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Investigation of a Marine Water-Breathing Ramjet Propulsor

Nachum E. Eisen, Alon Gany

Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa, Israel

ABSTRACT

This work analyzes and presents theoretical performance of a marine water-breathing ramjet propulsor. In addition, it describes and presents a unique static experimental setup and some preliminary experimental results. A conceptual scheme of the motor is shown, the equation of thrust is developed, and the dependence on cruise velocity is discussed. Different propellant compositions, representing a wide variety of propellants suitable for propelling a water-breathing ramjet are investigated. The theoretical results reveal that the specific impulse of a water-breathing ramjet can increase by as much as 30% compared to a standard rocket, when using a conventional hydroxyl terminated polybutadiene (HTPB) - ammonium perchlorate (AP) propellant, which does not react chemically with the water. When employing a water-reactive propellant containing metal particles such as magnesium or aluminum, the specific impulse may be more than doubled. A comparison was done between experimental results of static firing tests of standard rocket and water-breathing ramjet motors with a non-reactive solid propellant. It revealed 15% improvement of the specific impulse for the water-breathing ramjet, in accordance with the theoretical trend for the propellant/water ratio used.

Keywords

Underwater propulsion; Water-breathing ramjet; Marine ramjet; Water ducted rocket.

1 INTRODUCTION

The search for underwater high-speed cruising reveals that certain marine propulsion concepts are parallel in principle to their aeronautical counterparts (Muench & Garrett 1972). Rocket engines can propel high-speed underwater vehicles just like aeronautical vehicles. Independent of speed and ambience medium, rocket engines provide very high thrust and do not need air for their operation, hence, they can suite underwater vehicles. However, their specific fuel (propellant) consumption is very high (implying relatively low specific impulse) and, thus, they enable only a limited range. Therefore, propulsion principles utilizing the surrounding water as a working fluid as well as a chemical reactant (usually oxidizer), similarly to the air-breathing ramjet, have been considered (Greiner & Hansen 1967, Miller et al 2002, Yang & He 2010, and Huang et al 2011). One of the interesting concepts for propelling high-speed underwater vehicles is the water-breathing ramjet. It is a powerful propulsion means, independent of the atmospheric air, hence, it can operate fully and deeply underwater.

The basic principle of the marine water-breathing ramjet is to utilize the high dynamic (ram) pressure resulting from the high-speed motion in order to ingest water into the combustion chamber of the motor, thus increasing the thrust and energetic performance of the propulsor. This work focuses on theoretical prediction and experimental investigation on the performance of a water-breathing underwater solid propellant ramjet motor.

2 THEORY

The design of a water-breathing underwater solid propellant ramjet is similar to the design of an aeronautical ducted rocket. A conceptual illustration of a solid propellant water-breathing ramjet is presented in Fig. 1.

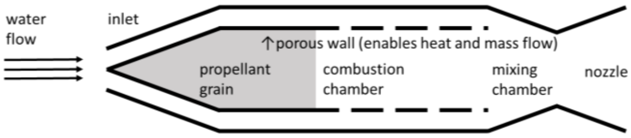


Figure 1. Conceptual illustration of a solid propellant water-breathing marine ramjet

Similarly to solid rocket motors (SRMs), the solid propellant grain can provide high thrust without the addition of water, as well. Nevertheless, the mere addition of water, entering through an inlet due to the vehicle motion, and its further conversion into steam because of the high heat release of the solid propellant combustion, increases the thrust and the specific impulse, even with no chemical interaction. The chamber pressure in the marine water-breathing ramjet is dictated by the cruise speed, and its maximum value at a given speed is equal to the stagnation pressure of the incoming water flow. As Shown in Fig. 2, the stagnation pressure increases with the motion speed. The energetic performance of the motor increases with the speed as well because of the increased chamber pressure and enhanced conversion of thermal energy to kinetic energy of the exhaust jet. It is noted that the momentum of the incoming water is much lower than that of the exhaust jet due to the relatively low vessel speed (compared to that of the aeronautical ramjet, where a similar stagnation pressure is obtained at flight speeds larger by more than an order of magnitude).

