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Theoretical investigation on water/ metal fuel ramjet motor-thermodynamic cycle and thermodynamic calculation

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Abstract : For achieving high-speed requirement of underwater vehicle, a conceptual engine, which utilizes the hydrosensitive characteristic of several metals under supercavitation environment, has been put forward. Especially, in order to obtain specific impulse as great as possible, a dual water injection system is taken into account. Then thermodynamic cycle model, which lead the improvement of power plant and energy system, is introduced in detail, and thermal efficiency is also analyzed. Furthermore, for investigating the performance of this kind of engine system, detailed thermodynamic calculation and analysis are achieved. Especially, regarding hydrosensitive metal fuel Mg/ AP/ HTPB as our target fuel-rich propellant, considering its obvious deficient oxygen property and the energy property of magnesium/ water reaction, theoretical calculation method is established by integrating chemical non-equilibrium with chemical equilibrium. Accordingly, low limit of primary water/ fuel ratio is determined. In addition, the qualitative and quantitative relationship of performance parameters, such as theoretical specific impulse, nozzle exit temperature, characteristic velocity, etc., versus water/ fuel ratio is investigated respectively.

Key words : hydrosensitive metal fuel; water ramjet; thermodynamic cycle; thermal efficiency; specific impulse

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Nomenclature

Al	Aluminum
AP	Ammonium perchlorate
c^*	Characteristic velocity
c_F	Thrust coefficient
c_p	Isobaric heat capacity
h	Specific enthalpy
HTPB	Hydroxyl-terminated polybutadiene
I_{sp}	Specific impulse
M	Molecular weight
m	Mass flow rate

Mg	Magnesium
p	Pressure
q	Specific heat quantity
Q_d	Density explosive heat
Q_s	Explosive heat
R_0	Universal gas constant
T	Temperature
V	Velocity
w	Work

Greek symbols

ρ	Density
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ϕ	Water/ fuel ratio
η	Efficiency
Subscripts	
c	Combustor
g	Gas; gas-turbine cycle
p	Primary injected water; propellant
R	Rankine cycle
s	Secondary injected water
sat	Saturation state
1~8	Sate points presented in Fig. 1

Introduction

At present , efforts are continually directed toward improving the technology to make underwater vehicles more effective , that is , large voyage and high speed. Especially , when an underwater vehicle travels at 200 kn (about 100 m/ s) , the flow around the body separates and a cavity is formed , this cavity generation due to high speed is called supercavitation. Actually , supercavitation is a hydrodynamic process in which an undersea body is almost entirely enveloped in a layer of gas initiated at a cavitator mounted at the forward end , and it's interesting to note that this process may be realized due to the natural e-vaporation at speeds more than 70 m/ s. In this case the free water surface does not touch a body surface any more , the vehicle seems travel in air instead of in water , and hence , it's especially attractive to reduce the friction drag , as air density is less in 800 times than water density. However , for achieving maximum performance available of candidate high-speed vehicle , supercavitation technology is just a precondition , a sustaining high thrust force to counteract the effect of drag force is essential. Hence , development of high-energy power system with effective jet propulsion becomes vital and urgent.

It's generally known that high-energy power system needs high-energy propellant accordingly , considering the special working environment and limit fuel space for an underwater vehicle , selection for propellant with high-energy density is significant. The number of candidate propellants for use in propulsion of underwater

vehicles by means of a heat engine is possibly as great as is the number considered employed in rocketry. Also , in general , similar considerations apply in choosing the optimum system for a given application in underwater applications. These include the important factor of performance capability , based on the intrinsic thermodynamics of the propellant , and practical considerations of suitability under use conditions.

It's worthwhile to mention that , Russian always kept ahead in field of high-speed underwater vehicles during last century and it's reported that those kinds of vehicles all employ new power system by using water as main oxidant , and high energy-density fuel called hydroreactive metal is carried , and the speed could reach 200 kn which is 3~5 times than that of ordinary vehicles , certainly , propulsive performance of new power system would be enhanced distinctly. In addition , related studies in Germany and USA have also made progress^[1].

