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(RESEARCH ARTICLE)

Performance parameters analysis of an organic Rankine cycle for power generation from the heat of cooling scramjet

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Abstract

An organic Rankine cycle (ORC) for power generation system is proposed for cooling scramjet. The heat which must be taken away by fuel coolant from cooling scramjet is converted to other forms of energy to decrease fuel coolant flow. A parametric study of an ORC power generation system has been performed. The multiplication ratio of fuel heat sink, the efficiency and output power of the system changing with the condenser outlet fuel coolant temperature are evaluated. The results show that the optimal condenser outlet fuel coolant temperature is 510K in a certain working condition, and the multiplication ratio of fuel heat sink is 0.0635, the efficiency of the system is 11.74% and the output power is 35.13kW. The effect of the cycle pressure ratio on the efficiency, output power and the multiplication ratio of fuel heat sink is also analyzed and it has a big significant influence. It is known through thermodynamic analyses that ORC power generation system for cooling scramjet would reduce the fuel coolant flow and give some output power for hypersonic vehicle.

Key words: Energy; Power Generation System; Scramjet; ORC; Output Power

1. Introduction

The key technology of hypersonic vehicle has been studied for many years, especially the issue for hypersonic airbreathing vehicle [1, 2, 3]. With the high speed of hypersonic vehicle the structure and thermal protection for overall vehicle is magnitude [4, 5]. The key technology of the scramjet is more important for hypersonic vehicle and the cooling of scramjet is one of key issues. Because the scramjet has great amount of heat fluxes which is about 7~8MW/m^2 in NASA-Langley airframe propulsion integrated ramjet engine [6]. Therefore, the fuel is unique coolant by flowing through the cooling passage for cooling the structure [7, 8], and then it flows to the combustion chamber for burning [9].

Hypersonic aircrafts and missiles powered by scramjet, which is encountered extremely high temperature and heat fluxes in the combustor [10]. There is large heat for cooling scramjet and it is necessary for energy recovery to supply the power for the auxiliary systems such as fuel feeding, environment control and radar on aircrafts or missiles [11].

So far, the method of cooling scramjet for safe is mainly regenerative cooling [12]. But the fuel coolant onboard can only meet the cooling requirements for some scramjet components such as combustion chamber. The heat is absorbed by the fuel and not utilized for produce output power. In order to indirectly increase fuel heat sink for cooling scramjet, the method of Recooled cycle which convert the thermal energy to mechanical work is proposed [13,14]. Qin et al. [13] utilized a turbine by the foundation of regenerative cooling and transfered enthalpy from fuel to mechanical work. Bao

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et al. [15] enlarged the Recooling cycle to hydrocarbon and pointed out output power. There is also a turbo-pump driven by fuel vapor which is used for cooling scramjet and the turbo-pump is connected to a motor [16]. Zhang et al. [17] evaluated the performance of a power generation system in which the working fluid is fuel and the generator was driven by the fuel vapor turbine. However, the output power and electrical efficiency of Recooling cycle system is relatively low.

Nomenclature	δ multiplication ratio of fuel heat sink
T temperature (K)	π pressure ratio
p pressure (Pa)	η efficiency (%)
Q heat flow rate (W)	Subscripts
c_p specific heat (J/(kg K))	1,2,3,4 state points of ORC
m mass flow rate kg/s)	0,5,6 in and out of fuel flow
h enthalpy (J/kg)	f fuel
W output power (W)	w working fluid
L length of the condenser flowing path (m)	t efficiency of ORC
L_0 Pinch Point temperature position (m)	con condensation
ΔT minimum temperature difference (K)	eva evaporation
Greeks symbols	exp efficiency of turbine
ε fuel flow saving ratio	pump efficiency of pump
	p pinch point

As a possible alternative to the effective use of limited resources to reduce the fuel flow for cooling, an ORC power generation system for cooling scramjet based on the thermodynamic principle is performed. ORC has been used in many fields for energy recovery [18,19,20]. Önder [21] has proposed an organic Rankine for power generation from waste heat recovery in steel industry. The study includes energy and exergy analysis on an ORC. Liu [22] has analyzed the sensitivity of system parameters to the performance of the ORC system quantitatively. A thermodynamic model of the ORC system has been developed and verified for building binary-cycle geothermal power plants. Carcasci [23] has proposed an organic Rankine cycle combined with a gas turbine in order to convert the gas turbine waste heat into electrical power. Miller et al. [24] tried to combine both TEG and ORC (Thermoelectric Generator and Organic Rankine Cycle) for power generation to recover heat from engines. However, the property of ORC power generation system for scramjet is relative scarce. The performance parameters analysis of ORC system is fewly studied.