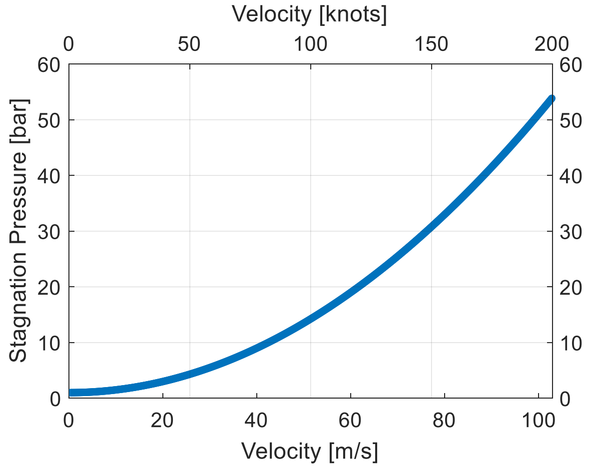


Figure 2. Stagnation pressure vs. cruise speed in water.

The thrust produced by a marine water-breathing ramjet with an adapted nozzle can be calculated using Eq. (1).

$$F = \dot{m}_e u_e - \dot{m}_w u_a \quad (1)$$

where F = thrust; $\dot{m}_e$ = exsust mass flow rate; u_e = exsust velocity; $\dot{m}_w$ = incoming water mass flow rate; u_a = cruise velocity.

The exit (jet) flow rate is equal to the sum of the propellant combustion products and water flow rates

$$\dot{m}_e = \dot{m}_p + \dot{m}_w \quad (2)$$

where $\dot{m}_p$ = combustion products mass flow rate.

Defining

$$\frac{w}{p} = \dot{m}_w / \dot{m}_p \quad (3)$$

one obtains:

$$F = \dot{m}_p \left[1 + \left(\frac{w}{p}\right)\right] u_e - \dot{m}_w u_a \quad (4)$$

The specific impulse (I_{sp}) is calculated according to:

$$I_{sp} = \frac{F}{\dot{m}_p g_0} \quad (5)$$

Thrust calculations for a solid propellant marine ramjet with different water/propellant mass ratios and for different propellant compositions were done according to Eq. (4) with the aid of the thermochemical code CEA (Gordon & McBride 1994), which yields the equilibrium flow conditions and jet performance (adapted nozzle). In this work, a number of propellant compositions were examined. The first composition is a common solid propellant formulation of 85% ammonium perchlorate (AP) and 15% hydroxyl terminated polybutadiene (HTPB), for which the water ingested into the motor, undergoes only a phase change into steam with no chemical interaction with the burning propellant.

Improved performance can be obtained when employing water reactive propellant compositions. Certain metals are known to react very exothermically with water and may be considered for inclusion as water reactive ingredients in propellants. The large amount of heat released in the metal-water reaction can be utilized to evaporate additional water and thus produce a significant amount of steam to increase the mass flow rate of the motor, thus increasing thrust. Table 1 presents theoretical physical and thermochemical properties of selected metals.

Table 1. Maximum theoretical gravimetric and volumetric heat of reaction and hydrogen generation for selected metals with liquid water, listed in the order of their volumetric heat of reaction (data taken from Gany 2018).

Fuel	Density $[g/cm^3]$	Gravimetric Heat of Reaction $[kJ/g]$	Volumetric Heat of Reaction $[kJ/cm^3]$	Specific H_2 Mole Production $[mol/g]$	Specific Volumetric H_2 Mole Production $[mol/cm^3]$
Be	1.85	36.1	66.7	0.111	0.21
B	2.35	18.4	43.2	0.139	0.34
Al	2.70	15.2	40.9	0.055	0.15
Zr	6.49	5.7	37.2	0.022	0.14
Mg	1.74	13.0	22.6	0.041	0.072
Li	0.54	25.5	13.8	0.072	0.039
Na	0.97	2.8	2.7	0.022	0.021

