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Review Article

A Numerical Study on the Effect of Strut on Scramjet Combustion Intensity at Various Mach Numbers

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ABSTRACT

A strut based injector is found to be one of the most promising designs for supersonic combustor. However, scramjet combustor is a complex aero-thermodynamic system having high speed flow with compression waves and thermochemical process. The performance of a supersonic combustor is influenced by various parameters like the inlet Mach number, type of fuel, combustor pressure and temperature. Combustor basically makes use of single and double strut fuel injectors. In the present study, numerical investigation on the effect of using number of struts on combustion is investigated. Also, the influence of the type of fuel used at various equivalence ratios on combustor performance is analyzed. From the investigation it was found that the combustion intensity is single strut is more than the double strut at high pressure with low fuel consumption. The concluding remarks state that hydrogen scramjet combustor is superior to methane scramjet combustor. With increase in equivalence ratio and air stream Mach number, the combustion intensity and fuel consumption rate increases.

Keywords: Supersonic combustion; Combustion intensity; Equivalence ratio; Fuel injection strut; Mach number

Nomenclature: A: Combustor Cross Sectional Area (unit: m^2); A/F: Air Fuel Ratio; CI: Combustion Intensity (unit: $J/(Pa \times m^3)$); M: Mach Number; $\dot{m}$: Mass Flow Rate (unit: kg/s); P: Pressure (unit: Pa); Q: Total Heat (unit: W); T: Temperature (unit: K); V: Combustor Volume (unit: m^3); v: Velocity (unit: m/s)

Greek letters: θ: Turn Angle (unit: degrees); β: Wave Angle (unit: degrees); φ: Equivalence ratio; ρ: Density (unit: kg/m^3); γ: Specific heat ratio

Subscripts: a: Air; f: Fuel; n: Normal Component; t: Total (sum of static and dynamic); 1: Upstream; 2: Downstream

INTRODUCTION

The scramjet is an impulsive air breathing propulsion system at hypersonic speeds. The combustion process in scramjet engine is complex which leads to challenging situations for estimating combustion intensity and attaining combustion stability. In the combustor, the air approaches at supersonic velocities and its compressibility effect plays an important role in the combustion process. The high-speed air inside the combustion chamber generates compression waves due to either sudden variation in combustor cross section area or fuel injector placement in combustor across which, the flow properties change drastically. The high energy supersonic air is further mixed with fuel from the injector to form combustible mixture. The fuel and air mixes at various stages along the length of combustor. The supersonic mixture of reactants consumes certain time for combustion but due to constrained combustor length, the path of reactants is made nonlinear with the presence of vortices due to the flow separation from the solid surfaces.

Initiation of combustion process is achieved using certain heat sources/ igniters and continuous flame is established downstream of flame holder. The process will be so rapid that the requirement of heat source is not continuous, the auto ignition of reactants carry the process further. The designed complete combustion process results into increase in combustor total temperature maintaining almost constant pressure.

The fuel consumption rate, calorific value of fuel and the flow properties in the combustor are used further to determine the combustor performance parameters. Some other aspects of combustor namely shock wave boundary layer interaction, boundary layer separation, combustor hot and cold pressure losses,

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mixing rate and heat transfer helps in estimating the performance parameters more precisely.

LITERATURE REVIEW

Ruifeng C et al. [1] found that in a supersonic combustor the properties of flow past compression waves are determined based on few thermodynamic assumptions namely quasi one dimensional flow through out combustor, geometric of the combustor are functions of the axial distance, uniformly distributed flow properties along the combustor cross section, flow to be ideal gas with variation in specific heat at the combustion zone and the thermochemical process of the flow is adiabatic in combustor. Few challenges in modeling scramjet engine combustion were consideration of heat dissipation from the walls, skin friction between strut and airflow, and boundary layer separation from solid surface due to supersonic flow, which need to be considered in the detailed design process to achieve exact results. Cecere, et al. [2] studied that with the basic assumptions on airflow and combustion process, the governing isentropic equations are used to determine the air flow properties before and after the compression waves. The oblique shock wave relation helps in constructing relation between various parameters across compression waves. In supersonic combustion, the type of fuel used and the pre-combustion processes decide the supersonic combustor length and combustion temperature. The mixing process between gaseous fuel and inlet air flow decides the combustion stability as well as the efficiency. The injection of sonic fuel into supersonic air flow leads to bow shock wave at the interaction zone across which the flow properties improves. The impact of injecting fuel at sonic speed is not considered in the current work.