In this paper, an ORC power generation system suitable for cooling scramjet is presented firstly. The scramjet wall is regarded as hot source. Aviation kerosene which is the hydrocarbon fuel is the main fuel for aerospace plane and the hydrocarbon fuel coolant as cold source. The heat from cooling scramjet would be converted to other forms of energy. Therefore, fuel flow rate for cooling is reduced and some output power is generated. The performance parameters analysis of an ORC system is presented. Synchronously, the effect of the condenser outlet fuel coolant temperature and the cycle pressure ratio on the performance parameters of the system is analyzed. And then the condensation temperature and the evaporation pressure of ORC have effect on the efficiency, output power and the multiplication ratio of fuel heat sink. It is helpful to improve the performance of the heat for cooling scramjet driven ORC and obtain some power for hypersonic vehicles.

2. An ORC power generation system description

Fig. 1 presents a layout of a power generation system with the heat source of scramjet wall and a direct ORC. There is large temperature difference between the scramjet wall and fuel coolant and additional power can be gotten by heat-work conversion. The output power would be used for hypersonic vehicle and the heat load of fuel coolant could be indirectly decreased [25].

The ORC power generation system consists of the first cooling passages (evaporator), condenser, pump, turbine and generator. The heat is absorbed by the working fluid of ORC in the evaporator to cool the scramjet wall and the temperature of the working fluid increases. Then the working fluid in high temperature and pressure could be transformed into mechanical/electrical energy by turbine and generator. The working fluid would be cooled to liquid by the fuel coolant in condenser. Last its pressure is increased by the pump and the working fluid reenters the initializing state of the cycle. The temperature of fuel coming out from the condenser is so low that it has cooling capacity to cool the other part of scramjet wall in the second cooling passage according to Fig. 1.

Part of the heat is converted to other forms of energy and the heat load of fuel coolant could be indirectly decreased. In addition, the output work of the turbine can drive the fuel pump and an electric generator to provide the power for vehicle subsystems. According to the high-temperature heat source and low temperature heat source, the organic working fluid has been used for simulating the ORC. In summary, both cooling the engine and power generation are achieved by the ORC thermal management system onboard.

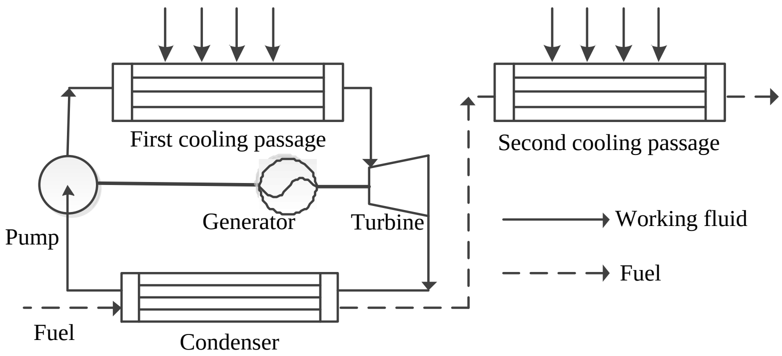

Figure 1 The conceptual scheme of ORC system for scramjet

3. Parameters analysis

The objective of ORC power generation system is to decrease the heat load of fuel coolant and provide the power for the vehicle. There is a new performance parameter to compare the performance of ORC thermal management system with that of regenerative cooling system. The simplified scheme of the system is shown in Fig. 2. Under the same external heating condition, it is assumed that (1) constant specific heat, (2) no pressure loss from cooling passage and heat exchanger, (3) no heat transfer loss.

In order to evaluate the performance of cooling scramjet, the fuel flow saving ratio and the multiplication ratio of fuel heat sink which are described as the increase of fuel cooling capacity according to comparing ORC power generation system with regenerative cooling are defined as follows [11]:

$$\varepsilon = \frac{m_{f2}}{m_{f1}} = \frac{(T_6 - T_0)}{\frac{(T_5 - T_0)}{1-\eta_t} + (T_6 - T_5)} = 1 - \frac{\eta_t (T_5 - T_0)}{(T_5 - T_0) + (1-\eta_t)(T_6 - T_5)} < 1 \qquad (1)$$

$$\delta = \frac{h_f^{'} - h_f}{h_f} = \frac{\frac{Q}{m_{f2}} - \frac{Q}{m_{f1}}}{\frac{Q}{m_{f1}}} = \frac{\frac{(T_5 - T_0)}{1-\eta_t} + (T_6 - T_5)}{T_6 - T_0} - 1 = \frac{\eta_t}{1-\eta_t}\frac{T_5 - T_0}{T_6 - T_0} \qquad (2)$$

Where h_f and h'_f are respectively actual heat sink and "indirect" heat sink. For regenerative cooling, cooling capacity relation of fuel is $Q = m_{f1} h_f$, while cooling capacity relation of fuel is $Q = m_{f2} h'_f$ for ORC thermal management system.