It is apparent from Table 1 that beryllium reacts extremely exothermically with water both in terms of weight and volume; yet, beryllium and its products are notoriously toxic and therefore ruled out. Second to beryllium is boron which demonstrates a promising theoretical heat and gas (e.g. H_2) release. In practice, it is hard to obtain high combustion efficiency of boron (though Rosenband et al 1998 have demonstrated combustion of boron in steam). In addition, boron is relatively an expensive ingredient; hence, for practical applications, aluminum is commonly considered. Aluminum reacts with water to form aluminum oxide (alumina) or aluminum hydroxide and hydrogen, while releasing a significant amount of heat; however, aluminum does not combust readily. Aluminum oxide naturally forms on the exposed surfaces of the aluminum particle and passivates the metal substrate to inhibit oxidation progression. Different approaches for overcoming the alumina coating problem are discussed extensively in the literature (Risha et al 2006, Franzoni et al 2010, and Elitzur et al 2014). Relatively to aluminum, magnesium has a lower energy density, but the magnesium-water reaction is easier to initiate. Therefore, some researchers suggested using magnesium instead of aluminum or using an aluminum-magnesium mixture (Yang & He 2010 and Huang et al 2011).

In addition to the non-hydro-reactive HTPB-AP composition mentioned above, this work deals with other water-reactive compositions, representing the potential range of propellants suitable for propelling a marine water-breathing ramjet. One reactive composition is pure aluminum, presenting the maximum theoretical performance of aluminized propellants, since it reacts solely with the incoming water with no oxidizer stored onboard. Another composition is a solid propellant enriched with magnesium, representing a more practical composition. A propellant consisting of 70% Mg and 30% polytetrafluoroethylene (PTFE, Teflon), contains a small amount of oxidizer (i.e. PTFE) that enables initial combustion to take place without the addition of water; but being fuel-rich, the excessive fuel reacts with incoming water. Yet another potential ingredient is boron, presented here because of its very high theoretical potential, although its practical application may be questionable.

3 THEORETICAL RESULTS

3.1 Non-Hydro-Reactive Composition

Figure 3 presents the calculated specific impulse and density specific impulse for a solid propellant water-breathing ramjet motor with a propellant grain containing 85% AP and 15% HTPB versus the water to propellant mass ratio for two cruise speeds, 25 m/s (implying chamber pressure of 4 bar) and 100 m/s (implying chamber pressure of 50 bar). In both cases, it is assumed that the exit nozzle is adapted to ambient pressure at sea level (1 bar), and that the chamber pressure is the ideal incompressible stagnation pressure of the incoming water. The values at zero water/propellant ratio represent the specific impulse of a pure rocket (no water addition). In general, the w/p ratio is limited by the decrease of the overall chamber temperature to the water equilibrium boiling (condensation) temperature (Fig. 4). It is obvious that the addition of water increases the specific impulse substantially. However, at the low cruise speed (low chamber pressure), the specific

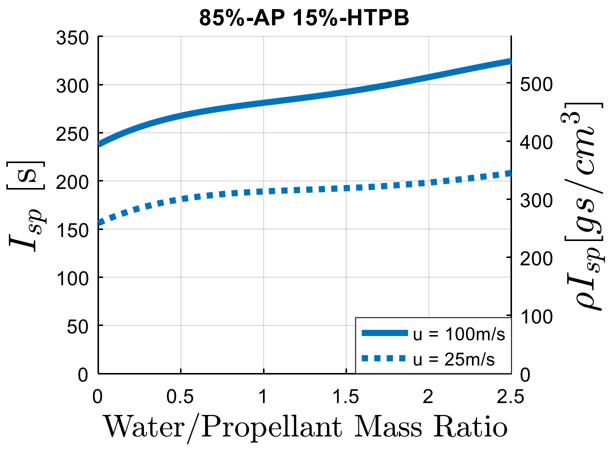


Figure 3. Calculated specific impulse (Isp) and density specific impulse (ρIsp) of an underwater water-breathing ramjet using a non-hydro-reactive solid propellant (85% AP + 15% HTPB) vs. water/propellant mass ratio.

