Exergy analysis of water cooling cycle system for scramjet engine

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Abstract. Thermal protection technology is one of the key technologies for scramjet engines. The traditional regenerative cooling technology using hydrocarbon fuel as coolant has some limitations, such as insufficient cooling capacity and easy pyrolysis coking. This paper presents a water cooling cycle system for scramjet engine based on the Rankine cycle, and introduces the system composition and working process. On the basis of the thermodynamic analysis, we have made the exergy analysis of each process and obtained the exergy loss and exergy efficiency. And the influence of the system operating parameters on the exergy loss and exergy efficiency has been analysed.

1. Introduction

Studies have shown that when the scramjet engine is flying at high Mach number, the total temperature of the combustion chamber can reach more than 3000K [1], which far exceeds the temperature resistance of the material of combustion chamber wall and will cause the engine deforming or even burning. Therefore, settling the thermal-production question of combustion chamber is a significant technology of the study and development of scramjet.

At present, there are mainly two methods used to realize thermal protection of scramjet engine: passive thermal protection and active thermal protection [2, 3]. The onefold passive thermal protection scheme is very demanding on the capability of materials [4]. It is not suitable for prolonged work or repeated use in the working conditions of the scramjet combustion chamber. Regenerative cooling technology applies the fuel as a coolant, and it has gained researcher’s prominence. The United States X-51A machine performed an regeneration cooling experiment using J-P7 hydrocarbon fuel as a coolant, and GDE-2 scramjet engine achieve combustion time 300s under the Mach 5 flight conditions [5].

Moreover, the flowing characteristics of kerosene in the supercritical state are complicated, and hydrocarbon fuel easily cracks and forms coking at a higher temperature, resulting in local heat-transfer deteriorating or even clogging the pipeline [6], which limits the maximum Mach number of the aircraft. Gascion et al. [7] studied the characteristics of pyrolysis and coking of hydrocarbon fuels under supercritical conditions and analyzed the effects of coking on the cooling effect and pressure loss.

However, with the limit of the thermal properties of fuel, there are lots of problems in the utilizations of regenerative cooling [8]. Under the basis of the thermal balance of regenerative cooling, researchers consider adopting heat collection processing or distribution processing. This thermal management system can indirectly improve the fuel heat sink and effectively improve the thermal protection system performance. Bowen et al [9, 10] designed a scramjet engine secondary cooling cycle system, using
high-temperature fuel to drive turbine work after decalescence through the engine wall, and the cooling fuel can cool the wall again. Qin et al. [11] analyzed the performance of RCC and introduced some thermodynamic parameters that characterize its performance. The results show that this open recirculation performance is superior to the traditional regenerative cooling technology. Wu Xianyu and Chen Xuefu [12, 13] proposed an expansion cycle scheme of ethylene-assisted start-up to transfer waste heat to other parts which requires energy.

Based on the theory of Rankine cycle, this paper constructs a water cooling cycle for scramjet engine. This system utilizes the heat flow of engine wall and converts it into electrical energy and preheats kerosene to achieve efficient energy utilization. This paper will also analyze the exergy of the cooling circulatory system, obtain the exergy loss and efficiency of each process, and study the effects of different operating parameters.

2. Working principle and thermodynamic analysis of water cooling cycle system

The cooling cycle system consists of four main parts: the engine cooling passage, the turbo expander, the condenser, and the water pump, which is shown in Figure 1. The specific working process is as follows. First, the circulating water enters the cooling channel and absorbs the heat flow of the engine wall. After absorbing heat, it vaporizes into the superheated steam. Then, the superheated steam pushes the blade through the expander to do work, and the rotating shaft of the blade is connected to generate electricity. The temperature and pressure of the steam will reduce. After that, the steam enters the condenser and exchanges heat with the cold kerosene. The water vapor condenses into liquid water. The preheated kerosene is injected into the combustion chamber. Finally, the circulating water flows into the engine cooling channel after being pressurized by the water pump to finish the next path. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper.