And thermal efficiency of ORC can be calculated as

$$\eta_t = 1 - \frac{Q_l}{Q_f} \quad (3)$$

For ORC power generation system, the heat rejection of working fluid is equal to the heat absorption of fuel in condenser can be interpreted as

$$Q_l = m_w(h_3 - h_4) = m_{f2}c_p(T_5 - T_0) \quad (4)$$

The heat absorption of working fluid in evaporator can be interpreted as

$$Q_f = m_w(h_2 - h_1) \quad (5)$$

The output power of ORC power generation system can be expressed as

$$W_t = Q_f - Q_l = m_w\eta_t(h_2 - h_1) \quad (6)$$

The parameters of an ORC system for scramjet are the multiplication ratio of fuel heat sink, the efficiency and output power.

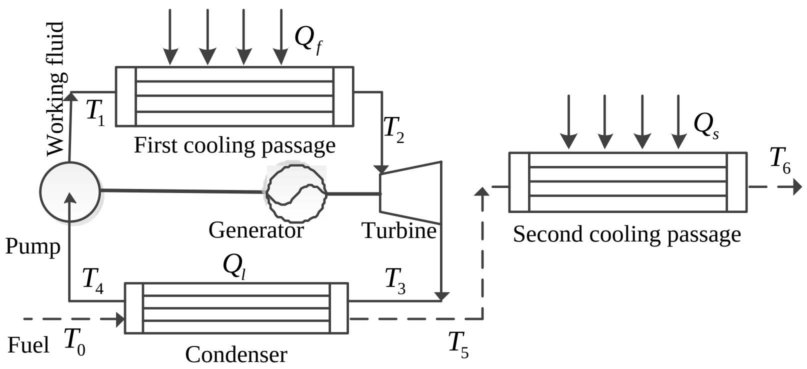

Figure 2 Simplified schematic ORC power generation system

4. Thermodynamic process analysis

As heat exchangers, turbine and pump are the key components in ORC power generation system. The thermodynamics analysis is just an appropriate theory which has been widely used to analyze the performance of ORC for the power, efficiency and so on. Therefore, thermodynamic analysis method for ORC power generation system will be performed in the following.

The dry working fluid of ORC has been selected toluene which has high critical pressure and temperature. At the same time, the selection of the working fluid for the ORC system is mainly aimed at analyzing the performance parameters. NIST (National Institute of Standards and Technology) software has been used to simulate the behavior of the working fluid. The thermodynamic properties of the selected fluid are obtained at the critical point values in terms of both pressure and temperature, which are 4.088MPa and 591K, respectively. Temperature-Entropy (T–S) diagram of irreversible ORC working is shown in Fig.3. 1-2-3-4-1 is the working process of cycle.

1-2 is the heat absorbing process from the hot source of scramjet wall. Taking into account of the wall of scramjet basically keep a high temperature, it is supposed that Heat exchange performance between working fluid and scramjet wall is perfect. The temperature difference of heat exchanging is enough large for cooling passage. The working fluid of ORC works under subcritical condition and the highest temperature at the state point of 2 is lower than the temperature of working fluid chemistry labilization (700K).

4-1 and 2-3 are irreversible compression and irreversible expansion processes, respectively. 3-4 is exothermic heat process to variable-temperature low temperature cold source. Supposed that the fuel coolant flow rate and the specific heat of fuel are constant, so the temperature distribution of hydrocarbon fuel coolant is about as

$$T_c(x)=kx+b, 0<x\le L \quad (7)$$

The temperature of fuel inlet is about T_0 and outlet is T_5. The fuel coolant of the condenser inlet is regarded as O of coordinate and the flowing path is along x. the length of the condenser fuel coolant flowing path is L, so the temperature distribution of fuel coolant is expressed as

