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Development of the Small-Size Air-Independent Power Station on the Basis of the High-Metallized Gas-Free Fuel

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Abstract. In this paper the experimental results of compact air-independent engine test for underwater object are presented. The proposed engine exploit a combustion of gas-free metallized fuel from the bulk solid state. The usage of solid-state fuel reduces its cost, facilitates the storage and refuel operation, increases fuel mass density and safety. In the proposed setup the main combustible is aluminum, the main oxidant is oxygen, though the secondary oxidants (the oxides of other more inert metals) could reduce the required oxygen volume aboard.

1. Introduction

The first system for air ventilation inside the submarine was a snorkel, which was first proposed in 1578 by English scientist William Bourne. One of the first submarines equipped with a snorkel was the Argonaut built in 1897. The snorkel herewith provided the air renewal only at periscope depth. Therefore, since the first submarines were created, various types of “single propulsion systems” (intended for both surface and underwater propulsion) were proposed to extend the range of the underwater propulsion. So in 1901-1905, the Frenchman Georg F. Jaubert patented several variants of a closed-cycle propulsion plant, including systems using pure oxygen. In 1902, the construction of the Q37 (Y) submarine with a closed-cycle internal combustion engine began as per his design. In the Russian Empire S. K. Dzhevetsky designed the submarine with gasoline engines used as a single propulsion system [1 - 3].

Since the 1920s the Soviet Union and Germany started active research in “single propulsion systems”, several submarine prototypes were designed before the end of the Second World War. In the USSR in the 1960s a series of A615 submarines (29 units) equipped with a single propulsion system with soda lime was built. To date, this is the largest series of AIP (air-independent propulsion) submarines. However, the development of nuclear power plants for submarines had stopped active implementation of AIP. Undoubtedly, nuclear submarines have the maximum underwater endurance, but despite all the undeniable advantages of nuclear power plants (including radioisotope thermoelectric generators), they are expensive not only in terms of construction and operation, but also in terms of creating an infrastructure for servicing and disposing nuclear power plants [3 - 5].

Therefore, currently a number of countries are developing AIPs based on closed-cycle diesel, steam and gas turbine generating systems, fuel cells and external combustion engines employing the Stirling cycle or cycles close to it. The most common AIPs are units fueled by hydrogen or hydrocarbons. In most cases, the oxidizer is oxygen [5 - 9].



It should be noted that the hydrocarbon fuel combustion products under normal conditions are gases and condensed water that need to be disposed of. Units for the combustion product recovery (freezing out, chemical absorption, etc.) require more space or more energy to remove combustion products overboard. So, the mass of the chemical absorber on the A615 submarine was 14.9 tons, with an oxygen mass of 8.5 tons [3]

Also, highly-metallized fuel plants have been developed, but only small power plants were actually used. Almost all developed highly-metallized fuel plants use a mixture of fuel and granular oxidizer. However, only small power plants were implemented in practice, in particular, hydroreactive-fuel aerial rocket torpedoes RAT-52, with hydrojet engine VA-111, Mk.50 Advanced Lightweight Torpedoes, etc. Thus, according to [4], the power consumption of "Stirling engine – heat accumulator" system with heat-accumulating substance Al_2O_3 is 8 times higher compared to that of classical "lead-acid battery – motor" system.

Practically speaking, aluminum is the best fuel option, because it is relatively cheap, safe to handle when monolithic at room temperature, its on-board stock is more compact in comparison with hydrocarbon fuels. At the same time, the calorific value of aluminum per kilogram of combustion products is 1.2 - 1.6 times higher than that of hydrocarbon fuel, due to a lower oxidizer consumption per 1 kg of fuel and the lack of disposal systems (Table 1) [11 - 13].

Table 1. Properties of the fuel and oxidizers used.