![Figure 1. Concept scheme of cooling cycle](image)

During the entire cycle, the circulating water absorbs huge heat from the wall of the engine. Through thermal cycling, heat is transferred from the high-temperature heat source to the low-temperature cold source, and the potential work between the heat source and the cold source is utilized. The turbine expander does work to drive the generator to generate electricity and realize the conversion of thermal energy into electrical energy. The generator can generate electrical power for use in water pumps and other electronic devices. The entire cooling cycle not only achieves cooling of the high-temperature wall, but also preheats kerosene fuel, and realizes waste heat power generation. The research value and significance are enormous.
The water cooling cycle system is designed based on the Rankine cycle. Figure 2 shows the operation of the cooling cycle system. It is divided into four-step thermodynamic processes: 1-2 is the isobaric endothermic process of water in the cooling channels; 2-3 is the adiabatic expansion process of superheated steam; 3-4 is the isobaric exothermic process of steam; 4-1 is the adiabatic compression process of water. Figure 3 is the T-s diagram of the cycle.

![Figure 2. Operation scheme of the water cooling cycle](image)

![Figure 3. T-s diagram of the cycle](image)

2.1. **Endothermic process in cooling channels**
The heat absorbed by the circulating water in the cooling channel is

\[ Q_1 = \dot{m}_w \cdot (h_2 - h_1) \]  

(1)

In the formula, Q1 is the heat to be absorbed of the engine; mw is the flow of the circulating water; h1 is the enthalpy of water at the inlet of the cooling channels; h2 is the enthalpy of the steam at the outlet of the cooling channels.

2.2. **Expansion in the turbine**
In the process of expansion, the reduced energy of the steam is Q2

\[ Q_2 = \dot{m}_w \cdot (h_2 - h_3) \]  

(2)
Then the power generated by the turbine expansion is calculated as the formula,

\[ W_t = \eta_t \cdot Q_2 \]  

(3)

in the formula, \( h_3 \) is the enthalpy of the steam at the outlet of the turboexpander. The expansion ratio of the circulatory system is defined as follows,

\[ \pi = p_2/p_3 \]  

(4)

2.3. Heat transfer process in the condenser

When the fuel coolant flow rate is \( \dot{m}_f \), the fuel coolant absorbs heat in the cryogenic heat exchanger can be expressed as the formula,

\[ Q_f = \dot{m}_f \cdot c_{pf} \cdot (T_{out} - T_{in}) \]  

(5)

During the cooling system, the heat absorbed by the fuel coolant is \( Q_3 \),

\[ Q_3 = \frac{Q_f}{\eta_e} \]  

(6)

And it can be expressed as

\[ Q_3 = \dot{m}_w \cdot (h_3 - h_4) \]  

(7)

In the formula, \( \eta_e \) is the heat exchange efficiency of the low-temperature heat exchanger.

2.4. Compression process in the pump

In the compression process, the energy of cycling water increases \( Q_4 \)

\[ Q_4 = \dot{m}_w \cdot (h_1 - h_4) \]  

(8)

The energy consumed in the compression process is calculated as follows,

\[ W_p = \frac{Q_4}{\eta_p} \]  

(9)

According to the Rankine cycle, the gas expansion causes the turbine to rotate to do work, and at the same time, the turbine feeds the water pump (compressor) through the coaxial rotation. The compression cycle fluid consumes a part of the work and the residual work outputs, and the useful power output of the cooling cycle system is calculated as

\[ W_{sys} = W_t - W_p = \dot{m}_w \cdot [(h_2 - h_3) - (h_1 - h_4)] \]  

(10)

Therefore, the energy conversion efficiency of the entire cooling cycle system is as follows,
3. Exergy analysis of water cooling cycle system

Due to the limitations of the scramjet engine's own environment and conditions, the quality of thermal energy in the process of energy transfer and conversion of the cooling cycle system is continuously reduced. In order to improve the output power and conversion efficiency of the system scheme, the exergy transfer model and the exergy loss model of the cooling circulatory system were established from the perspectives of heat transfer and thermodynamics, and the change of exergy of the different positions or components of the heat transfer and conversion process of the system were analyzed.