$$T_c(x)=\frac{T_5-T_0}{L}x+T_0, 0<x\le L \quad (8)$$

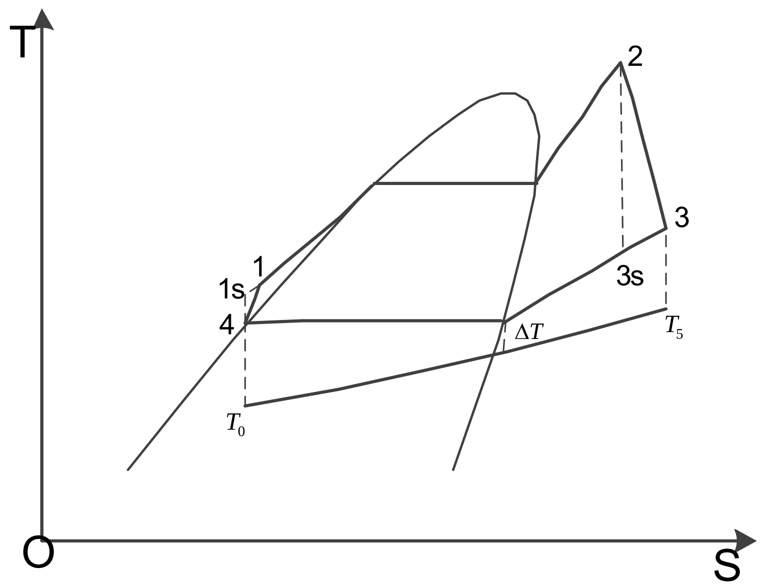

Figure 3 T–S diagram of the ORC

The condenser of ORC power generation system is treated as counter-flow heat exchangers. Temperature-Enthalpy (T–H) diagram is shown in Fig. 4, the heat released by the working fluid is equal to the heat absorbed by the fuel coolant. Based on Fig.4, the minimum temperature difference of heat exchange is located at the line of the working fluid saturated vapor. L_0 is the Pinch Point temperature position and the Pinch Point temperature is about as

$$T_p=\frac{T_5-T_0}{L}L_0+T_0 \quad (9)$$

The saturated temperature of working fluid in the condenser is expressed as

$$T_{con}=T_p+\Delta T=\frac{T_5-T_0}{L}L_0+T_0+\Delta T \quad (10)$$

The working fluid pressure of the condenser is p_{con} by basing the saturated temperature from NIST REFPEOP 8.0 [26]. From the condenser, the rates of working fluid and fuel coolant mass flows are m_w and m_f, respectively, according to the relationship of the heat equilibrium in the condenser, it is expressed as

