Numerical Simulations of a Typical Hydrogen Fueled Scramjet Combustor with a Cavity Flameholder

Wei Huang, Shi-bin Luo, Mohamed Pourkashanian, Lin Ma, Derek B.Ingham, Jun Liu and Zhen-guo Wang

Abstract—**As one of the most promising propulsive systems in the future, the scramjet engine has drawn the attention of many researchers. The two-dimensional coupled implicit *NS* equations, the standard *k-ε* turbulence model and the finite-rate/eddy-dissipation reaction model have been applied to numerically simulate the flow field of the hydrogen fueled scramjet combustor with a cavity flameholder under two different working conditions, namely, cold flow and engine ignition. The obtained results show that the numerical method used in this paper is suitable to simulate the flow field of the scramjet combustor. The static pressure distribution along the top and bottom walls for the case under the condition of engine ignition is much higher than that for the case under the condition of cold flow. There are three clear pressure rises on the top and bottom walls of the scramjet combustor. The eddy generated in the cavity acts as a flameholder in the combustor, and it can prolong the residence time of the mixture in the supersonic flow.**

Index Terms—**Aerospace propulsion system; Scramjet combustor, Cavity flameholder; Numerical simulation**

I. INTRODUCTION

The scramjet engine is one of the most promising airbreathing propulsive systems for future hypersonic vehicles, and it has drawn the attention of an ever increasing number of researchers. The mixing and diffusive combustion of fuel and air in conventional scramjet engines take place simultaneously in the scramjet combustor [1]. However, the incoming supersonic flow can remain in the combustor only for a very short time, i.e. for the order of milliseconds [1-3], and this restricts the further design of the scramjet engine. Since the whole process of combustion has to be completed during this short duration, research on supersonic combustion technologies is of great significance and many researchers pay attention to the hypersonic airbreathing propulsion.

In order to prolong the residence time of the supersonic flow in the combustor, installing cavity flameholders on the wall of the combustor is widely applied in hypersonic airbreathing engines[4-7], and this was used for the first time in a joint Russian/French dual-mode scramjet flight-test[8]. A cavity flameholder is an integrated fuel injection/flame-holding approach, and it is a new concept for flame holding and stabilization in supersonic combustors.

The presence of a cavity on an aerodynamic surface could have a large impact on the air flow surrounding it, and this makes a large difference to the performance of the engine, namely it may improve the combustion efficiency and increase the drag force. Although many researchers have done some work on the flow passing the cavity flameholder, the flameholding mechanism of the cavity in the supersonic flow is not clear.

In this paper, the two-dimensional coupled implicit Reynolds Averaged Navier-Stokes (RANS) equations, the standard *k-ε* turbulence model [9-12] and the finite-rate/eddy-dissipation reaction model have been employed to investigate the flow field in a hydrogen-fueled scramjet combustor with a cavity flameholder, including the conditions of engine ignition and cold flow.

II. PHYSICAL MODEL AND NUMERICAL METHOD

The geometric model has been built based on a typical two-dimensional scramjet combustor, see Fig.1. The overall length of the combustor is 0.666m. The length of the isolator is 0.22m, and its height is 0.032m. The entrance of the combustor is located at x=0.22m from the entrance of the isolator at x=0. The height of the combustor is 0.0384m.

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There is a divergence angle of 1.7° both on the top and bottom walls of the combustor at x=0.316m and a step of height 0.0032m at the entrance of the combustor, which only exists on the top wall of the combustor. The hydrogen is injected from the bottom wall at x=0.2328m, which is 0.0128m downstream of the entrance to the combustor, and the width of the injection slot is 0.001m. There exists a cavity flameholder on the bottom wall of the combustor with the upstream depth D_u=0.0032m, the ratio of the downstream depth to the upstream depth $R_1=D_d/D_u=1$, the ratio of the length to the upstream depth $R_2=L/D_u=5$ and the swept angle θ=45°. The distance between the injection slot and the leading edge of the cavity flameholder is 0.005m, and Fig.2 shows a schematic of a typical cavity flameholder.

Table 1 shows the boundary conditions employed in the computational model. At the entrance of the isolator, oxygen and nitrogen mol fractions of the air flow are set to be 0.21 and 0.79, respectively, with the Mach number of the flow being 4.5, the static temperature is 1300K, and the static pressure is 101,325Pa. The fuel, namely hydrogen, is injected into the core flow with sonic velocity, the static temperature is 1000K, and the static pressure is 506,625Pa.

