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Experimental study on chemical recuperation process of endothermic hydrocarbon fuel

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HIGHLIGHTS

- ▶ Endothermic hydrocarbon fueled scramjet is a chemical recuperation cycle.
- ▶ An experiment platform of chemical recuperation of endothermic hydrocarbon fuel is built.
- ▶ The recuperation of hydrocarbon fuel consists of chemical and physical recuperation.
- ▶ The recuperation effectiveness can be influenced by temperature and residence time.
- ▶ The total effectiveness of recuperation of endothermic hydrocarbon fuel can go up by 10%.

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ABSTRACT

The thermodynamic cycle of an endothermic hydrocarbon fuel cooled scramjet is a chemical recuperation cycle. An experimental system is built, and a series of comparisons are made at different fuel cooling conditions to investigate the influence of different factors on the chemical recuperation process of endothermic reaction of hydrocarbon fuel and the law governing the chemical recuperation process. Experimental results indicate that the recuperation process of endothermic hydrocarbon fuel consists of chemical and physical recuperation processes. The effectiveness of physical and chemical recuperations can be improved by increasing fuel heating temperature. And the effectiveness of chemical recuperation can also be influenced by the residence time of fuel in the chemical reactor. The low fuel flow rate and high working pressure of fuel can help the improvement of the effectiveness of chemical recuperation, the total effectiveness of recuperation of endothermic hydrocarbon fuel can go up by 10%.

1. Introduction

It is a significant challenge to do well the thermal management of fuel in an advanced aeroengine used to power aircraft, rocket, and or missile. As flight speed increases to a supersonic or hypersonic regime, the temperature of ram air taken on board a vehicle becomes so high that fuel has to be used as a primary coolant to cool the structure of vehicle [1]. The engines used to power future aircraft are projected to operate at high pressures and fuel/air ratios, which greatly increases the heat loads and exacerbate the thermal management task.

Thermal management has become one of the major concerns, and scramjet is one type of advanced aeroengine with the largest heat load. In order to meet the thermal management requirement for an aeroengine with a high flight Mach number, endothermic hydrocarbon fuel is used to replace the conventional hydrocarbon fuel and to provide extra heat sink for cooling through endothermic catalytic reaction and [2]. Because the heat sink of a conventional hydrocarbon fuel is limited by its sensible-heat cooling capacity [3].

Fuel flows through the cooling passage to cool the engine wall before it is used for combustion in regenerative cooling [4]. Wasted heat absorbed from engine thermal structure through regenerative cooling is reinjected to produce thrust. Therefore, regenerative cooling is thus a recovery process of wasted heat in an engine, the working process of a fuel cooled scramjet is a recuperative cycle [5]. The thermodynamic cycle of an endothermic hydrocarbon fuel cooled scramjet is a chemically more efficient regenerative cycle with a chemical reaction taking place in the heat recuperation process and thermal energy being converted into chemical energy.

While the cooling process of endothermic hydrocarbon fuel is complex, and so it is necessary to analyze the influence of different factors and the law governing the chemical recuperation characteristics of fuel. Meanwhile, the actual utilization level of heat sink and the actual level of chemical recuperation effectiveness must

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Nomenclature

C_p	specific heat of fuel, kJ/kg K	*Subscripts*	
H	heat value, J/kg	$A, B, C, \ldots$	products
I	current, A	c	cracked products
M	molar mass	*chem*	chemical
m	mass flow rate, kg/s	f	fuel
Q	heat, J	g	gas
R	recuperation effectiveness	l	liquid
T	temperature	*loss*	heat loss
U	voltage, V	*phy*	physical
V	volumetric flow rate of gas component	*res*	remaining non-cracking fuel
v	mole fractions	s	unreacted fuel
Z	conversion rate	*total*	total

be established with the restriction of the heat transfer, etc. taken into consideration, because the chemical recuperation process is carried out on the premise that the cooling passage wall temperature is under the allowable wall material temperature and the cooling passage itself is also a chemical recuperation reactor [6].

In order to analyze the influence of different factors on the chemical recuperation process of endothermic hydrocarbon fuel and the law governing the chemical recuperation characteristics of fuel, and reveal the particularity of chemical recuperation process of endothermic hydrocarbon fuel, an experimental system is built, and a series of comparative experiments are made with different fuel cooling operation parameters.

2. Working principle of chemically recuperated scramjet

The major components of a scramjet include inlet, isolator, combustor and nozzle, and there is no rotary component in the scramjet. Hypersonic free stream air is compressed in the scramjet inlet, and then the air enters into the combustor and completes the supersonic combustion with reinjected fuel. High-temperature and high-pressure air accelerates to be hypersonic in the nozzle and finally is released into atmosphere [7].

The working process of a regeneratively cooled scramjet is as shown in Fig. 1 above, from the view point of recuperation in the following sequence. The heat is dissipated and taken away through engine wall in the cooling passage cooled by fuel. This part of dissipated heat is brought back by fuel after cooling and is reinjected into the combustor to complete the combustion to produce thrust, i.e., the dissipated heat is thus recovered through fuel cooling. The heat recovered consists of two parts of heat recovered through physical recuperation and chemical recuperation.

The cooling passage is actually a chemical recuperative exchanger due to the chemical reaction accompanied with heat absorption. When endothermic hydrocarbon fuel is heated to a sufficiently high temperature, a thermal cracking reaction occurs, and a great amount of heat is needed to provide the reaction. Eventually, high-temperature pyrolysis mixture enters the combustor to complete the supersonic combustion. Fuel cooling makes the engine cycle capable of working at a higher temperature, which is useful to obtain higher cycle performance.

While thermal energy is converted to chemical energy through chemical recuperation, the conversion from physical energy to chemical energy is realized, and the energy grade of the whole scramjet is raised. Therefore, an endothermic hydrocarbon fuel scramjet can be regarded as the most advanced working cycle among various aeroengine cycles to some extent.

3. Experimental system and analytical method

The experimental system of the flow, heat transfer and cracking of endothermic hydrocarbon fuel at high temperature and high pressure is chosen as the experimental study platform of the chemical recuperation process in a scramjet. A system with electric heating is adopted in this article because the system can be used to properly simulate the real heating procedure with the combustion in the engine. The heat flux and the characteristic size of a cooling passage in the system are in good agreement with those of a real engine.

3.1. Experimental apparatus

As shown in Fig. 2, the flow schematic routing of an experimental set-up is built for the investigation of the chemical recuperation

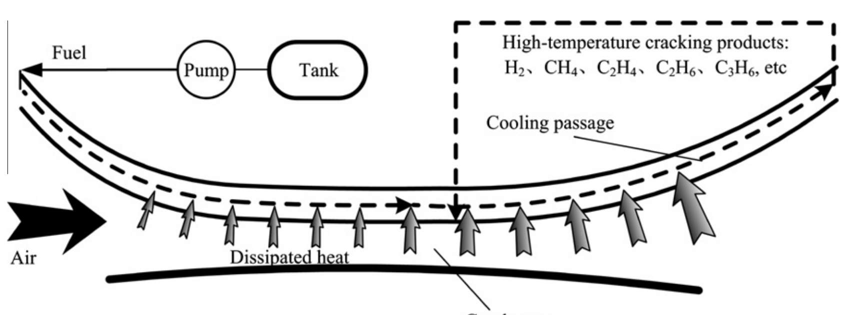

Fig. 1. T–S diagram of chemically recuperated scramjet.