수(水)반응성 고체추진제를 이용한 수중고속램제트엔진 시스템 개념 설계

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Concept Design of Hydro Reactive Solid Propellant for Underwater High Speed Ramjet Engine System

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ABSTRACT

For thrust motion of high speed underwater torpedo the special hydro reactive fuels that burns in vapor water and water supply from aboard is used. The main component of this hydro reactive fuel is the powder of active metal (Mg, Al) that can burn in water vapor with large heat generation in the rocket combustion chamber. The thermodynamic analysis of combustion properties of the burning of the particles of these active metal in the vapor water have been carried out. The conception for the possible content variants of the hydro reactive fuels have been discussed using the geometrical and thermodynamic combustion conditions with the basic recommendation for contents of designed hydro reactive fuels in future.

초 록

고속 수중 어뢰의 추진을 위해 외부에서 공급 받은 물과 증기로 연소 하는 수(水)반응성 연료를 이용하고 있다. 수(水)반응성 연료의 주성분은 마그네슘과 알루미늄처럼 반응성이 큰 금속들을 이용하며, 이 금속들은 수증기와 높은 열량과 함께 로켓 추력 실에서 연소 시킨다. 위 금속들의 연소 속성에 대한 해석은 이미 완료되었다. 수반응성 추진제의 가능성 있는 변형체에 대한 개념들은 수반응성 추진제 설계의 기초적인 제안들을 기하학 및 열역학적 연소 조건을 이용하여 논의 할 것이다.

Key Words: Hydro Reactive Solid Propellant(수반응성 추진제), Active Metal(반응성 금속), Water Vapor (수증기), Oxidizer(산화제), Combustion Chamber(추력실), Ramjet Engine(램제트 엔진), Underwater High Speed Torpedo(해저 고속 어뢰)

1. Introduction

Presently the modern sea weapon - the high

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speed torpedo moving with velocity ~100 m/s has been designed. The construction of this torpedo was realized in USSR in 1975-1980 as underwater high speed torpedo "Shquall" [3-5].

For successful design of underwater torpedo two main problems must be solved. One problem is the super-cavitation problem, that means the organizing of the moving of underwater high speed carrier in the super-cavitation gas water vapor bubble that decrease the hydraulic resistance in ~1000 times. Another problem is the organizing of the effective rocket thrust of ramjet engine utilizing the special hydro reactive solid propellant that uses aboard water as oxidizer.

In this paper we discussed the problems of the hydro reactive solid propellant, the basic principle of its operations in the combustion chamber of the ramjet underwater torpedo engine. The idea of utilizing of the hydro reactive solid propellants and the basic contents of these propellants are known and has been considered in many studies [1, 2 & 7]. The practical realization of the hydro reactive solid propellants can be done in many variants but for any variants the basic principle and basic concepts are the same, these basic backgrounds are considered in this paper.

2. Main Description of Problem

For the underwater high velocity underwater object as torpedo, only the reactive thrust can be used for moving force. This is related to the motion of the high velocity underwater torpedo obligatory taking place in the super-cavitation bubble. In this bubble only the reactive motion is possible as the traditional propeller motion is not effective and applicable.

For this underwater reactive motion appliance of the water breathed ramjet engine is more efficient and profitable which is alike air breathed ramjet engine used in the aviation for flying objects moving with high velocities. For combustion in the vapor water the special solid propellants named as hydro reactive fuel there are needed.

These hydro reactive solid propellants have the main component - the powder of active metal burning in water vapor and igniting at the combustion zone of the hydro reactive solid propellant. In the combustion chamber of underwater ramjet engine the processes of water atomization and evaporation and complete combustion of the cloud of burning particles must be efficiently organized. All these problems are analyzed in this paper.

3. Main Components of hydro reactive fuels

For applying the elements as the main component of hydro reactive solid propellant burning in vapor water we should consider following parameters: the weight specific heat reaction metal with water $Q_w = \frac{Q}{M_w}$ and the volume specific heat reaction $Q_V = Q_w \rho_m$, where Q - heat of reaction with water of gram - atom of element (metal), M_w - atom weight (in gram), ρ_m - density of metal.) These parameters Q_w and Q_V are presented on the Fig. 1 and Fig. 2 For practice appliance parameter Q_V is more important.