$$m_w(h_3 - h_{con,vapor}) = m_f \, c_{pf} (T_5 - T_p) \quad (11)$$

$$m_w(h_{con,vapor} - h_4) = m_f \, c_{pf} (T_p - T_0) \quad (12)$$

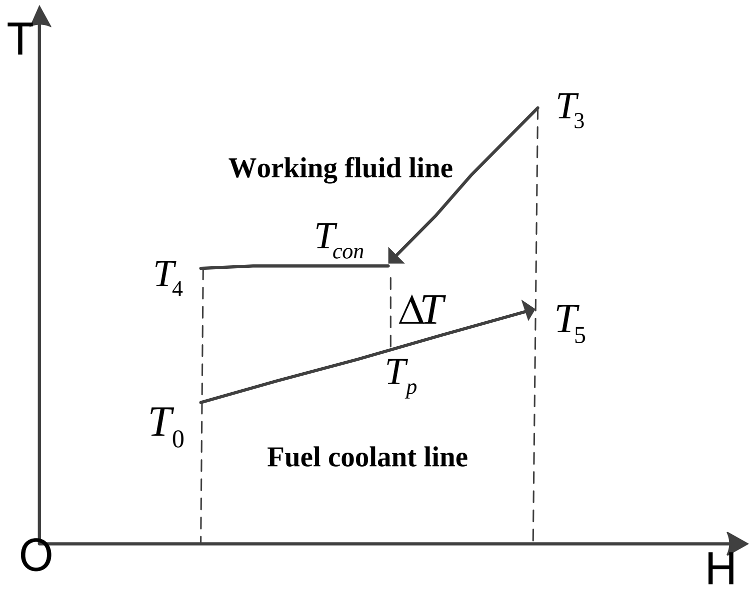

Figure 4 T–H diagram of the condenser

The fuel flow saving ratio and the multiplication ratio of fuel heat sink are calculated by Fig. 5, which depicts the flow chart of the proposed method. The working fluid condensation temperature and pressure of the condenser are T_{con} and p_{con} respectively by basing the saturated temperature. The evaporation temperature and pressure of first cooling passage are supposed T_{eva} and p_{eva} , respectively, according to the critical pressure and temperature of working fluid. And then the pressure ratio of thermodynamic cycle can be obtained from the condensation pressure and the evaporation pressure. Internal loss of turbine and pump are characterized with $\eta_{\exp}$ and η_{pump} , respectively. The highest temperature of the working fluid with toluene is limited by the chemical decomposing temperature T_{limit} . According to the parameters of the working fluid, T_1, T_2, T_3, T_4 and p_1, p_2, p_3, p_4 are obtained at state points 1, 2, 3, 4, respectively, the same as h_1, h_2, h_3, h_4 . With the rate of fuel coolant mass flow, the rate of working fluid mass flow, the heat absorption at first cooling passage, the heat exchange at the condenser, the output power and the efficiency of ORC can be calculated. And then the fuel flow saving ratio and the multiplication ratio of fuel heat sink would be analyzed with the known outlet temperature of fuel coolant in second cooling passage.

From the above analysis, T_5 affects the condensation temperature of working fluid and the heat absorption quantity of fuel in the condenser. Thus, it has an effect on the parameters of an ORC system such as the multiplication ratio of fuel heat sink, the efficiency and output power. If the T_5 is constant and the condensation temperature and pressure is obtained, the cycle pressure ratio will affect the evaporation temperature and pressure. Of course, it has an effect on the parameters of the multiplication ratio of fuel heat sink, the efficiency and output power.

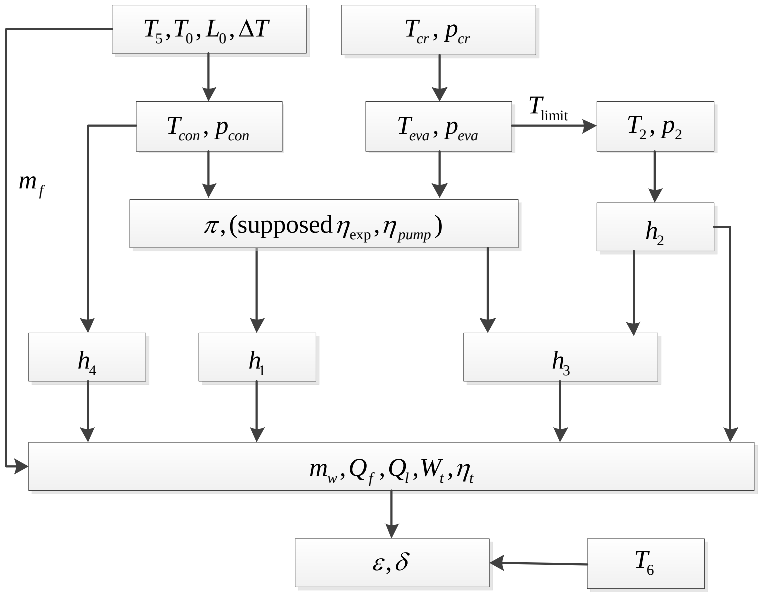

Figure 5 The flow chart of the proposed method for the parameters

5. Results and discussions

To see how the outlet condenser fuel coolant temperature and the cycle pressure ratio influence the efficiency and output power of the system, the fuel flow saving ratio and the multiplication ratio of fuel heat sink, there are some detailed numerical examples given to analyze the performance.

In order to have a numerical appreciation of the results, it is supposed that the turbine and pump efficiencies are 0.85 and 0.7, respectively, the condenser inlet hydrocarbon fuel coolant temperature is 290K, the evaporation temperature of working fluid is 550K and the temperature of working fluid at state point 2 is 700K, the temperature of fuel coolant in second passage outlet is 750K. The effect of the condenser outlet fuel coolant temperature and the cycle pressure ratio on the efficiency and output power, the fuel flow saving ratio and the multiplication ratio of fuel heat sink are studied, and the discussion of the results is given below.

5.1. Effect of the fuel coolant temperature of outlet condenser

We consider the condenser outlet fuel coolant temperature in the range 400K-550K. In order to decrease the area of heat exchange, the minimum temperature difference of heat exchange is bigger than 10K and it is original suggested 10K, 15K and 20K. The Pinch Point temperature is obtained by Eq. (10) in case of L_0/L with 0.5 and the working fluid condensation temperature can be calculated. The evaporation and condensation pressures of working fluid will be gained according to the evaporation and condensation temperature from NIST REFPEOP 8.0. The temperature, pressure, enthalpy and entropy of working fluid at state points 1, 2, 3, 4 will be gotten. The minimum temperature difference of heat exchange can be calculated by Eq. (11) and Eq. (12).