In general , much attention has been paid to this new conceptual power system subsequently. It's well known to us all , several metals such as aluminum , magnesium , lithium , etc. are at or above the melting temperature could react with water and then release vast heat. Based on this principle , engine with a carried fuel while oxidant water pumped from ambient conditions could be defined as metal/ water fuel ramjet motor. Actually , in early 1940s , the boosting concept utilizing combustion of hydroreactive metal aluminum has been put forward , and some relevant studies were carried on continuously in 1960s^[2]. Then from 1990s to recent years , the principle and performance of aluminum/ water reaction system are concerned intensively^[3-9]. Indeed , aluminum has a relative high density explosive heat , which has been presented in Table 1 , however , the ignition difficulty and reaction maintenance are still two intractable problems. Whereas , University of Pennsylvania has been placing the emphasis on study of aluminum/ water propulsion system , and a whirling combustor has been developed conceptually , the principle of

this device is to smash the aluminum oxidizing layer which prevents further reaction between aluminum and water. By the way , toward Table 1 , Q_s presents explosive heat , in customary units , $\text{kJ} \cdot \text{g}^{-1}$, the numerical value may be calculated from the energy available from the chemical reaction and the type of working gases produced. Yet density explosive heat $Q_d = Q_s \cdot \rho$ may be concerned for underwater vehicle , where ρ is propellant density. The reason could be explained from two aspects. In the first place , the proportion of vehicle weight that is carried fuel is relatively low , probably never exceeding 50 per cent and usually less , this is in decided contrast to rockets where ratios exceeding 90 per cent may be realized. Thus the total weight of the vehicle is not critical dependent on the propellant weight. Another factor contributing to lower the importance of weight is because the powerplant is operating against a given force , drag , in sustaining the system , and at high speeds , drag is much more a function of external configuration than that of weight. So the propellant parameter of most usefulness in characterizing underwater propellant performance is power output per unit volume. This parameter is of definite value in grading new propellants for underwater applications.

Table 1 Energy characteristics of metal/ water reaction

Chemical reaction	$Q_s/$ ($\text{kJ} \cdot \text{g}^{-1}$)	$Q_d/$ ($\text{kJ} \cdot \text{cm}^{-3}$)
$\text{Al} + 1.5\text{H}_2\text{O}(\text{l}) \rightarrow$ $0.5\text{Al}_2\text{O}_3(\text{s}) + 1.5\text{H}_2(\text{g})$	15.15	41.2
$\text{Mg} + \text{H}_2\text{O}(\text{l}) \rightarrow$ $\text{MgO}(\text{s}) + \text{H}_2(\text{g})$	13.34	24.71
$\text{Li} + \text{H}_2\text{O}(\text{l}) \rightarrow$ $\text{LiHO}(\text{s}) + \text{H}(\text{g})$	28.61	15.42
$\text{Li} + 0.5\text{H}_2\text{O}(\text{l}) \rightarrow$ $0.5\text{Li}_2\text{O}(\text{s}) + 0.5\text{H}_2(\text{g})$	22.54	12.15

Hence , for this new potential water ramjet , it's necessary to study the property of hydrore-active metal fuels , which influence the performance of power system to a great extent. Without

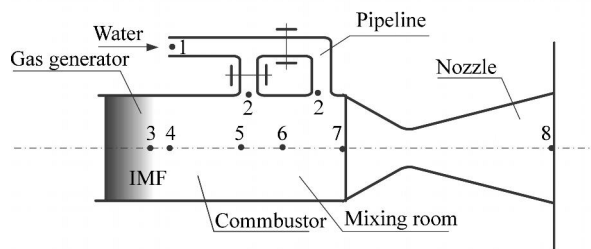
regard to aluminum , lithium has lower energy density from data listed in Table 1. Instead , magnesium has a relative high energy density , and it's available for magnesium to react energetically with water. Thus , from general viewpoint of energy property and viable study , magnesium will be regarded as target hydroreactive metal. In addition , a dual water-injection system was taken into account for obtaining a greater possible specific impulse. Moreover , thermodynamic calculation is a vital approach to developing the water ramjet , which could provide basic data in structural design and working process calculation of engine. Consequently , based on our notion of new water ramjet , it's necessary to pay much attention to theoretical investigation including thermodynamic calculation and performance analysis.

1 Thermodynamic cycle model

Since thermodynamic cycle of any heat engine holds importance in development of thermodynamics and power generating machine , also it could boost the development of thermal engine and energy power system. Aiming at special water/ metal fuel ramjet motor , no corresponding thermodynamic cycle models have been reported at present. Thus , study on theoretical analysis especially thermodynamic cycle system is significant.