Properties of the fuel and oxidizers	Fuel/oxidizer		
	aluminum/oxygen	aluminum/iron oxide	hydrocarbon fuel/oxygen
Calorific value, kJ, per 1 g of the fuel	31.04	15.81	42.7
Oxidizer consumption per 1 g of the fuel	0.89	2.96	3.33
Calorific value, kJ, per 1 g of combustion products	16.43	3.99	9.86
Specific weight of systems for storing, evaporating and feeding the oxidizer, g/g of oxidizer	0.1 – 1	0 (the oxidizer is mixed mechanically with the fuel)	0.1 – 1
Calorific value, kJ, per 1 g of combustion products plus oxidizer storage systems	11.17 – 15.68	3.99	5.57 – 9.16

The fundamental novelty of this project is the combustion of monolithic highly-metallized fuel. The use of monolithic fuel reduces its cost, simplifies storage and recharging, increases specific gravity and provides safety. The main fuel in the plant developed is aluminum, the main oxidizer is oxygen, while the secondary oxidizer (oxides of less active metals) allows to reduce the required volume of on-board oxygen. At the same time, by changing the oxidizer (oxygen) feed rate, it is possible to control the heat release, and the combustion reaction can be terminated when the oxygen delivery stops, which cannot be done in power plants based on the thermite mixture combustion.

2. Practical part

For practical verification of theoretical computations, a test stand was built, where the heat generation of a single fuel element (FE) was investigated, including the burning of a fuel block, including ignition, melting and burning of the fuel block, a decrease in the oxidizer consumption, and a temporary and complete oxidizer cutoff.

Based on the results of tests without a secondary oxidizer by determining the boundaries of the combustion-melting zone with the discharge of the fuel melt and combustion products, and their chilling with inert gas it was established that the form of the combustion zone is close to a ball with a diameter close to that of the element. The diameter of the cone base and its height depend mainly on the gas feed rate (Fig. 1).

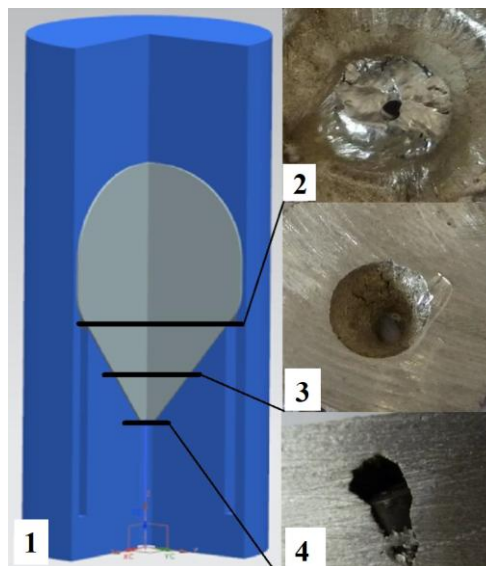


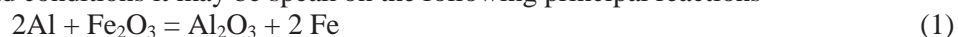
Figure 1. Example of tests for combustion of a highly-metallized element: 1—a diagram of FE combustion; 2—the upper part of the conical combustion zone; 3—the conical end; 4 – the nozzle end.

It is found that combustion of the fuel block is significantly different from combustion of single particles, the mathematical model thereof is described in the literature [11 - 16]. Melt overheating during combustion leads to the boiling of aluminum and its breakthrough through the layer of aluminum oxide in the conical end above the nozzle, i.e. metal combustion goes into the gas phase. This effect was previously confirmed experimentally and described in the literature. It follows that the propagation of the block combustion front differs significantly from thermite mixture combustion. The essential limitation is the presence of the following conditions.

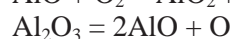
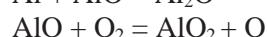
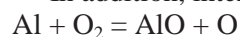
1. Heating of the metal block for sustainable combustion. It is conventionally assumed that the amount of transferred energy is proportional to the cross-sectional area of the fuel element (in particular, to the radius squared). Failure to meet this condition leads to incomplete combustion of the fuel or termination of the reaction.

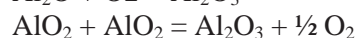
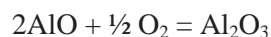
2. Heat transfer to coolants. In this case, the amount of heat dissipation proportional to the area of the heated part of the fuel element, proportional to the first-degree fuel radius, must be within certain limits. The failure to provide this condition leads to burning and distorting the geometry of fuel elements or incomplete combustion of fuel, which can also be accompanied by distortion of the geometry and / or breakthrough of oxygen into the coolant.

