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Thermal management of fuel in advanced aeroengine in view of chemical recuperation

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ABSTRACT

Advanced aeroengine with endothermic hydrocarbon fuel cooling works as chemical recuperative cycle. In order to study the thermal management of fuel in view of chemical recuperation, models of flowing cracked hydrocarbon fuel inside engine cooling channels are developed and validated. Based on 1-D model, different methods are put forwarded to control the chemical recuperation effectiveness and effective residence time is defined to distinguish global methods and local methods. The control of fuel mass flow rate or height of cooling channel can be regarded as global methods, while the control of operating pressure can be considered as a local method. The efficiency of the global method is limited by the allowable wall temperature. In contrast, the local method can both control the chemical recuperation effectiveness and improve the heat transfer performance. Based on the multiple dimensional models, conclusions got from the 1-D model can be modified and extended. The results of multiple dimensional models show that 3-D phenomena have significant effects on the chemical recuperation effectiveness. Nonuniformities of temperature and conversion caused by the 3-D phenomena are bad for improving the chemical recuperation effectiveness. Reduction of the cooling channel width is good for improving the conversion and the chemical recuperation effectiveness.

1. Introduction

Thermal management and energy utilization of all kinds of energy system have been continuing hot issues because of the limited energy resources: researchers have employed ammonia-water power/cooling cycle in Gas Turbine-Modular Helium Reactor to recover the waste heat [1], evaluated the performance and selected suitable parameter and reciprocating piston expander to better recover the waste heat of ICE (internal combustion engine) [2] etc. And for advanced aeroengines used to power aircraft, rockets, and missiles, thermal management is also a significant challenge. As flight speed increases to a supersonic or hypersonic regime, the temperature of ram air taken on board a vehicle becomes very high and the fuel is used as the primary coolant to cool the structure of vehicle [3]. In addition, for scramjet, the one with the largest heat load of all the advanced aeroengines, endothermic hydrocarbon fuels has to be used to replace the conventional hydrocarbon fuel and to provide extra heat sink for cooling through endothermic thermal cracking [4].

The heat absorbed through regenerative cooling is re-injected to produce thrust, which helps the improvement of engine performance. And this part of heat is the wasted heat dissipated from engine thermal structure, regenerative cooling is thus the recovery process of wasted heat in the engine. Therefore, the working process of a fuel cooled scramjet is actually a recuperative cycle. Especially, the thermodynamic cycle of an endothermic hydrocarbon fuel cooled scramjet is a chemically more efficient regenerative cycle, because a chemical reaction takes place in the heat recuperation process and thermal energy is converted into chemical energy. The energy grade of the whole scramjet is raised.

Chemical recuperation, which was always discussed in the reheat gas turbine cycles, is not a new word. Harvey S and Kane N.D. used aspen to analyze the chemical recuperation realized by steam reformer technically [5]. Heppenstall T. et al. pointed out that it is beneficial to use chemical recover cycle despite of its complexity [6]. Verkhivker G. and Kravchenko V. found that high pressure is good for improving the efficiency of the chemical recuperation [7].

However, for a scramjet engine, chemical recuperation is a newly established concept. Currently, more attention and efforts are being paid to studying and improving the fuel heat sink in a scramjet cooling system. A lot of work is being carried out about catalyst selection, heat transfer, thermal cracking, coke

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inhibition etc [8–10]. Recently, Jiang Qin et al. have conducted a study about the influencing factors of the fuel heat sink utilization and the methods to control it [11].

During the study of utilizing the fuel heat sink, some researches indicated that gas with smaller carbon molecules generated through cracking could help improve the combustion efficiency, and supersonic combustion with cracked gas mixture was also investigated [12]. From the view point of the whole engine, the effect of heat absorption and endothermic reaction on the engine performance has been investigated by Qin Jiang et al. [13]. And fuel cooling is regarded as a heat recuperation process. It has been pointed that a chemically recuperated scramjet cycle is an advanced aeroengine cycle. Physical and chemical recuperation effectivenesses are defined and both their effects on the engine performances are analyzed.

The previous studies have shown the methods to improve heat sink utilization and the effects of the chemical recuperation process on the engine performances. However, no work has been done to study the influencing factors on the physical and chemical recuperation effectivenesses and the way to improve them. And the research results of the chemical recuperation in a gas turbine cycle can not be simply used in a scramjet engine because in a scramjet engine, the cooling performances must be considered when trying to improve the recuperation effectiveness. So, in view of chemical recuperation, with a scramjet used as the object of study and endothermic hydrocarbon fuel used for cooling of the scramjet, 1-D model of the fuel cooling system is built to study the influencing factors of the physical and chemical recuperation effectivenesses and the way to improve them in a real engine. Multi-dimensional models are also built to study the effects of 3-D phenomenon on the recuperation effectiveness.

