Scientific Journal of Impact Factor (SJIF): 5.71
e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406
International Journal of Advance Engineering and Research Development
Volume 5, Issue 04, April -2018

INTERACTIONS BETWEEN SHOCKWAVES AND COMBUSTION PROCESS OF RAMJET AND SCRAMJET ENGINES - A REVIEW

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Abstract-*Shocks are utilizedat many stages in the operation of ramjet and scramjet engines.Shock isgenerated due to sudden change in flow properties and is used in diffusor and in nozzle expansion of high speed jet engines. Shocks may be stable or unstable depending on the design and cross-section of the region in which it is generated and advancing. The transition of air flow from supersonic speeds to subsonic speeds in ramjet enginestakes place through generation of shock. Gases in nozzle are also accelerated through shock generation. Vortices created due to shockwaves are used in scramjet engines for faster diffusion of air and fuel leading to efficient combustion process. The present study reviews and compares the various aspect of shock generation and shock flow interaction in both ramjet and scramjet engines.*

Keywords- *Ramjet engines, Scramjet engines, Ram effect, Supersonic combustion, Shockwaves, Shock induced mixing.*

NOMENCLATURE

p =pressure (Pa)
P = total pressure (Pa)
u =velocity fluctuation of normal shock (m/s)
x =position coordinate along axis of duct (m)
t =time (s)
M =Mach number
M_2 = Mach number after shock
γ =ratio of specific heats
ρ =density (kg/m^3)
T = temperature (K)
A_s = area at terminal shock (m^2)
m_2 = mass flow rate after terminal shock (kg/s)

I. INTRODUCTION

To allow greater mass flow rates for combustion, the static air pressure entering the inlet of an internal combustion engine increases, reducing the dynamic air pressure created by vehicle motion. This is known as *Ram Effect*[1].This is done by increasing the cross-sectional area of the intake duct resulting in decrease in dynamic pressure and increase in static pressure. This phenomenon is thus used as the working principle of ramjet and scramjet engines[2-3].Ramjet and scramjetengines are the type of air-breathing jet engines that use the engine's forward motion to compress the incoming air without using any actual compressor. Ramjet engines (Fig. 1) work most efficiently at speeds around Mach 3but the flow is decelerated to subsonic speeds for the combustion to occur efficiently. On the other hand, in scramjet engines (Fig. 2), combustion takes place at supersonic speeds.The speed limitations for ramjet enginesare mainly due to the generation of shock and its effect on various parameters which leads to inefficient operation of ramjet engine[4].

When a wave moves faster than local speed of sound in a fluid, a disturbance is created which propagates in the medium. This disturbance carries energy and is known as shock. It is characterized by an abrupt discontinuity and instantaneous changes in fluid properties [5-7]. Series of consecutive shocks is known as a shockwave. Shockwaves are generally formed when a pressure front moves at supersonic speed, pushing the surrounding air. Discontinuities in flow parameters are experienced in a cylindrical fashion around the body. These discontinuities produce a compression wave which moves in a lower pressure region and transforms into a planar shock [8]. The main area of concern in operation of ramjet and scramjet engines is the combustion process which needs to occur at super fast rate as the air encountered by inlet is at supersonic speed [9]. Shock generation can be considered as a positive aspect for combustion as it would tend to reduce the velocity of the incoming airflow.

This phenomenon thus helps to increase the combustion efficiency by facilitating sufficient time for the fuel to diffuse with air. On the other hand, change in flow properties such as decrease in pressure affects the combustion in a negative way as there are pressure losses, resulting in reduced density of incoming air available for combustion along with low expansion in the nozzle [10].