As shown in Fig. 6, the variation of the Pinch Point temperature station L_0/L is presented along the increase of T_5 when it original gives L_0/L with 0.5. It is about in the zone with 0.44 to 0.47 and it decreases with the increase of T_5. When the minimum temperature difference of heat exchange original suggested 10K, 15K and 20K, L_0/L changes in small zone.

As shown in Fig. 7, the minimum temperature difference is presented along the increase of T_5. The minimum temperature difference increases with the increase of T_5 and it is helpful for the heat exchanger design and decreasing the area of heat exchange. However, the efficiency of ORC decreases with the increase of T_5 in Fig. 8. Because the condensation temperature increases with the increase of T_5, the condensation pressure heightens and the cycle pressure ratio reduces.

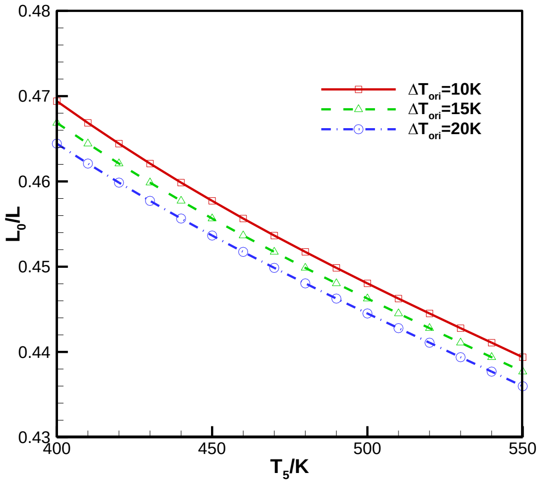

Figure 6 Variation of the Pinch Point temperature station with T_5

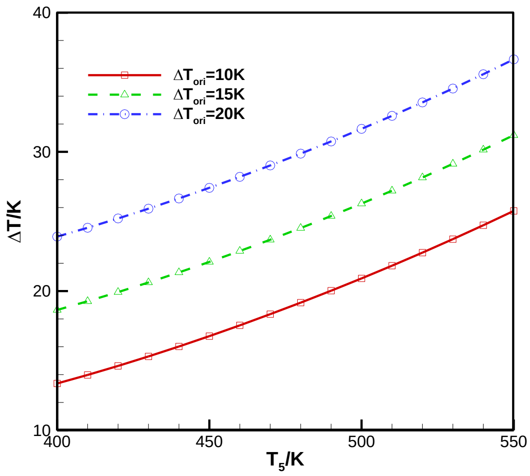

Figure 7 Variation of minimum temperature difference with T_5

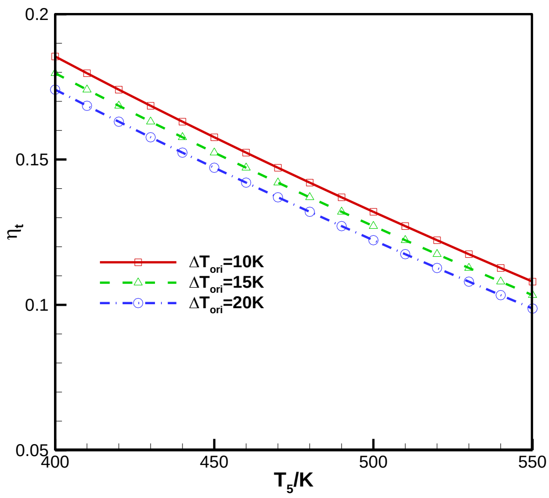

Figure 8 Variation of the efficiency of ORC with T_5

As shown in Fig. 9, the variation of the fuel flow saving ratio and the multiplication ratio of fuel heat sink presents parabola along the increase of T_5, and there exists an optimal temperature for each curve. The fuel flow saving ratio firstly decreases and then increases, the least of the fuel flow saving ratio is 0.9402. Otherwise, the multiplication ratio of fuel heat sink firstly increases and then decreases, the biggest of the multiplication ratio of fuel heat sink is 0.0635. So the optimal temperature of T_5 is in the range 490K-510K.