From the figure 2 it is followed that the metals can generate more heat in reaction with water (max Q_V) : Be, B, Mg, Al, Si, Ca, Sc, Ti, V, Y, Zr. Practical appliance of any metal as the component of the hydro reactive propellant depends on its ability of reliably igniting and burning completely, its accessibility and price, technological and ecological problems.

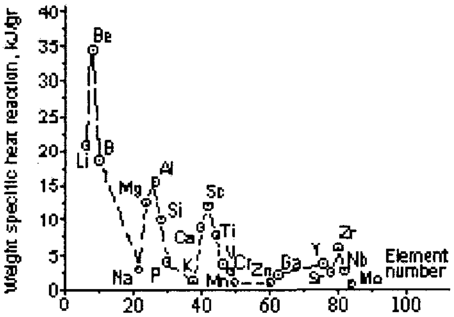

Fig. 1 Dependence weight specific heat reaction element with water on number

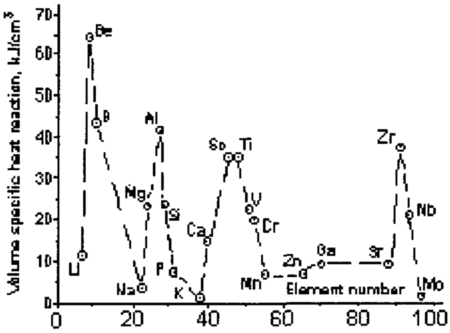

Fig. 2 Dependence of volume specific heat reaction element with water on number element

Sc, V, Y are very rare and expensive for appliance as common component for hydro reactive fuel.

Appliance of Be is difficult because of its poisonous properties and its oxide BeO_2. B has the difficulties for its ignition and combustion as the melting temperature (2050 ℃) and boiling temperature (2550 ℃) are large and the oxide film of B2O3 resists to combustion process. The good thermodynamic properties (Q_V=12.5 kJ/cm^3) of B as fuel stimulates investigations for its appliance as solid rocket fuel [6,7], but in practical system with hydro reactive fuel it is not applied.

Si is very difficult for ignition so as pyrotechnic component it is applied very rarely [7].

Ca is not applied by reason of large ability for chemical reaction with water in air (humidity).

Ti is perspective but now it is more expensive for this application.

The appliance for the hydro reactive fuel of metals Li, Al, Mg and Zr are known [7]. For these metals and B and its oxides the properties interesting for combustion are presented in the Table 1 .

Table 1. Properties of Metals for Hydro Reactive Fuels

Metal / Oxide	T_m, ℃	T_b, ℃	K_{P-B}
Mg/MgO	648/2827	1090/3600	0.81
Al/Al_2O_3	660.4/2044	2467/3530	1.45
Zr/ZrO_2	1852/2710	4377/4500	1.45
B/B_2O_3	2300/450	2550/2250	4.03
Li/LiO_2	180/1570	1342/2600	0.55

In this table temperature of melting Tm (℃), boiling Tb (℃), metals and its oxides are given. In the last column number Pilling-Bedworth values [7,8] $K_{P-B} = \frac{\rho_{mo} A_m}{\rho_m M_{mo} n}$

where ρ_m-density of metal, ρ_{mo}- density of oxide, A_m- atom weight, M_{mo}-molecular weight of oxide, n - number of metal atom in oxide are shown the. This Pilling-Bedworth number indicates the protective ability of oxide film covering the droplet surface. For K_{P-B} >1 oxide film covered the surface completely and resist for ignition and combustion, when K_{P-B} <1 oxide film destroyed and open metal surface for oxidation.

Mg - magnesium has no large temperature of melting (Tm=648 ℃) and boiling (Tb=1090 ℃) temperatures. Pilling-Bedworth number K_{P-B} for Mg is less than 1. So surface of Mg is free for contact with oxidizer and the reaction for Mg particles has occurred in gas phase near the surface of particle.

Al - aluminum has the melting (Tm=660.8 ℃) temperature more near to Mg but higher boiling temperature (Tb=2467 ℃). The Pilling-Bedworth number for Al is more then 1 (K_{P-B} >1) and the temperature of oxide melting (Tmo=2044 ℃) and boiling (Tbo=3530 ℃) temperatures are high enough that makes the large difficulties for ignition of particle aluminum. At combustion the reaction takes place partly in gas phase and partly on the surface with possible accumulation of oxide on the surface of burning aluminum particle.

