HYPERSONIC FLOWS AND ITS APPLICATIONS

A Seminar Report

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CERTIFICATE

This is to certify that the report entitled **“Hypersonic Flows and Its Applications”** submitted by **Adityan Rajesh** (TCR19ME013), to the APJ Abdul Kalam Technological University in partial fulfillment of the B.Tech. degree in Mechanical Engineering is a bonafide record of the seminar work carried out by him/her under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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DECLARATION

I Adityan Rajesh hereby declare that the seminar report "Hypersonic Flows and its Applications", submitted for partial fulfillment of the requirements for the award of degree of Bachelor of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of Prof. Dr. Manmohan C M.

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ABSTRACT

This report aims to introduce Hypersonic flows and highlight the wide range of applications in the industry, primarily in the Civilian and Military Aerospace Industries. Hypersonic flows can be defined as those flows where the Mach number reaches above Mach 5. Hypersonic flow behaviour is unique, as air molecules tend to dissociate. We do not see such a phenomenon in Supersonic Flows which range from Mach 1-5.

We will understand the overall performance of different regular shapes under Hypersonic Flow and investigate the heating of surfaces and boundary layers at such high-speed flows. The performance characteristics give valuable input towards designing a Hypersonic Vehicle Geometry.

We will then review the current Hypersonic Vehicle Technology which has been widely used in Military research for the past 30 years with its application soon entering the civilian aerospace sector in terms of the optimized design of the airframe and the propulsion systems that need to be developed to commit the human-rated standards as set by regulating bodies.

KEYWORDS: Hypersonic Flow, Glide Vehicle, Aerospace, Mach Number, Re-entry Vehicles

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Adityan Rajesh

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LIST OF SYMBOLS AND ABBREVIATIONS

$\varsigma(\phi)$ = normalized normal coordinate

ϕ = normalized lateral coordinate

η = normalized axial coordinate

C = class function

N = sectional section control factor

1.1 INTRODUCTION

Hypersonic flows can be defined as those flows where the Mach number reaches high values, typically above Mach 5 [1]. Hypersonic Flow is unique, a speed where dissociation of air begins to become significant and high heat loads exist. The Mach number is different depending on the medium in which the flow happens. The Mach number is defined as the ratio of the speed of flow in a particular medium to the speed of sound in that medium. The study of Hypersonic Flows is nothing new, and technologies related to it have been extensively developed during the post-World War period in the 1950s [2]. The first Hypersonic Flight was recorded in the early 1950s when X-15 developed by NASA broke the sound barrier powered by a rocket, achieving Hypersonic Flight. [1].

Hypersonic Flight has vast applications, primarily in the Defence and Space Industry. Intercontinental Ballistic Missiles developed initially by the Soviet Union, range around very high speeds of more than Mach 20. Re-entry vehicles/Space Capsules enter the atmosphere at Hypersonic Speeds, producing a Heating effect at an extensive scale, for which it requires protective heatshields to protect the Vehicle from blowing up during Re-entry.

Further, in the 1980s and 90s, we started seeing Space Shuttles which is a spaceplane that travels at Hypersonic Speeds. The space shuttle program has been helpful in completing the International Space Station project which is one of the most expensive multi-national projects ever done by humankind.

At around the same time in India, we see the Guided Missile Program, carried out by DRDO [2]. The Agni series of Ballistic Missiles when re-entering the atmosphere at Hypersonic Speeds ranging from Mach Number 20-28. Ballistic Missile offers credible deterrence in Defence Applications against a Nation’s adversaries.

The recent addition to these Hypersonic Weapons is the Hypersonic Glide Vehicles and Hypersonic Cruise missiles, which are now known for their tactical defence capabilities. The design of these Hypersonic Glide Vehicles makes them a unique weapon, in which the Vehicle can move in different directions at Hypersonic Speeds, escaping any countermeasures against this Vehicle [3]. The formation of Plasma of Hypersonic Cruise missiles makes it undetectable by any military RADAR and thus offers credible offensive capabilities. The spin-off technologies of Cruise Missile technologies are now being used to develop Hypersonic Vehicles for Civilian Purposes.

CHAPTER 2
LITERATURE REVIEW

2.1 Hypersonic Flow and Propulsion Systems

Hypersonic can be described as the regime of flight where aerodynamic heating takes place. Mach 5 and higher is the regime of hypersonic flight. Important results in hypersonic have mostly been experimental. Hypersonic is important because it has provided us with optimal solutions relating to thermal protection during atmospheric entry. Due to this, ballistic missile nose cones have been developed which have been vital during missions to the Moon and planets like Jupiter. The second most important application of hypersonic has been in propulsion science. Supersonic flight is achieved when an aircraft touches Mach 1, which continues up to a range of Mach 4. Hypersonic velocities are achieved with a flight regime ranging from Mach 5 and above. Ramjets become highly inefficient at this range, mostly because of aerodynamic heating. A new engine, the Scramjet is ideally used for hypersonic regimes. Scramjet stands for Supersonic Combustion Ramjet. Unlike the ramjet, the combustion inside a scramjet is supersonic throughout [2].