Toward candidate metal/ water fuel ramjet motor with a dual water-injection system , system diagram is simply described as shown in Fig. 1. The heat engine used in underwater vehicles has a gas generator in which the hydrore-active metal fuel (HMF) could burn by ignition to liberate their latent energy , and this process should be regarded as primary combustion. Especially , the solid propellant is oxygen deficient , not all magnesium involves in reaction , hence , primary combustion products including gases and residual magnesium would flow into combustor , and meanwhile appropriate primary water enters from ambient form pipelines. Obviously , a lager mount of heat would be released

by reaction between magnesium and water vapor, as a result, combustor temperature reaches a high value, and similarly, this process is called secondary combustion. Since secondary injected water is introduced as main working substance, specific impulse of engine would enhance greatly. Meanwhile, mixing room is designed to mix the high-temperature products and secondary injected water. Then all working substances including gases and small condensed particles from mixing room would expand through Laval nozzle to bring thrust. Thus, the working process of the new water ramjet has completed. In succession, a new round cycle will be initiated.



- 1 ambient water; 2 injected water;
 3 state during primary combustion ($p_3=p_4$);
 4 gas generator state after primary combustion;
 5 state during primary combustion ($p_5=p_6$);
 6 mixing room state of steam; 7 state of nozzle inlet;
 8 state of nozzle exit

Fig. 1 Schematic diagram of metal/water fuel ramjet motor system

Firstly, it's worthwhile to present the definition of water/fuel ratio ϕ :

$$\phi = m_{\text{H}_2\text{O}} / m_{\text{fuel}} \quad (1)$$

Where $m_{\text{H}_2\text{O}}$, m_{fuel} represent the mass flow rate of injected water and mass flow rate of fuel respectively, the latter is related with the burning rate of hydroreactive metal fuel.

In addition, it's worthwhile to mention that primary injected water is introduced sufficiently to consume all residual magnesium, meanwhile guaranteeing combustor temperature not lower than ignition temperature of magnesium/water reaction, which is about 800 K. Towards 1 kg Mg/ AP/ HTPB propellant with 50 % magnesium mass fraction, combustor temperature T_6 versus primary water/fuel ratio ϕ is displayed in

Fig.2. According to complete reaction $\text{Mg} + \text{H}_2\text{O} = \text{MgO} + \text{H}_2$, water/fuel ratio could be defined as ϕ_h , here ϕ_h is about 0.43 for 1 kg fuel. In other words, when $\phi = \phi_h$, combustor temperature T_6 will reach a maximal value, while $\phi = 2.0$, $T_6 = 836.88 \text{ K}$, so ϕ should be given a proper value between 0.5 and 2.0.

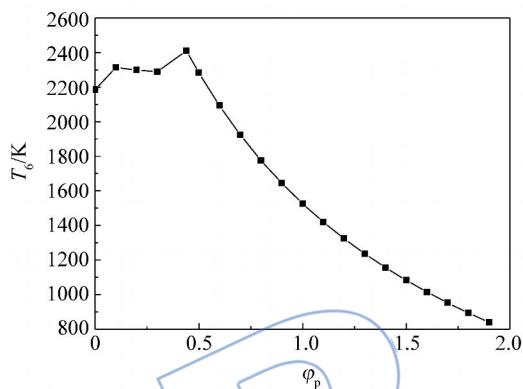


Fig. 2 T_6 vs ϕ

Considering two-phase flow characteristic and phase transition of water during work process of ramjet, thermodynamic cycle could be regarded as coupling of ideal gas-turbine cycle and ideal quasi-Rankine cycle, the former just indicates that magnesium reacts completely with primary ($\phi = \phi_h$), correspondingly, working medium is products of secondary combustion. While during latter cycle, all excessive injected water is assumed working medium, it involves liquid water and water vapor.

Given initial temperature of hydroreactive metal fuel and ambient water is 25°C and 10°C respectively, and navigational back pressure p_a can be achieved based on $p_a = p_0 + \rho gh$, here p_0 is sea-level pressure 101325 Pa (1atm), ρ is sea-water density $1023 \text{ kg} \cdot \text{m}^{-3}$, h is navigational depth 10 m, so $p_a = 0.2 \text{ MPa}$. Moreover, making combustion products expand optimally in nozzle, that is $p_8 = p_a$. Then assuming water injected into combustor with a high velocity 100 m/s, and meanwhile pressure losses along pipeline is nearly 2 to 3 MPa, while pressure loss in muzzle holds between 0.15 and 0.2 MPa. Thus at last, chamber pressure p_5 has been initiated 2.5 MPa in terms of Bernoulli equation, which is regarded invariable in present study.