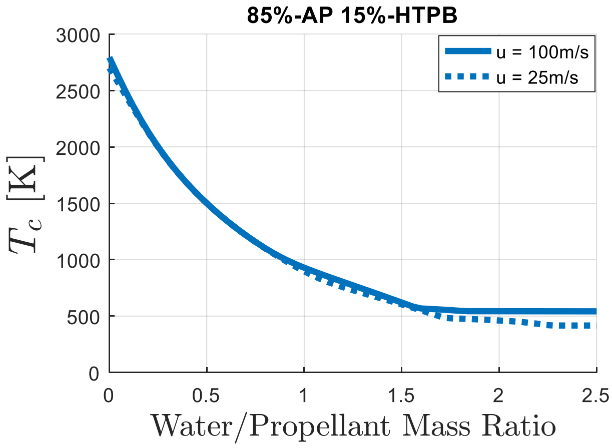


Figure 4. Calculated combustion chamber temperature of an underwater water-breathing ramjet using a non-hydro-reactive solid propellant (85% AP + 15% HTPB) vs. water/propellant mass ratio.

impulse is inferior to that of a rocket motor operating at standard conditions (chamber pressure of about 69 bar). Nevertheless, the performance of the water-breathing ramjet at the higher chamber pressure (50 bar) is noticeably higher than that of the lower pressure due to the contribution of the greater expansion in the nozzle. When cruising at 100 m/s, the specific impulse exceeds that of a standard rocket motor by as much as 30% when adding water at a w/p ratio of 2.5.

3.2 Hydro-Reactive Composition

The reaction of aluminum with water is presented in Eq. 6:

$$2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2 + 818\frac{kJ}{mol} \qquad (6)$$

Figure 5 presents the theoretical specific impulse and density specific impulse for a water-breathing motor with aluminum as a fuel versus the water to propellant (fuel) mass ratio for two cruise speeds, 25 and 100 m/s, corresponding to low (4 bar) and high (50 bar) chamber pressures, respectively. In this case, even at the low speed cruise conditions, the theoretical specific impulse of the water-breathing ramjet exceeds that of a standard rocket. Since the only oxidizer is water, no heat is produced when no water is inserted into the motor (i.e., w/p is zero). Figure 6 presents the calculated combustion chamber temperature versus water/Al mass ratio. To be more realistic, one can take into account the fact that the reaction products of aluminum with water contain large amounts of condensed material (Al_2O_3 or $Al(OH)_3$), that may be retained within the motor. Hence, calculations were repeated for the case where the condensed material remains in the reaction chamber and does not exit the nozzle. Even in such case, the motor performance may be doubled and more, compared to standard solid rockets.

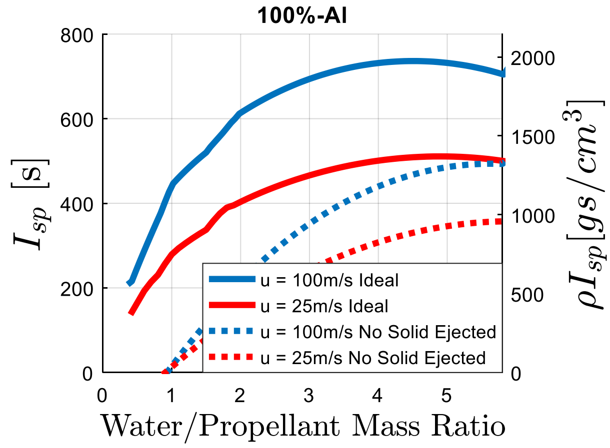


Figure 5. Calculated specific impulse and density specific impulse of an underwater water-breathing ramjet using aluminum as a hydro-reactive propellant vs. water/propellant mass ratio.