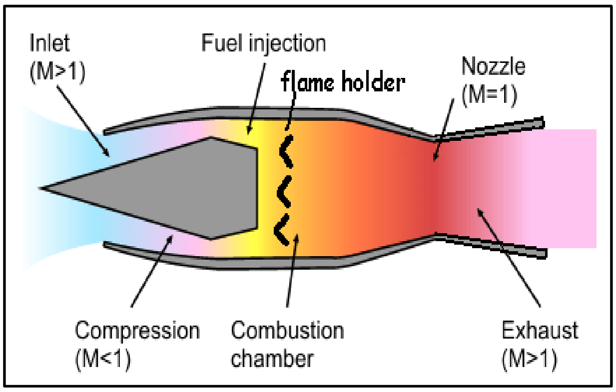

Fig. 1 Ramjet engine

(https://www.isro.gov.in/sites/default/files/article-files/node/6052/ramjets.jpg)

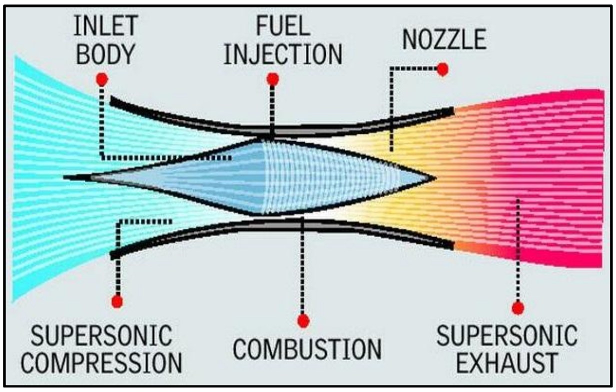

Fig. 2 Scramjet engine

(http://www.thehindu.com/migration_catalog/article10100024.ece/alternates/FREE_660/27tvtnk01_Scram+ki28scramjet.eps.jp.jpg)

II. BEHAVIOUR OF SHOCK IN AEROTHERMODYNAMIC DUCTS

The stability of shock waves in a convergingdivergingduct was analyzed by Kantrowitzo. He proposed a model which concluded that the deceleration of flow from the speed of sound, if smooth, would be unstable. This means that the transition of speed would occur through shock generation. It was also seen that a normal shock is stable in the diverging section and unstable in converging section.An assumption was made to treat the problem of shock stability that shock is stationary in the duct where it suffers a very small displacement from its initial position[11].Inlet of a ramjet engine can be considered as a duct encountering a non-uniform supersonic flow. Themodel was used to represent the unsteady behaviour of shock using non-uniformity and supersonic speed as the two boundary conditions used for the inlet of ramjetengine [12]. For duct of a uniformcross-section, the governing equations are the linearized form of conservation equations [13]:

$$\rho\frac{\partial u'}{\partial t} + \rho u\frac{\partial u'}{\partial x} + \frac{\partial p'}{\partial x} = 0 \qquad \text{(i)}$$

$$\frac{\partial p'}{\partial t} + u\frac{\partial p'}{\partial x} + \gamma p\frac{\partial u'}{\partial x} = 0 \qquad \text{(ii)}$$

Studies based on more elaborate analysis of two-dimensional transonic flows in converging-divergingsection conclude that weak nonlinear shocks are asymmetric in motion due to the sinusoidal disturbance that it may experience in the duct. Shock disappears as the pressure increases after a sudden decrease and then reappears rapidly at the farthermost downstream position where the pressure reaches minimum magnitude [12-14].As the shock proceeds further in the duct, it produces a reflected wave directly proportional to the ratio of the velocity and pressure fluctuations when the frequency of fluctuations is sufficiently low so that the shock responds in quasi-steady fashion due to rapid change in flow properties. It means that the shock affects the flow in its vicinity at each instant of time. The relation between the flows upstream and downstream of shockplays a key role in determining shock location. The governing equations representing the relation between the flow parameters upstream and downstreamof unsteady shocks are as below [13]:

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1) \quad \text{(iii)}$$

$$\frac{u_2}{u_1} = 1 - \frac{2}{\gamma+1}\left(\frac{M_1^2-1}{M_1^2}\right) \quad \text{(iv)}$$

Due to the different thickness of boundary layer, different shocks are generated. For instance,a normal shock is generated in duct with no boundary layer thickness, with an increase in thickness of boundary layer lambda shocks start to generate andan oblique shock is generated if the boundary layer thickness increasesfurther [15].

