Performance Simulation Analysis of Composite Thermal Management System for Hypersonic Vehicle

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Abstract. A hybrid thermal management system model of hypersonic vehicle with liquid hydrogen as heat sink and thermoelectric conversion of Brayton cycle was established. The cooling effect, fuel flow demand and thermoelectric conversion characteristics of the thermal management system in flight envelope were studied by numerical simulation. The results show that the cooling fuel demand of refrigerant loop is about 0.22 g/kW·s~0.24 g/kW·s, that of aerothermal cooling fuel is about 0.11 g/kW·s, and that of engine wall cooling fuel is about 0.08 g/kW·s. The flow rate of engine wall cooling fuel can be saved by 25%~40% during thermoelectric conversion. Thermoelectric conversion cycle efficiency and generation efficiency can reach up to 38% and 30%. When Mach number is 3.7~4.2 under the condition of large aerodynamic heat load, the flow rate required for engine combustion is not enough to meet the cooling flow rate, and the maximum difference is 10%.

1. Introduction

The liquid hydrogen fuel, as it has the characteristics of high energy content and low density, is the most ideal booster for the hypersonic vehicle in recent time[1]. The boiling point of liquid hydrogen is 20K, and the upper limit temperature of hydrogen entering engine combustion is about 1033K[2]. Therefore, liquid hydrogen has a large heat capacity and can be used as heat sink of hypersonic vehicle thermal management system[3]. Lei Yikun[4] proposed a scheme of integrated thermal/energy management system with combined turbine power plant as the core, and gave the system structure and overall working mode. However, the influence of fuel as heat sink on fuel system is not considered in the scheme. Gasner[5] et al. have simulated and evaluated the thermal management system of air-breathing hypersonic vehicle. Fuel is used to cool the airframe, engine and high temperature air. The result shows that the fuel radiator capacity can only meet the cooling requirements of hypersonic vehicle with Mach 5.5 during a specific design mission. With the development of hypersonic vehicle technology, especially the increase of flight Mach number, the aerodynamic thermal strength of aircraft body surface is getting higher and higher. Zhu Chunling[6] and others have raised an active and passive thermal protection structure for hypersonic vehicle based on the document[7]. C-C composite mat material structure is used as passive thermal protection measures in the outer layer of aircraft, and liquid hydrogen fuel is used as heat sink in the inner layer. The analysis shows that using liquid hydrogen fuel as heat sink can reduce fuel compensation loss. Aiming at the aerodynamic thermal cooling problem of hypersonic vehicle, Wang Peiguang[8] et al. proposed a thermal
management scheme of "liquid hydrogen fuel as main heat sink and phase change heat storage material as auxiliary heat sink". The research shows that this scheme has good adaptability to high dynamic thermal environment at high Mach number. In order to improve fuel economy and engine cooling efficiency of aircraft, Glickstein[9] et al. put forward a comprehensive thermal management scheme for centralized management of fuel heat sink and engine cooling air by thermal cycle. Using fuel pre-cooled air to cool the engine can save the cooling air flow and increase the fuel calorific value. The results show that the specific fuel consumption is reduced by 0.4% and the fuel consumption rate is reduced by 1.6% under cruise condition. Balland[10] et al. proposed a heat/energy integrated thermal management system for MR2 aircraft with liquid hydrogen as heat sink. Cooling of the body is carried out by means of low-temperature fuel evaporation of the propellant tank, followed by cooling of the other hot end components, and finally injected into the combustion chamber. The numerical simulation results show that the scheme can meet the aerodynamic heat and engine cooling requirements of MR2 aircraft at Mach 5~8. Matthew[11] et al. proposed a scheme of Brayton cycle thermoelectric conversion technology, which can reduce the surface temperature of aircraft body while converting aerodynamic thermal energy into electrical energy. The numerical results show that when the heat exchanger efficiency reaches 0.95, the power generation efficiency of the system can reach 60%. Qin[12] et al. proposed a closed Brayton cycle heat/energy management system with scramjet wall heat load as the hot side and fuel as the heat sink to solve the problem of insufficient fuel heat sink of hypersonic vehicle. The numerical results show that the system can convert part of the heat into mechanical energy and electrical energy, and the maximum thermal cycle efficiency can reach 40%, and reduce the engine cooling demand for fuel flow. From the above research, it is not difficult to see that scholars mainly focus on the thermal management system scheme with fuel as heat sink and the thermoelectric conversion methods such as closed Brayton cycle, in order to solve the problem of efficient thermal/energy management of hypersonic vehicle. However, in the past studies, there is a lack of detailed discussion on the performance change rule of the heat management system scheme which combines cooling and thermoelectric conversion, and the feasibility study of the composite heat management system scheme is urgently needed in engineering.