The fuel injecting strut in a supersonic flow generates an oblique shock wave from the strut leading edge. As compared to single strut combustor, in a double strut combustor the mixing of air and gaseous fuel is better. This is because of the relatively large vortices formation downstream of strut from flow separation. Two strut configuration forms small diamond shaped circulations near the strut with weaker expansion fan at the trailing edge of strut. These large vortices lead to higher flow separation as well from the combustor wall. With increase in pressure and temperature of air flow at the entry of combustor, it leads to enhancement in the scramjet combustor performance which is studied by Choubey Gautam, et al. [3]. The supersonic flow of reactants in the combustor is very sensitive to the strut tip and turn angle. If the strut leading edge is blunt instead of sharp, detached bow shock wave will form at the strut nose. Also with increase in turn angle of strut, the compression wave gets stronger leading to higher pressure and temperature of flow across them. Reactants mixing and combustion efficiencies for highly disturbing strut are higher than those with less disturbing strut because of large recirculation zone downstream of strut. The fuel injected perpendicularly from the strut provides better mixing and combustion efficiency with an increase in fuel rate ratio than fuel injected parallel to the air stream. This phenomenon of mixing and combustion efficiency is studied by Goro, et al. [4].

Wei Huang [5] investigated that in a supersonic combustor the shock waves between the walls of the strut forms an intersectional point and the sonic lines play an important role in the generation of the flow separation zone at the trailing of two struts, and increases the overall combustion efficiency. Also, as the strut nose gets far blunt, the bow shock wave will form resulting into complex and strong compression wave which results into shock trains in the combustor. The phenomena will increase the magnitudes of flow properties towards complete combustion; however the flow velocity reduces continuously across the shock train.

Swithenbank, et al. [6] analyzed that the combination of stirred/ stepped sections in the combustor provides enhancement in combustion intensity and stability. This enhancement is majorly due to the recirculation zone created from a step in the combustor wall. Wei Huang [5] found that the fuel is injected tangentially from the walls of a strut having a half angle of 6° located at the centerline of rectangular cross section combustor. Cecere and Waidmann [2,7] investigated the supersonic combustion in a rectangular cross section combustor is efficient at Mach 2 inlet air stream and sonic hydrogen supply from a base wedge. The injected fuel and air have to be mixed well to form a well-mixed reactant, ready for combustion with recirculation. Smaller inlet air Mach number results into sonic or sometimes subsonic flow in combustor resulting into different mode of combustion.

Aristides, et al. [8] studied that in supersonic stream the fuel air mixing and combustion initiation is accomplished through a large subsonic recirculation zone introduced using a physical wedge, where trapped hot fluid provides necessary conditions for ignition and combustor flame holding. However, such zones also cause pressure loss from shock waves. Swithenbank, et al. [9] analyzed that from turbulent flame theory, combustion stability is enhanced and combustion intensity is improved from reduced combustor length and increased width in flame using swirl. Tangential injection of fuel into centrally located swirl chamber results into spiral flow of reactants within the combustion chamber. In the combustor the gas stream is accelerated in both fuel off condition and combustion condition. Also, in combustor distributed combustion occurs which is different from distributed reaction.

Mitani, et al. [10] studied that the combustion raises the static temperature and reduces local acoustic speeds to decrease the local Mach number behind the flame. Ye and Wen [11,12] investigated that the Mach number, equivalence ratio and wall temperature decides the combustor mode of operation. Equivalence ratio 0.35 decides the mode of combustor operation. Based on these previous works, the impact of combustor pressure across the compression waves on combustion behavior was observed. The impact of having sharp strut nose on generating weak oblique shock wave for supersonic flow was noted. Also, the generation of vortices downstream of strut justifies the higher pressure and temperature zones. However, it varies with inlet stream Mach number, number of struts and strut angle.

METHODOLOGY

Numerical configuration and initial conditions

The combustor efficiency and other performance parameters decide the combustor geometrical and thermochemical configurations for certain thrust requirements. These parameters majorly depend on the thermodynamic properties of the fluid used in the system. However, combustion intensity is one of the major performance parameters of combustor/ combustion which include all the necessary variables to estimate the other combustor performance parameters.

