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# System Design and Analysis of Hydrocarbon Scramjet with Regeneration Cooling and Expansion Cycle

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A new expansion cycle scheme of the scramjet engine system including a hydrocarbon-fuel-based (kerosene) regenerative cooling system and supercritical/cracking kerosene-based turbo-pump was proposed in this paper. In this cycle scheme, the supercritical/cracking kerosene with high pressure and high temperature is formed through the cooling channel. And then, in order to make better use of the high energy of the supercritical/cracking fuel, the supercritical/cracking kerosene fuel was used to drive the turbo-pump to obtain a high pressure of the cold kerosene fuel at the entrance of the cooling channel. In the end, the supercritical/cracking kerosene from the turbine exit is injected into the scramjet combustor. Such supercritical/cracking kerosene fuel can decrease the fuel-air mixing length and increase the combustion efficiency, due to the gas state and low molecular weight of the cracking fuel. In order to ignite the cold kerosene in the start-up stage, the ethylene-assisted ignition subsystem was applied. In the present paper, operating modes and characteristics of the expansion cycle system are first described. And then, the overall design of the system and the characterisitics of the start-up process are analyzed numerically to investigate effects of the system parameters on the scramjet start-up performance. The results show that the expansion cycle system proposed in this paper can work well under typical conditions. The research work in this paper can help to make a solid foundation for the research on the coupling characteristics between the dynamics and thermodynamics of the scramjet expansion cycle system.

**Keywords: scramjet; supercritical/cracking hydrocarbon; regenerative cooling; expansion cycle**

## Introduction

As an economical and effective propulsion system for hypersonic cruise and space access, scramjet engines have attracted much research since sixty years ago. And a great amount of key scramjet technologies have been developed and demonstrated by numerical simulations, ground tests, and flight experiments such as X-43A and X-51A[1-3]. However, there are still many obstacles for further development of scramjet engine.

In order to make the scramjet engine operate in a wide range of Mach number and altitude for a long time, an effective scramjet control system, which can provide thermal protection for the combustor and the fuel supply system, is pre-requisite. As a key part of the scramjet control system, the scramjet engine system cycle and system integration technology has a great influence on the performance of the control system.

Fuel regenerative cooling is an attracting technology which can be used for thermal protection of the hydrocarbon scramjet. Furthermore, the supercritical/cracking hydrocarbon fuel formed after regeneration in the cooling

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channel can significantly improve the combustion performance within the scramjet combustor. The hydrocarbon fuel regenerative cooling technologies including the fuel physical/chemical properties, the heat transfer and the combustion have been studied widely [4-6].

The fuel supply and control system is one of the key technologies in scramjet engines. Because of the low cubage efficiency and the drawbacks of the high pressure extrusion fuel supply system in X-43A and the batteries-based motor pump system in X-51A, these fuel supply systems are restricted for the long-time hypersonic cruise vehicle. Therefore, a new expansion cycle system for scramjet engines including the hydrocarbon-based (the kerosene) regenerative cooling channel and the supercritical hydrocarbon-based turbo-pump fuel supply system was proposed and analyzed numerically in this paper.

The new scheme is different from the liquid hydrogen fuel expansion cycle system of rocket engines. For the new scheme proposed in this paper, the supercritical/cracking hydrocarbon fuel with high pressure and temperature formed in regenerative cooling channel. And then, the supercritical/cracking fuel from the exit of the cooling channel was used to drive turbo-pump to obtain a high pressure in the cold fuel at the entrance of the cooling channel. At last, the hot hydrocarbon from the turbine exit was injected to the combustor.

The entire expansion cycle system was first modeled numerically. Then the heat release analysis of the supersonic combustion, the heat transfer analysis, the operation analysis of the turbo-pump, system parameters design, and the analysis of the scramjet start-up process were carried out.

The hydrocarbon fuel regenerative cooling system and expansion cycle scheme has a potential in solving the problems such as high combustion performance, fuel supply efficiency, and long duration thermal protection and having advantages of simple configuration, light weight and high efficiency.