This article is going to talk about the composite thermal management system for hypersonic aircraft, which uses liquid hydrogen fuel as coolant and establishes the idea of closed Brayton cycle. The numerical simulation method will be used to study the thermal management effect and thermoelectric conversion efficiency of the system under different flight modes and parameters in the flight envelope. The influence of thermoelectric conversion on the thermal management effect of the system and the fuel economy of the aircraft will be studied in order to provide a reference for the design of hypersonic vehicle engineering.

2. System Scheme and Model

2.1. System Solution

Figure 1 is the schematic diagram of the hypersonic vehicle thermal management system with liquid hydrogen fuel as heat sink[13]. The thermal management system uses cryogenic liquid hydrogen fuel as heat sink combined with closed Brayton cycle thermoelectric conversion scheme, which is mainly divided into four parts. In the first part, liquid hydrogen is used to cool the refrigerant loop. Driven by the pump, the refrigerant absorbs the thermal loads of the electronic cabin, hydraulic oil system and lubricating oil system, then enters the heat exchanger of the refrigerant loop, transfers heat to the cryogenic liquid hydrogen fuel, and releases the heat carrier back to the liquid collecting tank to complete a cycle. After absorbing the heat of the refrigerant loop, the fuel enters the combustion chamber of the engine. The second part depends on whether the thermoelectric conversion is carried out on the engine wall. In view of the stable temperature of the engine wall, which is benefit for the design of high efficient thermoelectric conversion, the thermoelectric conversion using the engine wall heat source is only considered in this scheme. In the first scheme, no thermoelectric conversion occurs, and the liquid hydrogen directly cools the engine wall and then enters the combustion chamber; in the
second scheme, the thermal load on the engine wall is transformed into thermoelectric conversion before entering the combustion chamber[14]. Thermoelectric conversion adopts closed Brayton cycle. Low temperature and low pressure gas passes through compressor boost, then preheated by high temperature side fluid of heat exchanger, absorbs heat through engine wall, then enters turbine expansion to do work, exhaust gas is cooled by low temperature side fluid of heat exchanger, and then cooled by liquid hydrogen heat exchanger to the required inlet temperature of compressor. After that the gas will enter the compressor again, and complete the cycle. In the third part, liquid hydrogen enters the thermal protection system through the bypass connected with the pump, and directly cools the aerodynamic heat of the aircraft body. In the fourth part, when the fuel flow as heat sink can not generate enough thrust, the fuel in the fuel tank is directly transported to the engine by the bypass connected with the pump to compensate for the shortage of flow.

2.2. System Model

Figure 1 is a model of the combined heat management system of cooling and thermoelectric conversion. The parametric equation of refrigerant loop is shown in formulas (1) and (2).

\[ T_2 = \frac{Q_1}{m \cdot c_p} + T_1 \]  
\[ T_3 = \frac{Q_2}{m \cdot c_p} + T_2 \]

Set the liquid hydrogen storage environment of the low temperature fuel tank: The temperature and pressure were -253 °C and 101 kPa. The parametric equation of the liquid hydrogen loop is shown in formulas (3) and (4):

\[ T_5 = (T_3 - T_4) \times \varepsilon_1 + T_4 \]  
\[ T_7 = \frac{Q_4}{m_2 \cdot c_p} + T_4 \]

The parameters equation model of Brayton cycle thermoelectric conversion technology is as follows. The equations of compressor operating parameters are shown in formulas (5) and (6).

\[ T_8 = T_{13} + T_{13} \times (\frac{x_{13}^{eq}}{x_{13}} - 1) / \eta_k \]  
\[ W_c = m_4 \times (h_6 - h_3) \]
The working parameter equation of the intermediate heat exchanger is shown in formulas (7) and (8).

