CFD analysis of shock induced combustion in premixed flow of hydrogen-air over spherical projectile

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Abstract— Hypersonic air breathing propulsion is a key technology for the attainment of intercontinental transportation and Low Earth Orbit (LEO) vehicle's performance. A premixed shock induced combustion engine (schramjet) is a realizable choice for improving LEO's performance. In this concept, a shock is employed to start the combustion process in a premixed fuel/air mixture. The advantage of schramjet engine over a typical scram jet engine is its reduced length of combustor, which leads to reduced weight and heating load. The operating range of schramjet can be extended to the region of Mach number 10 to 15. This present paper objective is to simulate computationally the spherically blunted projectile experiment for shock-induced combustion of pre-mixed hydrogen air. The simulations are carried out to validate the CFD model. CFD simulations will be carried out using ANSYS CFX, CFD software.

Index Terms— ANSYS CFX, CFD, hydrogen-air, hypersonic, pre mixed flows, shock induced combustion, SCHRAMJET.

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1 INTRODUCTION

One of the current goals of research in hypersonic, air breathing propulsion is access to higher Mach numbers. The main research objective is to integrate a scramjet engine1 into a trans-atmospheric vehicle airframe in order to improve single stage or two stage performance to low Earth orbit [1]. Scramjet engine, an air breathing engine, have an advantage over non-air breathing in the view of specific impulse. The increase in the specific impulse is due to reduction pay load of the vehicle because of on-board availability of oxidizer (Oxygen). This makes the scramjet to be integrated with LEO within trans-atmospheric region to achieve better performance. Additional benefits potentially derived from a smaller, lighter vehicle include reduced cost, maintenance, and possibly improved reliability.

Technical hurdles for scramjets in the Mach regime of 10 and above is combustion instabilities and initiation. Two major factors to be considered for the effective scramjet combustion are: first one is residence time of the fuel-air mixture in the combustor as the residence time decreases as the free-stream velocity of the vehicle increases. The second is the internal heating loads experienced by the vehicle as velocity increases. In order to prevent vehicle materials from exceeding their design temperature limits, active cooling is often employed in scramjet designs. This active cooling may have a negative impact to efficiency if excess fueling is required.

The problems encountered above can be reduced by engines using premixed, shock-induced combustion. This concept employs the injection of fuel in the forebody section of the vehicle upstream of the inlet. This allows the fuel and air to mix along the forebody instead of in the combustor. Once the mixture reaches the inlet, the flow is passed through a shock wave of sufficient strength to induce combustion without the use of other ignition devices. Because the combustor only needs to support combustion and not mixing its length is reduced considerably, positively impacting the issues of combustor weight and heat loads. The burned gases then expand in the vehicle nozzle to produce thrust.

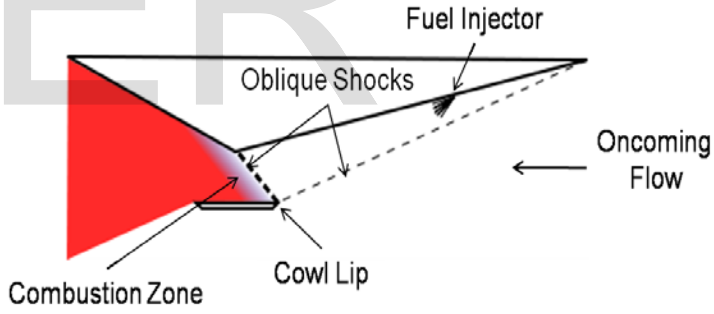


Figure 1. A schematic of SCHRAMJET engine concept.

The goal of the present paper is to validate the CFD simulation carried with ANSYS CFX , CFD software. In addition, to prove the concept of shock-induced combustion phenomenon in ramjets (shcramjet) for Hydrogen - air premixed flows.

2 LITERAURE REVIEW

In the past, many researchers have conducted ballistic range experiments to study the supersonic combustion/detonation. In these experiments, projectiles are fired in different premixed fuel air mixtures, and detonation structures around the projectiles are recorded.

Ruegg and Dorsey [2] carried out the experiment on 20 mm diameter spherical projectile in a passive combustible mixture made of hydrogen and air. The objective of their investigation is to study stabilizing combustion region. The experiment is carried at Mach numbers between 4 and 6.5 above pressure of 0.1 atmosphere and they found combustion generated noticeable effects on the shape and positions of shockwave. They noticed ignition delay, separation between shock wave and reaction front, which is formed behind the earlier one. Strong combustion driven oscillations are also noticed.

The similar projectile experiments are carried by Behranet al. [3]. They conducted experiments by firing 9 mm plastic spheres into hydrogen-air and hydrogen-oxygen mixtures at 1500-3000 ms -1. They also observed that at velocities higher than Chapmen-Jouget velocities a steady combustion front is established, while at lower velocities unstable forms of oscillations appear. The period of oscillations is found to be equal to the induction time for self-ignition.