## System Cycle and Coupling Characteristics

### Expansion Cycle Scheme

It is a key process in the hydrocarbon expansion cycle of scramjet engines that the supercritical/ cracking hydrocarbon fuel produced by the regenerative cooling is used to drive the turbo-pump for fuel pressurization. The supercritical/cracking hydrocarbon fuel is composed of about 50% methane, 20% ethylene, 10% ethane, 8% propylene, 5% hydrogen and other compounds under the pressure of 4 MPa and the temperature of 800~900K. Therefore the supercritical/cracking hydrocarbon consists mostly of small molecular weight alkyl and alkene which are suitable to drive turbo-pump.

In order to ignite the cold kerosene in the start-up stage, the ethylene-assisted subsystem is used. The gaseous ethylene is proper for the ignition and combustion in a scramjet combustor, and can accelerate the heating up of the scramjet cooling channels. This technology has been successfully used in X-51A [7].

The expansion cycle scheme of the scramjet with an ethylene-assisted subsystem is shown in Fig.1. The key issue of the scramjet ignition, turbo-pump operation and heating of cooling channels need to be resolved during the start-up of scramjet. In order to deal with the couple and contradiction of different requirements for mass flow and pressure of fuel injection, regeneration cooling and turbine driving, it is necessary to control the fuel flow, which can be achieved by adopting flow adjusted valves including distributary valve V3, turbine flow adjust valves V4 and V5, cooling flow valve V6, and cold flow injection valve V7. These active valves are used to control the switch of ethylene and kerosene to achieve some requisite working modes of scramjet engines.

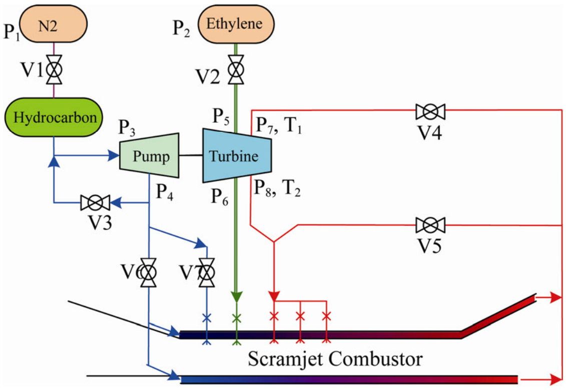

**Fig. 1** The expansion cycle scheme of the scramjet system with an ethylene assistant subsystem for engine start-up

There are three operating modes during the start-up process of a hydrocarbon expansion cycle scramjet. First, the turbo-pump is driven by the ethylene to pressurize the hydrocarbon fuel. And then, the ethylene from turbine exit is injected together with the hydrocarbon fuel to the combustor. At the same time, the cooling channels will be heated up rapidly. In this mode, valves V1, V2, V3 and V7 are opened, while others are closed. In the second mode, valve V6 will be opened and the cold hydrocarbon fuel is piped to cooling channels. Then the supercritical/cracking hydrocarbon is formed and injected to the combustor for increasing heat release. In the third mode, the ethylene is shut down, and the supercritical/cracking hydrocarbon is switched to drive turbo-pump, and injected to combustor in succession. Then, the hydrocarbon fuel expansion cycle process is set up, and the steady operating mode is realized consequently.

## Coupling Characteristics of System Dynamics and Thermodynamics

During the expansion cycle process of a scramjet engine, the state of turbine driving medium (ethylene or supercritical/cracking hydrocarbon) dominates the dynamic characteristics of the turbine pump. At the same time, the thermo physical properties of the supercritical/cracking hydrocarbon is influenced directly by the heat transfer during regeneration cooling, which is determined by the fuel injected conditions and the combustion heat release. Thus, the expansion cycle is a coupling loop of dynamics and thermodynamics process cycle system. The potential energy of turbine driving medium which acquired through heat transfer of the regenerative cooling and the combustion, is transformed into fuel pressurization by the turbo-pump rotation, as shown in Fig.2.

