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Numerical studies for performance improvement of a variable geometry dual mode combustor by optimizing deflection angle

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ABSTRACT

As part of our efforts to study the effect of the deflection angle on combustor performance of a variable geometry dual mode combustor, the flow field characteristics and mechanisms of the combustor performance loss, which comprised of compression loss, combustion heat addition loss and expansion loss, were investigated in the variable geometry dual mode combustor numerically with a Mach number of 3, a divergence ratio of 1.76, a fuel equivalence ratio of 0.6, and a deflection angle ranging from 8° to 16°. Numerical results indicated that the total pressure recovery coefficient and combustion efficiency increased with the deflection angle and there was a maximum to be obtained at the deflection angle of 12° due to the interaction between the dominant shock resulted by combustion heat release and the additional shock caused by the wedge system. Irreversible entropy generation loss was analyzed specifically in this paper to clarify and describe the combustor performance loss for the variable geometry dual mode combustor. Moreover, thrust-to-drag ratio was utilized to assess the effect of the deflection angle on combustor performance. By taking into account the flow field characteristics and combustor performance characteristics, the high combustor performance of a variable geometry dual mode combustor can be improved by selecting and optimizing the deflection angle.

1. Introduction

Many different launch vehicle concepts have been proposed in the search for a space shuttle replacement [1–4]. Each of these vehicles promised to reduce costs and increase reliability over current launch vehicles. Low cost, reliability, flight safety and quick access to orbit are the aims pursued by space transportation industries. They can be operated over a wide range of flight Mach numbers if a multi-cycle propulsion system [5–7] is used. Huang et al. [8] studied the combustion characteristics of a rocked-based combined-cycle engine combustor numerically. Much work has been done on this particular aspect in recent years. Candon et al. [9] studied the effect of different configurations by three design parameters, namely, the streamwise injection position, injection total pressure, and injection angle, on thrust augmentation. Mahto et al. [10] studied the effect of the length-to-depth ratio and Mach number on the performance of a typical double cavity scramjet combustor. There was an optimal length-to-depth ratio of 7 for the performance of the double cavity. Zhang et al. [11] studied the effect of heat release on movement characteristic of shock train in an isolator by an unsteady numerical simulation. The shock train movement is classified into these stages by the pressure distribution or shock train location. Gerlinger et al. [12] improved the mixing enhancement in turbulent high speed flows by a favorably chosen strut geometry for dual mode combustor. Malsur et al. [13] studied the effect of the mixing and combustion behavior of ethylene fuel on the combustion performance through numerical simulation with a series of fuel equivalence ratios in a supersonic combustor. Roncioni et al. [14] studied the performance assessment of the aero-propulsive balance by different CFD-codes. The emission index of NO (nitrogen monoxide) could be drastically reduced by shifting the injector struts further downstream without compromising the combustion efficiency. Tian et al. [15] studied the effect of the thermal throat location on the performance of the dual mode scramjet. Kuamr et al. [16] studied complex-box algorithm method to optimize the position of fuel injection struts for maximizing thrust and combustion efficiency in a dual mode combustor. The results indicated that a change in the position of struts, one at the front and two struts at the back resulted in better maximum thrust and combustion efficiency. However, as previously mentioned, considering the operating boundary constrains of scramjet and required thrust, it is very difficult to operate in a wide flight Mach numbers for the scramjet combustor with fixed geometry.

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Nomenclature

D	drag of total combustor, N
F	thrust of total combustor, N
h_1	vertical distance from wedge slider to upper wall of combustor, m
h_2	height of isolator, m
l	length of oblique shock train, m
r	length of section II, m
Ma	Mach number
p	static pressure, Pa
P_t	total pressure, Pa
s	static entropy, J/K
S_{irr}	entropy per mass, J/kg K
T	static temperature, K
T_t	total temperature, K
T_{AFT}	adiabatic flame temperature, K
x	axial distance from isolator entrance, m
y	longitudinal distance of combustor, m
Y	species mass fractions
η	combustion efficiency
ξ	divergence ratio
σ	total pressure recovery coefficient
??	fuel equivalence ratio
κ	thrust-to-drag ratio

Subscripts

0	isolator entrance
$\triangle$	increment

From a thermodynamic point of view, the extension of the flight Mach number range requires different divergent ratios for a combustor to balance the isolator–combustion interactions with engine safety operation. Indeed for a higher Mach number, it will be necessary to use less divergent ratio for a combustor to avoid the decrease in combustor performance. On the contrary, in order to extend the flight envelope to a lower Mach number, the divergence ratio of combustor must rise to accommodate large heat release.

