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Study on combustion mode transition of hydrogen fueled dual-mode scramjet engine based on thermodynamic cycle analysis

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ABSTRACT

Hydrogen fueled scramjet is a candidate for use as the engine of the aerospace plane for its high specific impulse. To further improve the engine performance, analysis of combustion mode transition for a hydrogen fueled scramjet engine was investigated in this study. In order to identify the differences between Scram- and Ram-mode cycles in propulsive and economic performances for selection and optimization of operation modes, a thermodynamic cycle analysis was made with a dual-mode scramjet engine. It was found through comparative analysis that the specific impulse of the Ram-mode cycle was superior to that of the Scram-mode cycle in meeting the specific thrust requirement. From the viewpoint of performance optimization, the combustion mode transition in a dual-mode scramjet engine should occur in the range of Mach number 6–7. It was therefore concluded that a dual-mode scramjet engine should be operated as much at the Ram-mode cycle as possible when the flight Mach number is less than 6, and the combustion mode transition between Ram-mode cycle and Scram-mode cycle should take place in the range of flight Mach number 6–7.

Introduction

There is now a great interest in the study and development of hydrogen fueled dual-mode scramjet engine for hypersonic flight applications. Hydrogen possesses superior characteristics to any other hydrocarbon fuel in terms of ignitability, low ignition delay, and higher flame stability. These inherent advantages turn it received increased attention [1–5]. The wide range operation of scramjet engine depends on the combustion mode transitions during the ascent trajectory. In addition, a reasonable selection of combustion mode can reduce the heat load effectively. Therefore, the combustion mode transition becomes a hot topic in current research on the scramjet engine [6,7].

A scramjet engine is very similar to a ramjet engine except that the combustion process in a scramjet engine occurs in the supersonic condition. A major impetus of the enthusiasm for the study on a scramjet engine is that the specific thrust of a scramjet engine surpasses that of any other propulsion system when the flight speed exceeds Mach number 6 [8]. The performance analysis and evaluation for a dual-mode

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Nomenclature

C_p	constant-pressure specific heat capacity, J/(kg·K)
f	fuel-to-air ratio
F	thrust, N
F_s	specific thrust, m/s
g	standard acceleration of gravity, 9.81 m/s^2
H_{PR}	lower heating value of fuel, J/kg
I_{sp}	specific impulse, s
k	specific heat ratio
$\dot{m}_0$	mass flow rate of air, kg/s
$\dot{m}_f$	mass flow rate of fuel, kg/s
M	Mach number
M_0^*	upper limit of Mach number for Ram-mode cycle operation
p	pressure, Pa
q	heat added or rejected per unit mass of air, J/kg
$\tilde{q}$	nondimensional heat added, $q_{add}/(C_p T_0)$
T	temperature, K
T_{max}	material temperature limit, K
s	specific entropy, J/(kg·K)
V	velocity, m/s
η_{th}	thermal efficiency
ψ	compression static temperature-rise ratio

Subscripts

0	state of freestream
3	state of isentropic compressed flow
3a	state after shock wave compression for Ram-mode cycle
3b	state of combustor entry for Ram-mode cycle
4	state of combustor exit
10	state of exit of expansion process
rej	heat rejection
add	heat addition
shock	shock wave compression

scramjet engine is therefore one of the key research subjects for an engine designer [9–14]. The performance analysis and evaluation for a dual-mode scramjet engine aims at the identification of an "optimal" operation mode and a mode transition point in an engineering sense from the thermodynamic point of view.

The theoretical basis for the performance analysis of an engine is the thermodynamic cycle analysis, which can be used to achieve a better understanding of the performance for an engine over its operating range. The thermodynamic cycle analysis of some aero-engines, just as turbojet and ramjet, are based on the Brayton cycle, which consists of two adiabatic and two constant-pressure processes [10,11]. For an ideal scramjet engine, the previous analyses of its thermodynamic performance were also based on the Brayton cycle as the inheritance of past research works [10–13]. Segal [14] and Prisell [15] discussed the performance and feasibility of a scramjet engine in detail from the viewpoint of thermodynamic cycle analysis. Roux [16–18] presented a Brayton cycle-based parametric cycle analysis for an ideal scramjet and discussed the cycle performance of a scramjet engine under some assumptions. The combustion process was assumed to occur at a constant pressure and a constant combustion Mach number, which implies that the total pressure remains constant throughout the combustion process. This assumption is incomprehensible because the heat addition in the supersonic flow could cause an inevitable loss of total pressure.

Generally heat is added into the flow at a combustion Mach number less than 0.3 in a ramjet engine and the residence time of reacted gas is long enough for the propagation and balance of static pressure [19]. Unlike the ramjet, the combustion process in a scramjet engine takes place at a supersonic speed. The combustion Mach number is approximately one third of M_0 [14]. The reacted gas leaves the combustor before the pressure becomes completely balanced [14]. Consequently the simplification of constant-pressure process in the combustor is not entirely appropriate for the performance analysis of a scramjet engine, and in reality, the combustion process in a scramjet is a complex polytropic process [14]. Therefore, one motivation of this study is to find a more realistic way for analyzing the performance of a scramjet engine in the viewpoint of thermodynamic cycle.

In order to broaden the operating range, a scramjet engine is always designed for dual-mode operation. Ram-mode is preferred at a low flight Mach number and as the flight Mach number increases, Scram-mode becomes the favored operation mode [20]. The difference in performance between the Scram-mode and Ram-mode comes from the difference in thermodynamic cycle [19]. For an ideal Scram-mode cycle, the compression and expansion processes become idealized isentropic processes and heat is released through supersonic combustion. For an ideal Ram-mode cycle, the flow at the exit of combustor is thermally choked and heat is added into the flow through subsonic combustion. The isentropic compressed flow is compressed once again by a normal shock to make the supersonic flow a subsonic flow. So the entropy increase in Scram-mode is caused by the heat addition process only, meanwhile the entropy increase in Ram-mode consists of a heat addition process and a normal shock compression.

Therefore, a thermodynamic cycle was made with a dual-mode scramjet engine for the purpose of identifying the differences between Scram- and Ram-mode cycles in propulsive and economic performances for selection and optimization of operation modes. It was found through comparative analysis that the specific impulse of the Ram-mode cycle was superior to that of the Scram-mode cycle in meeting the specific thrust requirement.

Ideal thermodynamic cycle analysis

General description of thermodynamic cycle

Fig. 1 shows the physical model of a scramjet engine. A model of scramjet includes an inlet, an isolator, a combustor and a nozzle. As shown in Fig. 2, a thermodynamic cycle is always consists of compression, combustion, expansion and heat release processes. To simplify the analysis, the following assumptions were used here: 1) thermodynamic equilibrium, 2) calorically perfect gas conditions of constant properties, and