Zr - zirconium has the large temperature of melting (Tm=1852℃) and boiling (Tb=4377℃). For ignition and combustion the surface oxidation is more preferable. Zr has no molten consistent on surface and the oxidation processes occurs on the surface. Zr is very simple for ignition and combustion in water vapor.

B - boron has so large temperatures of melting (Tm=2300 ℃) and boiling (Tb=2550 ℃) that makes the combustion of boron in gas phase very difficult. The liquid film of B_2O_3 covers the boron particle and protects from the diffusion of gas oxidizer.) The Pilling-Bedworth number for boron B is K_{P-B} =4.03.

Li-lithium is alkali metal with small temperatures of melting (Tm=180 ℃) and boiling (Tb=1342℃). So the lithium combustion is alike to variant of magnesium. All these variants of possible mechanism of combustion of metal particles are shown on Fig. 3.

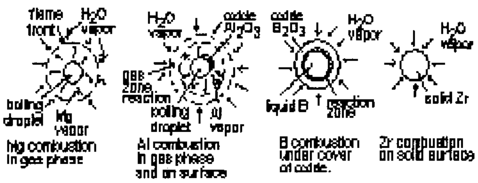

Fig. 3 Types of combustion mechanism of metal particles

The main parameter for rocket thrust - the specific impulse for combustion of metal in vapor water I_{SM} (without pressure component) can be estimated by equation $I_{SM} = \sqrt{\frac{Q_{reac}}{2 * g * M_{am}}}$ where Q_{reac} -the heat accumulated in internal energy of gas combustion products, M_{am} -average molecular weight of gas product and g - gravitation acceleration (g =9.8 m/s2). The heat accumulated in internal energy of gas Q_{reac} can be estimated by equation: $Q_{reac} = Q_R - Q_p$ where Q_R - the full heat of reaction, calculated from enthalpy products and reactants and Q_P - heat of phase transfer of products. The results of calculations are presented in table 2, where T_m - the estimated temperature of gas products after combustion in vapor water, V_g - the possible maximum velocity in critical throat of nozzle and maximum specific impulse. The velocity V_g in the critical throat of nozzle can be estimated by equation: $V_g = I_{SM} * g$

Table 2. Temperature, Velocity in Critical Area and Specific Impulse Metal + Water Vapor

Metal	T_m, ℃	V_g, km/s	I_{SM}, s
Mg	2887	3.5	360
Al	3117	5.1	520
Zr	3593	3.2	340
Li	2600	2.3	240

From the results of Table 2 it is seen that Mg and Al are more preferable for hydro reactive fuel with water as they have the more specific impulse for ideal case of combustion

Besides, the active metal for burning in water vapor can be used the alloys of these metals (Mg-Al alloys) and chemical substances as hydride AlH_3 or MgH_2.

The alloys have the intermediate combustion properties corresponding to metals. Hydrides do not have good properties for practical utilization mainly because of reason of thermal instability.

4. Concepts of hydro reactive solid propellants for underwater ramjet engine

For organizing the combustion process of this metal powdered fuel in water vapor in combustion chamber the hydro reactive solid propellant is applied. At the combustion of the hydro reactive solid propellant the particles of metal powder have blown to gas phase, igniting in gas to such level, that this moving cloud of particles can burn in self sustained mode in contact with flow of atomized and vaporized water droplets. For combustion of the hydro reactive propellant there exists next zones (shown on the Fig. 4) - zone of particle ignition and initial combustion, zone of water inputting, atomizing and intensive vaporizing, zone of the main combustion metal particles in water vapor until complete combustion.

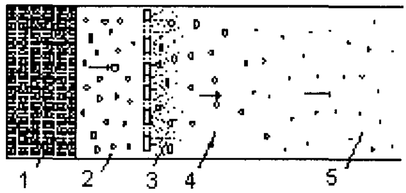

Fig. 4 Combustion hydro reactive propellant
1 - solid propellant.
2 - zone of ignition particles.
3 - zone water inputting, atomization, evaporation.
4 - zone combustion metal particles in vapor water.
5 - zone complete combustion.