Scramjet engines also have a flourishing military applications as ballistic missiles, rockets etc. usually belong to the hypersonic regime. Scramjet technology promises high-speed, efficient propulsion system design which may replace rocket propulsion for better advances in space exploration [2].

The hypersonic speeds result in high temperatures in the shock layer that envelops the vehicle and in the boundary layer where there are extreme levels of shear. The elevated temperatures in hypersonic flows give rise to many processes, such as vibrational and electronic energy excitation, chemical reactions, ionization, and gas-surface interactions. When these processes occur, the perfect gas shock relations are no longer valid and the equations of state become nontrivial [4].

For example, a Mach-6 normal shock wave produces conditions such that the vibrational energy is excited to about 10% of the total internal energy. At higher Mach numbers, additional processes become important, and therefore hypersonic flows are usually characterized by imperfect gas effects. The rates of vibrational excitation and chemical reactions depend on the local thermodynamic state, and these rates increase with increasing density and temperature. At typical hypersonic conditions, these rates are often like the advection rates [4].

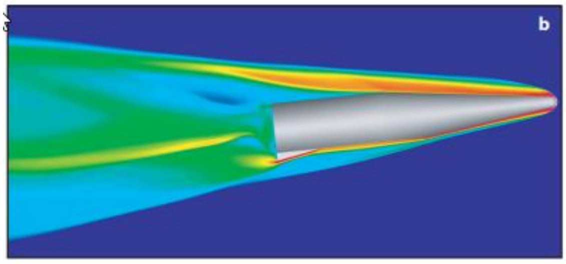

Fig. 2.1: Hypersonic Body

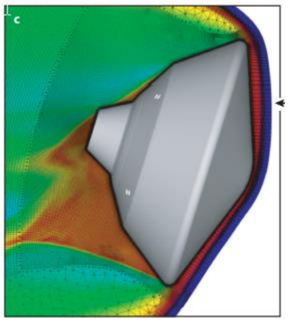

Fig. 2.2: Re-entry Vehicle

In the CFD figure (2.1), it shows a generic lifting hypersonic body while the figure (2.2) shows the shockwaves of a Re-entry Vehicle at Hypersonic Speeds.

Aerodynamic heating is a key issue in hypersonic flow research due to its strong relevance to the safety of ultra-high-speed flight. Accurate knowledge about where and why, and with what strength, strong heating peaks occur at the wall is of crucial importance to the performance and safety of hypersonic vehicles [5].

2.2 Design of Hypersonic Glide Vehicle

2.2.1 Performance of Basic Shapes

In the paper Kshitij Gandhi et al we got to understand how different shapes result in different aerodynamic parameters in a Hypersonic Flow Regime. Bluff bodies have a great impact on engineering applications (aeronautical, Aerospace, civil, mechanical, naval & Oceanic) & have their origin associated with the development of interaction between two shear layers and boundary layers including laminar, transition and turbulent flows. Surface like a circular cylinder which is commonly studied because of its collection of flow phenomena and surface roughness around a single rough circular cylinder is concerned with the complex flow over a bluff body [3].

We can define bluff body as a body that, due to its shape causes the flow to separate over its surface. The flow separation occurs due to formation of high-pressure regions at edges or surfaces, unsteady vortices are also formed. These phenomena lead to formation of high drag and unsteady forces opposite to the flow direction [3].

In the study there were 4 shapes taken for analysis. The various shapes were decided mostly based on their aerodynamic designs. These shapes are used so that we can observe the difference in the aerodynamic performance due to the changes in the shape.

The length of all the shapes is kept constant – 56mm and maximum thickness of all the shapes is 12mm.

