surface areas: 1) 3.5, 2) 30, and 3) 100% overall burning surface. The residence time of the motors in water was 270 and 40 min, respectively, for the first and second tests.

Rather interesting results have been obtained in experiments with the igniter located near the nozzle and the propellant channel completely filled with water. The time for sequential ignition of the entire surface of the channel was 7 s, i.e., the most gradual increase of thrust on motor initiation was realized. The experiments have shown the possibility of designing rockets in which the first-stage sustained SRM is filled with water preliminary to blast off.

Water Supply to Combustion Chamber

The second way of using water to improve the performance in solid propellant motors of commercial rockets launched from water is to provide a permanent water supply into the running motor of the rocket. This method makes it possible to increase the total thrust impulse of the rocket motor without increasing propellant mass, and allows control of the SRM thrust in flight. Water is supplied to the motor from a special tank by means of a special pump system. The tank is filled before starting. The current flow rate of the water and the net supply of water to the combustion chamber are determined by the following factors. As a rule, the rate of propellant consumption in real SRM is nonlinear; therefore, water can be supplied to the motor at a variable flow rate inversely proportional to the propellant consumption provided the maximum working pressure in the combustion chamber is not exceeded. Another factor that determines the current flow rate is the limiting ratio between solid propellant consumption and water flow rate that sustains steady-state combustion and provides the completeness of thermodynamic processes.

The main characteristics of such a motor can be estimated by solving a system of equations for the balance between gas supply due to combustion of the propellant and liquid evaporation and the exhaust of the reacted mixture through the nozzle. The effect of supplying water to the combustion chamber on the interior ballistic parameters of the motor was estimated under the following conditions: in-chamber pressure 120 atm, ratio of nozzle exit section to nozzle throat 25. Calculations were performed for a metallized HMX-containing propellant. Calculation results are given in Table 1.

The calculated estimate for the SS-N-20 first-stage rocket motor shows that the water supply to the combustion chamber while the motor is running increases the total thrust impulse by 25%. The total amount of water passing through the motor is 29 tons, the in-chamber pressure is maintained constant, and the time of motor operation reduces by 7 s.

For the design of special motors with a water supply to the combustion chamber, it is reasonable to optimize the propellant formulation with due account given to the effect of the water. A series of calculations were performed in order to optimize the metallized HMX-containing propellant. Results indicated that the optimal metal (aluminum) content for the modified propellant is essentially higher than that for the conventional solid propellant. The optimum value of metal content is determined by the water fraction, physicomechanical characteristics of the propellant, and the service conditions of the motor and its parameters (working pressure, loadings on charge, two-phase loss, etc.). The higher the aluminum content of the propellant formulation, the higher the density of the solid propellant composition. Figure 3 shows the qualitative results of calculations performed to determine the optimum aluminum content of the propellant for the operation conditions of the first stage of the SS-N-20 rocket motor (curves 1, 2, 3, 4, and 5 correspond, respectively, to the propellant-water compositions containing 0, 5, 10, 15, and 20% water).

Table 1 Interior ballistic parameters of an SRM with water supply

Weight fraction		I_{vac},	Thrust increment,	$T_{chamber}$,
Propellant	Water	s	%	K
1.0	0	315.3	0	3656
0.9	0.1	305.5	7.6	3356
0.7	0.3	276.6	25.4	2530
0.5	0.5	237.6	50.7	1820

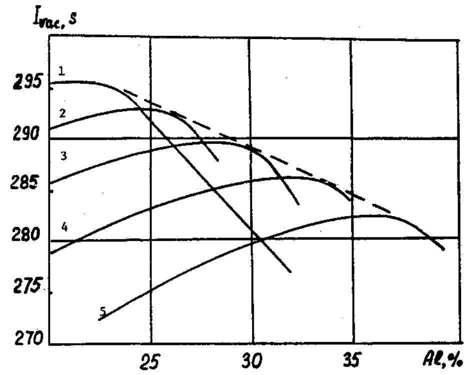

Fig. 3 Vacuum specific impulse vs aluminum content in solid propellant as a function of water content in total mass supply in combustion chamber (water percentage: 1) 0, 2) 5, 3) 10, 4) 15, and 5) 20%).

Calculations of the energy characteristics of the hydrocombined propellant motor have revealed a number of special features. Among them are, in particular, the essentially nonlinear dependence of total loss of specific impulse on water fraction, the strong dependence of the nozzle discharge coefficient of combustion products on water percentage, and the unusual pattern of nozzle walls erosion determined by changes in temperature and the oxidation potential of combustion products.