In the present work, the scramjet combustor having constant area of cross section is analyzed in which a strut of 6° half angle is placed at the centerline of the combustor. The strut in the varying supersonic flow from Mach 1.5 to 5.0 generates compression waves of certain strength and wave angle. The pressure and temperature of approaching air stream is considered to be 0.1 MPa and 500 K which flow across these compression waves and improves significantly and also the flow stream get deflected towards the compression wave. For the considered strut, the approaching air Mach number is decided such that the flow across the compression wave is retained in supersonic velocity.

One of the cases in the present study, a scramjet combustor having two adjacent struts is considered as shown in Figure 1, in which the compression wave generated due to one strut will intersect with the compression wave of another adjacent strut, leading to higher pressure and temperature of air stream across both the waves at the center of the combustor cross section. However, near the combustor wall the rise in pressure and temperature are similar to the single strut combustor. The high pressure and temperature inside the combustor leads to rapid mixing of reactants and also dissociation releasing heat to the system. However, the pressure and temperature across non intersected compression waves are relatively lesser. This also leads to pressure gradient downstream of strut along the cross section of the combustor which further creates a recirculation zone for mixing and combustion. In the combustion study the combustor wall boundary layer effects, shock boundary layer interactions and skin frictions are neglected to estimate the maximum magnitudes of performance parameters.

Supersonic combustor having single strut at center generates compression wave as shown in Figure 2. The pressure and temperature at the combustor are found relatively smaller than double strut combustor. Also the pressure gradient across the cross section is relatively smaller hence the recirculation zone is slight.

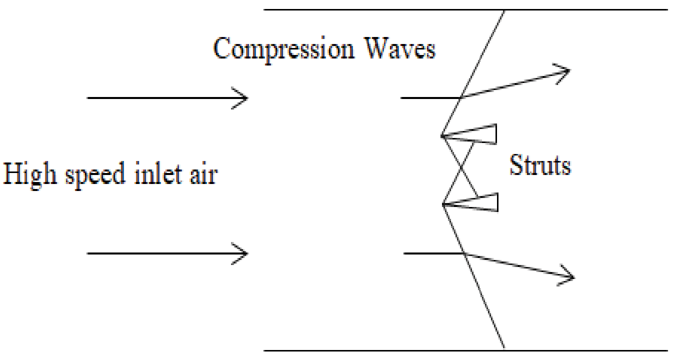

Figure 1: Scramjet combustor with two struts.

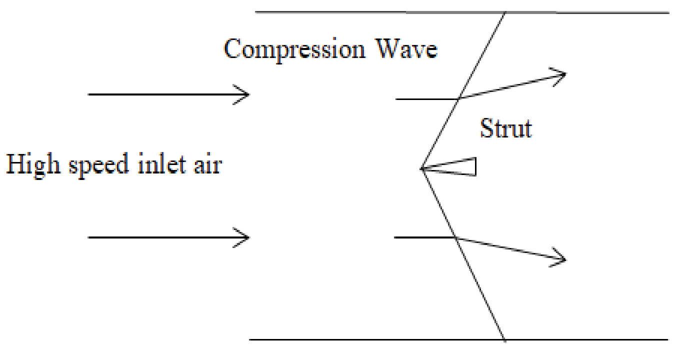

Figure 2: Scramjet combustor with single strut.

The pressure and temperature of the air stream across the compression wave of single strut are uniformly distributed along the streamlines, whereas in double strut combustor the distribution is random. Due to these facts, in a double strut combustor the inlet Mach number of the air stream has to be higher than the case of single strut combustor, for continuous supersonic combustion.

The inlet air flow stream is considered to be steady, viscous and isentropic. The magnitudes of temperature, density and pressure across the oblique compression waves are analyzed using basic isentropic relations of shock waves considering the normal component of Mach number as shown in Eq. (1) to Eq. (6) and Eq. (7) is used to deduce the strength of the compression wave.

