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Thermodynamic analysis on optimum performance of scramjet engine at high Mach numbers

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ABSTRACT

In order to predict the maximum performance of scramjet engine at flight conditions with high freestream Mach numbers, a thermodynamic model of Brayton cycle was utilized to analyze the effects of inlet pressure ratio, fuel equivalence ratio and the upper limit of gas temperature to the specific thrust and the fuel impulse of the scramjet considering the characteristics of non-isentropic compression in the inlet. The results show that both the inlet efficiency and the temperature limit in the combustor have remarkable effects on the overall engine performances. Different with the ideal Brayton cycles assuming isentropic compression without upper limit of gas temperature, both the maximum specific thrust and the maximum fuel impulse of a scramjet present non-monotonic trends against the fuel equivalence ratio in this study. Considering the empirical design efficiencies of inlet, there is a wide range of fuel equivalence ratios in which the fuel impulses remain at high values. Moreover, the maximum specific thrust can also be achieved with a fuel equivalence ratio near this range. Therefore, it is possible to achieve an overall high performance in a scramjet at high Mach numbers.

1. Introduction

Scramjet engine is believed to be a promising power for hypersonic flight vehicles such as cruise missiles and high speed aeroplanes [1,2]. Combined with rocket engine to form the RBCC (Rocket Based Combined Cycle) [3], it has the potential to achieve more affordable access to space by SSTO (single-stage-to-orbit) launch vehicle. Recent successful flight tests [4,5] have further proved its potential value in hypersonic flight. As shown in Fig. 1, compared to the rocket engine, the scramjet has a much greater fuel impulse [2], which makes it more economic for long range flight. However, the net thrust of scramjet is lower than rocket [6], meaning that the scramjet is not very suitable for accelerating missions. Therefore, long range vehicles cruising at hypersonic speeds will benefit the most from being propelled by scramjets.

There are two basic operation modes in a scramjet combustor including ram-mode and scram-mode. The mode transition will occur under particular conditions. Billig [7] firstly demonstrated mode transition in ground experiment. A ram-scram mode transition was studied by a direct-connect model scramjet experiment by Fotia [8]. The effects of fuel injection on mode transition were numerically studied by Huang [9]. Based on the previous work, Yang [10] analyzed the mechanism of mode transition from the point of engine operation. Generally, the scramjet engine works at ram-mode with a relatively low freestream Mach number and a high fuel equivalence ratio. The characteristics of this mode are that the main flow into the combustor is compressed to subsonic speed by the pre-combustion shock train in the isolator and the flow is thermally choked in the combustor. However, when the freestream Mach number increases or the fuel equivalence ratio decreases, the thermal choking in the combustor may not be achieved and the shock train in the isolator becomes weak, making the flow into the combustor supersonic, namely scram-mode. The operation modes have great effects on the engine performance. In general, better performance can be obtained with ram-mode at a relatively low freestream Mach number while scram-mode is preferred at high Mach numbers [11].

From the point of thermodynamic cycle analysis, the mode choice is actually a tradeoff between the irreversible loss in the compression process caused by shock waves and wall friction and the Rayleigh loss in the combustion process, which is proportional to the square of Mach number in the combustor. On the working conditions with low freestream Mach numbers, the compression

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Nomenclature

$a_1 \sim a_7$	constants
c_p	constant pressure specific heat, J/(kg·K)
F_a	specific thrust, N/(kg/s)
g	acceleration of gravity, m/s^2
h	specific enthalpy, J/kg
h_{PR}	low heat value of kerosene, J/kg
H	height from sea level, km
I_{sp}	fuel impulse, s
k	specific heat ratio
m_a	mass flowrate of air, kg/s
m_f	mass flowrate of fuel, kg/s
Ma	Mach number
M_w	molar mass of component, kg/mol
p	static pressure, Pa
R_g	gas constant, J/(kg·K)
R_u	universal gas constant, J/(mol·K)
s	specific entropy, J/(kg·K)
T	static temperature, K
u	air velocity, m/s
Y	mass fraction of components
η_c	isentropic efficiency of inlet
η_f	intermediate efficiency
η_{KE}	kinetic efficiency of inlet
π	inlet pressure ratio
ϕ	fuel equivalence ratio
ψ	inlet temperature ratio

