THE HYDRO-REACTING MARINE SOLID FUEL ROCKET ENGINES

I.V.Garanin
Moscow State Aviation Institute (Technical University), Russia.

Keywords: hydro-reactive engine, hydro-reacting fuel, turbo-pump aggregate outflow velocity, gas cavity, engine efficiency coefficient, effective thrust, mixture ratio coefficient, combustion chamber, mixture chamber, combustion chamber pressure, specific impulse, injection head, water jet engine, burning process.

Contents

Summary

In this chapter the foundations of theory, calculation and projecting of hydro-reactive engines of underwater apparatus using hydro-reacting solid fuel composition are described. Main schemes and peculiarities of their application are considered. Main principles of fluid mechanics and thermodynamics in application to engines of underwater apparatus are given. Calculations of main engine characteristics are based on the experimental data and comparative analysis of different schemes.

1. General Information about Hydro-Reacting Marine Solid Fuel Propulsion

Unlike in the general scientific approach wherein the new principles of forces and motions are developed, the results of a series of experimental and theoretical studies from both science and technology are used to study the first underwater apparatus. Due to the special requirements of motion of underwater apparatus, effective methods and engines have to be considered.

In ordinary energy power plants using an open thermodynamic cycle, the exhaust gases from engine are released directly into the surrounding medium and that is why the efficiency of such power plants decreases as the depth increases. The usage of a closed cycle engine where reaction products exchange heat energy with the working fluid of the engine is also possible for application.

The most characteristic directions of modern underwater apparatus development are their velocity, distance of motion and depth increase. Moreover, the increase of necessary power is proportional to velocity in the third order, and must be realized under severe dimensional limitations. The projecting motive part of power plant (PP) which represents either a jet nozzle or water flow tract with a system of blades, now reached a rather high level of energy perfection. So the main focus is on questions of investigation on engine parts such as gas generator and energy transformation devices.

The main drawbacks of heat engines are their inability for total transformation of heat energy into work and the limitations in this transformation process are due to the chosen cycle of work. Let us consider more detailed definite consequence of these limitations.

In an energy plant, which works on an open cycle, burned fuel products after passing through the engine are rejected into the surrounding medium taking with them unused heat energy. In an ordinary power plant, which works on a closed cycle, high temperature reaction products exchange heat energy with the working fluid, which is situated in closed loop, and then are exhausted. Different types of energy plants with combined open and closed cyclesw are possible depending on the properties of the fuels. In all these cases the efficiency of the plant will depend on energy maintenance in reaction products and their properties and also on such parameters as temperature, pressure, and so on.

Energy power plants for underwater apparatus are being designed so as to avoid the negative influence of the surrounding medium's definite parameters upon their work. In order to understand peculiarities and definite tendencies of modern directions of engine scheme development, it is necessary to introduce and to consider the propulsive efficiency of engines. According to [1,2], the useful or effective engine thrust, P_{EF} can be determined by the following equation:

$$P_{\mathrm{EF}} = m_{\mathrm{W}} (W_{\mathrm{a}} - V_{\mathrm{o}}) , \qquad (1)$$

where:

m_{W} - mass flow rate of thrown away working fluid;
W_{a} - velocity of thrown away mass;
V_{o} - velocity of underwater apparatus motion.

In order to achieve this thrust, an ideal driver must develop an effective power which is equal to:

$$N_{\mathrm{EF}} = P_{\mathrm{EF}} V_{\mathrm{o}} = m_{\mathrm{W}} (W_{\mathrm{a}} - V_{\mathrm{o}}) V_{\mathrm{o}} \qquad (2)$$

Furthermore, the power which is equivalent to the kinetic energy increment, caused by jet velocity increase after the driver is:

$$\Delta N = m_{\mathrm{W}} (W_{\mathrm{a}} - V_{\mathrm{o}})^2 / 2 \qquad (3)$$

Therefore, the power, named total spent one, which the engine develops, is represented by the following equation:

$$N_{\mathrm{T}} = N_{\mathrm{EF}} + \Delta N = m_{\mathrm{W}} (W_{\mathrm{a}} - V_{\mathrm{o}})[V_{\mathrm{o}} + (W_{\mathrm{a}} - V_{\mathrm{o}})/2] \qquad (4)$$