For a steady-state equilibrium thermodynamic system, ignoring the effects of kinetic energy and potential energy, the mass conservation and exergy balance equations can be expressed in each thermal process as

\[ \sum m_{\text{in}} = \sum m_{\text{out}} \]  \hspace{1cm} (12)

\[ Q + W = \sum m_{\text{out}} h_{\text{out}} - \sum m_{\text{in}} h_{\text{in}} \]  \hspace{1cm} (13)

\[ E_{x,Q} + W = \sum E_{\text{out}} - \sum E_{\text{in}} + I \]  \hspace{1cm} (14)

The “in” and “out” indicate the import and export of the selected thermal system. Q is the heat absorbed by the thermal system from the external environment. W is the work done by the external environment to the system. \( m \) is the mass flow rate of water. \( E \) is the exergy value, equal to \( ne \), where \( e = h - h_0 - T_0(s - s_0) \). In the formula, \( h_0, s_0 \) are the specific enthalpy and specific entropy of the circulating water at ambient temperature. \( T_0 \) is the ambient temperature. \( I \) is exergy loss. \( E_{x,Q} \) is the heat enthalpy, which is input by a heat source.

The following describes the exergy analysis method for the four processes of the cooling cycle, and gives the calculation formulas for the exergy loss and exergy efficiency.

3.1. Heat transfer process in cooling channels

1-2 thermal process is the absorption of heat from the engine wall by the working fluid, which ideally is an isobaric heat absorption process. The amount of exergy input into the system is the amount of heat exergy input to the wall of the engine \( E_H \), and the exergy change \( E_{1w} \) of the circulatory water is the difference amount of exergy between point 2 and point 1. The exergy balance equation during heat transfer can be expressed as

\[ E_H - E_{1w} - I_{\text{eva}} = 0 \]  \hspace{1cm} (15)

The exergy efficiency \( \eta_{e,eva} \) is as follows,

\[ \eta_{e,eva} = \frac{E_{1w}}{E_H} \]  \hspace{1cm} (16)

3.2. Expansion process in the turboexpander
2-3 is the expansion work process of the expander. The amount of exergy $E_{2w}$ input into the system is the exergy change of the circulating water. The exergy balance equation for the process is as follows,

$$E_{2w} - W_t - I_t = 0$$  \hspace{1cm} (17)

The exergy efficiency $\eta_{e,t}$ can be calculated as,

$$\eta_{e,t} = \frac{W_t}{E_{2w}}$$  \hspace{1cm} (18)

### 3.3. Heat exchange process in the condenser

3-4 is the isobaric heat release process. In the heat process, the input amount of exergy equals to the heat exergy $E_{3w}$ which is transferred into the condenser carried by the circulating water. The exergy change of the cold kerosene is $E_L$. The exergy balance equation for the process is as follows,

$$E_{3w} - E_L - I_{con} = 0$$  \hspace{1cm} (19)

The exergy efficiency $\eta_{e,con}$ of this process can be calculated as,

$$\eta_{e,con} = \frac{E_L}{E_{3w}}$$  \hspace{1cm} (20)

### 3.4. Compression process in the pump

The pump pressurizes the working medium to increase the pressure and consumes energy. The heat balance equation and the exergy balance equation for the 4-1 thermal process are as follows,

$$W_p = m_w(h_1 - h_4)$$  \hspace{1cm} (21)

$$E_{4w} + I_p - W_p = 0$$  \hspace{1cm} (22)

The exergy efficiency $\eta_{e,p}$ is calculated as,

$$\eta_{e,p} = \frac{E_{4w}}{W_p}$$  \hspace{1cm} (23)

### 3.5. Total exergy loss and exergy efficiency of the cooling cycle system

The total exergy loss of the cooling cycle is the sum of loss in each process. The total exergy loss of the cooling cycle is as follows,

$$I_{sys} = I_{eva} + I_t + I_{con} + I_p$$  \hspace{1cm} (24)

