Optimization of the Working Cycle for an Underwater Propulsion System Based on Aluminium-Water Combustion

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Abstract. The working cycle of a novel underwater propulsion system based on aluminium combustion with water is researched in order to evaluate the best performance. The system exploits the exothermic reaction between aluminium and water which will produce high temperature, pressure steam and hydrogen mixture that can be used to drive turbine to generate power. Several new system configurations corresponding to different working cycles are investigated, and their performance parameters in terms of net power, energy density and global efficiency are discussed. The results of the system simulation show that using the recirculation steam rather than hydrogen as the carrier gas, the system net power, energy density and efficiency of the system are greatly increased compared, however the system performance is close either using adiabatic compression or isothermal compression. And if an evaporator component is added into system in order to take full use of the solid product heat, the system performance will be improved.

1. Introduction

As the world pays more attention to the ocean, unmanned underwater vehicle power technology has become an important field of scientific research [1,2]. To a certain extent, the traditional power battery and the lithium battery has been hardly to meet the future demand for power system, and the development of new fuel cell technology is not mature enough, especially in the transport and storage of hydrogen which is a big problem in the power system [3-7]. Especially in recent years, scholars have put forward the underwater propulsion system based on aluminium-water combustion such as HAC(Hybrid Aluminium Combustor) system[8-12] and HAC-SOFC(Hybrid Aluminium Combustor - Solid Oxide Fuel Cell) [13-14]. At the same time, the application of aluminium-water in power generation and hydrogen production are discussed [15-17]. All of these similarly system exploits the exothermic reaction between aluminium and steam to produces thermal power to driven turbine and hydrogen as a by-product of the reaction. According to the results of the performance [13], this system has the advantages of high energy density that can meet the demand of power system to a certain extent.

The present paper is focused on the development of some new underwater propulsion system based on the combustion of aluminium and water described in Ref. [13]. Because these system consists of fuel seeder system, combustor, compressor and turbine et al, so we can improve the system performance by increasing some other components or change the system component layout. However, there is no research reported about this section by now. Consequently, several kinds of new systems are investigated and the system performance such as system net power output, energy density and the
efficiency are researched respectively by means of the establishment of mathematical model of each system.

2. Propulsion System Concept

These six systems are named with System A, B, C, D, E, and F respectively. Figure 1 shows a simplified scheme of the System A which is more extensively described in Ref. [13]. It includes eight main elements: combustor, fuel feeder system, separator, compressor, turbine, recuperator, condenser and pump. The system consists of a fluidized bed fuel feeder in which aluminium powder is suspended by hydrogen. The Al and H₂ are injected into combustor where they will be mix and react exothermically with the recirculation steam to form Al₂O₃ and additional H₂. The second water (quenching water) injected along the combustor walls prevents molten alumina particles from attaching to the combustor walls and fouling the system. This quenching water also evaporates to produce large amounts of high-temperature steam. The combustion products pass through a cyclonic separator to remove the solid Al₂O₃. Two streams of steam/hydrogen mixture are separated from the splitter, in which the small one is mixed with quenching water and moved into the combustor through compressor to form recirculation steam for the sustain the reaction of the combustor, and the most rest steam/hydrogen mixture is used for driving the turbine work. The steam/hydrogen mixture moves into exchanger through the drive turbine for preheating the seawater. The steam is fully condensed into liquid water downstream from the heat exchanger, separated from H₂ and returns back into the intake system of seawater. A part of the H₂ is compressed into the fuel feeder system through the compressor to be reused as the carrier gas, and the rest with the excessive for compression storage or discharged.

Figure 1. The diagram of System A.

Figure 2 shows a simplified scheme of the System B which is modified on the basis of System A. First, the amount of water used to separate solid particles is increased. Second, considering that the power are mainly consumed by the hydrogen compressing in System A, so the hydrogen as a carrier gas is replaced by high-temperature steam, thereby the compression power is reduced. Last, the recirculation steam will be compressed first before mixed. A method of fluidized bed [8] is used in fuel seeder traditionally and it’s possible to achieve with high-temperature steam as the carrier gas in principle. However, on one hand, after use steam as carrier gas, aluminium and water are premixed which means that it could accelerate combustion, on the other hand, the duct thermal insulation and safety issues should be considered. There is no mention about the fuel seeder design in this paper.

