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A conceptual design of shock-eliminating clover combustor for large scale scramjet engine

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ABSTRACT

A new concept of shock-eliminating clover combustor is proposed for large scale scramjet engine to fulfill the requirements of fuel penetration, total pressure recovery and cooling. To generate the circular-to-clover transition shape of the combustor, the streamline tracing technique is used based on an axisymmetric expansion parent flowfield calculated using the method of characteristics. The combustor is examined using inviscid and viscous numerical simulations and a pure circular shape is calculated for comparison. The results showed that the combustor avoids the shock wave generation and produces low total pressure losses in a wide range of flight condition with various Mach number. The flameholding device for this combustor is briefly discussed.

1. Introduction

From a very fundamental standpoint, the combustor in a scramjet engine needs to fulfill several requirements, namely, a high fuel penetration and sufficient mixing characteristics with the air, low total pressure losses and convenient cooling [1]. For large scale scramjet combustor, such as the combustor used in SR-72 of Lockheed Martin skunk works and the supersonic combustor of AFRL (Air Force Research Laboratory) [2], fuel-injection strategy, i.e., the penetration and mixing characteristics of the fuel is one of the main challenges. Doster et al. used pylon fuel injector for a scramjet combustor with a circular entrance in which the diameter is 254 mm [2]. Rock et al. [3] used strut injector for round scramjet combustors to achieve high fuel penetration into the core flow. Strut or pylon injectors cannot be removed from the flow and hence cause large pressure losses due to the strong shock waves. Additionally they have to be cooled. On the other hand, non-intrusive wall injectors are easy to be manufactured and easy to be cooled. However, in large size combustors there might be problems of the penetration of the fuel into the air flow.

The lobed configuration is a well-known shape to acquire enhanced mixing effects in gas-turbine engine or in the ejector. A lobed mixer is employed as a vortex generator, since it has been proved by many previous researches. Brankovic et al. [4] designed and evaluated a lobed diffuser-mixer that enhances the fuel-air mixing in the Trapped Vortex Combustor core for gas turbines. The lobed diffuser-mixer combustor rig is in a full annular configuration featuring sixfold symmetry among the lobes. Samitha et al. [5–7] used a lobbed clover nozzle to achieve enhanced mixing between the two high speed coaxial streams in a short mixing chamber of Dual Combustor Ramjet. However, these lobed configurations are only used in subsonic region and no shock-waves exist in the flowfield. In supersonic application, Gerlinger et al. [8] used a lobed strut to produce strong streamwise vortices and to enhance hydrogen/air mixing in a Mach 2 model scramjet combustor. Their calculation showed that the intrusive lobed struts produced an increase in entropy and large losses in total pressure. The lobed strut cannot avoid the heat protection problem either.

In scramjet application, the flush-wall injectors based on lobed configuration (for circular combustor the shape is like a clover) could be used in the combustor to provide better fuel penetration and mixing. Due to the low curvature of the wall shape, the cooling strategy is easy. Since a circular combustor cross-section is usually adopted for large scale scramjet combustor, this work focuses on a conceptual design methodology for circular-to-clover shape transition without shock pressure-loss. The clover wall offers direct fuel injection into the core flow in a supersonic combustor without high pressure supply, which is an important way for the large scale supersonic combustor design.

2. Circular-to-clover supersonic combustor design methodology

The conceptual combustor designs are performed for use in a 254 mm (10-in.) entrance circular cross plane combustor [2] with three section, including injection section, flameholding section and expansion section, as shown in Fig. 1a. In the flameholding section, flameholding devices could be used to stabilize the flame.

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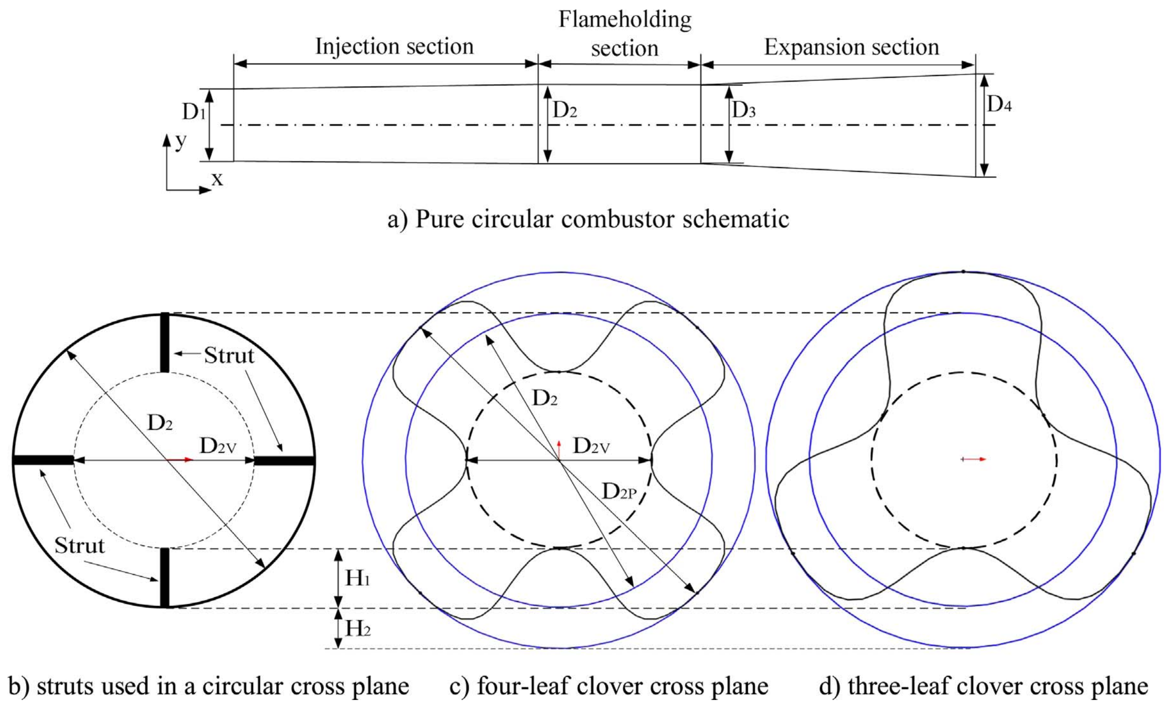