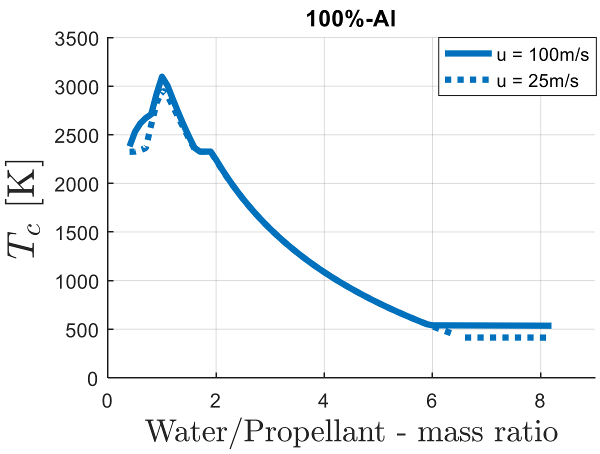


Figure 6. Calculated combustion chamber temperature of an underwater water-breathing ramjet using aluminum as a hydro-reactive propellant vs. water/propellant mass ratio.

In practice, water-reactive ingredients will be embedded within a fuel-rich propellant matrix containing a small fraction of oxidizer. Magnesium is one of the metal candidates. Equation 7 presents the high-temperature water-magnesium reaction:

$$Mg + H_2O \rightarrow MgO + H_2 + 312\,\frac{kJ}{mol} \qquad (7)$$

Figure 7 presents the calculated specific impulse and density specific impulse for a water-breathing ramjet motor with a propellant grain containing 70% Mg and 30% PTFE versus the water to propellant mass ratio for two cruise speeds. This propellant composition is fuel-rich, thus maximum temperature is achieved when water is introduced in the combustion chamber as an additional oxidizer, reacting with the excess Mg. It is apparent from Fig. 7, that the addition of a hydro-reactive fuel ingredient such as magnesium increases significantly the performance. When cruising at 100 m/s, it enables to achieve

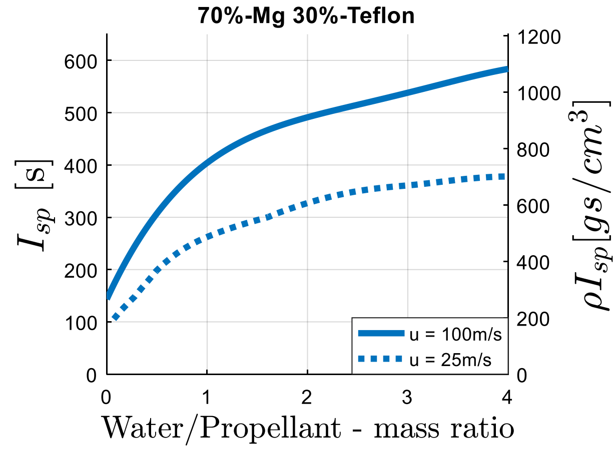


Figure 7. Calculated specific impulse and density specific impulse of an underwater water-breathing ramjet using a hydro-reactive solid propellant (70% Mg + 30% PTFE) vs. water/propellant mass ratio.

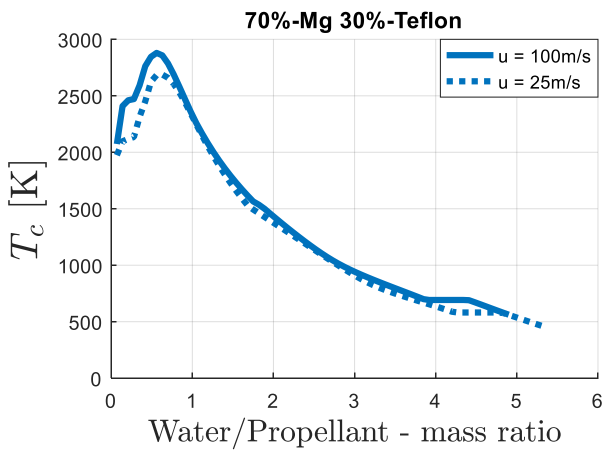


Figure 8. Calculated combustion chamber temperature of an underwater water-breathing ramjet using a hydro-reactive solid propellant (70% Mg + 30% PTFE) vs. water/propellant mass ratio.

a specific impulse double that achieved with a standard solid propellant rocket. From Fig. 8 it is apparent that adding water at a large w/p ratio reduces the temperature of the combustion products; yet Fig. 7 reveals that the specific impulse increases when increasing w/p ratio due to the increase in the mass flow rate.