Figure 3, Figure 4 shows System C and D diagram respectively. As we all know that the combustion of aluminium and water is difficult, especially with liquid water. So high-temperature steam is used in all of these systems. In order to ensure the efficiency of aluminium-water combustion, increasing the temperature of recirculation steam is considered in System A and B to obtain System C and D. The main improvement is that it will lead out high-temperature steam from the separator to enter into combustor and react as recirculation steam with aluminium under the compressor driving.
According to the results of reference, the mass fraction of the steam/hydrogen mixture return back to combustor from the separator is about 20%. On one hand, the power output of the turbine is reduced, on the other hand, a large amount of energy is consumed in order to compress the steam/hydrogen mixture back to the combustor. The performance of the system is reduced. Thus, an improved System E and F are put forward and respectively showed in Figure 5 and Figure 6. Compared to the previous System A, an evaporator and a solid heat exchanger component are added into these systems, and the high-temperature steam compressor is eliminated. The evaporator aims to cool water evaporated to slight superheated steam. The purpose of adding solid heat exchanger is using the high-temperature solid-phase products to turn the slightly superheated steam into the recirculation steam. However, combustion temperature needs to be improved in these systems.

3. Numerical Analysis
The performance calculation model of these six systems at present can be found in Ref. [13]. The global numerical model of each system is able to relate the system performance to the operating parameters, such as the aluminium mass flow, the water temperature, the water mass flow, the combustor pressure and temperature and the component efficiency. The thermo-fluid dynamics properties of hydrogen and steam are introduced in the numerical model according to the NIST database by means of lookup tables. An important feature of this model is that it can account for the phase change of the species as a function of the pressure and temperature variations. Because the combustor temperature is about 1200K and the combustor pressure is about 3MPa, the thermodynamic calculation software CEA result shows that the product after the reaction are alumina and hydrogen, other components are trace and negligible. Thus no chemical kinetics or surface reactions are included in the numerical model, and the heat release is calculated only in terms of the global aluminium-water reaction [15]:
$$2Al(s) + 3H_2O(g) \rightarrow Al_2O_3(s) + 2H_2(g) + 15152kJ / kg (T = 298.15; P = 1.0atm) \quad (1)$$

Suppose that the combustion chamber with external insulation, total enthalpy value before and after reaction is equal.

$$\sum_{j=1}^{n} \dot{m}_{i,r} (h^r_j + \int_{T_r}^{T} c_p dT) = \sum_{j=1}^{m} \dot{m}_{j,p} (h^r_j + \int_{T_r}^{T} c_p dT) \quad (2)$$

$\dot{m}_{i,r}$ is the mass flow of $i$th-reactant, $\dot{m}_{j,p}$ is the mass flow of $j$th-product, $h^r_j$ is the Standard enthalpy, $c_p$ is specific heat capacity, $T$ is the combustion temperature and $T_r$ is the reference temperature.

Suppose that there is no external heat exchange in the evaporator, and a mathematical model is

$$\dot{m}_{cold} (h_{in,cold} - h_{in,cold}) = \dot{m}_{hot} (h_{in,hot} - h_{in,hot}) \quad (3)$$

$\dot{m}_{cold}$ is the mass flow of cold side, $\dot{m}_{hot}$ is the mass flow of hot side, $h_{in,cold}$ is the outlet specific enthalpy of cold side, $h_{in,hot}$ is the inlet specific enthalpy of cold side. $h_{in,hot}$ is the inlet specific enthalpy of hot side and $h_{in,hot}$ is the outlet specific enthalpy of hot side.

Other components of the mathematical model and the calculation method of the component volume and mass can be found in Ref. [13]. The volume and mass of the evaporator refers to heat exchanger results.

In order to estimate the overall performance of the six systems, the net power can be expressed as:

$$\dot{W}_s = \dot{W}_{turb} - \dot{W}_{comp} - \dot{W}_{pump} \quad (4)$$

$$\dot{W}_{turb} = \dot{m} C_p T \eta_t \left[ 1 - PR \frac{\gamma - 1}{\gamma} \right] \quad (5)$$