III. VORTICES FORMATION AND TURBULENCE DUE TO SHOCK GENERATION

Shock generation creates a region of low pressure. Fuel and the incoming flow are of different densities and subjecting them to impulsive acceleration leads to unstable interface between the fluids of two different densities. This instability is known as Richtmyer-Meshkov (R-M) instability. Complex vortices-driven turbulence is created in contrast to the R-M instability[16-17]. This turbulence can be used for faster mixing of air and fuel in the combustor. Analytical and computational studies show that there are two forms of dynamics of R-M instability driven complex flow. Complex geometries like the double interface are covered in R-M instability [18].Cylindrical columns of mixing gases are formed due to the vortices created at the interface of the mixture [19].The interaction between the shockwave and the shear layer of supersonic incoming flow generates vorticity because of the non-collinearity of the density and pressure difference before and after the shock [20].Pair of two counter-rotatingvortex is created by these vortices.

Secondary instability is subsequently evolved on the outer edge and in the core centre leading to a turbulent vortex core. This promotes aprematureacceleration of the gases [19]. Initially, the cross-section geometry of gaseous cylinder isfound to be the main cause for the number of dominant vortex pair columns that would roll in vorticity after the interaction with shock [21]. On the basis of shape taken by combinations of three vortices, most common morphologies (Fig. 3) are Weak Bridge jet morphology, Strong-Bridge jet morphology, Bunny ears and spike. Using these vortex rollups, the increased molecular mixing of fuel and air can be accomplished by increasing turbulent mixing for an efficient combustion [22]. This concept of vorticity is used in the application of scramjet engines by mixing co-flowing supersonic air stream injected with one or more fuel jet. Temporal passage of normal shock in the two-dimensional flow is comparable in many aspects to three-dimensional, steady gas-jet interactionwith an oblique shock wave. Vortices thus created are desirable as they help in the dissipation of heat evenly and not allow the heat to focus on a particular location. Greater misalignment of density and pressure gradient initially is used to produce vorticity suggesting to injector positioned perpendicular to the direction of shockwave. In combustor of a scramjet engine, primary shock after hitting the walls get divided into many secondary shocks downstream of primary shock and are called as reflected shocks [23].