1) Ideal gas-turbine cycle

As indicated in Fig. 3 , state 3 is an assumed state during primary combustion when pressure of products is just equal to back pressure 0. 2 MPa. State 5 is another assumed state during secondary combustion when p_5 just reaches up to 2. 5MPa. Since reaction process including partial primary combustion and partial secondary combustion is achieved instantly , and reaction heat is completely used to heat products without any heat loss , so process 3-5 can be regarded as isentropic process. Then from state 5 to state 6 , secondary combustion will continue under circumstance of constant pressure 2. 5 MPa , combustor temperature will increase sharply on account of liberated combustion heat , in general , T_5 is defined as adiabatic combustion temperature. Then all products will expand through nozzle , process 6-8 could be regarded as isentropic , during this process , temperature and pressure will descend while velocity increases. However T_8 is higher than T_3 , so process of heat release 8-3 exists under environmental pressure 0. 2 MPa. Neglecting small part of condensed particle , main working medium is the gaseous products N_2 , CO , CO_2 , H_2 , H_2O (g) , etc.

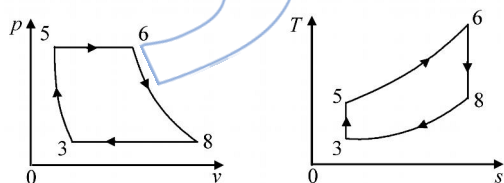


Fig. 3 p - v and T - s scheme for ideal gas-turbine cycle

Based on presentation of ideal gas-turbine cycle , thermodynamic analysis could be accomplished by through endothermic process 5-6 and exothermal process 8-3 , evidently , corresponding heat capacity are q_1 and q_2 respectively. Thus based on 1 kg fuel , net work w_g , with $J \cdot kg^{-1}$ unit , can be obtained by heat difference , which can be expressed by area S_{3568} . Thus , according to the First law of thermodynamics :

$$w_g = q_1 - q_2 \quad (2)$$

$$q_1 = c_{p1} \left(T_6 - T_5 \right) = h_6 - h_5 \quad (3)$$

$$q_2 = c_{p2} \left(T_8 - T_3 \right) = h_8 - h_3 \quad (4)$$

In formula (3) and (4) , c_{p1} and c_{p2} are average isobaric specific heat capacity of secondary combustion products in combustor and nozzle respectively , $J \cdot kg^{-1} \cdot K^{-1}$, while h_6 , h_5 , h_8 , h_3 are specific enthalpy at corresponding state respectively , $J \cdot kg^{-1}$.

Then substitute formulas (3) and (4) into formula (2) , net work can be expressed as :

$$w_g = (h_6 - h_5) - (h_8 - h_3) \quad (5)$$

According to definition of thermal efficiency :

$$\eta_{.g} = \frac{w_g}{q_1} = \frac{(h_6 - h_5) - (h_8 - h_3)}{h_6 - h_5} \quad (6)$$

Obviously , performance of ideal gas-turbine cycle can be predicted by obtaining T_3 , T_5 , T_6 , T_8 or h_3 , h_5 , h_6 , h_8 .

2) Ideal quasi-Rankine cycle

Obviously , ideal quasi-Rankine cycle involves a phase transition , as revealed in Fig. 4. Firstly , water is injected into combustor through pipeline , so kinetic energy of water will transform into pressure energy from state 1 to state 2 , accordingly , pressure and temperature both increase while specific volume has a relative small change as indicated in Fig. 4. Coupled with thermodynamic process of ideal gas-turbine cycle , it's evident that heat liberated from secondary combustion is employed to evaporate all excessive water , so water will turn into water vapor gradually under 2. 5MPa , evidently , temperature and volume increase evidently during process 3-6. While during process 6-8 , water vapor will accomplish an isentropic expansion through Laval nozzle , consequently , temperature and pressure both decrease while specific volume presents increasing trend , certainly , liquid