\[ T_9 = (T_{11} - T_8) \times \epsilon + T_9 \]  
\[ T_{10} = Q_1 / (q_{in} \cdot c_{p2}) + T_9 \]  

The engineering parameter equation of turbine operation is shown in formulas (9) and (10).

\[ T_{11} = T_{10} - T_{10} \times (1 - \pi_{t}^{t}) \times \eta_t \]  
\[ W_t = q_{in} \times (h_{10} - h_{11}) \]  

The calculation of cold-side heat exchangers is shown in formulas (11) and (12).

\[ T_{12} = T_{11} - (T_{11} - T_{10}) \times \epsilon_t \]  
\[ T_{13} = T_{12} - (T_{6} - T_{4}) \times \epsilon_t \]  
\[ Q = h_{10} - h_9 \]  
\[ \eta_t = (W_t - W) / Q \]  

In the process of system calculation, Newton-Raphson algorithm is used to solve the equation to ensure that the convergence accuracy residuals are less than 10\(^{-6}\).

2.3. Determination of System Parameters

2.3.1. Design of System Parameter. (1) fuel flow of hypersonic vehicle: In general, the mass flow rate of cryogenic liquid hydrogen fuel for thermal management will not exceed the fuel flow requirements of hypersonic vehicle flight. In this paper, the mass flow rate of liquid hydrogen fuel is calculated by using the hypersonic vehicle engine model [15], which provides the input condition for the heat sink flow rate of liquid hydrogen fuel for thermal management. The thrust variation of typical flight envelope, flight trajectory and typical flight trajectory of the hypersonic vehicle used in this paper [16] is shown in Figure 2. In this paper, the specific heat capacity of hydrogen is 14.3kJ/(kg·K) and the calorific value is 1.43×10^5kJ/kg. The fuel mass flow rate required for hypersonic vehicle engine combustion chamber is obtained by keeping the thrust variation in flight trajectory in Figure 2, as shown in Figure 3.

(2) Brayton cycle parameters of thermoelectric conversion: The fluid medium in the Brayton cycle is set to He, and the parameters of the Brayton cycle are designed as shown in Table 1[11]:

![Figure 2. Thrust Variation under Typical Flight Envelope and Flight Trajectory](image1)

![Figure 3. Mass Flow of Fuel Required in Engine Combustor](image2)
Table 1. Initial parameter

| parameter                              | value                   |
|----------------------------------------|-------------------------|
| specific heat capacity $c_p$ of He     | 5.19kJ/(kg·K)           |
| He adiabatic index $k$                 | 1.66                    |
| compressor efficiency $\eta_c$        | 0.85                    |
| turbine efficiency $\eta_t$           | 0.9                     |
| heat exchanger efficiency $\epsilon$  | 0.9                     |
| hot side heat load $Q_3$               | 100kW~800kW             |

2.3.2. Determination of System Parameters. Based on the above liquid hydrogen fuel flow rate, the cooling effect under different heat loads and the fuel consumption change of engine with or without thermoelectric conversion are studied in this paper, which can provide reference for the design of thermal management system under different aircraft design parameters and heat loads. Specific parameters range of electronic cabin and hydraulic oil, lubricating oil system, engine wall and aerodynamic heat load are selected according to existing literature and actual engineering data[17][18] as shown in Table 2.

Table 2. Change range of system heat load(kW)

| system parameter | Electronic cabin heat load $Q_1$ | Heat Load $Q_2$ of Hydraulic Lubricating System | Engine Wall Heat Load $Q_3$ | Aerodynamic Heat Load $Q_4$ for Turbojet State | Pneumatic Thermal Load $Q_5$ in Ramjet State |
|------------------|----------------------------------|-----------------------------------------------|-----------------------------|-----------------------------------------------|---------------------------------------------|
| Range of parameters | 100~500                          | 50~200                                       | 100~800                     | 500~1800                                    | 2000~20000                                  |

3. Simulation Result

3.1. the Cooling of Coolant Loop

![Figure 4](image_url)  