For various upstream Mach numbers corresponding air stream conditions in the combustor are determined for double strut combustor and single strut combustor as shown in the Tables 1 and 2.

$$\frac{\rho_1}{\rho_2} = \frac{(\gamma+1)M_{n1}^{\ 2}}{(\gamma-1)M_{n1}^{\ 2}+2} \tag{1}$$

$$M_1 = \frac{M_{n1}}{\sin\theta} \tag{2}$$

$$\frac{Pt2}{Pt1} = \left[\frac{(\gamma+1)M_{n1}^{\ 2}}{(\gamma-1)M_{n1}^{\ 2}+2}\right]^{\frac{\gamma}{(\gamma-1)}}\left[\frac{(\gamma+1)M_{n1}^{\ 2}}{2\gamma M_{n1}^{\ 2}(\gamma-1)}\right]^{\frac{1}{\gamma-1}} \tag{3}$$

$$\frac{T_2}{T_1} = \frac{\left[2\gamma M_{n1}^{\ 2}-(\gamma-1)\right]\left[(\gamma-1)\mathrm{M}_{n1}^{\ 2}+2\right]}{(\gamma+1)^2\,\mathrm{M}_{n1}^{\ 2}} \tag{4}$$

$$M_{n2}^{\ 2} = \frac{(\gamma-1)M_{n1}^{\ 2}+2}{2\gamma M_{n1}^{\ 2}-(\gamma-1)} \tag{5}$$

$$M_2 = \frac{M_{n2}}{\sin(\beta-\theta)} \tag{6}$$

$$\tan\theta = 2\cot\beta\left[\frac{M_1^{\ 2}\sin^2\beta-1}{M_1^2(\gamma+\cos 2\beta)+2}\right] \tag{7}$$

In Table 1 the parameters estimated are only at the zone across the intersected compression waves downstream of both the struts and not near the combustor wall. For the complete range of inlet air Mach numbers, the pressure and density rise in double strut combustor is more than single strut combustor. This behavior results into faster thermochemical process and complete combustion due to the formation of recirculation zone.

The combustion process in supersonic stream increases the enthalpy of the system. The total heat of combustion is proportional to the calorific value of fuel and the amount of fuel consumed which further decides the combustion intensity (influenced by

Table 1: Inflow parameters of combustor across the double strut.

Variables	Mach 2	Mach 2.5	Mach 3	Mach 3.5	Mach 4	Mach 4.5	Mach 5
Pressure (kPa)	1271.8	1363.7	1453	1543.3	1635.9	1741.5	1855
Density (kg/m^3)	14.24	18.35	23.44	29.65	36.89	45.55	55.71
Combustor Mach	1.73	2.15	2.56	2.95	3.33	3.7	4.06

Table 2: Inflow parameters of combustor across the single strut.

Variables	Mach 1.5	Mach 2	Mach 2.5	Mach 3	Mach 3.5	Mach 4	Mach 4.5	Mach 5
Pressure (kPa)	1221.3	1188.6	1179.7	1179.4	1188.9	1194	1207.7	1225.5
Density (kg/m^3)	11.35	13.56	16.55	20.21	24.52	29.49	35.15	41.51
Combustor Mach	1.287	1.785	2.25	2.7	3.14	3.56	3.97	4.39

compressible effects as well). In deducing the combustion intensity, lower calorific value of fuel is considered. The fuel is injected into the supersonic air stream at various equivalence ratios ranging from 0.5 to 1.0 which results into different combustion temperatures and combustion intensities.

Eq. 8 is the mass conservation equation, used to estimate the amount of approaching air to the combustor across the compression waves and Eq. 9 for equivalence ratio is used to deduce the amount of fuel consumed in the combustor maintaining certain equivalence ratios and various Mach numbers.

$$\dot{m}_a = \rho A \upsilon \qquad (8)$$

$$\dot{m}_f = \frac{\varphi \dot{m}_a}{(A/F)_{stoichiometric}} \qquad (9)$$

Based on the combustor inlet air mass flow rate and certain equivalence ratio, the amount of fuel flow required in the combustor is determined. Using conservation of energy equation, the energy flow across the combustor is balanced and the temperature rise from combustion is deduced considering constant pressure heat addition process. Using the calorific value of the fuel, combustor volume and combustor pressure the combustion intensity is estimated using Eq. 10.

$$CI=Q/PV \qquad (10)$$

RESULTS AND DISCUSSION

In the present work, the inlet Mach number to attain supersonic combustion having single and double struts is analyzed and corresponding fuel consumptions with combustion intensities are reported. For a certain Mach numbers ranging from 1.5 to 5.0, the flow properties across the compression waves generated from strut are deduced. The total pressure loss in double strut combustor is observed to be more than single strut combustor due to the intersection of compression waves. The flow temperature and density also found to be more in double strut combustor than single strut combustor. The estimated wave angle for certain Mach number and 6° turn angle further used to deduce the downstream Mach number and its normal component (Figures 3 and 4).