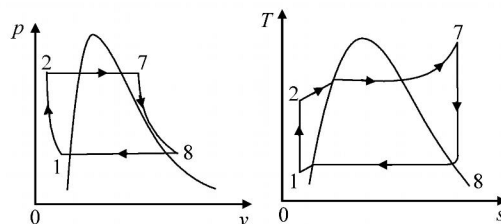


Fig. 4 p - v and T - s scheme for ideal quasi-Rankine cycle

water should be avoided in nozzle. End of expansion, vapor temperature T_8 is still higher than that of ambient T_1 , hence process 8-1 is regarded as exothermic process under constant pressure 0.2 MPa, and then water vapor will turn into liquid water as initial state of cycle.

Similarly, on the basis of the First law of thermodynamics, net work $w_{\text{net},R}$ can be obtained by difference of exothermal and endothermic heat capacity:

$$w_R = q_{l,H_2O} - q_{2,H_2O} \tag{7}$$

Which q_{l,H_2O} is specific endothermic heat of liquid water while q_{2,H_2O} is specific exothermal heat of water vapor, they can be calculated as follows:

$$q_{l,H_2O} = h_7 - h_2 \tag{8}$$

$$q_{2,H_2O} = h_{8,H_2O} - h_1 \tag{9}$$

As presented in gas-turbine cycle, h_7, h_2, h_1 are specific enthalpy at corresponding state, $\text{J} \cdot \text{kg}^{-1}$. It's worthwhile to mention that h_{8,H_2O} is specific enthalpy of water vapor in nozzle exit different from h_8 , which indicates specific enthalpy of secondary combustion products instead.

Then substitute formulas (8) and (9) into formula (7), net work of ideal quasi-Rankine cycle can be expressed as:

$$w_R = (h_7 - h_2) - (h_{8,H_2O} - h_1) \tag{10}$$

Hence, thermal efficiency can be achieved as follows:

$$\eta_{\text{R}} = \frac{w_R}{q_{l,H_2O}} = \frac{(h_7 - h_2) - (h_{8,H_2O} - h_1)}{h_7 - h_2} \tag{11}$$

It is known that under constant pressure, specific enthalpy of water can be correlated in terms of a simple polynomial of T , that is, $h = f(T)^{[10]}$.

In general, given total water/fuel ratio ϕ , $\phi_p = \phi_h$ is water/fuel ratio of ideal gas-turbine cycle, so thermal efficiency of water ramjet motor is calculated by following formula:

$$\eta = 1 - \frac{\phi_h q_2 + (\phi - \phi_h) q_{2,H_2O}}{\phi_h q_1 + (\phi - \phi_h) q_{l,H_2O}} \tag{12}$$

In conclusion, two cycle models describes above are not independent each other, instead, they are interconnected based on combustion and evaporation processes mainly. As presented in part 1, upper limit of primary water/fuel ratio is 2.0 for hydrotreactive metal fuel with 50 % magnesium mass fraction, thermal efficiency can be achieved through above formulas. Thus, Table 2 reveals the results of thermal efficiency η of water ramjet motor when $\phi_p = 0.5$ and $\phi_p = 1.0$ typically, it's noted that η value between that of two ideal thermodynamic cycles. In further, coupled with thermodynamic analysis on propulsive performance of water ramjet, some improved idea for expectant efficiency would be inspired.

Table 2 Thermal efficiency analysis ($\phi_p = 0.5, \phi_p = 1.0$)

	State	p/MPa	T/K	$q_l(q_{l,H_2O})/(\text{kJ} \cdot \text{kg}^{-1})$	$q_2(q_{2,H_2O})/(\text{kJ} \cdot \text{kg}^{-1})$	$w_{\text{net}}/(\text{kJ} \cdot \text{kg}^{-1})$	η
Ideal gas-turbine cycle	3	0.2	962.10	784.44	343.05	441.39	0.5627
	5	2.5	2200.00				
	6	2.5	2444.68				
	8	0.2	1069.11				
Ideal quasi-Rankine cycle	1	0.2	283.15	4709.97	3626.79	1083.18	0.2300
	2	2.5	283.16				
	7	2.5	1340.92				
	8	0.2	852.99				
Motor				5494.41	3969.84	1524.57	0.2775

2 Thermodynamic calculation theory

Theoretically, during the thermodynamic calculation of water ramjet motor, determining equilibrium components of products in each working process is most essential. In general, based on known conditions of HMF, including elements, mass fraction distribution, initial thermodynamic parameters, while given water/fuel ratio and working pressure, equilibrium components of products could be estimated by using mass conservation equation and chemical equilibrium equation together, furthermore, equilibrium temperature could be achieved by employing energy conservation equation correspondingly.