In the CFD model, the standard k-ε turbulent model is selected. This is because of its robustness and its ability to fit the initial iteration, design lectotype and parametric investigation. Further, because of the intense turbulent combustion, the finite-rate/eddy-dissipation reaction model is adopted. The finite-rate/eddy-dissipation is based on the hypothesis of infinitely fast reactions and the reaction rate is controlled by turbulent mixing [14]. Both the Arrhenius rate and the mixing rate are calculated and the smaller of the two rates is used for the turbulent combustion [15]. While no-slip conditions are applied along the wall, but due to the flow being supersonic, at the outflow all the physical variables are extrapolated from the internal cells.

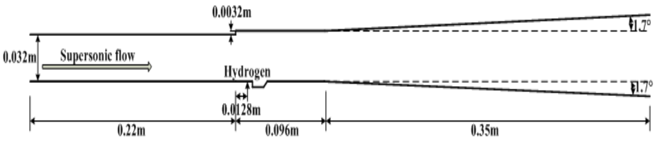

Fig.1 A schematic of a typical scramjet combustor with cavity flameholder.

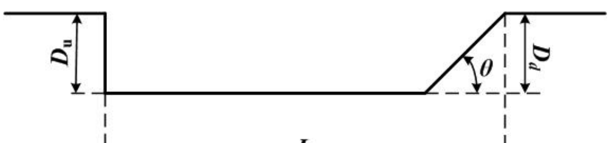

Fig.2 A schematic of a typical cavity flameholder.

Table 1 The boundary conditions employed in the computational model

Parameters	The injection	The supersonic flow
Ma	1.0	4.5
T_e/K	1000	1300
P_e/Pa	506,625	101,325
C_{H2}	1.0	0.00
C_{O2}	0.0	0.21
C_{N2}	0.0	0.79

III. CODE VALIDATION

In order to investigate the accuracy of the program code, a cavity flow is applied in order to discuss the code validation, and the experimental model is considered following the experimental work of Cruber et al. [13], who studied several cavity configurations for an unheated flow at Mach 3. Cavities with D_u of 8.9mm and R_1 of 1.0 were used in the experimental work and for the conditions of R_2=3, R_2=5 without a swept angle, and R_2=3 with the swept angle (θ) of 30°, see Fig.2. In addition, the initial stagnation temperature, T_0, and stagnation pressure, P_0, of the free stream are 300K and 690kPa, respectively.

Fig.3 shows the wall pressure distribution comparisons as obtained from Cruber et al. [13] and the numerical simulations for R_2=3, R_2=5 without a swept angle, and R_2=3 with the swept angle 30°. The wall pressure is normalized by the stagnation pressure of the free stream. Two sets of mesh, with different numbers of cells, have been employed in order to investigate the grid independency of the numerical simulations, namely approximately 36,400 and 147,200 cells have been employed.

In Fig.3, the effective distance of the cavity flameholder comprises of the cavity leading edge, the cavity floor face and the cavity trailing edge. Good agreement is observed between the computed and experimental results, and the difference in the results obtained for the two different grid systems employed in the simulations produce predictions that are not significant for the unheated cavity flow. Therefore we conclude that the numerical method employed in this investigation can be used with confidence to simulate the flow field in the scramjet combustor with the cavity flameholder.

IV. RESULTS AND DISCUSSION

Fig.4 shows the static pressure contours of the scramjet combustor with a cavity flameholder working under different conditions, namely the cold flow and the engine ignition, and we observe that the static pressure for the case under the condition of engine ignition is much higher than the case under the condition of cold flow, which can also be observed in Fig.5. In Fig.5, the static pressures along the walls are normalized by the static pressure of the core flow.

At the same time, we observe that the flow fields in the isolator are almost the same under the conditions of cold flow and engine ignition, and this means that the shock wave system in the combustor does not significantly affect the flow field in the isolator, and the static pressure distributions on the top and bottom walls of the isolator are almost the same for the two different working conditions.

Because of the step on the top wall of the combustor, there exists an expansion fan generated just on the top wall at the entrance of the combustor, which is interacts with the oblique shock wave formed upstream of the cavity flameholder on the bottom wall of the combustor due to the shear layer deflecting into the core flow, and this oblique shock wave is located almost on the bottom wall of the isolator, see Fig.6. A low pressure region is generated in the vicinity of the step, and there exists a recirculation zone in the corner region.

