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Mathematical Modelling of In-Chamber Processes in Hydrocombined Propellant Solid Rocket Motors

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ABSTRACT

The special conditions of employment of commercial rockets in the sea environment has opened up new possibilities of improving motor performance. The interesting method suggests supplying water into the running motor. This paper reports the calculations and experiments carried out with solid propellant model setups. The results prove the validity of the proposed method and allow the refinement of calculation techniques for the prediction of solid rocket motor 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 i^{th} 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

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ρ_c Particle density

ρ_i Particle gas density

Subscript

i Particle fraction number

1. INTRODUCTION

The fresh approach to improve the performance of solid rocket motor (SRM) of commercial rockets launched from water is using water as an additional working medium supplied to the combustion chamber of running motor. This method makes it possible to increase the total thrust impulse of the rocket motor without increasing propellant mass, and allows control of SRM thrust in-flight. Water is supplied to 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 two factors. Firstly, 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. Secondly, the other 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 was 120 atm, ratio of nozzle exit section to nozzle throat was 25. Calculations were performed for a metallised HMX-containing propellant. (Table 1).

For the design of special motors with water supply to the combustion chamber, it is necessary to optimise the propellant formulation with due weightage to the effect of water. A series of calculations were performed in order to optimise the metallised HMX-containing propellant. Results indicated that the optimal metal (*Al*) content for the modified propellant was essentially higher than that for the conventional solid propellant. The optimum value of metal content was determined by water fraction, physico-mechanical 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 *Al* content of the propellant formulation, the higher was the density of the solid propellant composition. Figure 1 shows the qualitative results of calculations performed to determine the optimum *Al* content of the propellant (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	T chamber
Propellant	Water	(S)	increment (%)	(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

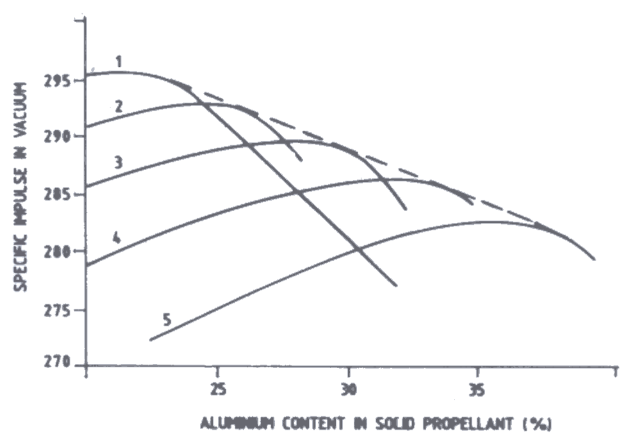

Figure 1. Vacuum specific impulse *vs* aluminium content in solid propellant as a function of water content in total mass supply in combustion chamber (water percentage: (1) 0, (2) 5, (3) 10, (4) 15, and (5) 20 %).

Calculations of the energy characteristics of the hydrocombined propellant motor have revealed a number of special features. Among these 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 that the *Al* content of propellant was increased due to the reduced percentage of ammonium perchlorate (AP). The AP reduction is acceptable up to a certain limit, depending on the physico-mechanical properties of a particular solid propellant and on the rheological characteristics of the propellant mass that provides 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 *Al* as a water suspension. This complicates the water supply system somewhat. However, a controlled-water suspension flow rate 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.

A method of smooth-increasing of SRM thrust during ignition and initial period of operation is connected to the regulation of propellant burning surface by means of formation of swirling liquid film. This liquid film covers the portion of charge surface and protects it from ignition. The film is formated by injection of water into combustion chamber through tangential injecters located at the head-end of the motor. When water injection through such injecters is terminated, the film is disappeared and overall charge surface is ignited. Here after, the water is injected into the chamber through other injecters to increase a total thrust impulse.

2. MATHEMATICAL MODELLING OF IN-CHAMBER PROCESSES

The above results were obtained based on the complete interaction 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 factor, such as the size of liquid particles, their residence time in the combustion zone, and the thermodynamic and the 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. It is assûmed 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 inter-penetration 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 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 considering the phase transformation at the moving external boundary. The expression for the specific (per particle mass unit) heat flux from particles to gas is

$$q = (6\alpha_i / d_i\rho_c)(T_i - T) \qquad (1)$$

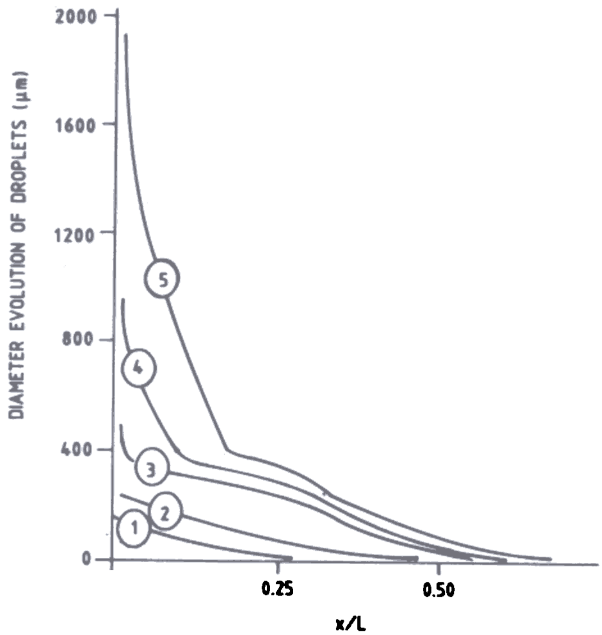

Figure 2. Change in diameter of water droplets over length of channel: (1) d = 100 μm, (2) d = 200 μm, (3) d = 500 μm, (4) d = 1000 μm, and (5) d = 2000 μm.