The refrigerant loop generally requires that the temperature of the electronic cabin, hydraulic oil and lubricating oil system should not exceed 80℃. Under this condition, the mass flow of liquid hydrogen fuel $q_{m1}$ is calculated. Figure 4 shows the temperature of the refrigerant loop and the mass flow rate of
liquid hydrogen fuel. While the mass flow rate of liquid hydrogen fuel in refrigerant loop remains unchanged at 3.34kg/s, the mass flow rate of liquid hydrogen fuel in refrigerant loop increases with the increase of heat load of electronic cabin, hydraulic oil and lubricating oil system. When the heat load of the electronic cabin is 100kW and that of the hydraulic oil and lubricating oil system is 50kW, the flow rate of liquid hydrogen fuel is 35.54g/s; when the heat load of the electronic cabin is 300kW and that of the hydraulic oil and lubricating oil system is 150kW, the flow rate of liquid hydrogen fuel is 106.63g/s; when the heat load of the electronic cabin is 500kW and that of the hydraulic oil and lubricating oil system is 200kW, the flow rate of liquid hydrogen fuel is 154.02g/s. When the total heat load of the electronic cabin and the hydraulic oil and lubricating oil system increases from 150kW to 700kW, the temperature of the electronic cabin, hydraulic oil and lubricating oil system does not exceed 80°C. The liquid hydrogen flow rate increases from 35.54g/s to 154.02g/s, and the cooling fuel demand is about 0.22g/kW·s~0.24g/kW·s. 

3.2. the Cooling of Aerodynamic Heat

The aerodynamic heat load of hypersonic vehicle increases gradually with the increase of Mach number, so the aerodynamic heat load is smaller in the stage of turbojet power, larger in the stage of stamping power, and the total aerodynamic heat load varies with the area and shape of random body. In this paper, the total aerodynamic heat load in the stage of turbojet power is 500kW~1800kW, the total aerodynamic heat load in the stage of stamping power is 2000kW~20000kW, and the temperature of the body is generally not more than 400°C[18]. The mass flow rate \( q_m^2 \) of liquid hydrogen fuel for cooling pneumatic heat load is calculated under the condition of satisfying body temperature. Figure 5 shows the outlet temperature and flow rate of liquid hydrogen cooling aerodynamic heat in the turbojet power state, and Figure 6 shows the outlet temperature and flow rate of liquid hydrogen cooling aerodynamic heat in the stamping power state. It can be seen from the figures that with the increase of aerodynamic heat, the flow rate required for liquid hydrogen cooling will increase. With the increase of heat load, the flow rate of liquid hydrogen required for cooling under turbojet power state increases from 54.5g/s to 194.3g/s. With the increase of heat load, the flow rate of liquid hydrogen required for cooling under stamping power state increases from 215.63g/s to 2203.65g/s. When the body temperature of turbojet and stamping power stage does not exceed 400°C, the demand for cooling fuel is about the same. 0.11g/kW·s.

![Figure 5. Aerodynamic heat outlet temperature and required flow rate of liquid hydrogen cooling under swirl injection](image)

3.3. the Cooling of Engine Wall

Generally, the exit temperature of the engine wall should not exceed 600°C. Under this condition, the mass flow \( q_m^3 \) of liquid hydrogen fuel is calculated when the thermal load on the engine wall is converted into thermoelectric fuel or not. The simulation results are shown in Figure 7. The range of...
engine wall heat load varies from 100kW to 800kW. When the temperature of engine wall outlet does not exceed 600°C, the mass flow of liquid hydrogen fuel increases with the increase of engine wall heat load. When the engine wall heat load does not undergo thermoelectric conversion, more fuel is needed for cooling than when thermoelectric conversion is carried out. When the thermal load on the engine wall is not converted into thermoelectric power, the flow rate of liquid hydrogen required for cooling increases from 8.29g/s to 63.98g/s, and the demand for cooling fuel is about 0.08g/kW·s. When the engine wall heat load is converted into thermoelectric power, the liquid hydrogen flow rate for cooling increases from 5.89g/s to 37.9g/s, and the demand for cooling fuel is about 0.047g/kW·s~0.058g/kW·s, which is 25%~40% lower than that without thermoelectric conversion.