Under the test stand conditions it may be speak on the following principal reactions



In addition, intermediate reactions of aluminum oxidation are possible





In this case, the reaction (1) occurs in a charge intended for preheating, and the released heat is initially used for heating, melting and overheating of the fuel. Later it occurs in the zone of the secondary oxidizer channel providing more complete combustion near FE walls. The reaction (2) is the main one, and its heat is used for heating, melting and overheating of the fuel during the entire combustion cycle. As shown below, the reaction (3) proceeds with a decrease in the oxidizer feed rate, with aluminum and iron melts forming an intermetallic compound.

When this system operates, there is a significant limitation of the oxidizer feed— in the event of a prolonged oxidizer cut off, the fuel melt and combustion products enter the oxidizer channel and crystallizes in a while, which makes it impossible to continue work. Therefore, it is necessary to constantly maintain the oxidizer feed pressure, not less than the hydrostatic pressure of the fuel melt and combustion products. At the same time, the oxidizer consumption may be insignificant and be determined by the heat losses in the system. However, the reduced consumption of the oxidizer (oxygen) causes the cone end of the combustion zone to decrease, while the temperature of the nozzle end rises, and its intense burning occurs, the combustion zone moves down faster than in the case of a developed jet stream, and incomplete fuel combustion takes place.

The tests showed that the oxidizer cut off makes the heat release caused only by the interaction of the fuel with the secondary oxidizer stop after a while. Figure 2 shows pictures of the crystallized combustion front in the channels filled with fine (less than 5 μm) or coarse oxide particles.

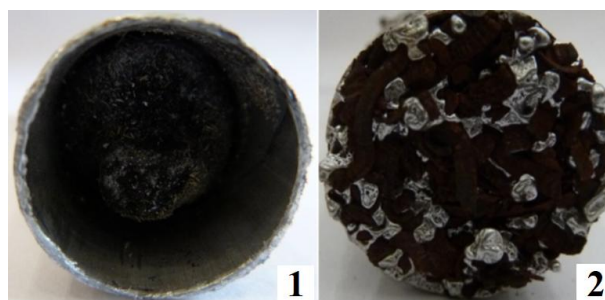


Figure 2. Crystallization of the combustion front of the melt in the secondary oxidizer channel: 1—the channel filled with fine secondary oxidizer particles after combustion termination; 2—the channel filled with coarse secondary oxidizer particles after combustion termination.

The surface temperature of the fuel element being developed at the design operation parameters should not exceed the melting temperature of aluminum, or when using a protection sleeve, the melting temperature of the material it was made of.

In the case of a design-basis accident (the rupture of a pipeline feeding the coolant to the steam generator and cutting off the oxygen feed to the fuel element), the surface temperature of the steam generator should not exceed the melting temperature of the steam generator material. A beyond-design-basis accident is the complete melting of a heat accumulator body and a steam generator housing, while the melt is held by thermal insulation and an external metal duct. It should be noted that the amount of secondary oxidizer in the FE should exclude ignition and self-propagating combustion.

Figure 3 shows an example of partial melting FE without a protection sleeve, the arrow indicates a burn at the joint of the steam generator sections, the zone with insufficient heat removal.

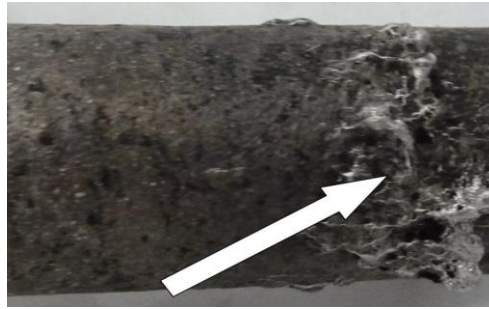


Figure 3. Burned FE, the arrow points to a burn at the joint of the steam generator sections.



Figure 4. Results of simulation of accidental destruction of a fuel element with a protection sleeve.