In the supersonic combustor, inlet air mass flow rate depends upon the combustor inlet Mach number, combustor cross sectional area and air flow density. In a single strut combustor, the static pressure

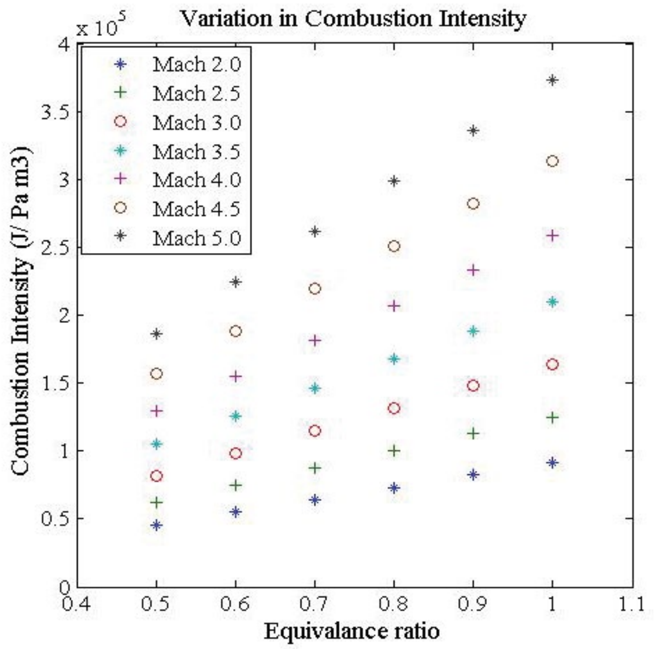

Figure 3: Combustion intensity of double strut hydrogen scramjet combustor.

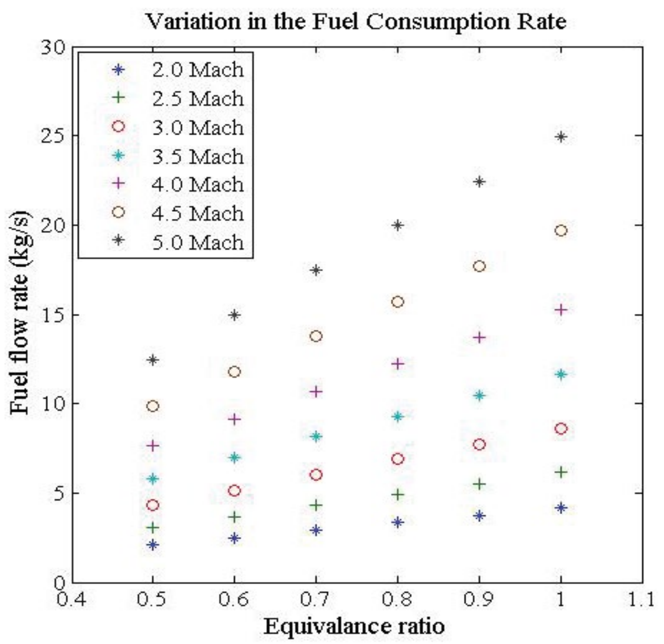

Figure 4: Fuel consumption rate in double strut hydrogen scramjet combustor.

rise across compression wave is less compared to the double strut combustor and also the density of flow in these combustors will be diverse. Hence the mass flow rate of air after the shock using eq. 1 is more for double strut combustor than single strut combustor. In the vicinity of strut wake, the reactants mixes forming a combustible mixture. This phenomenon is because of different pressure, density and temperature maintained in the combustor from compression waves and strut turn angle. Upon ignition downstream of strut, the thermochemical process begins releasing the heat to the system. Two different fuels namely hydrogen and methane are considered in this work. The enthalpy in the combustor varies based on calorific value of fuel, Mach number, equivalence ratio and number of struts used (Figures 5 and 6).

The conservation of energy equation for combustor is used to determine the combustion temperature for various equivalence ratios and Mach numbers, which is found to be varying from 2162 K to 3141 K for methane fuel and from 2367 K to 3373 K for hydrogen fuel. These temperatures are deduced based on adiabatic heat addition conditions. In the supersonic combustor, the local pressure and temperature in the combustor is high which leads to higher combustion flame temperature. Downstream of strut, the temperature, density and pressure are distributed distinctly in a double strut combustor which leads to different fuel requirement at certain zone of combustor to maintain the uniform equivalence ratio (Figures 7 and 8).