It was assumed in the calculations that the aluminum content of propellant was increased due to the reduced percentage of ammonium perchlorate. The ammonium perchlorate reduction is acceptable up to a certain limit, depending on the physicomechanical properties of a particular solid propellant and on the rheological characteristics of the propellant mass that provide the possibility of perfect casting of the charge into the motor case. Under the above conditions, the metal content in the propellant-water composition can also be increased by supplying aluminum as a water suspension. This complicates the water supply system somewhat, however, with a controlled water suspension flow rate, and makes it possible for the energy characteristics of the whole composition to be close to optimal.

Among avenues available for further improvement of such rocket engines is the supply of not only water and water suspension of metal powder, but also aqueous solutions of other components, including those incompatible in conventional propellant formulations. These can increase the energy potential of the motor and the number of plausible energetic components used for propulsion purposes.

Mathematical Modeling of In-Chamber Processes

The above results were obtained within the framework of the approach based on the complete interaction of the entire amount of water supplied to the motor with the combustion products of solid propellant charge. However, this condition is not always met, and depends on several factors such as the size of liquid particles, their residence time in the combustion zone, and the thermodynamic and hydrodynamic conditions in the motor chamber.

The completeness of in-chamber processes in hydrocombined propellant motors can be calculated using a computer code developed for a mathematical model designed by the authors in cooperation with researchers of the Institute of Applied Mathematics and Mechanics (Tomsk, Russia). It is assumed that at the initial moment, the motor operates quasistationarily and the distribution of the thermogasodynamic parameters in the charge channel corresponds to the gas supply from burning solid propellant. A liquid component is injected into the charge channel. The resulting mixture is treated as a multivelocity and multitemperature medium involving interpenetration motion and momentum and energy exchange, including the thermogasodynamic effects describing interphase (mass, force, and energy) interactions.[1,2] It is also assumed that all gas components (initially filling the volume, supplied from various areas of the charge channel surface, and resulting from liquid evaporation) are different in nature and do not interact chemically. Metal combustion is described by a stoichiometric equation.[3] The liquid component is supplied as a polydisperse ensemble of droplets. Evolution of the droplets involves their transient heating and evaporation. The temperature field inside a liquid particle and the rate of particle diameter change are determined by solving a thermal conductivity equation for a spherical coordinate system with account taken for phase transformation at the moving external boundary. The expression for the specific (per particle mass unit) heat flux from particles to gas is

$$q_i = (6\alpha_i/d_i\rho_c)(T_i - T) \tag{1}$$

The heat exchange coefficient is determined from the relationship

$$Nu_i = d_i\alpha_i/\lambda \tag{2}$$

where

$$Nu_i = \frac{2 + 0.459Re_i^{0.55}Pr^{0.33}}{1 + 3.42[M_i/(Re_i Pr)](2 + 0.459Re_i^{0.55}Pr^{0.33})} \tag{3}$$

Here

$$M_i = \frac{|v - v_i|}{\sqrt{\gamma RT}}, \qquad Pr = \frac{\mu c_p}{\lambda} \tag{4}$$

The change of liquid particles in mass is determined by the evaporation of the droplets at a mass rate of G_i. The mass rate of steam resulting from evaporation of droplets of the ith fraction is determined by

$$G_i = \int_w \frac{3u_i\rho_i}{r_i}\,\mathrm{d}w \tag{5}$$

where ρ_i is the mass of particles of the ith fraction in a chamber unit volume (particle gas density).

The problem of heating the metal particles supplied with the water up to ignition temperature is solved in a similar manner. The conditions of the mass supply of liquid and metal powder at the motor head end are specified. The particles of metal powder and liquid are injected at given velocities and initial temperatures. The above mathematical model is realized in the form of a computer code using the method of large particles. The program allows one to perform parametric studies on the influence of design features and physical factors on the completeness of processes and motor characteristics.

In particular, this technique was employed in the parametric studies of water droplet evolution in an SRM with a bored cylinder charge (channel length $L = 3.1$ m, channel diameter 0.41 m, nozzle throat diameter 0.206 m). The flow rate of combustion products from the propellant surface was assumed to be constant. The water mass supply through injectors located at the head end of the motor was equal to half of the propellant combustion product mass supply. In calculations, the water flow rate was chosen higher than that practically attainable in order to demonstrate clearly the qualitative behavior of droplets. Water was supplied in the combustion chamber in the form of a polydisperse ensemble of droplets in five fractions (from 100 to 2000 μm) uniformly distributed in mass. The velocity of water droplets at the channel inlet was 100 m/s, and the water temperature was 300 K. Calculation results are given in Figs. 4 and 5.