According to the principle of Brayton cycle, the generation conditions under different heat loads are calculated. Formula (15) is generation power Wh and formula (16) is generation efficiency F of Breton cycle.

\[
W_h = W_T - W_c
\]  
(15)

\[
\eta_f = (W_T - W_c) / W_T
\]  
(16)

As shown in Figure 8, with the increase of thermal load at the hot side (engine wall), the cycle thermal efficiency increases from 3% to 38%, and the generation efficiency increases from 17% to 30%. When the wall thermal load is about 200 kW, the increase of efficiency becomes smaller and smaller, resulting in more and more electric energy, from 17.5 kW to 244 kW.

3.4. Comparative Analysis of Total Cooling Flow Rate and Engine Combustion Flow Rate
In this section, the total cooling flow rate is compared with that required by engine to maintain thrust.
combustion, and the total cooling liquid hydrogen flow rate under different heat loads, such as refrigerant loop, engine wall and aerothermal load, and whether the combustion flow rate meets the total cooling flow requirement are discussed. The refrigerant loop in flight trajectory and the heat load on engine wall are generally stable, so it is considered as steady state. The maximum and minimum states in the previous study are selected as shown in Table 3, Working Conditions one and two respectively.

| Working condition number | Heat load $Q_1$ of electronic cabin (kW) | Thermal Load $Q_2$ of Hydraulic and Lubricating Oil System (kW) | Engine Wall Heat Load $Q_3$ (kW) |
|-------------------------|------------------------------------------|------------------------------------------------|-------------------------------|
| 1                       | 100                                      | 50                                           | 100                           |
| 2                       | 500                                      | 200                                          | 800                           |

The aerodynamic heat load $q_m$ in flight trajectory varies with Mach number $Ma$[18]. The larger and smaller aerodynamic heat loads are selected as shown in Figure 9, Working Conditions A and B respectively. The total cooling flow rate is discussed in three cases. In the first case, the heat load of the refrigerant loop and the engine wall is selected according to the smaller working condition one, which is 150 kW and 100 kW respectively. The aerodynamic heat load is considered under the smaller working condition A. In the second case, the heat loads of refrigerant loop and engine wall are selected according to the larger working condition two, 700 kW and 800 kW respectively, and the aerodynamic heat loads are considered according to the smaller working condition A. In the third case, the heat loads of refrigerant loop and engine wall are selected according to the larger working condition two, 700 kW and 800 kW respectively, and the aerodynamic heat load is considered according to the larger working condition B. The total flow rate $q_m$ required for cooling of the refrigerant loop, the engine wall and the aerodynamic heat load in three cases is compared with the liquid hydrogen flow $q_m$ required for combustion of the engine in the flight trajectory in Figure 4. The simulation results are shown in Figure 10. Within the range of the parameters studied in this paper, the changes of the refrigerant loop and the heat load on the engine wall have little effect on the total liquid hydrogen flow required for cooling. The liquid hydrogen fuel flow required for the first and second case can meet the cooling requirements for the whole thermal management system in the flight trajectories. The change of aerodynamic heat load has a great influence on the total cooling liquid hydrogen flow rate. In the second case, the aerodynamic heat load is smaller under working condition A, and the liquid hydrogen fuel flow required for combustion in flight trajectory can meet the cooling requirements of the whole thermal management system. In working condition B, the aerodynamic heat load is larger when the Mach number $Ma$ in flight trajectory is 3.7~4.2. There are many fuels needed for cooling aerothermal load, and the flow rate of liquid hydrogen fuel required for combustion cannot meet the cooling requirements of the system. The maximum difference is 10%.

Figure 9. Variation of Aerodynamic Heat Load in Flight Trajectory

Figure 10. Liquid Hydrogen Flow Rate in Refrigerant Loop and Engine Wall Heat Load Change
4. Conclusion
In this paper, a hybrid thermal management system for hypersonic vehicle is proposed, which uses liquid hydrogen fuel as the main heat sink and combines closed Brayton cycle thermoelectric conversion technology. Within the parameters of this study, the main conclusions are as follows:

(1) Under the condition that the refrigerant loop, engine wall and airframe do not exceed the prescribed temperature, the mass flow rate of liquid hydrogen fuel required for cooling each part is simulated and calculated. The demand for refrigerant loop cooling fuel is about 0.22g/kW·s~0.24g/kW·s, and the demand for aerodynamic heat load cooling fuel is about 0.11g/kW·s. The cooling fuel requirement is about 0.08g/kW·s when the engine wall heat load is not converted to thermoelectric power, and 0.047g/kkW·s~0.058g/kW·s when the thermoelectric conversion is carried out, which is 25%~40% lower than that when the thermoelectric conversion is not carried out.