Theoretically, boron as a fuel may set the highest performance of a water-breathing ramjet propulsor and hence it is presented here, in-spite of the uncertainty regarding practical application. The reaction between boron and water is presented in Eq. 8.

$$2B + 3H_2O \rightarrow B_2O_3 + 3H_2 + 397\,\frac{kJ}{mol} \qquad (8)$$

Figure 9 shows the theoretical specific impulse and density specific impulse when boron is used as a fuel while cruising at 100 m/s.

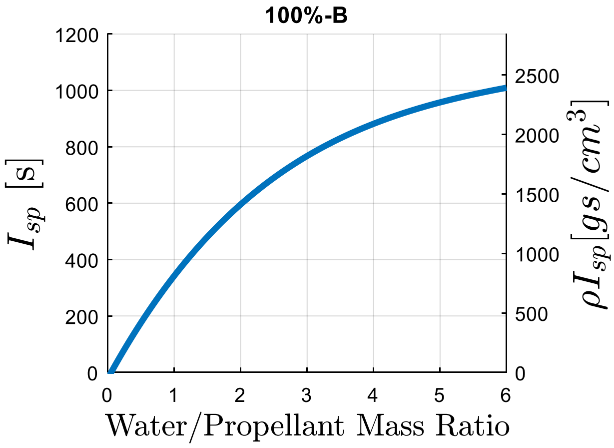


Figure 9. Theoretical specific impulse and density specific impulse of an underwater water-breathing ramjet using boron as a hydro-reactive propellant vs. water/propellant mass ratio.

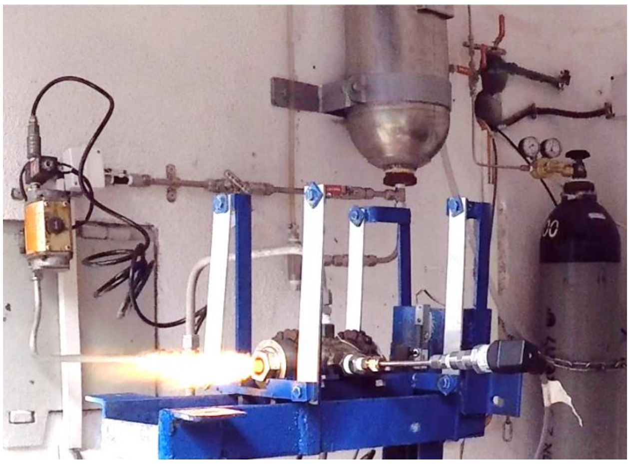
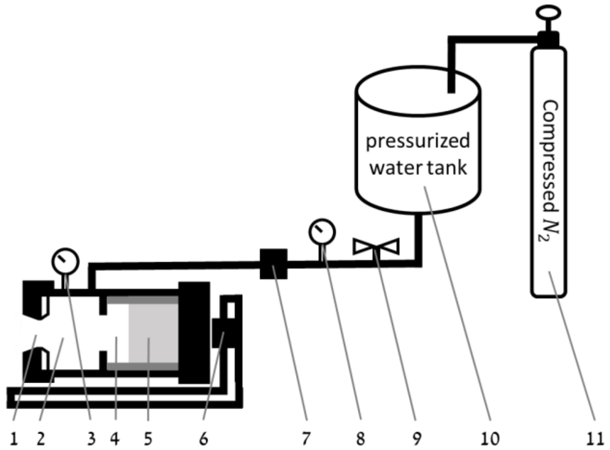


Figure 11. Static experiment setup of an underwater water-breathing ramjet during firing.

4 EXPERIMENTAL SETUP AND RESULTS

In order to validate the trends observed above, an experiment setup for conducting static firing tests with a water-augmented rocket was constructed. A scheme of the setup is shown in Fig. 10 and a photograph of the setup during one of the static firing tests is shown in Fig. 11. The thrust produced by the motor, the chamber pressure, and the flow rate of water into the motor are continually monitored, in addition to HD video of the firing test. The apparatus can supply up to 10 liters per minute (167 g/s) of water at a pressure up to 100 bar. As can be seen in Fig. 2 above, 50 bar is the stagnation pressure at a velocity of 100 m/s, thus the experimental setup can mimic cruising conditions at very high velocities.