In particular, thermodynamic calculation should depend on behavior of thermodynamic process, for there existing transition of chemical energy, heat energy and kinetic energy. Especially, from viewpoint of above presentation, two-phase flow is an important feature, and proportion of condensed phase has a substantial influence on motor performance. However, some essential assumed conditions should be taken into consideration in theoretical study:

1) Neglecting additive in target deficient oxygen solid propellant, magnesium (Mg), oxidant (AP) and binder (HTPB) are candidate components.

2) Regarding both primary combustion and second combustion as adiabatic process. Meanwhile, in mixing room, heat exchange between excessive water and final combustion products is sufficient.

3) Neglecting two-dimensional loss and two-phase flow loss, and all products implement complete expansion through nozzle.

In addition, primary injected water must be sufficient, that is, residual magnesium from gas generator can be oxidized completely in combustor. Since some certain physical conditions coupled with thermodynamic process, thermodynamic calculation could be divided into four parts as follows:

1) Primary combustion. In gas generator, latent chemical energy of hydroreactive metal fuel transforms into thermal energy of gas products and melting magnesium. Aiming at target fuel Mg/AP/HTPB, only small mass fraction of magnesium can be oxidized in combustor, which becomes MgO and MgCl₂, while the remainder would warm up as heat sink, and meanwhile, carbon particle C will separate out, some gaseous products such as N₂, H₂, H₂O, etc. also generate. So the non-equilibrium method is just fit for this process^[11].

2) Secondary combustion. In combustor, magnesium/water reaction is just main thermodynamic process, obviously, the products may include gaseous N₂, H₂, H₂O, CO, etc. and condensed substances MgO and MgCl₂. Owing to high combustor temperature, some dissociation products H, Cl, O, N, OH, etc. should be included. In this process, thermodynamic parameters including adiabatic combustion temperature T_6 can be estimated by using chemical equilibrium method coupled with the energy conservation equation.

3) Mixing process. In mixing room, combustion has been assumed to be achieved completely, excessive water is used to balance temperature and add working substances instead of being engaged in reaction. Similarly, corresponding thermodynamic calculation should be done by using chemical equilibrium method, and mixing temperature T_7 is estimated by employing energy conservation equation.

4) Expansion process. In Laval nozzle, all products including gases and condensed particles will apply work through expansion, and heat energy will transfer into kinetic energy which is employed to impulse underwater vehicles. The calculation involves determination of the enthalpy drop during isentropic expansion. Especially, two extreme models named equilibrium flow and frozen flow are concerned here, the former means that products are in chemical equilibrium state at each cross-section of nozzle, in other words, compound reaction will fulfill along with

variable temperature. While the latter has an opposite implication, components of products keep invariable during whole expansion process, that is, chemical reaction rate is much lower than that of thermodynamic parameters. However, the specific impulse deviation based on these two flow models is less than 3%. Since calculation method has a small impact on integral performance of engine, therefore, equilibrium flow model concerning in our study is feasible.

3 Results and discussion

Based on thermodynamic cycle and thermodynamic calculation presented above, detailed calculation analysis has been performed. The qualitative and quantitative relationship of performance parameters, such as thermal efficiency η , theoretical specific impulse I_{sp} , nozzle exit temperature T_{8,H_2O} , characteristic velocity c^* , etc. versus water/fuel ratio ϕ has been obtained respectively. Necessarily, definition or calculated formula for above parameters would be expressed as follows:

Firstly, specific impulse I_{sp} is an most important parameter for water ramjet motor, theoretically, specific impulse is determined directly by enthalpy value of products at inlet and outlet of nozzle respectively. In this study, p_8 has been assumed to be equal to p_a , thus, specific impulse can be estimated by following formula:

$$I_{sp} = (1 + \phi) V_8 - \phi V_1 \quad (13)$$

In Eq. (13), ϕ indicates total water/fuel ratio, V_8 is products velocity at nozzle exit, V_1 presents velocity of underwater vehicle.