For the basic contents of the hydro reactive solid propellant double based mixture containing the active metal Mg or Al and pyrotechnic oxidizer is more applicable. And the more efficient hydro reactive solid propellant contains more active metal as possible for its combustion operation.

Among pyrotechnic oxidizers that can be used in hydro reactive fuels with metal may be chlorates ($KClO_3$, $NaClO_3$), per chlorates (NH_4ClO_4, $KClO_4$, $NaClO_4$), nitrates ($NaNO_3$, KNO_3, $Ba(NO_3)_2$, $Sr(NO_3)_2$). These oxidizers with their main properties are presented in Table 3, where theoretical equation decomposition of salt oxidizer, the melting temperature Tm (℃) and decomposition temperature (in brackets) Td (℃), the share of active oxidizer and comments about these salts(column C), where

H- mean humidity, S- sensitivity, N- difficult for igniting are presented.

But for practical utilization these oxidizer properties as humidity and sensitivity to impact make some variants of these oxidizers are difficult for fuel producing and exploitation.

The mixtures of metal with oxidizers $NaClO_3$ and $KClO_3$ are highly sensitive to mechanical impact, $NaClO_3$ is very hygroscopic and fuels with it are not reliable for long time conservation. $NaClO_4$ is hydroscopic and sensitive, $KClO_4$ is sensitive too. The nitrate $NaNO_3$ is hydroscopic. The mixtures of metal with NH_4NO_3 are difficult for ignition and combustion at pressure 1-100 atm.

So the more applicable as oxidizer for hydro reactive fuels with metal are NH_4ClO_4, KNO_3, $Ba(NO_3)_2$ and $Sr(NO_3)_2$. But $Ba(NO_3)_2$ and $Sr(NO_3)_2$ are more expensive for common appliance for solid hydro reactive propellant.

Table 3. Properties of Oxidizers for Hydro reactive fuels

Oxidizer	Ideal reaction of oxygen generation	T_m,(T_d) ℃	% O2	C
$NaClO_3$	2NaClO3 → 2NaCl+3O2	263 (~465)	45	H S
$KClO_3$	2KClO3 → 2KCl+3O2	357 (~470)	39	S
NH_4ClO_4	2NH4ClO4 → N2+4H2+Cl2+4O2	270 (~480)	85	
NaClO4	NaClO4 → NaCl+2O2	480 (~480)	52	H S
KClO4	KClO4 → KCl+2O2	570 (~580)	46	S
NH4NO3	2NH4NO3 → 2N2+4H2+3O2	170 (~270)	60	N
NaNO3	4NaNO3 → 2Na2O+2N2+5O2	308 ~600	47	H
KNO3	4KNO3 → 2K2O+2N2+5O2	336 (~700)	40	
Sr(NO3)2	2Sr(NO3)2 → 2SrO+2N2+5O2	650 (~600)	38	
Ba(NO3)2	2Ba(NO3)2 → 2BaO+2N2+5O2	592 (~600)	30	

5. Contents of hydro reactive fuels

Hydro reactive propellants having more metal in his contents must be reliably ignited and burned in self sustained mode. The main problem for the hydro reactive solid propellant is amount of powder metal can it contain that can blow to gas and ignite reliably for burning in cloud of water droplets.

The content of metal fuel in double based hydro reactive fuel is answered to next conditions:

1. Geometrical condition.

The oxidizer share may be enough for organizing the cloud of burning metal particles separated one from other for distance that did not allow its contact and conjunction.

2.Thermodynamic condition.

The heat of reaction must be enough for igniting all metal particles and vaporization water for beginning combustion in vapor water. The heating of cloud burning metal particles and gas products must be enough that vaporizing water can not quench the particles burning.

According the geometrical conditions the distance L_{pg} between burning and boiling particles can be estimated by equation: $L_{pg} \approx 25 * d_p \sqrt[3]{n_{gg} * \rho_m * \frac{(\alpha_f - 1)}{\alpha_f} \frac{T_{com}}{T_{S0}} \frac{p_{S0}}{p_{com}}}$ where d_p - diameter of metal particle; α_f - the share of metal component n_{gg} - amount of gas product (cm3) for combustion of 1 gram stoichiometric metal-oxide mixture; ρ_m - metal density, T_{com} - temperature of products, p_{com} - pressure in combustion chamber; T_{S0} =298 K; p_{S0} = 105 Pa. For geometrical condition the distance between particles may be $L_{pg} \geq (2-3)d_p$.