Fig. 1. Combustor shape with struts and the corresponding four-leaf or three-leaf clover configuration.

As shown in Fig. 1a, the diameter of the circular entrance and outlet of the injection section is denoted as D_1, D_2 respectively and D_1=254 mm, D_2=274 mm. The length of the injection section is L_i=1064 mm. Since the heat release principle is related to the area change rate, the clover configuration should fulfill with the cross section area requirements. Fig. 1b shows the D_2 circular cross section with four struts and the corresponding clover cross section with equal area. Shown in Fig. 1c, the clover shape is compared to the baseline circular shape, it is seen that the clover valley with the H_1 depth is tangent with the inscribed circle with diameter D_{2V}. The clover peak is tangent to the excircle with diameter D_{2P}, which exceeds D_2 to keep the cross section area and an additional height H_2 is given. If three leaf clover shape is considered, the combustor cross plane shape is shown in Fig. 1d, where the cross plane area is kept equal to circular cross section shape with a diameter D_2. In this paper the four leaf clover shape is considered for the primary design.

The main focus of the design is on how to treat the shape transitions. If the transition is not smooth in aerodynamics, the compressive waves might concentrate to generate shock waves, which lead to a large aerodynamic loss and drag. And it is also possible to form a separation region which also induces a large pressure loss. The clover configuration should be designed using a shock-eliminating methodology. An appropriate choice is the streamline tracing technique discussed by Smart [9], which has been proven to be a powerful design tool for hypersonic inlets [10]. Recently Mo et al. [11,12] have used the similar technique to design asymmetric scramjet nozzles with non-uniform inflow, asymmetric scramjet nozzle with circular to rectangular shape transition and has verified its feasibility by conducting cold flow experimental tests.

For this design method, an inviscid parent flowfield based on method of characteristics (MOC) is generated firstly, and then a locus of points on the inlet and outlet are traced respectively. A morphing method is used to blend these two shapes to generate a shape transition. The morphing procedure may introduce non-aerodynamic disturbance and additional loss. An appropriate blending function is important since it determines the major shape and feature of the final result. This method was chosen to generate the combustor which morphs two different shapes.

To start the design, the generation of an inviscid parent flowfield is very important. The axisymmetric supersonic expansion nozzle is selected as the parent flowfield by using MOC. Based on Zucrow and Hoffman's description [13], the compatibility equations for the axisymmetric irrotational MOC are as follows,

$$\frac{dV_\pm}{V} \mp \tan\alpha d\theta_\pm - \left[\frac{\sin\theta\sin^2\alpha dx_\pm}{y\cos\alpha\cos(\theta\pm\alpha)}\right] = 0 \tag{1}$$

Eq. (1) hold along the left and the right-running Mach lines given by

$$\left(\frac{dy}{dx}\right)_\pm = \lambda_\pm = tg(\theta\pm\alpha) \tag{2}$$

where θ is the local flow (streamline) angle and $\alpha$is the Mach angle.

The aforementioned equations are solved numerically to obtain the parent nozzle flowfield by discretising them on a grid that is created by intersecting characteristics lines, as shown in Fig. 2. The numerical algorithms used to solve the equations are based on the modified Euler predictor−corrector method discussed in Ref [13]. A program code was written to numerically integrate the equations. The supersonic inlet boundary AE can be solved based on the inlet supersonic condition, and the arc expansion region EADB can be obtained by using the values calculated from Eqs. (1–2) directly since AD is a section of circular arc with radius=r. To design the transition region DBC, two constraints including the constant mass flow rate and the specified nozzle length are needed as follows,

$$\dot{m}_{BC} = \int_B^C \rho V 2\pi y \mathrm{d}y = \pi\rho_{B'}V_{B'}y_{B'}^2 + \int_{B'}^{D'} \rho V_x y \mathrm{d}y = \text{constant} \tag{3}$$

$$L_{OF} = x_B + \int_B^C \cot\alpha \mathrm{d}y = L_i \tag{4}$$

Combining Eqs.(1–4) for steady axisymmetric irrotational flow, nozzle flowfield and coordinates of each point on the line DC can be calculated by MOC. The parameters R_{OA} (radius of inlet, $R_{OA}=D_1/2$), R_{FC} (radius of outlet, $R_{FC}=D_{2P}/2$), r and L_{OF} (length of the nozzle, $L_{OF}=L_i$) would be prespecified and an expansion flowfield could be determined by the iteration procedure. The unit processes for the

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