$\dot{W}_s$ is the system net power, $\dot{W}_{turb}$ is the turbine power, $\dot{W}_{comp}$ is the compression power, $\dot{W}_{pump}$ is the pump power, $\dot{m}$ is the mass flow rate of turbine, $C_p$ is the hydrogen and steam mixture’s specific heat capacity, $\eta_t$ is the turbine efficiency, $PR$ is the turbine pressure ratio and $\gamma$ is the mixture’s ratio of specific heats. Because the hydrogen is overboard, hydrogen utilization is not considered here. The energy density $ED_v$ is defined as:

$$ED_v = \dot{W}_s \frac{\rho_{Al} V_{Al}}{\dot{m}_{Al} V_s} \quad (6)$$

$\rho_{Al}$ is the aluminium density, $\dot{m}_{Al}$ is the aluminium mass flow, $V_{Al}$ is the aluminium fuel total volume, $V_s$ is the system total volume ($V_s = 1000L$ see Ref.[13]), the aluminium fuel total volume: $V_{Al} = V_s - V_C$, $V_C$ is the component volume. On the condition of neutral buoyancy:

$$V_{Al} = \frac{\rho_{water} V_s - M_C}{\rho_{Al}} \quad (7)$$

$M_C$ is the component mass.

The overall system efficiency:

$$\eta_{sys} = \frac{\text{net power output}}{\text{chemical energy input}} = \frac{\dot{W}_s}{\dot{m}_{Al} \Delta H_{reac}} \quad (8)$$
is the volumetric energy content of reactants.

4. Results and discussion
The results are compared with the values of Ref. [13] and the results showed in Figure 7. The turbine power is slightly larger than the reference value, and the system net power is slightly less than the value in the reference. Under the condition of adiabatic compression, system net power slightly less than the reference value and under the condition of isothermal compression is greater than reference values. Combustion chamber temperatures were taken from the reference value, so the temperature value is basically the same. Mass flow calculation results are slightly lower than the reference value. The overall results are in good agreement with the reference results prove the accuracy of the model calculation.

Figure 7. Calculation and reference results.

Following, a detailed analysis of these six different systems would be introduced. According to the results from the reference, low pressure turbine ratio can improve the energy density of the system. Therefore, this paper assume turbine pressure ratio PR equal to 20. According to the new system using high temperature steam as the carrier gas, the hydrogen fuel feeder system will become less; therefore, this paper selects the seeding ratio with 10 when hydrogen is used as the carrier gas, consistent with the reference. Non-idealities in the combustion process are estimated by considering the combustion efficiency equal to 95% [15], which represents the effective oxidized amount of aluminium.

Table 1 shows the initial calculation conditions of the program [13], and Figure 8 to Figure 14 show the main results of each system.

| Table 1. System operating condition |
|------------------------------------|
| Operating parameters               | Value | Units |
| Combustor pressure                 | 2.76  | MPa   |
| Pump pressure                      | 4.0   | Mpa   |
| Hydrogen store pressure            | 4.8   | Mpa   |
| Combustor temperature              | 1150  | K     |
| Recirculation steam temperature    | 755   | K     |
| Sea water temperature              | 298.15| K     |
| Aluminum fuel                      | 17.6  | g/s   |
| Recirculation steam                | 17.6  | g/s   |
| Carrier hydrogen                   | 1.76  | g/s   |
| Turbine efficiency                 | 0.65  |       |
| Adiabatic efficiency               | 0.7   |       |
| Isothermal efficiency              | 0.7   |       |
Recuperator efficiency 0.5  
Condenser pressure ratio 0.9  
Recuperator pressure ratio 0.9  
Turbine pressure ratio 20  

Table 1 shows the initial calculation conditions of the programs[13], and Figure 8 to Figure 14 show the main results of each system.

Figure 8 shows that the turbine mass flow of System B, D and F are greater than System A, C and E. This result is due to System B, D and F using the recirculation steam replace hydrogen as the carrier gas which means much more quenching water could be injected into the combustor. Figure 9 shows that the distribution of the turbine power is C>A>E>D>B>F, and the largest difference is 8kW. Moreover the turbine power of System A, C, E is much bigger than system B, D, F but the power of System A, C and E are substantially equal, so as System B, D and F. According to the formula eq(5), the turbine power is related to the mass flow, turbine efficiency and the mixture property. Since System B, D and F using the recirculation steam replace hydrogen as the carrier gas, the mass fraction of hydrogen in turbine entrance is decreased. Because hydrogen’s specific heat capacity is several times higher than steam’s, relatively small changes in the hydrogen gas mass fraction can have a significant impact on $C_p$ of the mixture, so the mixture specific heat capacity is decreased. Although the mass flow is increased (shown in Figure 8), the turbine power is decreased still. Because the aluminum mass flow is equal (shown in table 1) and turbine inlet temperature is basically consistent (about 1100K), the turbine power of System B, D and F are substantially equal to each other, and similarly the same result for System A, C and E.