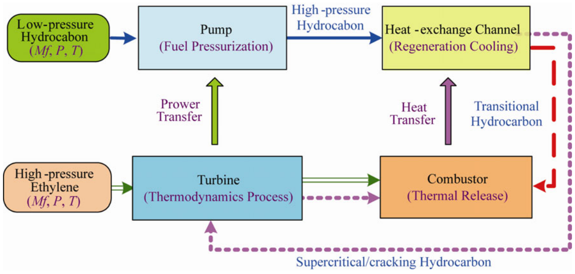

**Fig. 2** The coupling relationship of dynamics and thermodynamics for hydrocarbon expansion cycle scramjet

The state of kerosene is altered mostly during two phases. One is the regenerative cooling process where the cold liquid kerosene converts to supercritical/cracking kerosene. And the other is the turbo-pump thermodynamics process where the supercritical/cracking kerosene is expanded to produce turbine power and the cold kerosene is pressured by pump. Therefore, during the scramjet start-up, because of unsteady scramjet working state, the development of non-equilibrium state of the kerosene is coupled strongly with the combustion, heat transfer and thermodynamics cycle of the scramjet.

Accordingly, the thermodynamic and dynamic process of the expansion cycle scramjet system is complex because of the strong coupling of the combustion, flow and the heat transfer. It is a challenge for the system design, dynamic characteristic analysis and operating mode control.

## System Analysis Method

### Analysis procedure

It is difficult to build an exact dynamic analysis model because of the complicated coupling phenomena of the scramjet combustion, heat transfer and turbo-pump operation. A quasi-equilibrium analysis procedure is considered to acquire the operating parameters of the scramjet system. For every calculation step, a set of steady formula based on experiments is used to describe the combustion and heat transfer of the scramjet. At the same time, the mathematic models are used to describe the dynamic process of turbo- pump operation and kerosene state in cooling channels. The system analysis procedure of hydrocarbon expansion cycle scramjet is shown in Fig.3.

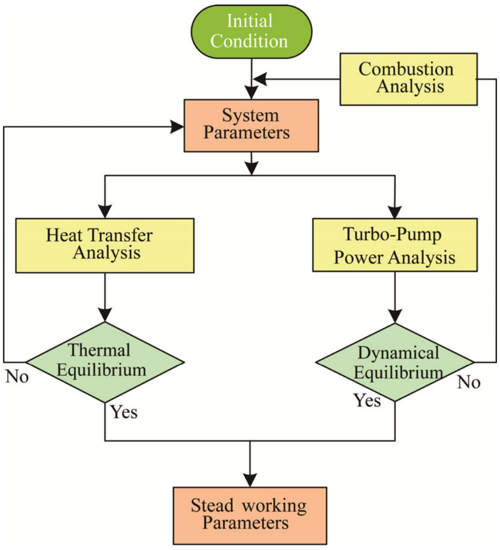

**Fig. 3** The system analysis procedure of a hydrocarbon expansion cycle scramjet

The initial scramjet parameters are first set based on the general requirements. At the beginning of the scramjet start-up, kerosene is pressured by a turbo-pump which is driven by the high pressure ethylene, and both fuels are injected for the combustion. Assuming that the combustion is completed immediately, the thermal condition is obtained at the current calculation step. And then, the heat transfer analysis of the combustor and the cooling channels will be carried out with other parameters unvaried in order to obtain the condition of supercritical/cracking kerosene. At other calculation steps, results of heat transfer analysis are used to calculate the power balance of the turbo-pump to obtain the condition of cold hydrocarbon pressurization and exhaust of turbine. The iteration process is performed to achieve the steady working status.

The analysis models for the heat release in the combustor, the heat transfer in the cooling channels, and the power analysis of the turbo-pump are described in the following section.

### Heat release analysis of combustor

An empirical formula for total temperature is used to calculate the total heat release in the scramjet combustor based on inflow conditions of scramjet combustor entrance and injection conditions of the fuel, as follows:

$$T_0^* = \frac{1}{\dot{m}_3 c_{p3}}\left(\dot{m}_1 c_{p1} T_1 + \dot{m}_1 \frac{v_1^2}{2} + \dot{m}_2 c_{p2} T_2 + \dot{m}_2 \frac{v_2^2}{2} + \dot{m}_2 q_f\right) \quad (1)$$

Where $v_1, \dot{m}_1$, $T_1$ and $c_{p1}$ are the velocity, mass flow rate, static temperature and specific heat of the air flow at combustor entrance respectively, which are determined by flight Mach number and altitude. $v_2, \dot{m}_2$, $T_2$ and $c_{p2}$ are the injection speed, mass flow rate, static temperature and specific heat of the supercritical/cracking kerosene, respectively which are determined by the heat transfer of regenerative cooling. $q_f$ is the heat flux released from the fuel combustion per unit mass flow. $\dot{m}_3$, $T_0^*$, $c_{p3}$ are the mass flow rate, total temperature and specific heat of combustion gas, respectively.