Lehr [4] in 1972 has investigated experimentally the effect of projectile shape on shock induced combustion phenomenon in different combustible mixtures to expand the database. The shapes of projectile tested are spheres, cones, bi-cones, and flat-nose projectiles. The mixtures are hydrogen-air, hydrogen-oxygen, methane-air, and methane-oxygen. They captured three-dimensional structure of the flow with shadowgraph technique.

Numerical analysis is carried by Wilson et al. [5] to study the shock-induced combustion phenomena. They used Euler equations and a 13-species and 33-reactions chemistry model. They validated the CFD code of the reaction models successfully and established the importance of grid resolution to capture the flow physics effectively. They simulated the experiments of Lehr's at Mach 5.11 and Mach 6.46 cases with adaptive grid concept. They are not able to visualize the unsteady combustion phenomenon because of inaccurate time steps. Nevertheless, they have captured the combustion instability phenomenon for cases lower than Mach5.11.

Sussman et al. [6] also numerically simulated the instabilities in the reaction front at a Mach 4.79. They employed governing equations and reaction chemistry model same as that of Wilson et al. [5]. They substantially lowered the number of nodes to capture the reaction front with a new technique based on logarithmic transformation. They successfully simulated the unsteady case. However, the frequency is slightly under predicted.

Matsuo and Fujiwara[7]-[8] have investigated the shock-generated combustion instabilities of around an axisymmetric blunt body. They used Euler equations and a simplified two-step chemistry model. They investigated the growth of periodic instabilities by a series of simulations with various tip radii and showed that these periodic instabilities are related to shock-standoff distance and induction length. They proposed a new model based on McVey and Toong's model [9]. Their model explained the instabilities in the reaction front.

3 SIMULATION METHODOLOGY

The equation of transport for the I component with mass fraction Y_I is:

$$\frac{\partial(\rho Y_I)}{\partial t} + \frac{\partial(\rho u_j Y_I)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\Gamma_{I_{eff}} \frac{\partial Y_I}{\partial x_j}\right] + S_I \qquad (1)$$

Where source term S_I is term due to chemical reaction

The finite rate chemistry model employed in CFX, assume that rate of progress of elementary reaction k can be reversible only if backward reaction is defined.

The rate of progress R_k is computed as:

$$R_k = \left(F_k \Pi_{I=A,B,\dots}^{N_c} [I]^{Y'_{kI}} - B_k \Pi_{I=A,B,\dots}^{N_c} [I]^{Y''_{kI}}\right) \quad (2)$$

Where $[I]$ is the molar concentration of I and$F_k$and B_k are the forward and backward rate of constants respectively.

$$F_k = A_k T^{\beta_k} exp\left(-\frac{E_k}{RT}\right) \qquad (3)$$

$$B_k = A_k T^{\beta_k} exp\left(-\frac{E_k}{RT}\right) \qquad (4)$$

where A_k is the pre exponential factor, β_k is the dimensionless temperature exponent, E_k is the activation energy and T is the absolute temperature.

Separate sets of coefficients A_k, β_k and E_k are applied to forward and backward rates.

4 RESULTS & DISCUSSIONS

The present paper represents the results of the simulations carried out based on the experiments of Ruegg and Dorsey []4 using the ANSYS CFX in order to qualitatively assess the suitability of the code. The experiments conducted are on shock induced combustion for pre mixed flows of hydrogen - air by firing spherical, 20 mm diameter projectiles into a stoichiometric hydrogen-air mixture around Mach 5 at pressures ranging from 0.1 to 0.5 atm. Over the range of experimental conditions investigated, three distinct regimes of behavior of the reaction/shock front system are observed: stable; regular, unsteady; and large-disturbance, unsteady. A qualitative comparison between the 2D simulation results and experimental shadowgraphs at the conditions in Table 2 are represented. The simulated results consist of an evolution of water mass fraction , density gradient and Mach number contours.

Figure 3 shows quasi-1D simulation and experimental results for the stable regime of oscillation. The simulated and experimental results indicate reaction and shock front locations that are invariant with time. This invariance is observed experimentally by smooth shock and reaction fronts. The reaction and shock fronts are separated by a relatively large induction distance with no direct interaction between the two beyond the shock wave raising the temperature of the hydrogen/air mixture above its autoignition limit. There is qualitative agreement between simulation and experiment for this case.

Figure 2 shows 2D computational simulation and experimental results for the stable regime of combustion inform of logarithmic density gradient contour. Computational results are matched with experimental results and both are showing that the regions of bow shock and reaction front are not changing with time. A separation distance is observed between shock and reaction front and beyond the shock wave raising the temperature of the hydrogen/air mixture above its auto ignition limit.