For thermodynamic conditions if the water input balances combustion of metal then there are no problems for heat consumption from the combustion to evaporation. The results of estimations for determination of possible metal contents in double base hydro reactive propellant are given in Table 4 with the parameters for double based mixture oxidizer-metal: the stoichiometric content of metal, metal share possible for combustion with burning ~0.1 part of metal, the metal share for the distance between particles Lpg~3dp, recommended contents of metal and oxidizer balance (OB) for these recommended double based mixtures. The oxidizer balance is negative as the hydro reactive solid propellant is more reach by fuel - metal.

Table 4. Parameters of double based hydro reactive propellant

Content	Sth. met	Metal share possib comb	Metal share Lpg~3dp	Metal share recom.	OB (%)
NH4ClO4 + Al	0.41	0.75	0.72	~0.75	-75
KNO3 + Al	0.35	0.63	0.66	~0.6	-50
Ba(NO3)2 + Al	0.26	0.61	0.55	~0.6	-50
NH4ClO4 + Mg	0.48	0.83	0.55	~0.7	-40
KNO3 + Mg	0.42	0.68	0.57	~0.7	-40
Ba(NO3)2 + Mg	0.32	0.7	0.4	~0.6	-30

So the double metal hydro reactive solid propellant contents ~0.6-0.7 metal component by mass. But it is only recommendation and real contents must be determined in experimental testing.

The real hydro reactive solid propellants includes many other small additives for good solidification of propellant charge, catalyze or inhibitor for regulation of burning velocity and conservative additives. Amounts of these additives are no more then 1-5% by weight and can not influence strongly on the main thermodynamic properties of the fuels.

6. Combustion chamber of underwater ramjet engine

The typical construction of the rocket chamber for combustion of hydro reactive solid propellant for underwater torpedo is shown on Fig. 5.

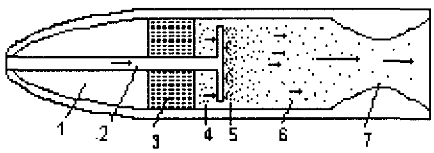

Fig. 5 Combustion chamber of water breathed ram jet for burning of hydro reactive propellant 1 - load, 2 - water channel, 3 - solid propellant, 4 - zone of ignition, 5 - zone of water input evaporation, 6 - zone of burning particles in vapor, 7 - nozzle

According to the burning processes in combustion chamber for combustion processes three zones exist.

The first zone is the zone of initial burning of hydro reactive fuel with ignition and partly burning of metal particles, then follows the second zone of atomizing and evaporating of input water with beginning combustion of metal particles in water vapor and then continues the third zone of complete combustion of metal particles that in ideal case has finished before entry in the nozzle part. And the combustion products came out from nozzle with producing of reactive thrust. The length of the first zone is small, the length of the second zone is more and depends on the processes of water spray atomization and the length of third zone is more too and depends on intensity of combustion processes of moving cloud burning particles of active metal. All these stages are related and continuously transform each other along the chamber.

7. Processes in combustion chamber for underwater ramjet engine

For process in combustion chamber the main parameter is the time of complete combustion. This time can be determined for Mg and (as the first approximation) for particles of Al by Spoulding theory of diffusion combustion of boiling drops [9,10].

The time of complete particle burning t_{com} estimated by equations $t_{com}=\frac{d_p^2}{K_{com}}$

$$K_{com}=\frac{k_g}{\rho_l c_p}\ln(1+\frac{c_p*(T_{env}-T_S)+h_{reac}}{h_l})$$

where K_{com} - burning rate constant, d_p-particle diameter, k_g - gas thermal conductivity; h_l-latent heat of vaporization, ρ_l- density of liquid droplets, c_p - heat capacity of gas phase, T_{env}-temperature of media, T_S- surface temperature of boiling droplet, h_{reac}-heat combustion per unit mass of fuel, ν- oxidizer to fuel weight stoichiometric ratio. Results of estimations were obtained for Mg in water vapor K_{com} ~0.57*10-2 cm2/s and for aluminum K_{com} ~0.78*10-2 cm2/s. The times of complete combustion for Mg and Al particles in water vapor in dependence on diameter particle are presented on Figure 6.