The total effective energy $E_{sys}$ of the cooling cycle system is as follows,

$$E_{sys} = E_H + W_p - I_{sys}$$  \hspace{1cm} (25)

The total exergy efficiency $\eta_{e,sys}$ of the cooling cycle is as follows,
\[ \eta_{e,sys} = \frac{E_{sys}}{E_H + W_p} = 1 - \frac{I_{sys}}{E_H + W_p} \] (26)

In the following, the calculation of the system is based on the actual conditions of a known scramjet engine combustion chamber. When the scramjet engine is working, the wall temperature can reach 2000K, which will seriously damage the engine. After regeneration cooling, the wall temperature can be reduced to 1000K. The heat to be absorbed in the combustion chamber is \( Q_1 = 609.7 \text{MW} \). The temperature and pressure of the cooling water at the inlet of the cooling channels are \( T_1 = 25^\circ\text{C}, p_1 = 6\text{MPa} \), and the temperature and pressure of the water vapor at the outlet of the cooling channels are \( T_2 = 700^\circ\text{C}, p_2 = 6\text{MPa} \). The value of water in a certain state is calculated using IAPWS-IF97 [14] software, and we can get that \( h_1 = 110.38 \text{kJ/kg}, h_2 = 3894.47 \text{kJ/kg} \), \( s_2 = 7.425 \text{kJ/kg/K} \). So the cooling water flow is as followed,

\[ \dot{m}_w = Q_1 / (h_2 - h_1) = 0.161 \text{kg/s} \]

We suppose that the adiabatic efficiency is \( \eta_t = 0.85 \), the expansion ratio is \( \pi = 3 \), and the specific heat ratio is \( r = 1.3 \), then the pressure of the water vapor at the outlet of the expander is \( p_3 = 2\text{MPa} \).

According to the formulas which are as followed,

\[ h_{3s} = \text{REFPROP}(p_3, s_{3s}) \] (27)

\[ h_3 = h_2 - (h_2 - h_{3s})\eta_t \] (28)

\[ T_3 = \text{REFPROP}(p_3, h_3) \] (29)

We can get the temperature of steam at the outlet of the turbine is \( T_3 = 790.18^\circ\text{K} \). The output power of the turbo expander is (ignoring the adiabatic efficiency of the expander)

\[ W_t \approx Q_2 = \dot{m}_w(h_2 - h_3) = 62.38 \text{kW} \]

Similarly, the pressure of water at the inlet of the pump is \( p_4 = 2\text{MPa} \), we set \( T_4 = 297.15^\circ\text{K} \), then the power consumption of the pump is as followed,

\[ W_p = \dot{m}_w(h_4 - h_3) = 1.29 \text{kW} \]

Because \( W_p < W_t \), the mechanical work generated by the turbine can meet the power consumption of the feed pump.

In the condenser, the value of heat release of water vapor \( Q_3 \) can be calculated as,

\[ Q_3 = \dot{m}_w(h_3 - h_4) = 548.61 \text{kJ} \]

Considering the heat transfer efficiency is \( \eta_{icon} = 0.8 \), the average constant-pressure specific heat of kerosene is \( C_{pf} = 2.6 \text{kJ/kg/K} \), the initial temperature of cold kerosene is \( T_{in} = 15^\circ\text{C} \), and the vaporization temperature of kerosene is \( T_{out} = 450^\circ\text{C} \), so the flow rate \( \dot{m}_f \) of kerosene is as followed,

\[ \dot{m}_f = \frac{Q_3\eta_{icon}}{C_{pf}(T_{out} - T_{in})} = 0.388 \text{kg/s} \]
Under the given initial conditions, with the designed cooling cycle, the matching of energy and power can be achieved. The heat absorbed from the wall of the combustion chamber can preheat the kerosene to vaporization temperature, and the mechanical work generated by the turbine can satisfy the work of the water supply pump. The whole cycle conditions are shown in Table 1.

After knowing the process parameters of the circulatory system, the physical properties of the working fluid at each state point were found and calculated by REFPROP software. The results are shown in Table 2.