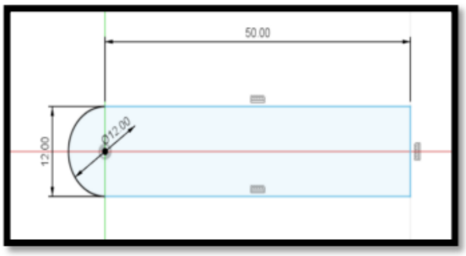

Fig. 2.3(a): Circular Tip

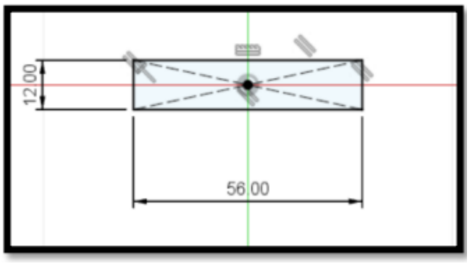

Fig. 2.3(b): Rectangular Geometry

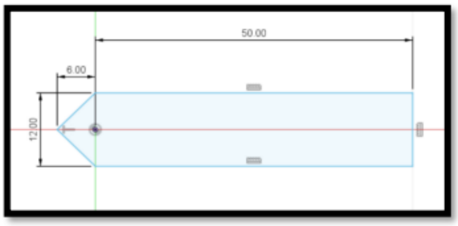

Fig. 2.3(c): Triangular Tip

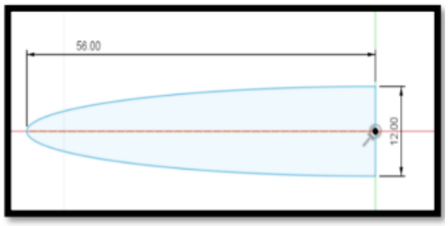

Fig. 2.3(d): Elliptical Nosecone

Fig. 2.3: Selected Geometries

The boundary conditions used in the simulation are as follows [3].

1. The bluff body is kept as no-slip wall.
2. The velocity is changed at the inlet for analysis of the shapes at various Mach numbers.
3. The operating pressure is kept at sea level for all the cases.

Other parameters like the Solver and Solution Methods are as follows.

1. A pressure-based solver is used.
2. The energy equation is turned on
3. SST K-omega turbulence model is used.
4. The air is kept as ideal gas.
5. The scheme is kept as coupled
6. Green gauss node-based method is used.
7. The second order upwind discretization is used.

Table 3.1: Drag Force Table (1)

Mach Number	Drag of Rectangular body (N)	Drag of Triangular tip (N)	Drag of Circular tip (N)	Drag of Elliptical nose shape (N)
1.5	2825.56	2199.12	2129.92	1718.83
2	5684.78	5019.59	4628.57	2519.47
3	12746.82	9619.14	9886.84	4211.20
5	34462.85	27817.04	26023.42	9084.50
10	144458.53	98920.07	93313.456	36810.8

Table 3.2: Drag Coefficient Table (2)

Mach Number	C_d of Rectangular body	C_d of Triangular tip	C_d of Circular tip	C_d of Elliptical nose shape
1.5	0.164	0.122	0.117	0.098
2	0.186	0.150	0.137	0.081
3	0.185	0.134	0.135	0.063
5	0.180	0.139	0.128	0.046
10	0.190	0.124	0.115	0.040

The subsequent results showed that the rectangular shape had the maximum drag coefficient as compared to the other 3 shapes. The least drag is produced by the elliptical nosecone, with its drag coefficient systematically decreasing at higher fluid velocities.

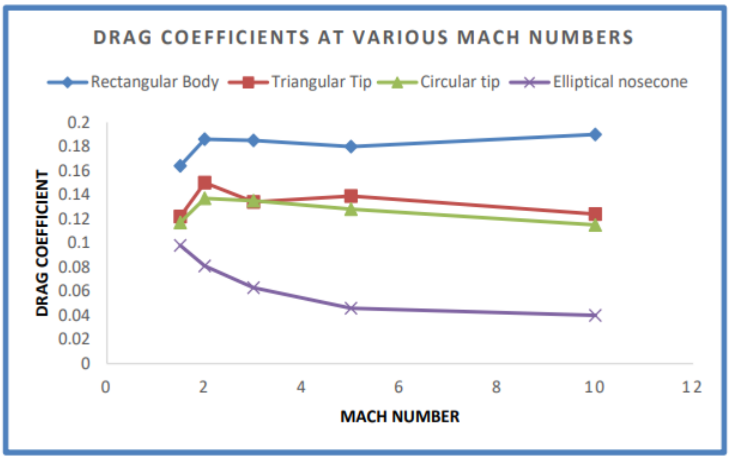

Fig. 2.4: Cd VS Mach Number

A similar trend is observed in the Pressure values at the shock waves, of both Rectangular and Elliptical Nosecones.