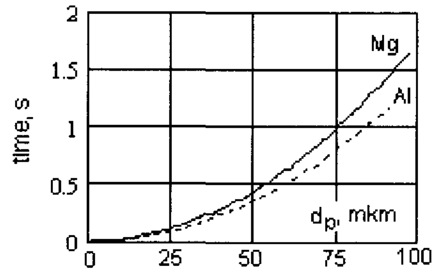

Fig. 6 Burning time for Mg(line) and Al(dot line) droplets in water vapor in depend on diameter

Times for diameters of particles in the range 20-50 mkm are ~ 0.3-0.5 s.

These calculations have been made for ideal case of spherical droplet burning in a stagnant medium [19]. For the case of moving droplets the time of combustion was decreased by our estimations no more then 3 times.

Another main process is water vaporization. The time of full water droplet evaporation depends on the diameter of droplet by Spoulding theory [9] and can be estimated by equation: $t_{vap}=\frac{d_w^2}{K_{vap}}$ $K_{vap}=\frac{8*k_{gw}}{\rho_{lw}c_w}*\ln(1+B_{hw})$

$$B_{hw}=\frac{c_w*(T_{env}-T_{wb})}{h_{fw}}$$

where t_{vap}-time of full evaporation of droplet with diameter d_w ; K_{vap}-evaporation constant , B_{hw} - transfer number, ρ_{lw} - water density, c_w- heat capacity of water vapor, k_{gw}-heat conductivity of water vapor and h_{fw}- latent heat vaporization of water. The results of calculations of time water droplet vaporization present on Figure 7.

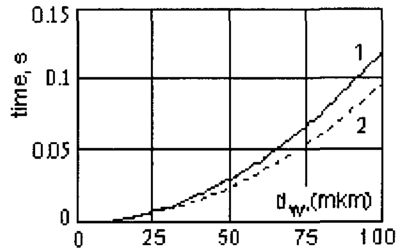

Fig. 7 Dependence time evaporation water droplets in gas products of metal particles combustion on droplets diameter d_w

1 - temperature gas products 2000℃ (line)

2 - temperature gas products 3000℃ (dot line)

These results have shown that droplets of water with diameter ~ 100 mkm evaporated very quickly for time ~0.1s.

Time of full metal particle combustion and time of water droplet vaporization must be compared with time residence in combustion chamber.

The average time residence for case of linear gas motion can be estimated by the net system of equations: $\tau_{res} = \frac{L_{ch}}{\overline{U}_g}$ $\overline{U}_g = \frac{\dot{m}_f}{S_{ch} * \overline{\rho}_g}$ $\overline{\rho}_g = \frac{p_{ch} * \overline{M}_g}{R * \overline{T}_g}$ where τ_{res} - time residence in combustion chamber; L_{ch} - length of combustion chamber, S_{ch} -area of cross-section of combustion chamber, $\overline{\rho}_g$ - average density of gas products, $\overline{M}_g$ - average gas density, $\overline{T}_g$ -average product temperature R =8.31 J/(g-mole*K).

Time of residence for linear gas products moving for length of chamber 3-4 m and diameter ~0.4 m equal ~ 1 s, that more then time evaporation of small water droplets (~0.1 s) and full combustion of metal (Mg or Al) particles (~ 0.5 s), so it is enough for complete combustion of hydro reactive metal containing fuel.

For analyzing combustion processes in chamber the full mass burning velocity must be determined. This full mass burning velocity consists from the mass of burning metal and mass of water inputting and can be determined from equation of reactive thrust: $F_{thr} = I_s * g * \dot{m}_f = V_g * \dot{m}_f$

Table 5. Mass burning velocity for rocket chamber with thrust 3*104 N

Metal	β	$\dot{m}_f$, kg/s	$\dot{m}_m$, kg/s	$\dot{m}_w$, kg/s
Mg	0.75	8.3	4.73	3.57
Al	0.5	6.0	3	3.0
Zr	0.4	8.7	6.2	2.5
Li	1.29	12.5	5.46	7.04

For variant of torpedo "Sqwall" with force thrust F_{thr} =3*104 N we obtain for metal used for combustion in water the data in table 5. There are given : β - ratio of mass water and mass of metal for stoichiometric combustion, $\dot{m}_f$ - the full mass burning velocity, $\dot{m}_m$ - mass velocity of metal component, $\dot{m}_w$ - mass velocity of water input. The results of table 5 shows that metal Mg and Al have the better parameters for component of hydro reactive solid propellant as needed less weight of solid propellant for making the same reactive thrust.