The protection sleeve allows to increase the temperature of the outer FE surface, however, the potential specific energy of FE is reduced. Fig. 4 shows an example of testing a fuel element with simulation of a beyond-design-basis accident – a complete and sudden loss of a coolant with the continuous oxidizer feed. In the course of the experiment, the oxidizer was fed normally for 20 minutes, and heat was removed from the FE surface, while the temperature of the FE surface was maintained at 700-800°C by a change in the coolant feed. The combustion zone reached approximately the middle of the fuel element. After that, the coolant feed was cut off, and, as a result, the FE temperature of reached 1200°C within 5 minutes, and the FE wall was destroyed with the fuel and combustion products entering the coolant feed channel. At the same time, the fuel, combustion products and protection sleeve elements were caught by the tray, and the FE was removed normally.

3. Conclusion

The research conducted has evidenced feasibility of combustion of a gas-free fuel block with development of heat. Test beyond-design-basis accidents showed the possibility of localizing the consequences of an accident.

Analysis of the options for thermal-to-mechanical energy conversion has shown that at present only the use of a turbine-generator is feasible. The external combustion engine (Stirling engine) was invented before the internal combustion engine, and currently Stirling engines are used in various fields, including in submarines as air-independent propulsion. However, in Russia, these engines are not commonly used, although they are offered by various companies.

Therefore, as the variants of a power generator, two main options are being elaborated: the use of a high-temperature steam turbine and a steam-turbine plant with a low-boiling coolant. ORC is an example of a condensing cycle using a mixture of organic compounds instead of steam. The advantage of this cycle is that at a temperature of about 200-300°C, the working medium is kept liquid at a pressure lower than that of water. ORC turbines can have a higher internal efficiency ($\eta_{oi} = 0.85$) than steam turbines with power of less than 1.5 MW ($\eta_{oi} = 0.75$) [8, 9].

The choice of ORC is also conditioned by the fact that after the end of combustion, the fuel cell acts as a heat accumulator. In particular, the specific heat capacity of aluminum oxide is about 830-

1000 J/(mol*K) at 20-500°C, or about 0.27 W/(kg*K), which allows for additional heat removal. This is comparable to lead-acid batteries with a specific energy of 30-60 W*h/kg.

Power plants for small-sized underwater facilities, including rescue vehicles, and emergency life support equipment for divers are a promising area for implementing this project.

4. References

- [1] Laudeuf M, Stroh H 1923 *Sous-marins* (Paris)
- [2] Moller E 2004 *The encyclopedia of U-boats: from 1904 to present day* (London: Greenhill Books)
- [3] Shirokorad A B 1997 *Soviet submarines of post-war construction* (M. Arsenal)
- [4] Kormilitsin Yu N, Halizev O A 2009 *Device of submarines* (SPb.: Elmor)
- [5] Dyadik A N 2016 *Ship airindependent power stations* (SPb.: Shipbuilding)
- [6] Zamukov V V, Sidorenkov D V 2012 Choice of the airindependent power station of not nuclear submarines *Shipbuilding* chapter 4 pp 29-33
- [7] Psoma A, Sattler G 2002 Fuel cell systems for submarines: from the first idea to serial production *Journal of Power Sources* 106 pp 381-383
- [8] Valero J 2013 Submarinos S-80 para la Armada Espanola *Fuerza Naval* 4 pp 72-79
- [9] Dmitriyev A L, Ikonnikov V K, Kirillov A I, Ryzhkin E A 2008 The independent combined power stations with fuel elements working at products of hydrothermal oxidation of aluminum *International scientific magazine "Alternativnaya Energetika I Ekologiya"* 11 pp 10-16
- [10] Yagodnikov D A 2009 *Ignition and burning of powdery metals* (M.: MSTU publishing house of N.E. Bauman)
- [11] Shidlovsky A A 1973 *Fundamentals of pyrotechnics* (M.: Mechanical engineering)
- [12] Udyama P G 1973 *Devices with submersible torches* (M.: Mechanical engineering)
- [13] Levenberg V D, Weaver M R, Golstr V A 1993 *Accumulation of heat* (Kiev.: Equipment)
- [14] Beksted M V, Liang U, Padduppakkam K V 2005 Mathematical modeling of burning of a single aluminum particle *Physics of burning and explosion* 6 pp 15 - 33
- [15] Kutepov A M, Sterman L S, Styushin N G 1986 *Gidrodinamika and heat exchange at steam formation* (M, Higher school)
- [16] Magaril R Z 1970 *Mechanism and kinetics of homogeneous thermal transformations of hydrocarbons* (M. Chemistry)

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