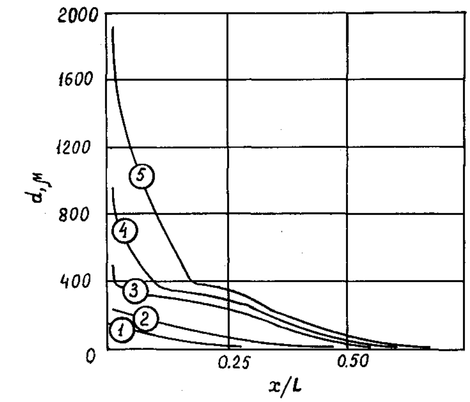

Fig. 4 Change in diameter of water droplets over length of channel: 1) d = 100 μm, 2) d = 200 μm, 3) d = 500 μm, 4) d = 1000 μm, and 5) d = 2000 μm.

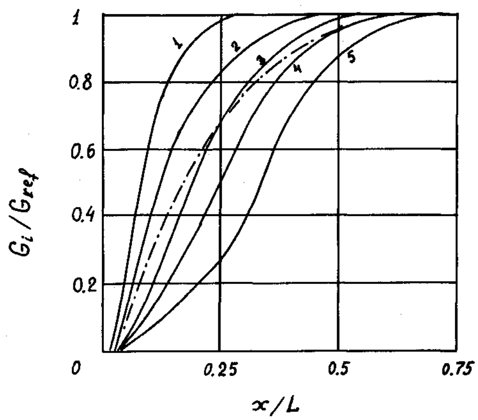

Fig. 5 Dimensionless steam supply from particles of fractions 1–5 at different cross sections of channel: 1) d = 100 μm, 2) d = 200 μm, 3) d = 500 μm, 4) d = 1000 μm, and 5) d = 2000 μm. Dash–dot line corresponds to total steam supply into chamber.

An analysis of the calculation results shows that large water droplets (fractions 3–5) are unstable in the flow, and are broken in the beginning part of the inlet section of the combustion chamber due to the loss of hydrodynamic stability. As droplets move along the combustion chamber, their velocity increases (regaining the critical value of the Weber number) and the evaporating droplets disintegrate. Figure 4 shows calculated curves that describe the diameter evolution of droplets of different fractions due to evaporation and fragmentation. The change of the slope of $d(x/L)$ curves for fractions 3–5 at x/L less than 0.20 is determined by fragmentation of the droplets, followed by relatively slow evaporation. In the further movement of droplets along the channel, the critical condition of fragmentation is again reached, determining the change of the slope at $x/L = 0.3$. For the given motor under the given conditions, it was determined that droplets of all fractions disappear at $x/L = 0.75$. The contributions of droplets of different fractions to vapor formation are shown

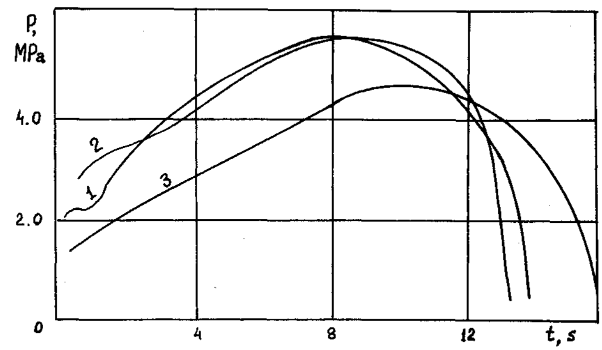

Fig. 6 Comparative diagrams of operation of experimental motor: 1) experimental curve, 2) calculated pressure with water supply, and 3) calculated pressure without water supply.

in Fig. 5, where the dash–dot line indicates the fraction of overall vapor mass related to the water mass supplied to the chamber.

Concluding Remarks

The serviceability of a motor that uses water as an additional working medium supplied to the combustion chamber has been proved experimentally. The testing was performed in a subscale motor loaded with a charge of a metallized solid propellant 100 kg in mass. The head end of the motor was equipped with a cellular injector. Water was supplied to the charge channel through the injector. The mass of the water supplied to the combustion chamber was 14 kg. The testing was performed on a vertical stand. Water supply started simultaneously with motor initiation.

Pressure evolution in the motor is shown in Fig. 6 (1, experimental curve; 2 and 3, calculated pressures, respectively, for the given motor with and without a water supply to the combustion chamber). The results of the testing have corroborated the serviceability of the hydrocombined propellant motor and the applicability of the calculation model to determining the interior ballistic parameters of SRM. Post-trial examination of the construction parts shows that the motor experienced less thermal stress than that typical of a motor burning conventional solid propellant.

The aspects of designing rocket motors using hydrocombined propellants considered do not cover all of the problems arising in the practical use of rocket motors of this kind; however, they do open reasonable and realistic avenues for future research in designing SRM.

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