The mass fraction of fuel required at equivalence ratios 0.5 to 1.0 and Mach numbers 1.5 to 5.0 in a methane based scramjet is found

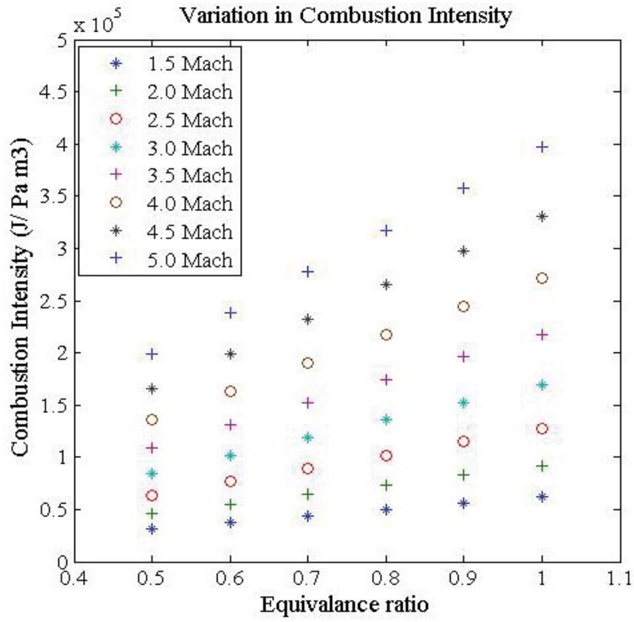

Figure 5: Combustion intensity of single strut hydrogen scramjet combustor.

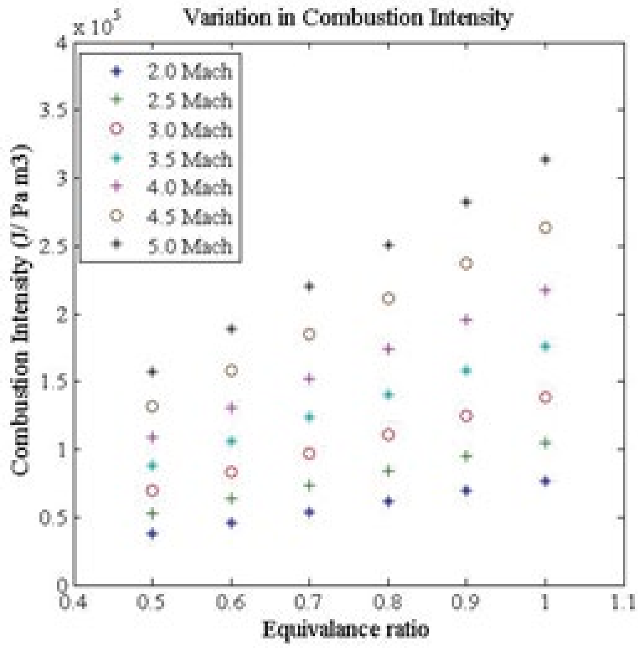

Figure 7: Combustion intensity of double strut methane scramjet combustor.

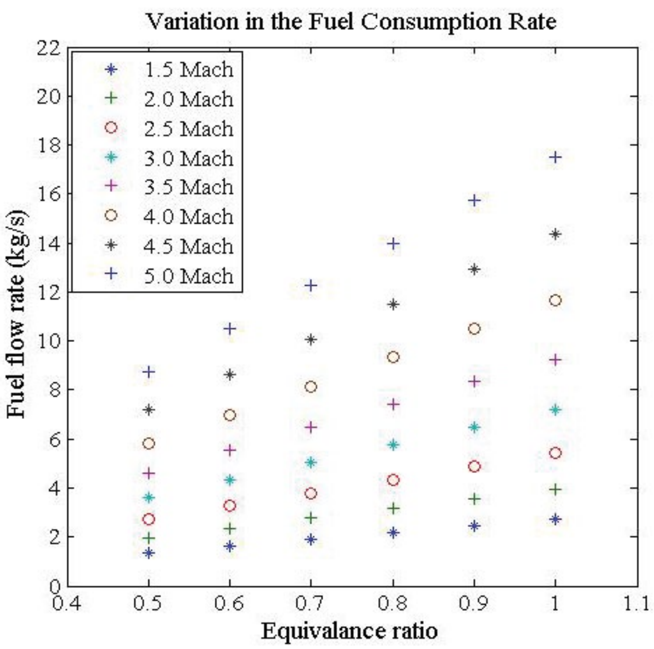

Figure 6: Fuel consumption rate in single strut hydrogen scramjet combustor.