Table 1. Parameters of the entire cycle

| $T_1$ [K] | $p_1$ [MPa] | $T_2$ [K] | $p_2$ [MPa] | $T_3$ [K] | $p_3$ [MPa] |
|-----------|-------------|-----------|-------------|-----------|-------------|
| 298.15    | 6           | 973.15    | 6           | 790.18    | 2           |
| $T_{in}$ [K] | $T_{out}$ [K] | $W_t$ [kW] | $W_p$ [kW] | $m_w$ [kg/s] | $m_f$ [kg/s] |
| 288.15    | 723.15      | 62.38     | 1.29        | 0.161     | 0.388       |

Table 2. Thermodynamic parameters at each state point of circulatory system

| $h_1$ [kJ/kg] | $h_2$ [kJ/kg] | $h_3$ [kJ/kg] | $h_4$ [kJ/kg] | $T_1$ [K] | $Q_2$ [kW] |
|---------------|---------------|---------------|---------------|-----------|------------|
| 110.38        | 3894.47       | 3507.13       | 102.39        | 1442.7    | 548.61     |
| $s_1$ [kJ/kg/K] | $s_2$ [kJ/kg/K] | $s_3$ [kJ/kg/K] | $s_4$ [kJ/kg/K] | $T_2$ [K] | $T_3$ [K] |
| 0.366         | 7.425         | 7.513         | 0.353         | 472.76    | 298.15     |

Based on the formulas for the exergy loss and exergy efficiency of each process, the exergy loss and efficiency of the components of the cooling cycle are calculated, as shown in Table 3. During the exergy transfer process, the exergy efficiency of each component was different. The exergy efficiency in the cooling channel, turbo expander, condenser, and water pump was 55.94%, 93.64%, 99.02%, and 51.64% respectively. It can be seen that the exergy efficiency of the high temperature heat transfer process and the pump compression process is relatively low.

Table 3. Exergy loss and exergy efficiency of each process

| Process                                    | Exergy loss [kW] | Exergy efficiency [%] | The proportion of process exergy loss to the total exergy loss [%] |
|--------------------------------------------|------------------|-----------------------|---------------------------------------------------------------|
| Heat transfer process in cooling channels  | 213.12           | 55.94                 | 96.88                                                         |
| Expansion work process in the turboexpander| 4.24             | 93.64                 | 1.93                                                          |
| Heat exchange process in the condenser     | 2.01             | 99.02                 | 0.91                                                          |
| Compression process in the pump            | 0.622            | 51.64                 | 0.28                                                          |
| The total cycle system                     | 219.98           | 53.35                 |                                                               |

4. Effect of circulatory system operating parameters on exergy loss and exergy efficiency

4.1. The influence of the maximum temperature of the working fluid during the cycle

Under the condition of satisfying the heat change requirements, the maximum temperature of the working fluid during the cycle is changed from 933.15K to 973.15K. The changes of exergy loss in the different thermal processes are shown in Figure 4. As the maximum temperature increases, the exergy loss in the cooling channel, the turbine expansion process, and the water pump compression process all decrease. However, the exergy loss in the condenser increases because the temperature of the fluid
entering the cryogenic heat exchanger increases as the maximum temperature increases, which causes the increase of the heat exchange temperature difference and the exergy loss.

Figure 4. Variation of exergy loss of different thermal processes under different maximum temperature during the cycle

The exergy efficiency of each thermal process is shown in Figure 5. The change of exergy efficiency of the turbo expander and the pump is very little and remains basically constant with the increase of the maximum operating temperature. The exergy efficiency in the heat transfer process of the cooling channels increases with the increase of the maximum operating temperature. However, the exergy efficiency of the condenser decreases as the maximum operating temperature increases.