According to the law of mass flow conservation

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 \quad (2)$$

### Heat transfer analysis

There are two phases for the heat transfer of the scramjet regenerative cooling, one of which is the heat transfer from the combustor gas to the combustor wall. And the other is from the combustor wall to the hydrocarbon fuel through cooling channels.

The heat transfer between combustor gas and combustor wall can be evaluated by the method of Eckert reference enthalpy [8]. The heat transfer between combustor wall and cooling fuel can be evaluated by the method of the forced convective heat transfer of the turbulence in pipe [9].

During the scramjet start-up process, the wall temperature increases rapidly until the thermal equilibrium. The hot wall temperature variation process can be expressed as follows:

$$\frac{dT_w}{dt} = \frac{(q_w - q_c)s}{mc} \quad (3)$$

Where $q_w$ and $q_c$ are the heat flux of the hot wall side and the cold wall side respectively. $s$ is the area of wall, and $m$ is the mass of the combustor wall. $c$ is the specific heat capacity of the combustor material。

### Operation analysis of turbo-pump

The output power of the pump $P_{pef}$ is calculated as follows:

$$P_{pef} = q_{mp} g H_p = q_{mv}(P_{p2} - P_{p1}) \quad (4)$$

Where $q_{mp}$ is the mass flow rate of the pump, and $g$ is the gravitational acceleration. $H_p$ is the delivery-head of the pump, and $q_{mv}$ is the volume flow rate of pump. $P_{p1}$ and $P_{p2}$ are the pressure at the pump entrance and exit respectively.

The output power of turbine $P_t$ is calculated as follows:

$$P_t = q_{mt} L_{ad} \eta_t \quad (5)$$

Where $q_{mt}$ is the mass flow rate of turbine medium (ethylene or supercritical/cracking kerosene), $\eta_t$ is the efficiency of turbine. $L_{ad}$ is equivalent entropy expansion power of turbine driven by unit mass medium, and can be computed by:

$$L_{ad} = \frac{k}{k-1} R T_0^* \left[1 - \left(\frac{P_{t2}}{P_0^*}\right)^{\frac{k-1}{k}}\right] \quad (6)$$

Where $k$, $R$, $T_0^*$, and $P_0^*$ are the specific heat ratio, the gas constant, the total temperature and the total pressure of medium at the turbine entrance, respectively. $P_{t2}$ is the static pressure of medium at turbine exit.

According to the momentum conservation law, the turbo-pump momentum conservation equation can be expressed as follow:

$$J\omega \frac{d\omega}{dt} = P_t - P_p \quad (7)$$

Where $J$, $\omega$ are the moment of inertia and the rotational speed of turbo-pump respectively. $P_t$ is the power of turbine, and the $P_p$ is the input power of the pump.

## Results of Design and Analysis

### System parameters design

Suppose the kerosene fuel mass flow rate is 1.5kg/s during scramjet operated at the cruise status. The system parameters of the scramjet under the steady operation state are designed as shown in Table 1.

**Table 1** The Parameters of the Scramjet System operated at the cruise flight

| Parameters | NOMENCLATURE | Value |
|---|---|---|
| $\dot{m}_1$ | Mass flow rate of air (kg/s) | 22.2 |
| $\dot{m}_2$ | Mass flow rate of hydrocarbon fuel (kg/s) | 1.5 |
| $P_{p1}$ | Up flow fuel pressure at pump (MPa) | 0.2 |
| $P_{p2}$ | Down flow fuel pressure at pump (MPa) | 8.0 |
| $P_{t1}$ | Up flow fuel pressure at turbine (MPa) | 3.5 |
| $P_{t2}$ | Down flow fuel pressure at turbine (MPa) | 2.0 |
| $P_{pef}$ | Output power of pump (kW) | 14.7 |
| $P_t$ | Output power of turbine (kW) | 57.0 |
| $T_c$ | Supercritical/cracking fuel temperature of cooling channels exit (K) | 920 |
| $\omega$ | Rotational speed of turbo-pump (r/min) | 25000 |