(2) Discusses whether the flow rate of liquid hydrogen fuel for combustion meets the flow rate requirement for cooling under the change of heat load, such as refrigerant loop, engine wall and aerodynamic heat. The results show that the change of refrigerant loop and engine wall heat load has little effect on the total cooling liquid hydrogen flow rate, and the change of aerodynamic heat load has greater effect on the total cooling liquid hydrogen flow rate. When the Mach number is 3.7~4.2, the flow rate of liquid hydrogen fuel can not meet the cooling requirements of the system, and the maximum difference is 10%.

(3) The thermal load of the engine wall surface is thermoelectrically converted. The greater the thermal load on the engine wall, the higher the cycle heat efficiency. From 100 kW to 800 kW, the cycle thermal efficiency increases from 3% to 38%; the generated electric energy is increasing, increasing from 17.5kW. By 244kW, the power generation efficiency has increased from 17% to 30%, but the growth rate is getting smaller and smaller.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| $T_1$  | inlet temperature of electronic cabin, ℃ |
| $T_2$  | outlet temperature of electronic cabin, ℃ |
| $T_3$  | outlet temperature of hydraulic oil and lubricating oil system, ℃ |
| $T_4$  | initial temperature of cryogenic liquid hydrogen fuel, ℃ |
| $T_5$  | inlet temperature of engine wall, ℃ |
| $T_6$  | outlet temperature after liquid hydrogen cooling, ℃ |
| $T_7$  | outlet temperature of pneumatic heat, ℃ |
| $T_8$  | outlet temperature of compressor, ℃ |
| $T_9$  | outlet temperature of plate-fin heat exchanger, ℃ |
| $T_{10}$ | inlet temperature of turbine, ℃ |
| $T_{11}$ | outlet temperature of turbine, ℃ |
| $T_{12}$ | inlet temperature of cold-side heat exchanger, ℃ |
| $T_{13}$ | inlet temperature of compressor, ℃ |
| $q_m$ | flow of the cooling medium, kg/s |
| $q_{m1}$ | flow rate required for liquid hydrogen cooling refrigerant loop, kg/s |
| $q_{m2}$ | flow rate required for liquid hydrogen cooling aerodynamic heat, kg/s |
| $q_{m3}$ | flow rate required for liquid hydrogen cooling engine wall, kg/s |
| $q_{m4}$ | pipe medium flow rate, kg/s |
| $c_p$ | specific heat capacity of cooling medium, kJ/(kg·K) |
| $c_{ph}$ | specific heat capacity of liquid hydrogen, kJ/(kg·K) |
\( c_{p2} = \) specific heat capacity of pipeline fluid, kJ/(kg·K)
\( Q_1 = \) thermal load of Electronic cabin, W
\( Q_2 = \) thermal load of hydraulic oil and lubricating oil system, W
\( Q_3 = \) engine wall heat load, W
\( Q_4 = \) aerodynamic heat load, W
\( \dot{Q} = \) Brayton cycle system heat absorption, kJ/kg;
\( \eta_r = \) system cycle thermal efficiency
\( \epsilon_i = \) the efficiency of all heat exchangers in the system is the same
\( \pi_k = \) pressure ratio
\( \eta_k = \) compressor efficiency
\( \pi_t = \) expansion ratio
\( \eta_t = \) turbine efficiency
\( k = \) adiabatic index of pipeline gas
\( h_{l3} = \) inlet enthalpy of compressor, kJ/kg
\( h_{o8} = \) outlet enthalpy of compressor, kJ/kg
\( h_{l10} = \) inlet enthalpy of turbine, kJ/kg
\( h_{l11} = \) outlet enthalpy of turbine, kJ/kg
\( W_c = \) work consumed by adiabatic compression of compressor, W
\( W_T = \) expansion output work of turbine, W

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