Figure 5. Variation of exergy efficiency of different thermal processes under different maximum temperature during the cycle

4.2. Effect of expansion ratio

The different expansion ratios of the cooling circulatory system change the parameters of each state point, and then affect the exergy changes of each thermal process. Under the conditions of satisfying the heat exchange requirements, assuming that the expansion ratio of the cycle varies between 1.2 and 3.2, and the change of exergy loss in different process is shown in Figure 6. With the increase of the expansion ratio, the exergy loss in the heat exchange process of the cooling channels is almost unchanged, the exergy loss of the turbo expander is slightly increased, and the exergy loss in the condenser and the water pump is reduced. At the same time, the exergy loss in the condenser is reduced to a large extent, and the exergy loss in the pump is reduced to a small extent. In general, as the expansion ratio increases, the system exergy loss decreases. The exergy efficiency of each thermal process changes with the expansion ratio as shown in Figure 7. As the expansion ratio increases, the exergy efficiency changes in each process are as follows: the heat transfer process in the cooling channel is almost
unchanged, and the expansion in the expander decreases slightly. There is a significant increase in both the condenser and the pump.

![Graph](image-url)

**Figure 6.** Variation of exergy loss of different thermal processes under different expansion radio during the cycle

![Graph](image-url)

**Figure 7.** Variation of exergy efficiency of different thermal processes under different expansion radio during the cycle

### 4.3. The effect of the flow rate of cold kerosene

Cold kerosene absorbs the heat of water vapor in the condenser. The change of its flow rate affects the temperature of the cold source, and then affects the exergy change of the process. Under the condition of meeting the requirements of heat exchange, the flow rate of kerosene was changed from 0.5kg/s to 1.0kg/s. The calculations of the changes of exergy loss and exergy efficiency of the processes were shown in Figure 8. With the increase of the flow rate of kerosene, the exergy loss in the condenser increases significantly and the exergy efficiency decreases significantly, and other processes do not change significantly.

![Graph](image-url)

**Figure 8.** Variation of exergy loss and exergy efficiency of different thermal processes under different flow rate of cold kerosene during the cycle
4.4. Influence of ambient temperature

Ambient temperature is the reference point temperature in the exergy analysis process, and its change affects the calculation of the input exergy and the changes of exergy of the system, and then affects the exergy loss and exergy efficiency of each process. Under the condition of satisfying the heat exchange requirements, the ambient temperature is changed from 398.15K to 348.15K. The calculation of the changes of exergy loss and the exergy efficiency are shown in Figure 9 and Figure 10, respectively. With the increase of the ambient temperature, the exergy loss of all processes increase, and the exergy efficiency of all processes decreases.

![Figure 9. Variation of exergy loss of different thermal processes under different ambient temperature during the cycle](image1)

![Figure 10. Variation of exergy efficiency of different thermal processes under different ambient temperature during the cycle](image2)

5. Conclusion

This paper describes the composition and working principle of the water cooling cycle system of the scramjet engine. Based on the thermal analysis of the system, the exergy in various processes of the cooling cycle system are analyzed, and the exergy loss and exergy efficiency of each process are obtained. Furthermore, the influence of the cyclic operation parameters on the exergy loss and exergy efficiency of each process was analyzed, and the following conclusions were obtained.

- The biggest exergy loss is at the endothermic process in the cooling channels, which is caused by the huge heat exchange temperature difference;
- With the increase of the maximum temperature of the working fluid in the cycle, the exergy loss of the endothermic process in the cooling passages, the turboexpansion process, and the compression process is reduced, and the exergy efficiency is increased; the exergy loss in the condenser is increased, and the exergy efficiency is reduced.
- With the increase of the cyclic expansion ratio, the exergy loss of the turboexpansion process increases and the exergy efficiency decreases; the exergy loss of heat transfer process in the condenser...
and the compression process in the pump decreases, and the exergy efficiency increases; The exergy loss and exergy efficiency in the cooling channels is basically unchanged;

- With the increase of the flow rate of cold kerosene, only exergy loss of the heat exchange process in the condenser increases, and the exergy efficiency decreases; the other processes all remain basically unchanged;
- With the increase of the ambient temperature, the exergy loss of the four process all increases, and the exergy efficiency all decreases.

Under the guidance of the above conclusions, appropriate expansion ratio, lower ambient temperature, adjustment of the cooling channel configuration, etc., can be used to reduce the system damage and improve the cycle thermal efficiency.

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