### Analysis of the scramjet start-up process

The analysis of the scramjet start-up process is performed by dynamic simulation. The temperature variations of the combustion chamber wall and the fuel at cooling channel exit can reflect the start process distinctly as shown in Fig. 4. $T_w$ is the temperature of the combustor wall, and $T_c$ is the temperature of the supercritical/cracking fuel temperature at the cooling channels exit.

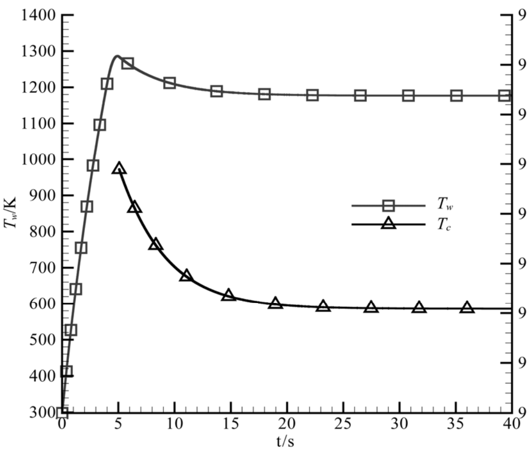

**Fig.4** Variations of the wall temperature $T_w$ and the fuel temperature $T_c$

In order to accelerate the start-up process by decreasing the time of the combustor heating up, it is necessary to choose an appropriate time to pump the cold hydrocarbon fuel into the cooling channel. When the temperature of the combustion chamber wall reaches a desired temperature, the cold liquid fuel is switched into the cooling channel to cool the combustion chamber. As shown in Fig.4, the temperature of the combustor wall increases rapidly at the beginning. When the cold hydrocarbon fuel enter the cooling channel at $t$=5s, the wall temperature descends gradually to a steady value which is equal to about 928K.

In the start-up stage, the turbine is first driven by the ethylene. When the temperature of the combustor wall increase beyond a critical value, the cold fuel is switched to the cooling channel, and is immediately converted into the supercritical/cracking state fuel which is used to drive turbo-pump. In the end, the heat transfer between the combustor wall, the cooling channel and the fuel gradually to a balanced state.

Fig.5 shows the operation process of turbo- pump with the main parameters including the mass flow rate of the pump $q_{mp}$, the turbine power $P_t$ and the pump power $P_p$. In the beginning, the turbo-pump is driven by the ethylene with a constant mass flow rate and pressure, and thus the output power and rotating speed of the turbine increases almost linearly. Therefore, the mass flow rate and the power of the pump increase correspondingly. When the supercritical/cracking fuel is switched to drive the turbine, the driving power has reduced remarkably, and the rotating speed of the turbine pump increases slowly with lower acceleration until a power balance is reached.

The effect of the switch time of the turbine driven gas on the scramjet start-up process is also analyzed. Fig. 6 shows curves of the combustor wall temperature and the supercritical/cracking fuel temperature at the exit of the cooling channels under the condition of three different switch times. There is considerable difference in the initial period of start-up process between the different conditions while almost the same balance state of the system is reached. Therefore, the time of the coolant fuel switched to the cooling channel has a significant effect on the maximum value of the combustor wall temperature. If the switch time point is too late, the wall temperature will become too high and fail the wall material. If the switch time point is too early, the supercritical/ cracking state fuel may have insufficient potential energy for driving the turbine pump, which can cause the failure of the scramjet start-up.