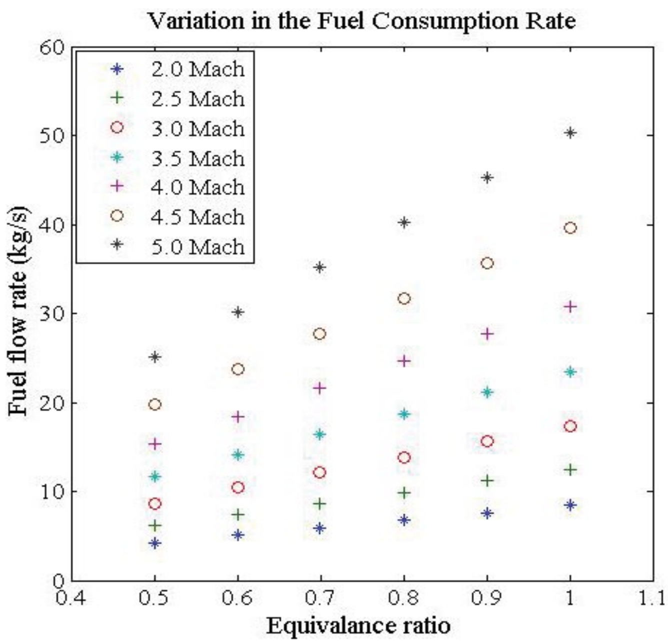

Figure 8: Fuel consumption rate of double strut methane scramjet combustor.

varying from 0.028 to 0.055, whereas for hydrogen based scramjet it is found varying from 0.014 to 0.028. If a single strut is used in a combustor then the fuel requirement will be relatively less than the double strut combustor due to combustor zone properties. Furthermore, the mass fraction in both the type of combustors for specific fuel is found to be constant. Higher the inlet air Mach number in combustor, higher will be the mass fraction of fuel (Figures 9 and 10).

In a constant pressure heat addition process the combustion intensity is inversely proportional to the combustor pressure and combustor volume, and the fuel consumption rate is directly proportional to the oxidizer density and Mach number at certain equivalence ratio. Across single strut, the increase in combustor pressure and air stream density is relatively lesser than double strut. Hence, the combustion intensity and fuel consumption are different for single and double strut combustors. The plots represent

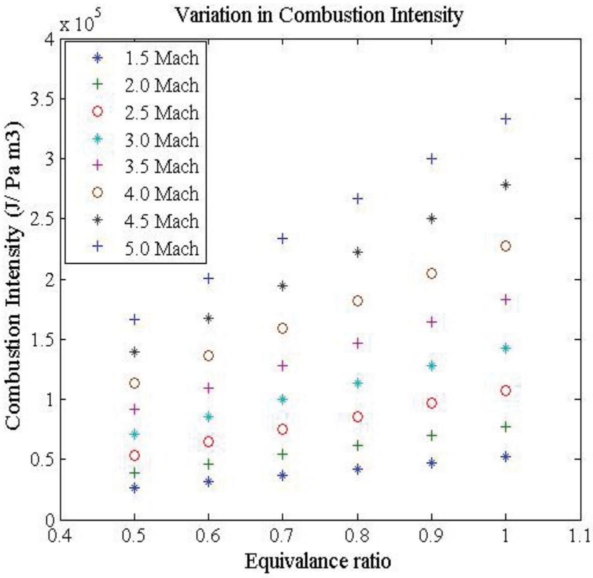

Figure 9: Combustion intensity of single strut methane scramjet combustor.