Fig. 10 shows the variation of the working fluid flow rate and the output power with the increase of T_5. The Mach number of airstream to scramjet isolator inlet is about 1.5~3.5 when the Mach number of airstream is about 6 and the fuel flow rate for combustion is about 0.4kg/s, so the fuel coolant flow rate is 0.4kg/s. Dodecane is regarded as fuel and the average specific heat is about 3000j/Kg.K when the temperature changes in the range 290K-750K. The working fluid flow rate increases with the increase of T_5, while the output power firstly increases and then decreases and the largest of the output power is 35.13kW. Because the heat absorption of fuel coolant in the condenser increases with the increase of T_5, So the working fluid flow rate increases. At the same time, the condensation temperature of ORC heightens and the efficiency decreases. So there exists an optimal temperature for the largest output power and the optimal temperature of T_5 is 510K.

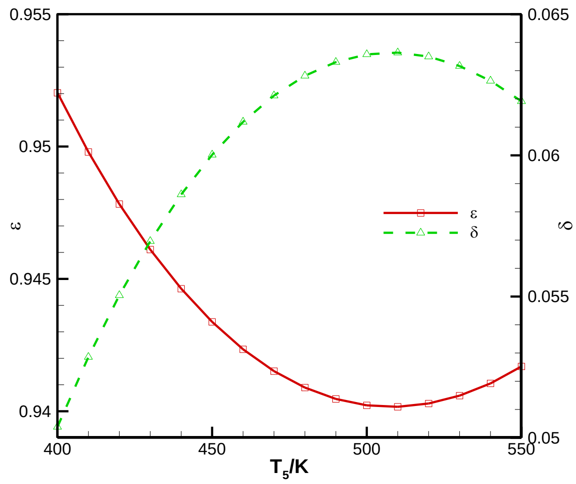

Figure 9 Variation of the fuel flow saving ratio and the multiplication ratio of fuel heat sink with T_5

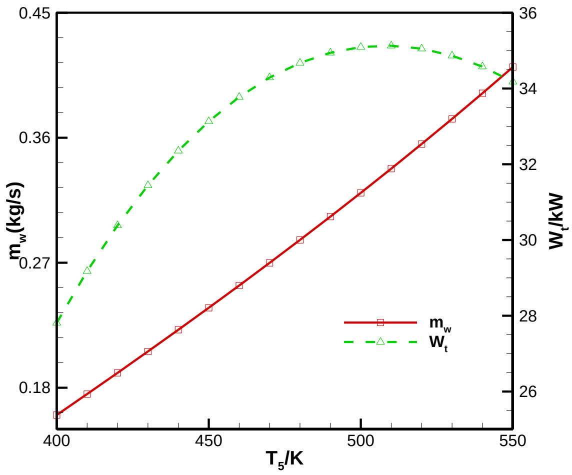

Figure 10 Variation of the working fluid flow rate and the output power with T_5

5.2. Effect of the cycle pressure ratio

We consider the condenser outlet fuel coolant temperature 500K and the working fluid condensation temperature can be calculated. The condensation temperature and pressure of working fluid are 415K and 0.228MPa, respectively. The temperature difference of heat exchange is calculated 31.6K. The evaporation temperature and pressure are lower than the critical temperature and pressure (591K, 4.088MPa), which the thermodynamic process is under subcritical condition. The temperature, pressure, enthalpy and entropy of working fluid at state points 1, 2, 3, 4 will be gained from NIST REFPEOP 8.0.

Fig. 11 shows the variation of the efficiency with the increase of the cycle pressure ratio and the efficiency of ORC increases. However, the ratio of the increasing efficiency becomes slowness with the cycle pressure ratio. Likewise, the fuel flow saving ratio decreases, the multiplication ratio of fuel heat sink increases while the ratios of the fuel flow saving ratio and the multiplication ratio of fuel heat sink become slowness in Fig. 12.