8. Discussion

The consideration of basic problems for hydro reactive solid propellant has shown the possibility to design the underwater ramjet engine with parameters more near to the underwater torpedo "Shqual".

In general the hydro reactive solid propellant solved two problems - the supply of metal particles of the combustion zone and igniting these particles.

We discussed here the basic principle and concepts for the hydro reactive solid propellant. But for design of the real construction of underwater ramjet engine the problem will be interesting to study:

1. optimal content of hydro reactive solid propellant with applicable level and pressure law of linear combustion velocity in chamber of rocket engine;
2. design the system of water input in chamber including the water scoop and water atomizing system optimal for water input in combustion chamber;
3. design of the optimal construction combustion.

The practical design of these problems can be done in many variants and depends on the aim, parameters of future high speed underwater carrier.

The material, that are presented in this paper demonstrates the background of the one of the main key problem - the hydro reactive solid propellant that can be used for general modeling calculations of ramjet underwater carrier.

9. Conclusions

The modern hydro reactive solid propellants applied for the water breathed ramjet engine of underwater high speed torpedo mainly uses basic fuel component the active metals Al and Mg in the form of powder particles containing in the hydro reactive solid propellant. The thermodynamic analysis and analysis of ignition-combustion properties shows the basic specific properties of metal components for combustion in ramjet engine. Mg is very easily ignited and burned in gas phase by diffusion mechanism Al is more difficult for ignition for the reason of the protective properties of its oxidizer film covered the particle surface.

The contents of the hydro reactive fuel must be included the usual pyrotechnic oxidizers (more preferable KNO_3, NH_4NO_3, $Ba(NO_3)_2$) that organize at its combustion the cloud of metal particles and igniting for the following combustion in vapor of abroad water. The contents of metal and oxidizer components that enough for reliable ignition and the following effective combustion and water evaporation have been determined by the geometrical conditions of metal particles combustion and share of metal in the hydro reactive fuel equal ~0.6-0.7 by weight.

The calculation of the times of water droplets evaporation and the times of metal particles combustion for average particle sizes in the range ~100 mkm shows that these times are less than the average time residence of reacting products in the combustion chamber of underwater ramjet with length corresponding to the sizes of typical underwater torpedo ~2-4m.

The results presented in this report are interesting for understanding the combustion processes in the water breathed ram jet engine and may be useful for designing of new variants of hydro reactive solid propellant for underwater water breathed ramjet engine.

References

1. Satton, G., P., Ross, D.,M., Rocket Propulsion Elements. An Introduction to Rocket Engineering. John Wiley&Sons Intern., USA,1976.
2. Roy, G., Propulsion Combustion. Fuels to Emissions. Combustion International Series. New York. 1972.
3. Wilson, J., Concrete Submarine. Popular Mechanics, December, 1998.
4. Shakhidzhanov, E.,S., Region Enterprise: Expert in High Precision Guide Weapons. Military Parade. Issue 33, May-June, 1999.
5. Litovkin, D., STORM of inevitable retaliating. Journal Voennoe Znanie. (11), 1996. (in Russian).
6. Kuo, K., K., Principle of Combustion. John Wiley & Sons, New York, 1986.
7. Shidlovskiy, A., A., Pyrotechnic. Mashinostroenie, Moscow, 1973.
8. Ellern, h., E., Military and Civilian Pyrotechnic. Chemical Publishing Company Inc., 1968.
9. Spaulding, D., B., Combustion and Mass Transfer. Pergamon Press, Oxford New York, 1979.
10. Turns, S.,R., An Introduction to Combustion Concepts and Application. Mc.Graw-Hill International Edition, 2000.