Another essential parameter is characteristic velocity c^* , the value of c^* is in proportion to energy response of propellant. Especially, when c^* holds a relative higher value, less propellant mass flow is required for achieving an equal thrust force and working pressure. According to a solid rocket engine, characteristic velocity c^* can be estimated by similar formula:

$$c^* = \frac{\sqrt{R_0 T_7 / M_7}}{\tau} \quad (14)$$

Where k_7 , M_7 and T_7 are ratio of specific heat, molecular weight of products and mixing temperature respectively, R_0 is universal gas constant.

A further performance parameter is thrust coefficient c_F , which can be obtained directly via known specific impulse I_{sp} and characteristic velocity c^* , it presents the expansion level of gas products in nozzle. Then:

$$c_F = \frac{I_{sp}}{c^*} \quad (15)$$

In conclusion, specific impulse I_{sp} is influenced by both combustor (mixing room) feature c^* and nozzle feature c_F with expression $I_{sp} = c^* \cdot c_F$. That is, the integral performance of engine is determined by performance of combustion and expansion together.

3.1 Influence of ϕ on T_6

As we all know, for all kinds of motors, combustor temperature has superior limit due to material of shell. Especially, aiming at water ramjet system with carried fuel, the magnitude of primary water has vital influence on combustor temperature. As plotted in Fig. 2, it reveals that when primary water/fuel ratio ϕ is 0.44, combustor temperature T_6 reaches up to maximum 2410.41 K.

In addition, considering the requirement of higher specific impulse coupled with safety assurance of combustor, primary water/fuel ratio ϕ should be more than 0.44. In this study, $\phi = 0.5$ is regarded as the lower limit. Then incorporating with analysis represented in part 1, ϕ is given between 0.5 and 2.0.

As is known, after complete secondary combustion, excessive water won't engaged in chemical reaction any more, instead, it will play an important role in cooling and increment of working medium. Hence, from Fig. 2, it may be noted that combustor temperature presents a decreasing trend with ϕ .

3.2 Influence of ϕ on I_{sp} , η , c^*

Now that some essential assumptions have been given in part 2, guaranteeing a complete secondary combustion, corresponding variable trend of performance parameters versus total water/fuel ratio ϕ can be obtained. In addition, work process in nozzle has been assumed as complete expansion, the exit pressure of Laval nozzle is set as ambient pressure 0.2 MPa, thus corresponding saturation temperature is 393.39 K^[10].

In this study, for guaranteeing normal work of engine, the condensation of water vapor should be avoided at nozzle exit, it means that exit temperature could not be less than saturation temperature T_{sat} . If liquid water appears, it could not apply work during expansion in nozzle, instead, it would erode the nozzle severely, and then the performance of engine will be influenced negatively. Hence, total water/fuel ratio ϕ guaranteeing $T_{8,H_2O} > 393.39$ K is to be predicted.

Based on analysis in part 3.1, ϕ is given 0.5, making secondary water/fuel ratio ϕ change, performance analysis has been accomplished versus total water/fuel ratio ϕ . In Fig. 5, specific impulse I_{sp} and thermal efficiency η are described respectively. It's noted that η keep decreasing monotonically with ϕ while I_{sp} increases, when $\phi = 4.2$, I_{sp} reaches maximal value 5 150.94 N · s · kg⁻¹, then I_{sp} decreases with ϕ .

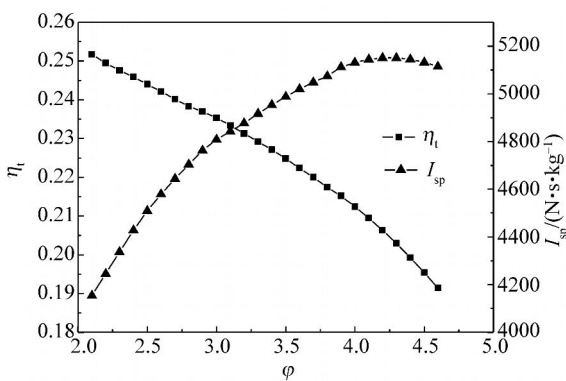


Fig. 5 I_{sp} , η vs ϕ ($\phi_p = 0.5$)

For thermal efficiency η , when $\phi_p = 0.5$, secondary combustion finishes completely, thermal efficiency η is determined by $\eta_{1,2}$, while T_7 and T_{8,H_2O} both decrease with ϕ , and temperature difference in ideal quasi-Rankine cycle keep decreasing, so thermal efficiency η decreases with ϕ . However, specific impulse I_{sp} concerned with not only ϕ but also velocity V_8 as defined in Eq. (13), ϕ keeps an increasing trend while V_8 decreases based on variation of temperature difference in ideal quasi-Rankine cycle, so when decrease of V_8 becomes dominant instead of ϕ increment, specific impulse I_{sp} becomes decreasing.