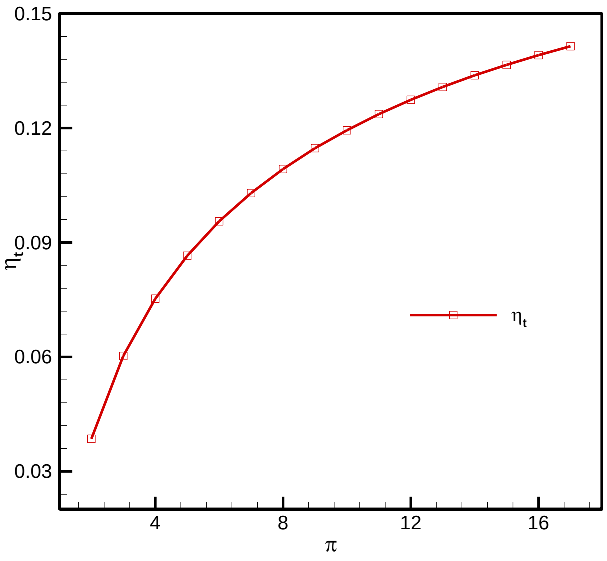

Figure 11 Variation of the efficiency of ORC with the cycle pressure ratio

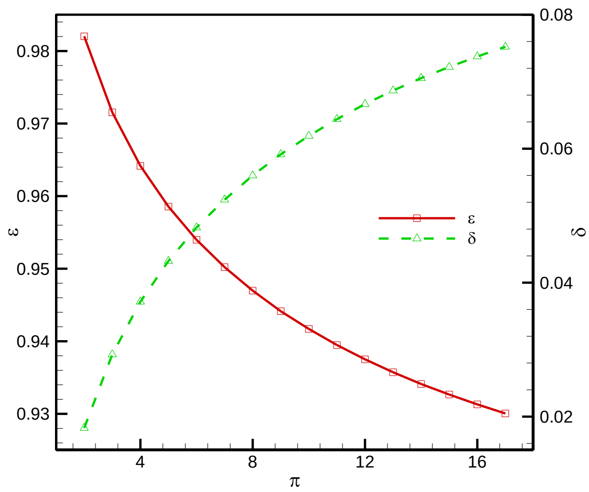

Figure 12 Variation of the fuel flow saving ratio and the multiplication ratio of fuel heat sink with the cycle pressure ratio

Fig. 13 shows the variation of the working fluid flow rate and the output power with the increase of the cycle pressure ratio. The working fluid flow rate and the output power increases. The heat absorption of fuel coolant in the condenser is constant and the enthalpy of working fluid at state point 3 decreases, so the working fluid flow rate increases. With the increase of the efficiency of ORC, the output power will be increased. However, the limit of the working fluid critical temperature and pressure and under subcritical condition, the cycle pressure ratio is lower 17 in the working condition.

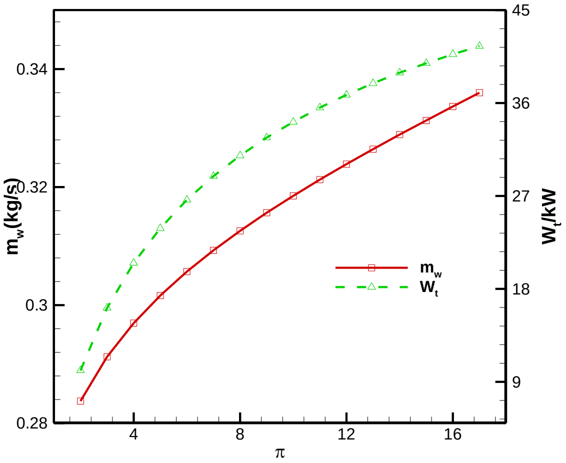

Figure 13 Variation of the working fluid flow rate and the output power with the cycle pressure ratio

From the variety of analysis discussed above, the ORC power generation system under subcritical condition is applied for scramjet. The value of the multiplication ratio of fuel heat sink can reach more than 6 percent and the heat load of fuel coolant could be decreased, fuel flow rate for cooling could be also decreased. The ORC power generation system also produces electric power, which can be utilized for the fuel feeding subsystem and power generation subsystem.

6. Conclusion

The ORC power generation system under subcritical condition is applied for scramjet. The performance parameters are defined to evaluate the performance of the system. The heat exchange in condenser is analyzed. According to the relationship of the heat equilibrium in the condenser, the minimum temperature difference of heat exchange is given and the Pinch Point temperature is obtained.

The effects of various parameters on the ORC system performance have been studied. When the minimum temperature difference of heat exchange original supposes 10K, 15K and 20K, respectively, the fuel flow saving ratio and the multiplication ratio of fuel heat sink have an optimal value with the increase of T_5, and the efficiency of ORC decreases. The least of the fuel flow saving ratio is 0.9402 and the biggest of the multiplication ratio of fuel heat sink is 0.0635. At the same time, the largest of the output power is 35.13kW and the efficiency of the system is 11.74%, which the optimal temperature of T_5 is 510K. The efficiency of ORC, the multiplication ratio of fuel heat sink and the output power increases with the cycle pressure ratio. However, the ratios of them become slowness with the cycle pressure ratio which is limited lower 17 in the certain working condition from the working fluid critical temperature and pressure.

The ORC power generation system under subcritical condition has a big significance for scramjet. The output power of the system can be utilized for the hypersonic vehicle.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors hereby attest to the fact that there is no any conflicting interest of any sort in this study.

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