The quantity of driver work is characterized by relation of useful or effective power to the total spent one and is named as propulsive efficiency:

$$\eta_{\mathrm{P}} = \frac{N_{\mathrm{EF}}}{N_{\mathrm{T}}} = \frac{2V_{\mathrm{o}}}{V_{\mathrm{o}} + \dfrac{W_{\mathrm{a}}}{V_{\mathrm{o}}}} \qquad (5)$$

Equations (1), (2) and (5) allow us to make several general conclusions regarding the estimation of ideal driver efficiency:

- in the case of a set motion velocity, value it is necessary to aspire towards a decrease of outlet velocity;
- in the case of set motion velocity, valueit is necessity to decrease the outlet velocity in order to have the definite thrust valuenecessary to increase the mass flow rate of drop water; in other words, in the case of hydro-reacting engine, it is necessary to increase the mass of water for the purpose of outlet working fluid mass flow increase.

As is known, propulsive capabilities of underwater rockets are rather low due to the weak relation between the rocket velocity and the nozzle outlet flow velocity. This seems to be a serious limitation for rocket engine application in comparison to power plant systems using gas generator in combination with axial pump as a driver. However, the latest investigations in the sphere of hydro-reacting solid fuel compositions based on such metals as aluminum and magnesium with high energy efficiency, high density, and possibility to use outboard oxidizer, indicate the possibility of increase of propulsive qualities of underwater apparatus.

2. Underwater apparatus propulsive quantities investigation

Let us consider first of all the main correlation between rocket construction and its propulsive efficiency during the motion with constant velocity. Let us consider that the dimensions of the rocket are the same during the total distance of motion. In this case the force of hydrodynamic resistance during the motion is described as:

$$X = C_{\mathrm{X}} F_{\mathrm{M}} \rho \, \mathrm{Vo}^2/2 \qquad (6)$$

where: C_X-hydrodynamic force coefficient; F_M-the area of the rocket; V_o-velocity of motion; ρ-the medium density.

The thrust, which is being created by the engine can be described as:

$$P = (m_t / t_b) J_{SP} \qquad (7)$$

where: m_t-mass of the cartridge; t_b-the time of burning; J_{SP}-specific impulse.

In the case of constant velocity, it is necessary to equate equations (6) and (7). Having done the necessary transformations and considering C_X=const., it is possible to obtain:

$$V = \chi \sqrt{(m_t / t_b) / J_{SP}} \ ,$$

where: $\chi = \sqrt{2 / (C_X F_M \rho)} = \text{const.}$

Taking into account the equation for the distance of motion $L = V t_b$ it is possible to obtain the following equation for the distance of motion:

$$L = \chi \sqrt{m_t J_{SP} t_b} \qquad (8)$$

and substituting in (8) the equation for the fuel cartridge volume $W_t = m_t / \rho_t$, it is possible to get:

$$L = \chi \sqrt{W_t \rho_t J_{SP} t_b} \qquad (9)$$

As follows from (9) in the rocket energy plant system it is necessary to use the fuel with high specific impulse of density $J_{SP} \cdot \rho_t$, and in the case, when it is necessary to obtain large distance of motion one must optimize construction using criterion $t_b = t_{b\ max}$.
The equation for velocity is :

$$V = \sqrt{\left(\frac{2}{C_X \rho}\right)\left(\frac{P}{F_M}\right)} \qquad (10)$$

For rocket engines using solid fuel compositions, it is possible to have a high valuevalue of the ratio P/F_M while having at the same time a high combustion chamber pressurevalue. For example, value P/F_M= 2631 kN/m^2 can be obtained for the rocket nozzle with optimal value of the expansion coefficientvalue; for a rocket moving at a depth of 61m, having the combustion chamber pressure of 13.8 MN/m^2 and outlet nozzle area equal one half of the rocket body section area. In the case of moderate hydrodynamic force coefficient value C_X=0.1 the maximum rocket velocity will be in the order of 226.46 m/s. It is necessary to mention that in the case of such high velocity value(excluding only the motion at large depths), the regime of flow along the rocket body will be characterized by the appearance of developed cavitation.