In addition, characteristic velocity c^* is a vital parameter which reflects the energy response of hydroreactive metal fuel and completeness of combustion rightly. According to Eq. (14), c^* presents a direct proportional relationship with $(T_7/M_7)^{1/2}$. It's known that T_7 keeps a falling trend with total water/fuel ratio ϕ . When ϕ value is small, hydrogen H_2 comes from combustion chamber is regarded as main product, M_7 value is small obviously. However, steam H_2O becomes dominant product with increasing water/fuel ratio, hence mean molecular weight increases, so the mutative trend has been revealed in Fig. 6. To sum up, M_7 and temperature T_7 present a contrary trend against water/fuel ratio ϕ , so characteristic velocity c^* decreases with ϕ as described in Fig. 7.

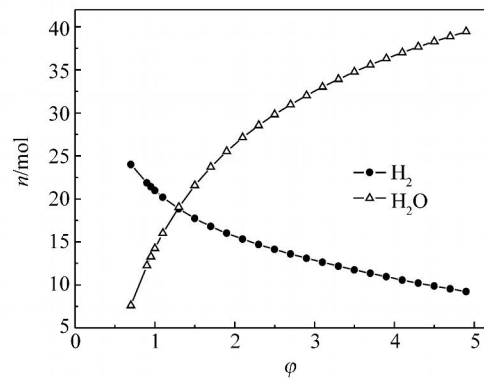


Fig. 6 n_{H_2} , n_{H_2O} vs ϕ ($\phi_p = 0.5$)

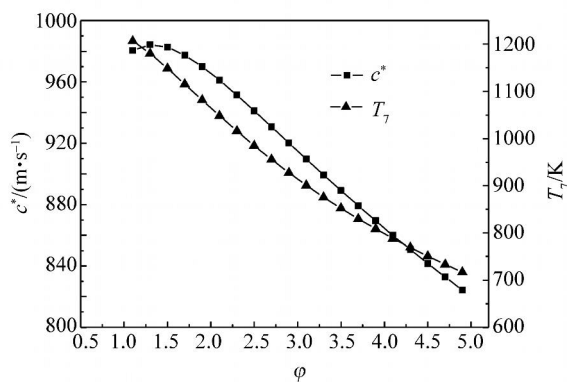


Fig. 7 c^* , T_7 vs ϕ ($\phi = 0.5$)

4 Conclusions

Along with development of supercavitation technology, advanced propulsion system becomes urgent. Accordingly, an attractive concept of water/metal fuel ramjet motor system yielding magical high energy has arisen. Especially in this research, magnesium-based water ramjet system was regarded as target model, and taking hydrosensitive metal fuel Mg/AP/HTPB with 50% magnesium mass fraction as example, the ideal thermodynamic cycle model was put forward, and thermodynamic performance analysis has been accomplished meanwhile.

1) Upper limit of primary water/fuel ratio ϕ is 2.0.

2) Thermal efficiency η presents decreasing trend with water/fuel ratio ϕ .

3) Specific impulse I_{sp} reaches up to a maximal value $5150.94 \text{ N} \cdot \text{s} \cdot \text{kg}^{-1}$ when $\phi = 4.2$.

4) Characteristic velocity c^* decreases with water/fuel ratio ϕ .

All in all, initial study on magnesium-based water ramjet motor could provide theoretical basis for structural design of high-speed underwater vehicle, and meanwhile can guide the improvement and optimization for such new concept engine system.

Furthermore, the work in this paper provides an open notion committed to improvement

of water/metal fuel ramjet motor. For instance, for achieving an optimal performance, a proper amount of aluminum could be substitute for part of magnesium, determination of proper mass proportion, which satisfy energy response as well as combustibility, would be a vital aspect. Hence, the authors will probe into correlative investigation profoundly.

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