2. Physical model and boundary conditions

As shown in Fig. 1, the combustor section of the scramjet are encircled by cooling channels which can be described using channel width (W), channel height (H), fin thickness (t), and heated wall thickness (s) and it experiences the highest heat flux. The typical ramp heat fluxes of a scramjet vary from 2 to 20 MW/m^2.

The working process of the cooling system can be described as follows: the fuel of the engine is firstly pumped into the cooling channels to fully cool the thermal structure of the engine, and then the heated fuel is injected into the combustor as propellant to generate the thrust. In order to avoid the heat transfer deterioration caused by boiling phenomenon, the pressure in the cooling channels is kept above the critical pressure of the fuel.

Both the even heated pipe and asymmetrical heated rectangular ducts are adopted as physical model for comparison and experimental validation. The reason why an even heated pipe is adopted to compare with the experiments is that in an experiment aiming to simulate the cooling procedure in an advanced engine, the pipe heated by electric is always used limited by the experimental condition. The rectangular ducts are adopted to simulate the real engine cooling channel which is asymmetrical heated. The physical models and boundary conditions presented in this paper are based on what is presented by Wen Bao and Silong Zhang in Ref. [14]. The details are listed below.

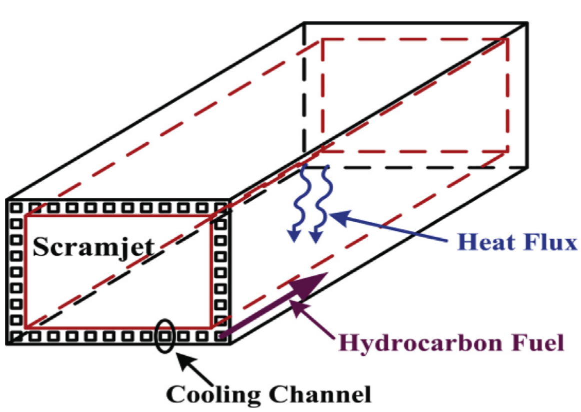

Fig. 1. Scheme of the cooling channel of the engine.

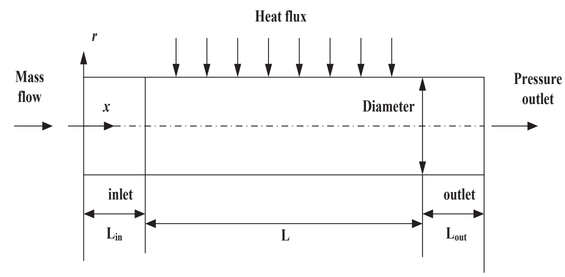

Fig. 2. Schematic diagram of even heated pipe and its boundary conditions.

Fig. 2 shows the physical model of uniformly heated horizontal pipe and its boundary conditions. The inlet section shown in Fig. 2 is used to realize a fully developed flow field before the heat transfer process starts, and the outlet unheated section is included to avoid the effect of pressure outlet boundary condition on the numerical results. During the calculation, the inlet fuel mass flow rate m_f, the inlet temperature T_i and the outlet pressure P_o are given as the boundary conditions according to the experiments. The wall heat flux for the heated section $q_{(x)}$ is given according to the experiments and the wall heat flux for the unheated section is 0. All the walls in the models are non-slipping.

Fig. 3 shows the physical model of asymmetrically heated rectangular duct and its boundary conditions. As we can see from Figs. 2 and 3, the only difference between the two models is the shape of the cross section and they have the same boundary conditions except the boundary conditions for the walls. For the inlet and outlet sections, the heat flux of the four sides is set to be 0. For the heated section, the heat flux of the down side wall is set to be $q(z)$ and it does not vary along the x or y axis. The other three sides of the heated section are set to be adiabatic.

3. Computational model

3.1. One-dimensional model

An one-dimensional model is usually used to study the flow and heat transfer characteristics of a reactive flow and design the

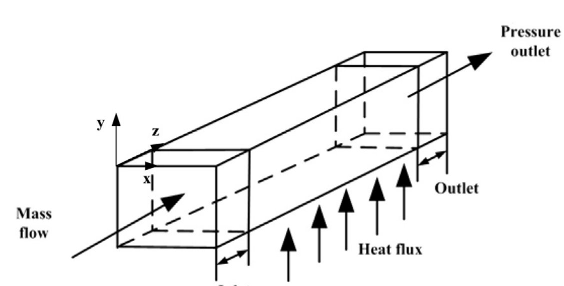

Fig. 3. Schematic diagram of asymmetrically heated rectangular duct and its boundary conditions.