It is also possible to obtain the following equation for propulsion efficiency:

$$\eta_P = \left[1 + \frac{1}{2}\left(\frac{W_a - V_o}{V_o}\right)\right]^{-1} \tag{11}$$

So, for underwater rocket using highly effective solid fuel and moving with different velocities having the pressure ratio 20:1 and constant value of outlet nozzle velocity 2040 m/s, value of $\eta_p = f(V_o)$ are shown at Fig.1.

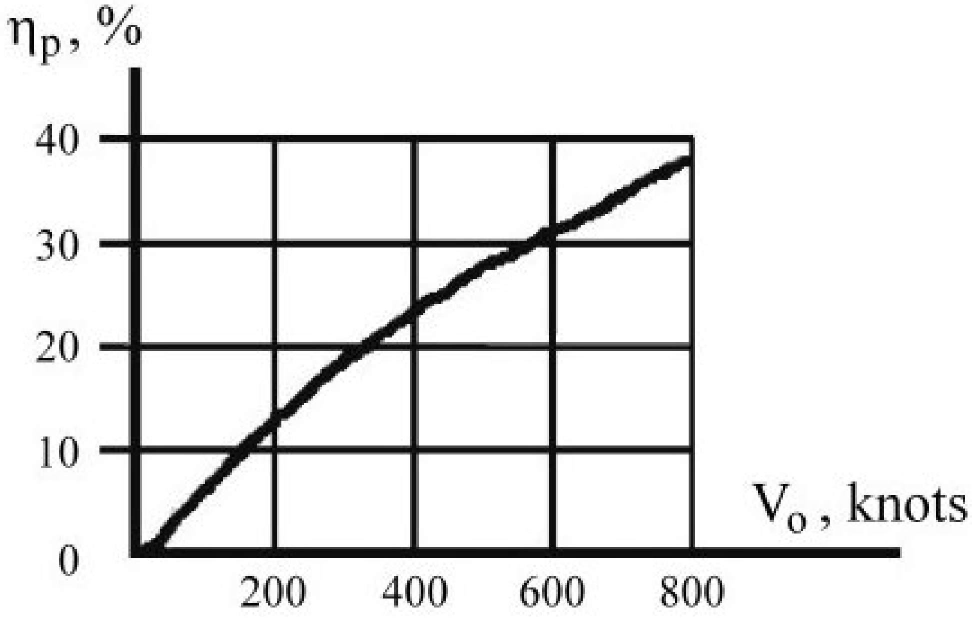

Figure 1: Propulsive efficiency as a function of velocity

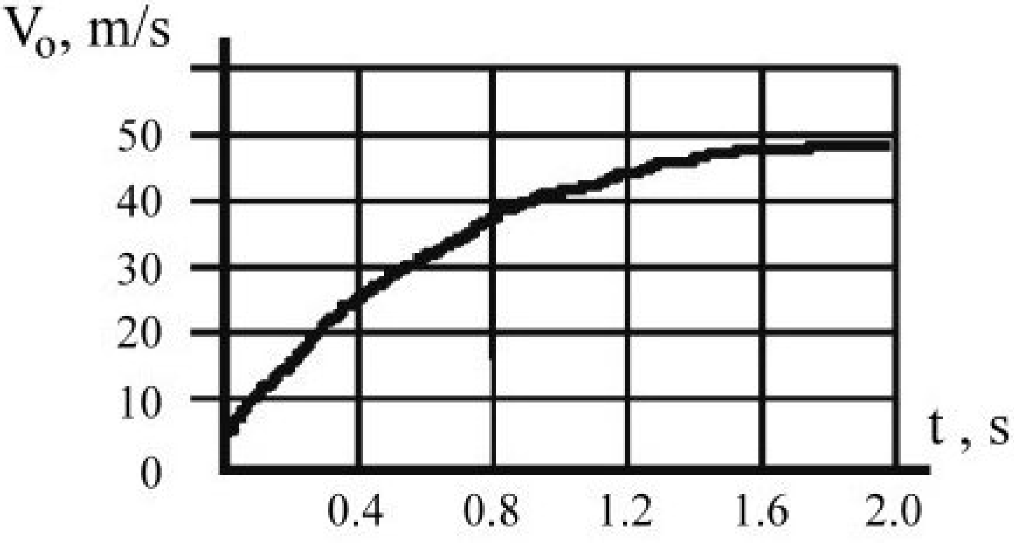

Figure 2: Rocket velocity increase as a function of time (depth H=61m, thrust P=3000N)

In the case of uncontrolled heavy underwater rocket, the time interval of engine thrust action, during which the rocket must reach the necessary final velocity valuevalue, is rather short. However, in the case when the only main engine of the rocket is used for thrust creation, as shown in Fig.2, this time interval is increased up to several seconds. That is why for improving the control of the rocket and decreasing the time of starting it is desirable to introduce into construction additional starting stage for the purposes of acceleration.

3. Foundations of HRE classification

Up to now there are no generally agreed principles for classification for engines of underwater rockets; in Fig.3 is shown one of possible approaches towards this aspect. According to the functions that have to be fulfilled, all engines of underwater apparatus can be divided into the main and secondary categories. Main engines are designed for the realization of rocket parameters during the main regime of motion. Secondary engines and gas generators provide rocket motion at the regimes of injection into the nominal depth, acceleration and gas cavity pressurization. Their peculiarities are characterized by short valueinterval of time which represents from one tenth up to 10...15s. The mass of fuel, which is spend for secondary purposes usually is not greater than 10% of the total fuel mass situated on board the rocket.