Figure 10 shows the net power of adiabatic compression and isothermal compression conditions of each system. Obviously, the net power of isothermal compression conditions is greater than adiabatic compression which is consistent with the results of Ref.[13]. under the condition of adiabatic compression, the net power distribution is F>B>D>E>A>C. The net power of System F is the maximum because it makes full use of the alumina heat and the net power of System C is the minimum because the consumption of compression power to compress the high-temperature circulation steam is large despite the fact that the turbine power is the largest (shown in Figure 9). It is

| Table 2. Hydrogen parameter distribution |
|----------------------------------------|
|                                      |
| Carrier gas(g/s) | A | 1.76 | 0 | B | 1.76 | 0 | C | 1.76 | 0 | D | 1.76 | 0 | E | 1.76 | 0 |
| Back to fuel feeder(g/s) | 1.7663 | 0.0063 | 1.7663 | 0.0063 | 1.7663 | 0.0063 |
| Overboard(g/s) | 1.8514 | 1.8514 | 1.8514 | 1.8514 | 1.8514 | 1.8514 |
| Adiabatic compression power(kW) | 20.3 | 0.8 | 20.3 | 0.8 | 20.3 | 0.8 |

Figure 8. Mass flow of turbine in for each system.  
Figure 9. Turbine power for each system.
interesting to notice that the system net power is greatly increased while using the recirculation steam to replace hydrogen as the carrier gas (such as System A and B, an increase of 42% approximately): this result is due to the mass flow of hydrogen which need to compress sharp decrease when using the recirculation steam as the carrier gas (shown in Table 2). Under the condition of isothermal compression, the net power distribution is also F>B>D>E>A>C and the difference of each system is significantly reduced compared to adiabatic compression: the reason is that the consumption power of isothermal compression is lower than adiabatic compression.

![Figure 10. Net power for each system.](image1)

![Figure 11. Energy density for each system.](image2)

![Figure 12. Aluminium fuel volume for each system in adiabatic compression.](image3)

According to the formula eq(6), the energy density is both related to the net power and aluminium fuel volume. Figure 10 illustrates the negatively buoyant energy density for each system. Under the condition showed in the figure, the energy density distribution is F>B>D>E>A>C. Such variation can be obtained from the net power (shown in Figure 10) and aluminium fuel volume (shown in Figure 12,
and decrease 10L respectively when using isothermal compression) of each system. Besides, the energy density of isothermal compression conditions is below adiabatic compression in System B, D and F. This result is due to an additional 10L volume of compressor for isothermal compression with the almost equal net power [13].

Figure 13 shows the total efficiency for each system during the present work. In the case of the constant aluminium mass flow, overall efficiency is proportional to the net power of system. The highest efficiency is System F (about 18.84%), the lowest is System C (about 13.07%), under two compression conditions.

![Figure 13. Total efficiency for each system.](image)

5. Conclusions

The performance of these six underwater propulsion system based on aluminium combustion with water has been researched. The results demonstrated that it is possible to improve significantly the energy density and efficiency of the proposed system by modifying the working cycle.
The net power of isothermal compression conditions is greater than that of adiabatic compression. In addition, the difference of each system in isothermal compression is significantly reduced compared to adiabatic compression, and the energy density of isothermal compression conditions is below adiabatic compression in System B, D and F.

In particular, according to the neutral-buoyancy energy densities, the energy density distribution is A>C>E when using hydrogen as carrier gas; system B, D and F are obtained a relatively high energy density after using the recirculation steam replace hydrogen as a carrier gas, and the highest energy density is achieved to 824Wh/L.

The results of present work implied that System B, D, E and F can improve the performance of the system compared with the original System A. However, the circulation steam temperature is increased in System C, and it’s conducive to the aluminium water combustion efficiency meanwhile the system performance decline slightly.

Although so far, there have not been related application examples or related experiments are reported, so the research of this paper is highly important. According to the calculation results, we are trying to solve a series of problems and complete the development of the system finally.

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