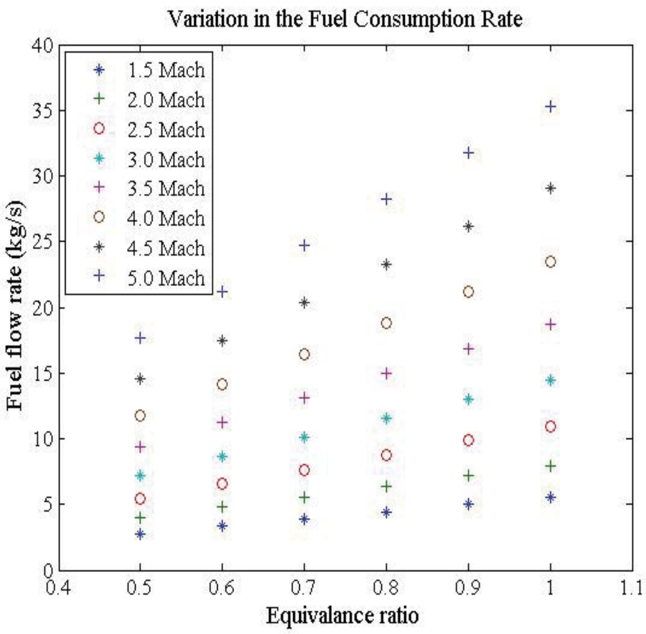

Figure 10: Fuel consumption rate of single strut methane scramjet combustor.

the fuel consumption and combustion intensity in a single strut and double strut combustors. In a single strut combustor, if the approaching air Mach number is 1.5 then the flow Mach number across compression wave will be supersonic but for double strut combustor this leads to subsonic flow. Hence for double strut combustor, inlet airstream at Mach 2.0 is considered.

s 3 and 4 shows the combustion intensity and fuel consumption rate in hydrogen based double strut scramjet combustor whereas 5 and 6 shows the combustion intensity and fuel consumption rate in a hydrogen based scramjet combustor having single strut. The combustion intensity in a single strut scramjet combustor is ranging from 31.20 kJ/ Pa × m^3 to 396.83 kJ/ Pa × m^3, whereas in a double strut combustor it varies from 45.64 kJ/ Pa × m^3 to 373.58 kJ/ Pa × m^3. The fuel consumption rate in a single strut combustor varies from 1.37 kg/s to 17.50 kg/s, whereas in a double strut combustor it varies from 2.08 kg/s to 24.94 kg/s.

s 7 and 8 shows the combustion intensity and fuel consumption rate in methane based scramjet combustor with double strut, and s 9 and 10 shows for methane based single strut scramjet combustor. In comparison to hydrogen combustor, methane based combustor also shows same trend with regards to combustion intensity and fuel consumption. The combustion intensity in a single strut combustor varies from 26.23 kJ/ Pa × m^3 to 333.58 kJ/ Pa × m^3 whereas in the double strut combustor, the combustion intensity varies from 38.36 kJ/ Pa × m^3 to 314.03 kJ/ Pa × m^3. The fuel consumption rate in a single strut combustor varies from 2.76 kg/s to 35.31 kg/s whereas for double strut combustor the fuel consumption varies from 4.216 kg/s to 50.33 kg/s. The fuel consumption rate is less for hydrogen as fuel in both single and double strut combustor at high combustion intensity. This is because of its higher calorific value and low density as compared with methane as fuel in scramjet combustor. The combustion intensity and fuel consumption rate contrast linearly with equivalence ratio and significantly with increasing Mach number. The combustion intensity increases as the fuel equivalence ratio gets close to the stoichiometric ratio, higher the inlet air Mach number and smaller the combustor pressure. Similarly the fuel consumption rate increases with increase in equivalence ratio and inlet Mach number.

CONCLUSIONS

A numerical study on the effect of single and double struts of combustor on its combustion intensity, at various supersonic Mach number are analyzed. From the present numerical study the following conclusions are drawn:

- The combustor temperature and pressure distribution across double strut is 1.12 and 1.5 times the single strut combustor.
- The combustion intensity in single strut is in between 20 kJ/ Pa × m^3 to 23 kJ/Pa × m^3 more than double strut due to higher combustor pressure.
- The fuel consumption rate in single strut combustor is 1.7 times less than double strut combustor because of less oxidizer density across the compression wave.
- Therefore, Mixing of oxidizer and fuel is better in double strut combustor due to higher pressure and temperature in combustor. Lower fuel consumption rate and higher combustion intensity

indicates that hydrogen scramjet combustor is superior to methane scramjet combustor.

- With increase in equivalence ratio and air stream Mach number the combustion intensity and fuel consumption rate increases.
- Rise in combustor equivalence ratio, the fuel consumption rate and the combustion intensities are found to be varying linearly in both the types of combustors and fuels.
- Rise in combustor inlet Mach number impacts on the fuel consumption rate and combustion intensity exponentially. Hence, the combustor inlet Mach number majorly controls the combustion intensity and fuel consumption rate in both single and double strut combustor having hydrogen and methane fuel.
- Further studies can be conducted on impact of combustor efficiency and combustor pressure loss for supersonic combustion performance.

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