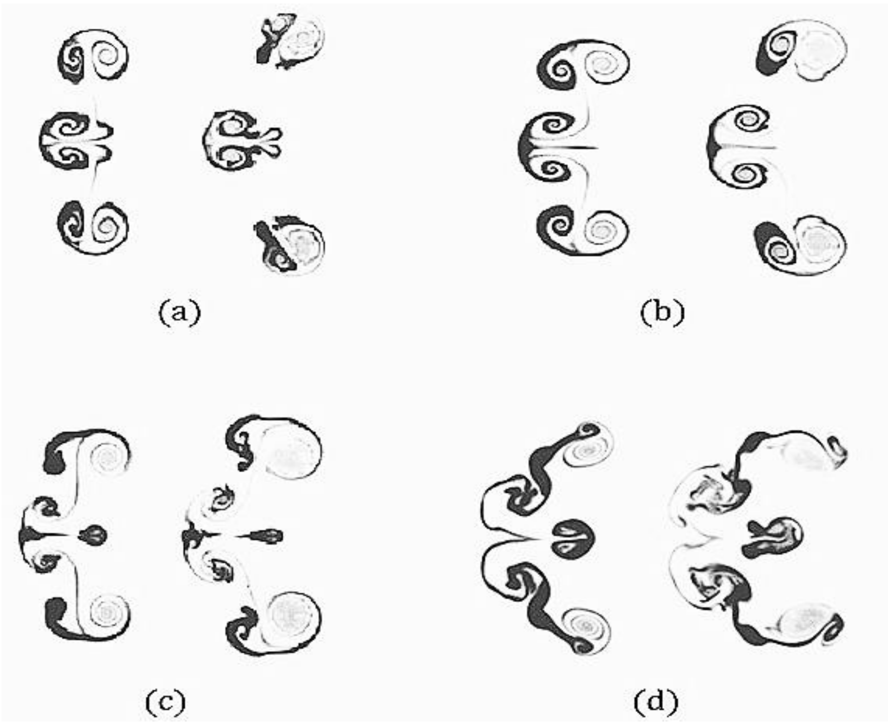

Fig. 3 (a) Bunny ear, (b) Spike, (c) Weak bridge, (d) Strong bridge

IV. DETERMINATION OF SHOCK POSITION IN RAMJET ENGINE

One or more oblique shocks compress the supersonic flow externally and a series of weak shocks compress it internally till a terminating shock is generated [24]. Total temperature, pressure and mass flow rate can be calculated using the relations ofoblique shock in adiabatic process andassuming the values same as that of a calorically perfect gas. There is no difference in flow parameter before and after oblique shock but a significant change in pressureoccurs [25]. Experimentally determined pressure loss coefficient is recorded as a function of free-stream Mach number and angle of attack. If the extent of shock travel is limited, pressure change due to shock motion is small as compared to subsonic total pressure loss. Taking this assumption of limited allowance to terminal shock,it can be applied to supersonicintake of ramjet engines. Normal shock relations are used to determine the flow properties at downstreamposition of subsonic flow and upstream of supersonic flow. Position of terminal shock can be obtained from conservation of mass and isentropic relations using the Mach-area relation [26]:

$$A_s = \frac{m_2}{P_2\{\left(\frac{\gamma}{RT_2}\right)\left(\frac{2}{\gamma+1}\right)\}^{\frac{1}{2}\left(\frac{\gamma+1}{\gamma-1}\right)}} \frac{1}{M_2}\left[\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}M_2^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}} \qquad \text{(v)}$$

New total pressure is generated behind terminal shock due to the effects of pressure wave propagating upstream on the position of shock generated at intake. Flow properties of combustor are altered by this changed total pressure. After a series of changes in upstream pressure wave and downstream entropy and pressure waves, an equilibrium condition is obtained. Operating margin and mutual relation between terminal shock and fluctuation in combustor pressure is determined by the dynamic models of fuel supply. Mach number decreases from free-stream to combustor inlet contrary to static pressure and temperature in terms of supersonic and subsonic deceleration. For subsonic combustion, Mach number and static temperature increases whereas the static pressure decreases with the decrease in Rayleigh flow [27].

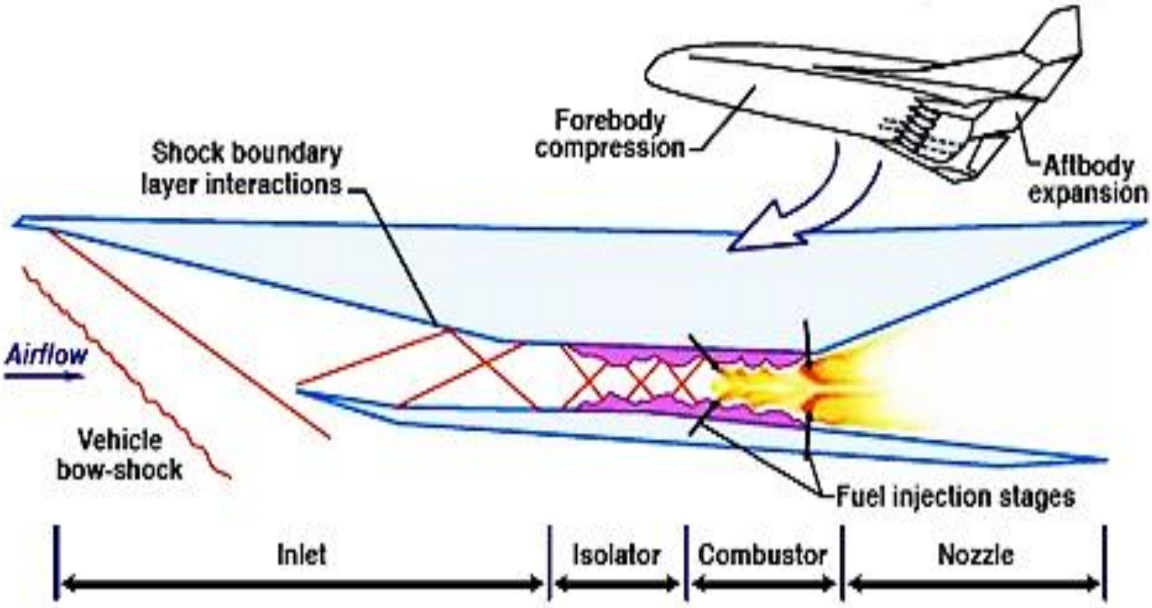

Fig. 3Scramjet Engine Combustor

(https://www.nasa.gov/centers/langley/images/content/142861main_x43a_intscramjet_550.gif)