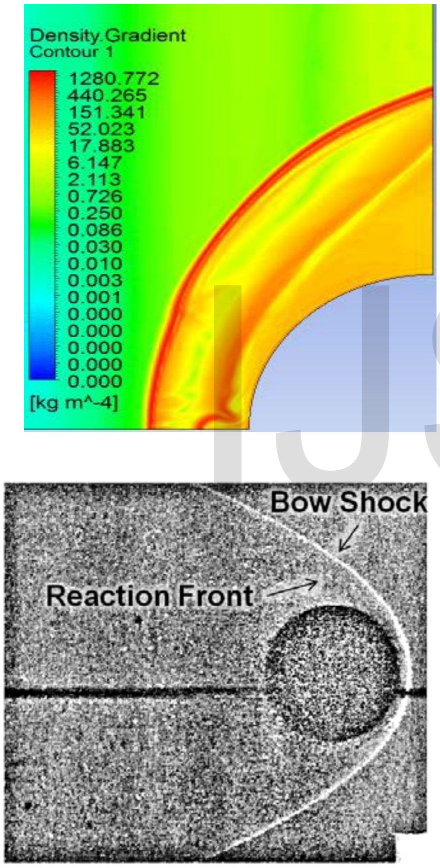


Figure 2: density gradient contour and experimental shadowgraph for stability regime in shock induced combustion.

The figure 3 shows the H2O mass fraction contour which indicates the initiation of reaction front at the reaction front which is beyond the bow shock.

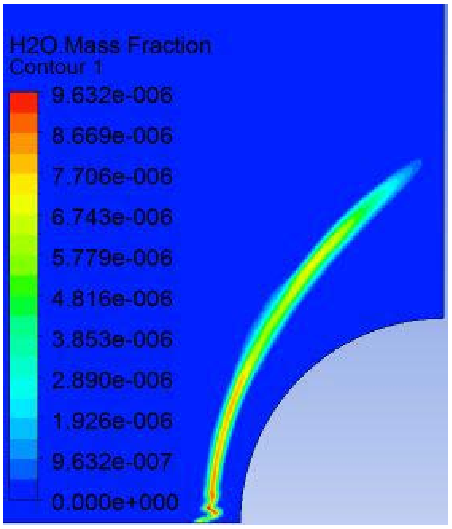
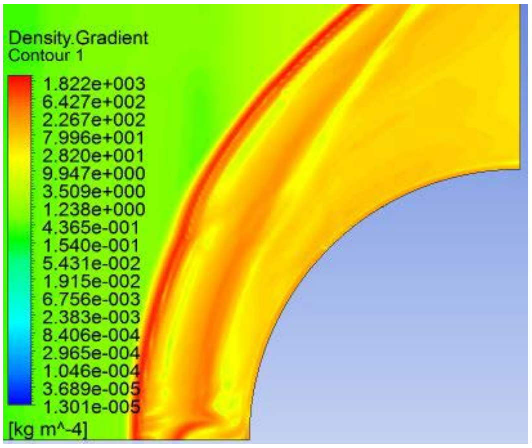


Figure 3: H2O mass fraction in the stable regime

The regular instability in combustion regime is represented in form of contour with logarithmic density gradient colour and experimental image are shown in Figure 4. The experimental shadowgraph shows a wrinkled pattern in front of the sphere. The reason is periodic change in density due to formation of new reaction fronts periodically in the stagnation region of the flow. Lines of density variation in the unburned region are due to periodic contact discontinuities traveling from the bow shock to the beginning of each new reaction zone. There is qualitative agreement between the experiment and the present computations because the physical mechanism observed in the simulated results match the flow features witnessed in the experimental shadowgraph. Figure 5 represents the H2O mass fraction.



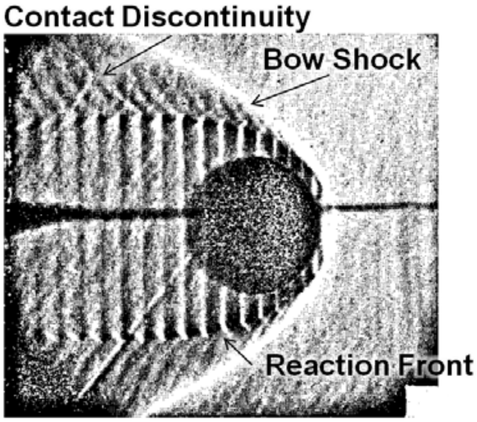


Figure 4: density gradient contour and experimental shadowgraph for regular unsteady regime in shock induced combustion