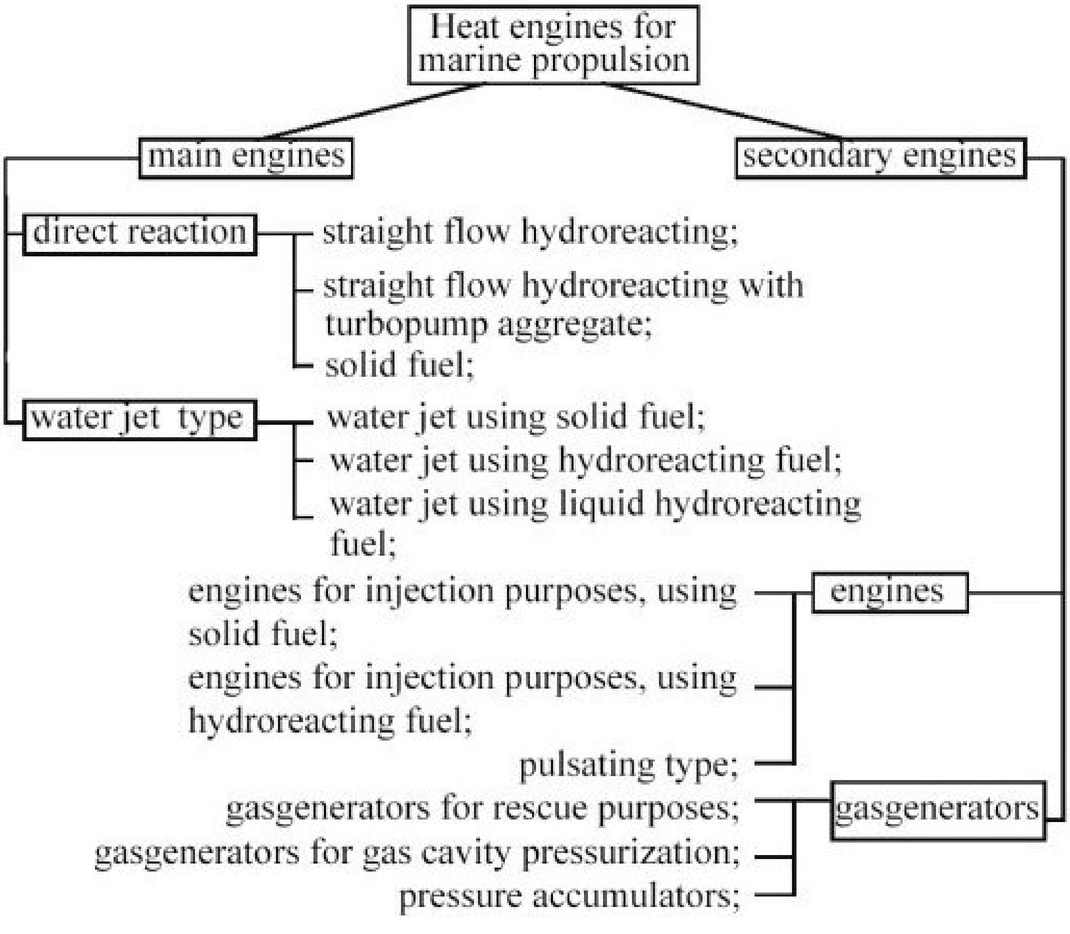

Figure 3. Classification of marine propulsion engines

The main engines are classified according to the type of driver device. There are engines of direct reaction, in other words, with jet nozzle as a driver and water jet flow engines. Water jet flow engine allows the attainment of higher specific characteristics of engine but, at the same time, makes more strong limitations upon the working fluid parameters. Particularly the working fluid temperature must not be greater than 1600...1700K, and the content of condensed phase in the products of reaction must be minimum. There are used unified fuels and hydro-reacting fuels, which can be both solid and liquid fuel ones.

In direct reaction engines, it is justified to use only solid fuels without essential limitations upon the reaction products composition. In hydro-reactive engines, it is useful to apply hydro-reacting fuels in order to enhance the energy characteristics. Such fuels have large negative oxidizer balance, in other words, they have the metal fuel composition (magnesium or aluminum) up to 80% by mass. Such fuels are able to achieve sTable burning in wide rangerange of pressure. During this process, only about one third of the fuel interacts with the oxidizer (oxygen) included in the fuel and the remaining part of metallized fuel reacts with outboard water, which is being fed in the chamber. The variety of hydro-reactive engines are pulsating hydro reactive ones which workusing the principle of throw away the water pistons by way of gas which is being generated in the gas-generator. Continuous addition of water portions towards the gas window of gas-generator is being realized by special rotor. The rotor rotating with required frequency is being provided by spiral blades.

Usually for secondary engines, charging are used unified solid fuels having the combustion chamber pressure not greater than 10 MPa.