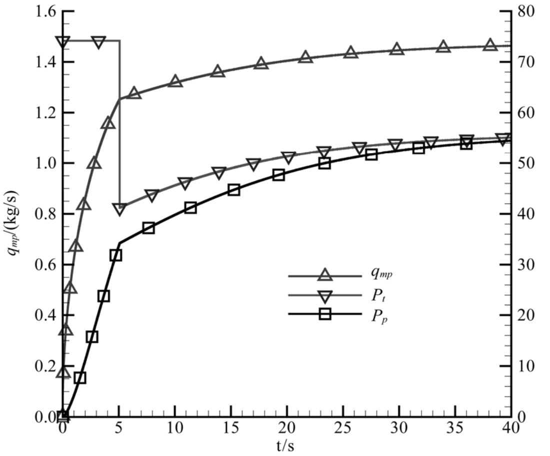

**Fig. 5** Variations of the mass flow rate of the pump $q_{mp}$, the turbine power $P_t$, and the pump power $P_p$

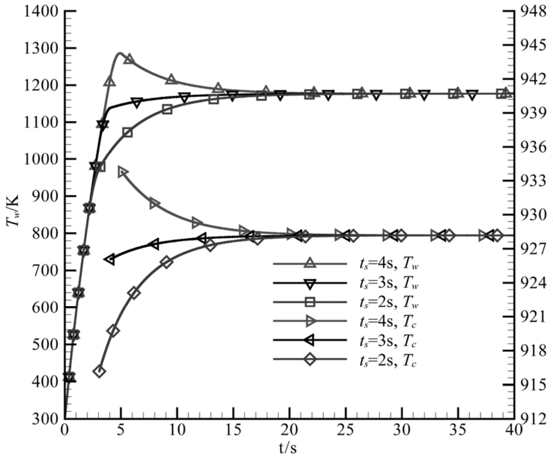

**Fig. 6** Variations of the combustor wall temperature $T_w$ and the cooling fuel temperature $T_c$ under the condition of the different switch time $t_s$

It's very important to get a successful design in the cooling channel design process, in order to enhance the heat transfer efficiency. The effect of the channel aspect ratio (ratio of the width of the cooling channel *b* to the width of the channel rib *i*) on the scramjet start-up process is analyzed and demonstrated in Fig.7. The simulation results show that the heat transfer can be enhanced by increasing the cooling channel aspect ratio. And the combustor wall temperature will decrease and the supercritical/cracking kerosene fuel temperature at the cooling channel outlet will increase when the cooling channel aspect ratio increase gradually. With the augment of the cooling channel aspect ratio, the hydraulic area of the channel decreases. This can enhance the convective heat transfer in the cooling channels, while the flow resistance will also increase.

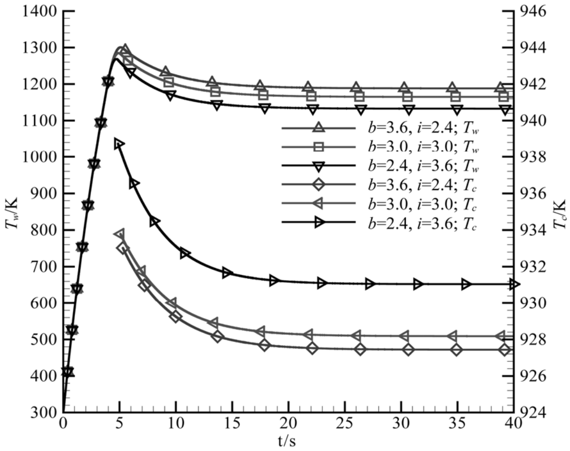

**Fig. 7** Variations of the combustor wall temperature $T_w$ and the cooling fuel temperature $T_c$ under condition of different channel aspect ratio

## Conclusions

The design and analysis of the scramjet system with hydrocarbon fuel regenerative cooling and turbine pump fuel supply system was discussed. It is a creative scheme that the supercritical/cracking hydrocarbon fuel with a high pressure and temperature produced by regenerative cooling is used to drive turbo-pump to supply hydrocarbon fuel. This scheme is beneficial for combustion organization, fuel supply and thermal protection with advantages of simple configuration, light weight and high efficiency. Some valuable conclusions have been driven through ground tests.

Since there is a strong coupling between the complex thermodynamic and dynamic process, it is a huge challenge for the system design, the dynamic characteristics analysis and the operating mode control. According to the present results of the system design and analysis, this system scheme is feasible, and will be adopted prospectively for hypersonic cruise vehicle in the future.

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