Optimum combustor performance is always influenced by the interactions between the combustor geometry and heat release for a wide range of flight Mach numbers. Several approaches have been proposed in the literature for fulfilling this required adaptation between combustor geometry and heat release. Since 1993, French and Russia have developed a variable geometry dual-mode ramjet called the Wide Range Ramjet (WRR) [17,18], following the concept of variable geometry in the scramjet flow path. Experimental and numerical studies have been conducted to design the WRR prototype and develop the system technology tests for several years. By comparing a fixed geometry combustor with the WRR, the performance of the fixed geometry combustor was obviously lower than the performance of WRR at a flight Mach number range from 1.5 to 3.5 because of the lack of a geometrical throat and the deficiency of lower divergence ratio. As the flight Mach number was increased, WRR still had a performance better than that of the fixed geometry combustor. The French program [19–21] carried a variable geometry dual-mode combustor, which globally rotates the cowl around an axis placed upstream of the minimum cross section area, and operates in the Mach number range from 2 to 8. For a low Mach number flight, the upstream part of the cowl was moved up to limit the divergence ratio of the combustor to a certain level. In the subsonic combustion mode, the combustor could be strongly diverging. When Mach number was increased, the divergence ratio of combustor was then progressively increased. In the supersonic combustion mode, the divergence ratio of combustor was then reduced for a Mach number of 8. These research results provided a good basis for an understanding the effect of different contributions on the aero-propulsive balance of a highly integrated hypersonic vehicle.

An optimum combustor performance is always influenced by the interactions between the combustor geometry and heat release for a wide range of flight Mach numbers. The French and Russian proposed a variable geometry combustor by simply moving the engine cowl in the flight test program [22–25] taking place since 2003. A large part of technology development effort has been done in ground testing and then is dedicated to optimizing the combustor to deficiency ensure high performance. The modeling of the combustor was validated using basic experiment results taken from literature. The supersonic combustion with cavity-strut injection [26] was investigated to improve the combustor performance in a model scramjet engine by studying the ignition schemes [27] and the fuel transport and mixing progress [28]. Avrashkov et al. [29] studied the gas-dynamic structure of the variable geometry dual mode combustor in detail. The results showed that tests of the variable geometry dual mode combustor of a wide-range ramjet engine had stable operation and the required performance over the entire model range of flight conditions. Based on French–Russian variable geometry dual mode combustor, Feng et al. [30] studied the effect of divergence ratio on flow field characteristics and mechanism of combustor performance loss. However, the effect of deflection angle on the flow field characteristics and combustor performance loss by using hydrocarbon fuel for the variable geometry dual mode combustor was not reported.

Therefore, the French–Russian variable geometry dual mode combustor [29] was introduced to study the effect of deflection angle on flow field characteristics and the mechanism of combustor performance loss, including compression loss, combustion heat addition loss and expansion loss, with a Mach number of 3, a divergence ratio of 1.76, a fuel equivalence ratio of 0.6, and a deflection angle ranging from 8° to 16°. The effect of the deflection angle on the wall static pressure distribution, total pressure recovery coefficient, and combustion efficiency were investigated numerically for the variable geometry dual mode combustor with different deflection angles by taking into account the interaction between the dominant shock system caused by combustion heat release and the additional shock generated by the wedge slide system. Irreversible entropy loss analysis was utilized to study the mechanism of combustor performance loss for the variable geometry dual mode combustor. Moreover, the thrust-to-drag ratio was used to assess the combustor performance of the variable geometry dual mode combustor with different deflection angles. By taking into consideration the total pressure recovery coefficient, combustion efficiency, and thrust-to-drag ratio, the optimum deflection angle can be selected and obtained for the high performance of the variable geometry dual mode combustor with different deflection angles.

2. Combustor model and computational fluid dynamic model

2.1. Combustor setup

The current set of numerical results was obtained using the variable geometry dual mode combustor model. A schematic of the variable geometry dual-mode combustor can be found in Fig. 1. The air entered the isolator segment of the combustor at a Mach

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