In water jet type engines are used mostly unified solid or liquid fuels with the level of burning products temperature about 1600...1700K. In this case the pump initiating is being realized by gas turbine, the working ability of which can be provided only in the case of total absence or minimum containing of the condensed phase inside reaction products. Now is being investigated the possibility to increase energy characteristics of such engines by ways of application fuels with higher burning temperature and at the same time reaction products neutralization by water in order to suppress the temperature.

The possibility of both solid and liquid hydro-reactive fuels application in water jet engines is considered as a promising direction of work. It is possible to realize this idea only on conditions of solution the problem of condensed phase separation in burning products. As for gas generators it is necessary to mention that such power plant systems are able to work using both unified and hydro-reactive fuels. It is more reasonable to use in gas-generators unified fuel in the case when duration of their work is not more than 10seconds and hydro-reactive fuels in the case of more than 100 seconds.

In spite of the higher specific gas productivity of hydro-reactive fuel (HRF) in comparison to solid fuel (1.2...1.4 times), their advantages are realized only over prolonged operation because of the fact that an application of HF supposes the losses of gas generator free volume for the purposes of injection head and combustion chamber of higher dimensions disposition inside it.

-
-
-

Biographical Sketch

I.V. Garanin, professor, doctor of technical sciences, the faculty “Engines and power plant systems of flying apparatus”, Moscow State aviation institute (Technical University), Russia.