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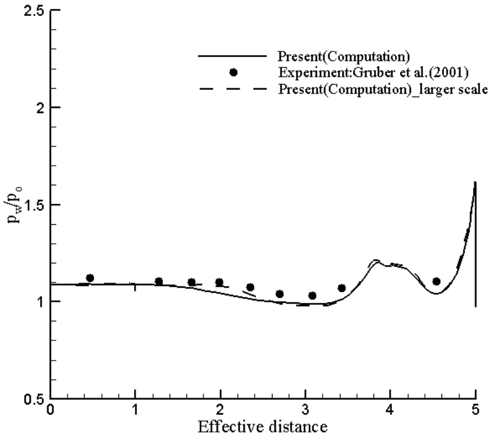
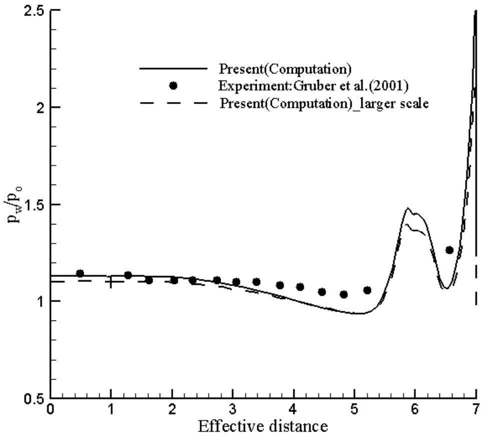
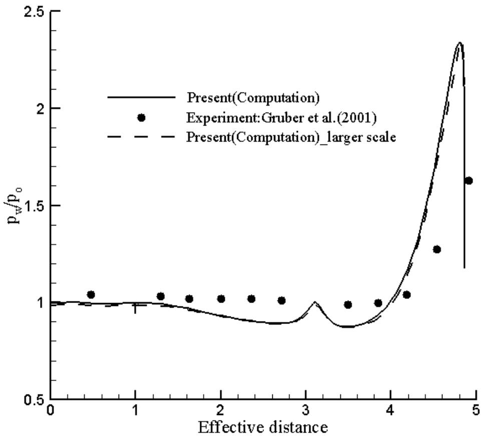


(a) L/D_u=3 without swept angle



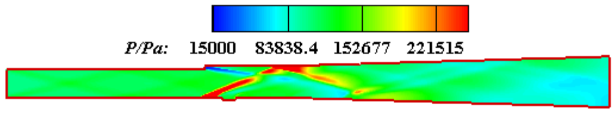
(b) L/D_u=5 without swept angle



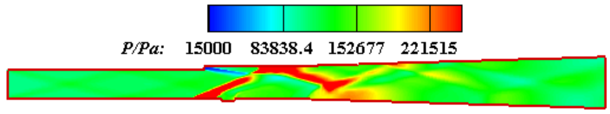
(c) L/D_u=3 with the swept angle 30°

Fig.3 Wall static pressure distributions for (a) L/D_u=3 and no swept angle, (b) L/D_u=5 and no swept angle, and (c) L/D_u=3 with the swept angle 30°.

Since the intensity of the shock wave is much stronger than that of the expansion wave, after the interaction of these two waves, a high pressure region is formed on the top wall of the combustor, which is just ahead of the divergent part of the combustor. In Fig.5 (a), we observe that the static pressure in this region is the highest along the top wall, and there are two other clear pressure rises along the top wall.

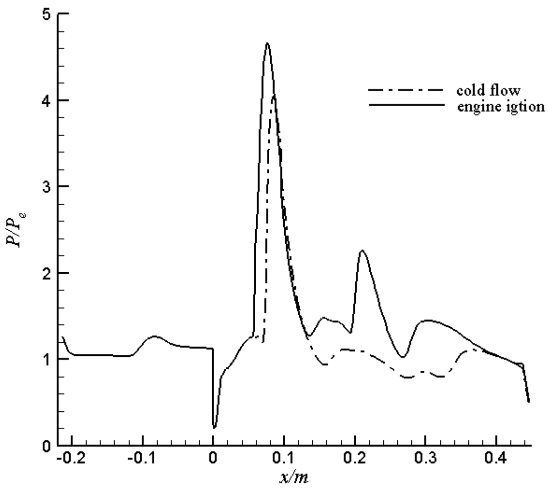


(a) Cold flow

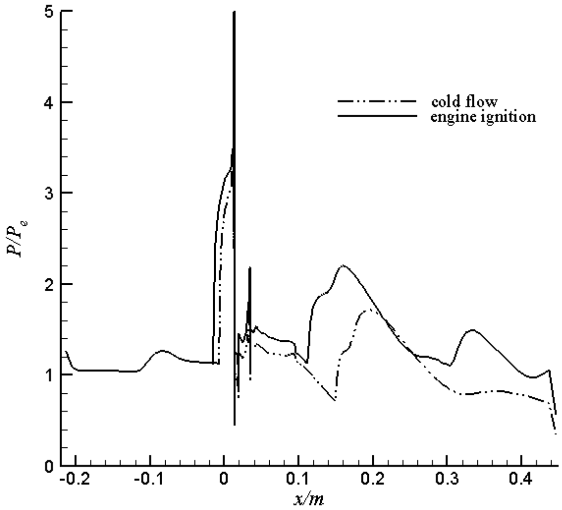


(b) Engine ignition

Fig.4 The static pressure contours of the scramjet combustor with a cavity flameholder for (a) cold flow, and (b) engine ignition.