1 – nozzle, 2 – mixing chamber, 3 – pressure transducer, 4 – combustion chamber, 5 – propellant grain, 6 – thrust transducer, 7 – pneumatic actuated ball valve, 8 – electronic flow meter, 9 – flow regulating needle valve, 10 – pressurized water tank, 11 – compressed nitrogen cylinder

Figure 10. A scheme of the experimental setup.

The motor that was tested was relatively small with an internal diameter of 39 mm with a conical converging nozzle, 2 mm in diameter at the throat. The propellant grain used in the motor was an end burning cylindrical grain weighing 40 g composed of 75% AP and 25% polyester.

Figure 12 presents a comparison between the pressure measured during two experiments conducted at similar conditions with and without addition of water indicating the water flow rate, when supplied. In order to prevent extinguishing of the flame, the line suppling the water to the motor was opened only after the propellant was fully ignited and the pressure reached working conditions. From the graph presenting the water flow it can be observed that at start there is a significant flow of water filling the water line, then the flow rate stabilizes until the propellant burns out and the motor pressure decreases parallel to an increase in the water flow. It is apparent that the addition of water increases the integral of the pressure, thus increasing the total impulse of the motor. By calculating numerically the area under the experimental curve during steady water flow conditions ($5.5s < t < 8.5s$), it was found that the average specific impulse increased by 15% when water was added during the operation of the motor. During steady conditions, the mean flow rate of the propellant products was approximately 8 g per second and the water flow rate was about the same value, therefore the water/propellant mass ratio was roughly 1. Using the method mentioned above for calculating the theoretical performance of a water-breathing ramjet, it was found that for the propellant composition, chamber pressure, and w/p mass ratio at the experiment, theoretically an improvement of 20% in the specific impulse is possible. The somewhat lower improvement in the measured specific impulse can be attributed partially to the fact that the theoretical prediction assumes chemical equilibrium, namely, complete evaporation of the water added inside the motor. In practice, some water droplets may have not evaporated completely in the motor, thus infuriating performance; supposedly, spraying smaller water droplets may increase actual performance.

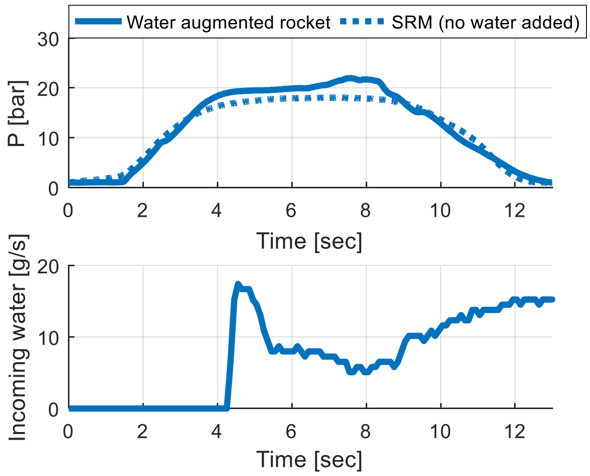


Figure 12. Chamber pressure with and without addition of water and incoming water flow rate vs. time.

5 CONCLUSIONS

The concept of a water-berating ramjet for underwater propulsion has been evaluated theoretically based on thermochemical calculations and available practical propellants and energetic components. It is revealed that theoretically, even without chemical interaction, a solid propellant ramjet motor augmented by water entering from the surrounding through an inlet, can deliver specific impulse higher by 30% than a standard solid rocket. In a unique static test facility, an improvement of 15% was demonstrated. By introducing a fuel-rich propellant containing large amounts of a water-reactive metal such as magnesium or aluminum, the specific impulse may be doubled.

6 FUTURE WORK

Further parametric investigation is planned in order to enhance the knowledge and data about marine water-breathing ramjet propulsors. Specifically, more experiments will be conducted in the near future with different water/propellant mass ratios in order to determine the optimal ratio for different propellant compositions.

ACKNOWLEDGMENT

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