The heat exchange coefficient is determined from the relationship

$$Nu_i = d_i \alpha_i / \lambda \qquad (2)$$

where

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

therefore

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

The change of liquid particles in mass is determined by evaporation of the droplets at a mass rate of G_i. The mass rate of steam resulting from evaporation of droplets of the i^{th} fraction is determined by

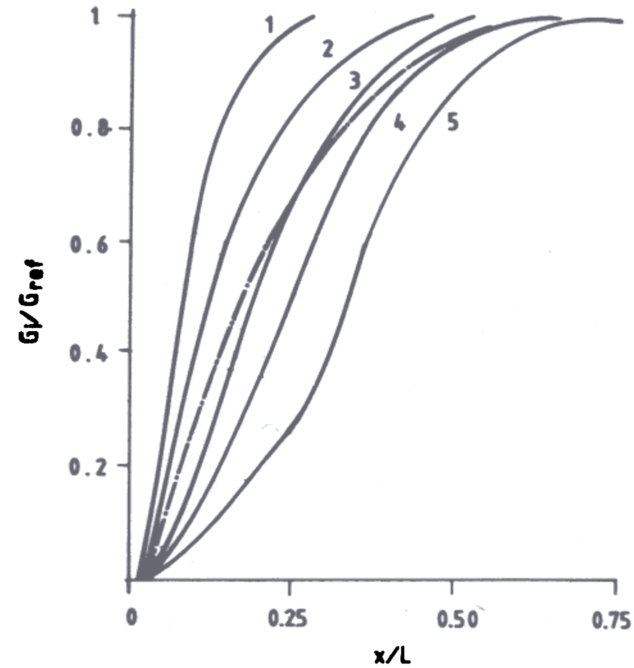

Figure 3. Dimensionless steam supply from particles of fractions 1-5 at different cross-sections of channel: (1) d = 100 μm, (2) d = 200 μm, (3) d = 500 μm, (4) d= 1000 μm, and (5) d = 2000 μm. chain line corresponds to total steam supply into the chamber.

$$G_i = \int_w \frac{3u_i\rho_i}{r_i} dw \qquad (5)$$

where p_i is the mass of particles of the i^{th} fraction in a chamber unit volume [particle gas density(ρ_i)].

The problem of heating the metal particles suspended in 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 specified velocities and initial temperatures. The above mathematical model is realised 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 wrt completeness of processes and motor characteristics.

In particular, this technique was employed in the parametric studies of water droplet evolution in

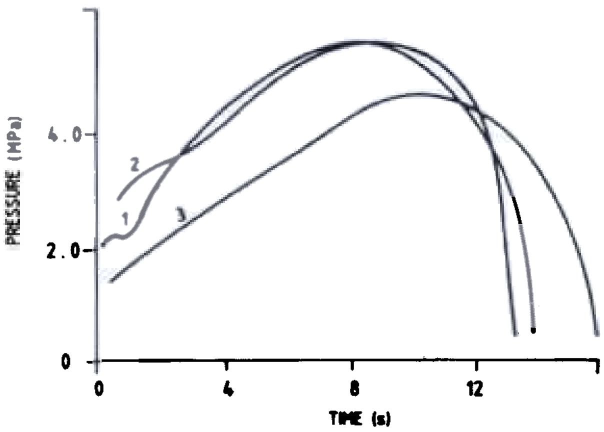

Figure 4. Comparative diagrams of operation of experimental motor: (1) experimental curve, (2) calculated pressure with water supply, and (3) calculated pressure without water supply.

an SRM with a bored cylinder charge (channel length L : 3.1 m, 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 to demonstrate clearly the qualitative behaviour of droplets. Water was supplied in the combustion chamber in the form of a polydisperse ensemble of droplets in five fractions (100–2000 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 depicted in Figs 2 & 3.

Analysis of the 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 2 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 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 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 vapour formation are shown in Fig 3, where the chain line indicates the fraction of overall vapour mass related to the water mass supplied to the chamber.

3. EXPERIMENTAL RESULTS

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 sub-scale motor loaded with a charge of a metallised 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. 4 (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 tests 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.

Hydrodynamics of formation and moving of the liquid film formated by injection of water into the chamber tangentially has been studied experimentally. Distribution of heat flux along charge channel calculated by measured temperatures indicates that heat flux is significantly insufficient to ignite the charge portion, covered by film. Results prove the ability of the method to protect the part of propellant surface from ignition and control the thrust during starting processes.

4. CONCLUSION

The aspects of designing rocket motors using hydrocombined propellants 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 the SRM.

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