(a) Top wall

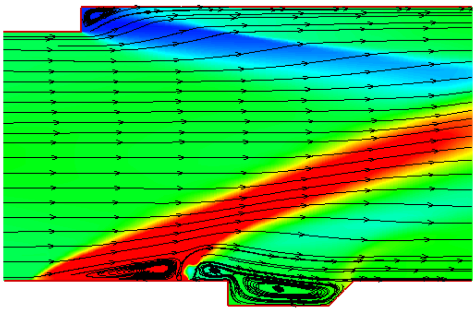


(b) Bottom wall

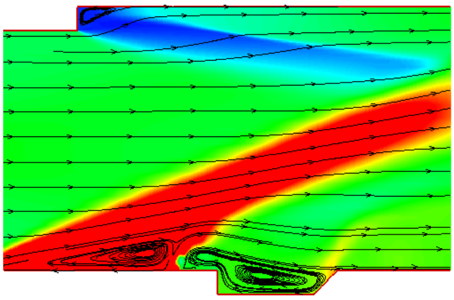
Fig.5 Comparisons of the static pressure distributions along the walls of the scramjet combustor.

These are formed due to the reflected shock wave and the expansion wave impinging on the top wall, respectively.

Due to the fuel being injected upstream of the cavity flameholder, there is a separation region generated just upstream of the injection slot by the intersection of the boundary layer and the oblique shock wave, see Fig.6. Further, when the fuel is ignited, the separation zone upstream of the injection slot is much larger than that under the cold flow condition. Fig.6 shows the local streamline path distribution around the cavity flameholder for different

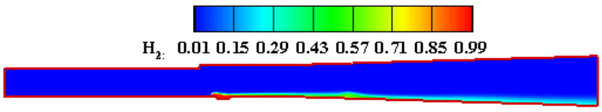


(a) Cold flow

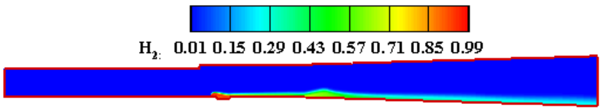


(b) Engine ignition

Fig.6 Local streamline path distribution around the cavity flameholder under different working conditions.



(a) Cold flow



(b) Engine ignition

Fig.7 Comparisons of H_2 mass fraction contours for scramjet combustor under different working conditions.

working conditions, namely, cold flow and engine ignition. At the same time, the eddy formed downstream of the injection merges with the large eddy generated in the cavity flameholder, and the eddy generated in the cavity is deflected into the core flow. Another oblique shock wave is generated on the trailing edge of the cavity flameholder due to the impingement of the shear layer on the trailing edge, see Fig.6. The injected flow interacts with the strong trailing edge shock wave, which plays an important role in chemical reaction of the fuel and the air [16].

Fig.7 shows the hydrogen mass fraction contours of the scramjet combustor under different conditions, namely cold flow and engine ignition. The cavity on the bottom wall acts as a flameholder in the scramjet combustor and the hydrogen mass fraction in the cavity is much higher than elsewhere in the combustor due to the recirculation zone formed in the cavity. The fuel distributes mainly along the bottom wall of the combustor.

V. Conclusions

In this paper, in order to investigate the flameholding mechanism of the cavity in supersonic flow, the two-dimensional coupled implicit RANS equations, the standard k-ε turbulence model and the finite-rate/eddy-dissipation reaction model are introduced to simulate the flow field of the hydrogen fueled scramjet combustor with a cavity flameholder under different conditions, namely the cold flow and the engine ignition. We observe the following:

- The numerical method employed in this paper can be used to accurately investigate the flow field of the scramjet combustor with cavity flameholder, and capture the shock wave system reasonably.
- The static pressure of the case under the engine ignition condition is much higher than that of the case under the cold flow condition due to the intense combustion process.
- There are three obvious pressure rises on the top and bottom walls of the scramjet combustor because of the impingement of the reflected shock wave or the expansion wave on the walls. This illustrates that there exists the complex shock wave/shock wave interaction and the separation due to the interaction of the boundary layer and the oblique shock wave.

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