V. SHOCK INDUCED COMBUSTION IN RAMJET ENGINES

The time available for efficient combustion in ramjet and scramjet is very small. Thus, for complete combustion, a longer combustion chamber is required which in return would increase the structural weight of the engine. To counter this scenario, shock induced combustion is used in ramjet engines [28]. Due to structural formation and presence of oblique plane, shockwave is generated while fuel is injected (Fig. 4). Second shock is generated which enhances air-fuel mixing. The mixture is ignited by a detonation generated at the entrance of combustor but the temperature is maintained below 900K. Due to drastic increase in temperature of shockwave, the reaction time of shock induced combustion decreases. The air fuel mixture is further compressed pushing it into hot boundary layer. Nitrogen is injected prior to the shock, providing longer distances for mixing of air and fuel. At present two methods are used for detonation for ramjet engines i.e. shock induced direct detonation and non-contact ignition. A blunt body or a wedge is used in front of combustor to generate normal shock after the injection of fuel. Detonation might fail as the result of low pressure and temperature due to weak shock generated by small angle of wedge. On the other hand,production of a stronger oblique shock tends to result in large total pressure loss and aerodynamic resistance. To overcome this, the mixture should be pre-compressed and must be heated to be implemented for shock induced direct detonation. Secondly, the total pressure loss must be reduced by decreasing the angle of oblique shock. Here, oblique shock angle is to be maintained so that decrease in pressure and temperature doesn't bring disadvantage to initialisation and self-sustainability of detonation [29].

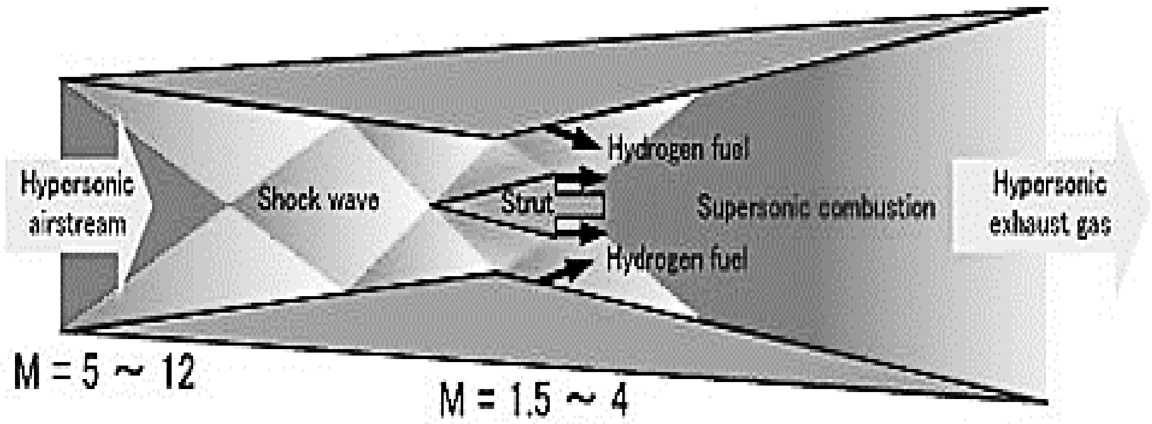

Fig. 4Shock induced combustion

(https://www.isro.gov.in/sites/default/files/article-files/node/6052/dual-modes-ramjet.jpg)

VI. CONCLUSION

The present study concludes that the pressure loss due to shock generation won't be large enough to drop the exit pressure and affect the nozzle expansion. Different shocks are generated due to different aspects of the flow which also depend on the thickness of boundary layer inside duct. Shock is a major part of many stages of engines working on ram effect, so making them useful will be of great advantage. Proper experimentation and further studies can help to understand and utilize shock up to their full potential as these flight vehicle engines can be used in advanced space vehicles. Shocks are supportive in supersonic compression and transition of flow from supersonic to subsonic. Vortices created in supersonic flow helps in more efficient mixing of air and fuel. Shock induced combustion are the latest advancement in ramjet engines technology.

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