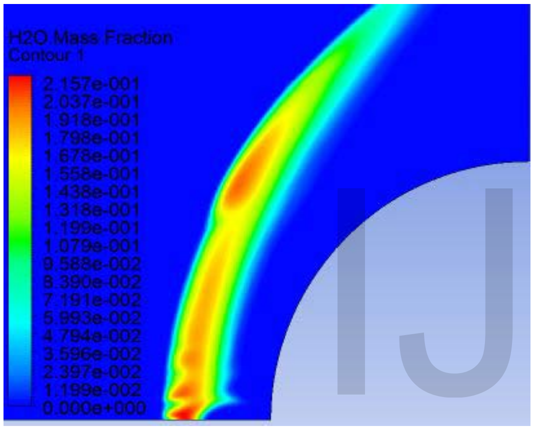
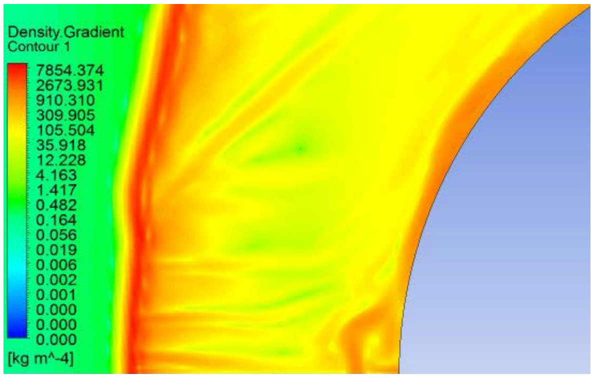


Figure 5: H2O mass fraction in the regular unsteady regime

Figure 6 represents the large-disturbance instability regime captured in form of logarithmic density gradient distribution. Experimental results of the flow at the Case 3 condition show a large-amplitude heaving of both the bow shock and the reaction front. Both the bow shock and reaction zone oscillate with a much lower frequency than that observed in the regular regime and apparently non-periodic features are visible in the shadowgraph. Both the experiment and the present numerical results show large amplitude.



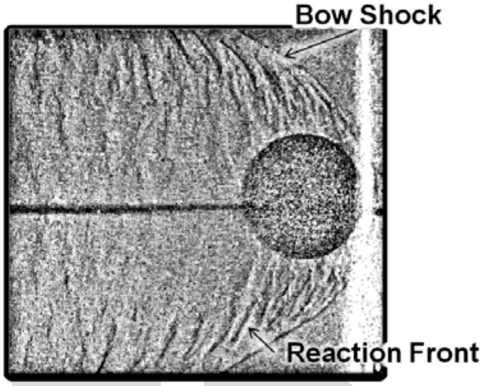
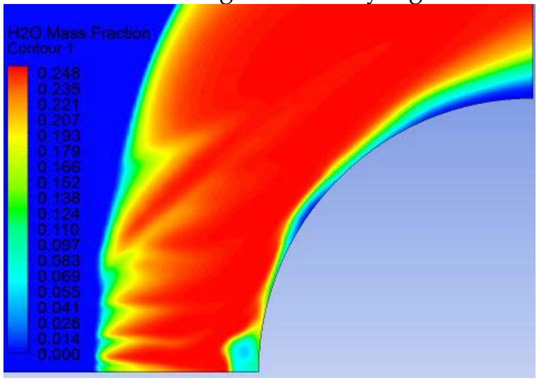


Figure 6: density gradient contour and experimental shadowgraph for large disturbance unsteady regime in shock induced combustion

Figure 7 represents the H2O mass fraction formed and mach contour of large un-stability regime.



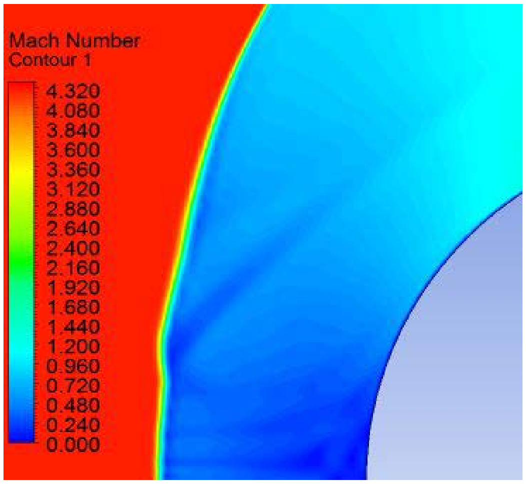


Figure 7: H2O mass fraction and Mach contours in the large un-stability regime.

5 CONCLUSION

A computational study is carried out to investigate the shock-induced combustion in premixed hydrogen-air mixture. The simulations have been carried out for Mach 5, 4.9 and 4.3 in the atmospheric range of 0.1 to 0.5 atm. The mach 4.3 is found to be unsteady with periodic oscillations. The Mach 5case is found to be steady state regime in combustion.. There is a qualitative agreement with the experimental results. Thus supporting the existing view that it is possible to stabilize the shock-induced combustion phenomena with sufficient level of overdrive.

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