Subscripts

0	freestream at the inlet entrance
2	combustor entrance
2s	isentropic state of the inlet exit
3	combustor exit
4	nozzle exit
i	components
j	locations in the scramjet

Superscripts

0	at reference pressure of 1 atm

loss corresponding to ram-mode is still advantageous compared to the Rayleigh loss in the combustion corresponding to scram-mode. However, as the freestream Mach number further increases, the compression loss corresponding to ram-mode becomes unacceptable and it gradually beats the Rayleigh loss corresponding to scram-mode in the combustor [12]. To avoid the extremely high loss of total pressure in the compression process at high freestream Mach numbers, the combustor is usually designed to operate with scram-mode to obtain an overall optimum performance [13].

Another important issue to the scramjet is the upper limit of gas temperature in the combustor, which is determined by both the engine material and the dissociation of gas. The former is related to the safe operation of the engine [14] and the latter will absorb the heat released by combustion and offset the benefit [12]. The temperature limit has obvious effects on the engine performance and should be taken into account especially in thermodynamic analysis on scramjet at high Mach numbers. It's worth noting that the temperature limit also has an important effect on the mode choice of scramjet engine especially at high Mach numbers. Ram-mode at high Mach numbers will encounter extremely high temperature in the combustor, which is unbearable in practice. Comparatively, scram-mode can relieve this problem. According to present technical level and engineering experience, scram-mode is believed to be more advantageous in overall engine performance with a freestream Mach number higher than 7 [11]. Despite its uncertainty related to the detailed engine structure, it could be considered as a general principle of mode choice in scramjet design.

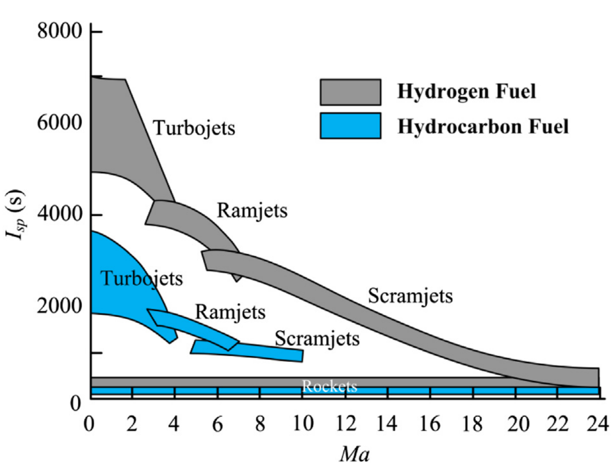

Fig. 1. Hypersonic engine specific fuel impulse vs. freestream Mach number [2].

There have also been many studies on the combustor configurations, which are very important to the engine performance. The dynamic characteristics of combustion mode transition in a strut-based scramjet combustor model were studied by Bao [15]. The effect of fuel injection allocation on the combustion characteristics of a cavity-strut model scramjet were analyzed by Zong [16]. The characteristics of drag caused by the cavity flameholder in the combustor were numerically studied by Huang [17]. The mixing techniques for transverse injection flow fields were also focused in supersonic crossflows [18]. Besides, there have been studies on subsystems such as fuel feeding [19] and power generation [20] systems, which also have influences upon the entire engine performance. However, the total performance of a scramjet can't be revealed clearly because there are intense interactions between the combustor and the inlet. Instead, the engine performance can be predicted by thermodynamic cycle analysis, which emphasizes the performance of the entire thermodynamic system and gives theoretical results regardless of the detailed engine design. It is a valuable tool for engine design prior to ground tests or flight tests, and it is capable of predicting important trends and sensitivities in engine performances. Roux et al. [21,22] carried out thermodynamic analysis on ideal scramjets. Yang et al. [23] conducted thermodynamic analysis on specific thrust of hydrocarbon fueled scramjet and considered the effects of temperature limit. Although these studies have shown clear predictions on the total performances of scramjets, either the analysis model was too idealistic to take the compression efficiency of the inlet into account, or the conditions with high Mach numbers were not analyzed. As we pointed above, the irreversible loss in the inlet has a great effect on the scramjet engine performance.

The aim of this work is to develop a thermodynamic cycle analysis model specifically for scramjets working at high freestream Mach numbers with scram-mode. It can be used to investigate the influences of designing parameter choices, such as the