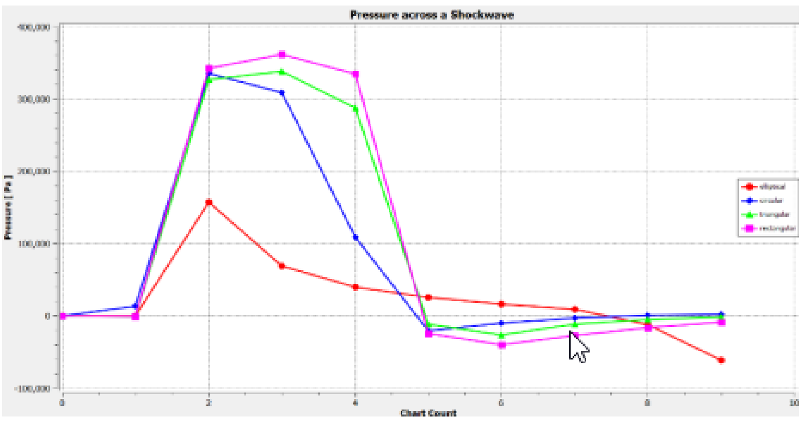

Fig. 2.5: Pressure VS Mach Number

The contour plots obtained in the CFD study are as follows. The highest pressure is recorded in the leading tip of each of these bluffed shapes

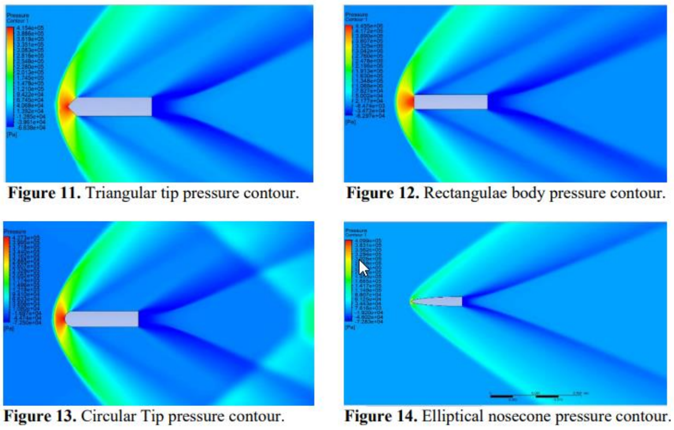

Fig. 2.6: Pressure Contour

2.2.2 Design of the Slender Body

Now, in another well-known paper, T.-t. Zhang et al. we get to understand the different parameters involved in designing a Hypersonic Glide Vehicle.

Multi-objective design optimization approach applied in the design of aircraft requires enormous number of cases. In order to decrease the computation cost, efficient aerodynamic estimation method is necessary. Although the CFD method has been popularized because of its high accuracy, the computational cost and great amount of numerical results brought by it will be unacceptable [6].

In this paper, the three-dimensional CST method is improved by introducing more parameters so that the interface between the upper and lower surface of the body can be controlled and the parametric capability is advanced. The method is applied during conceptual design phase of HGV thus expanding HGV's design space.

The CST method was universally used as an air foil parametric method, which solves two-dimensional problem, although it can also be a three-dimensional parametric approach. The geometry is mathematically composed by class function C N1 N2 (ϕ) and shape function S(ϕ), and it is shown in Eq. (1).

$\varsigma(\phi) = C\ N1\ N2\ (\phi) \times S(\phi)$ .... (1)

Herein, ϕ stands for the non-dimensional length in the axial direction and $\varsigma(\phi)$ is the relevant function value. The classification of a curve is determined by the parameters N1 and N2 in the class function, which is shown in Eq. (2).

C N1 N2 (ϕ) = ϕN1 (1 − ϕ) N2 .... (2)

The most popular function used as the shape function is Bernstein's polynomial

$$S(\varphi) = \sum_{i=0}^{n} b_i \cdot \binom{n}{i} \varphi^i (1-\varphi)^{n-i}$$ .... (3)

When it goes to three-dimensional space, the coordinate of the surface should be expressed in a Cartesian coordinate system. The non-dimensional axial coordinate η can be mapped into the X direction as:

X(η) = η .... (4)

We get the final expression as

$$Z(\varphi, \eta) = C_{N_2}^{N_1}(\varphi) C_{M_2}^{M_1}(\eta) \sum_{i=0}^{n} \sum_{j=0}^{m} b_{i,j} B_n^i(\varphi) B_m^j(\eta) + \Delta \varsigma_{M,N}(\varphi, \eta)|_{upp,low}$$

Since the HGV is traditionally a symmetric model with sharp nose and wide back-wall, some class function parameters can be treated as follows:

T1 left = T1 right = T ....Symmetry property

N1 upper = N2 upper = N upper.........................Symmetry property

N1 lower = N2 lower = N lower..........................Symmetry property

N3 = N4 = H..Symmetry property

T2 left = T2 right = M2 upper = M2 lower = M4 = 0...wide back-wall

M3 = F

We get the following shape of the Glide Vehicle

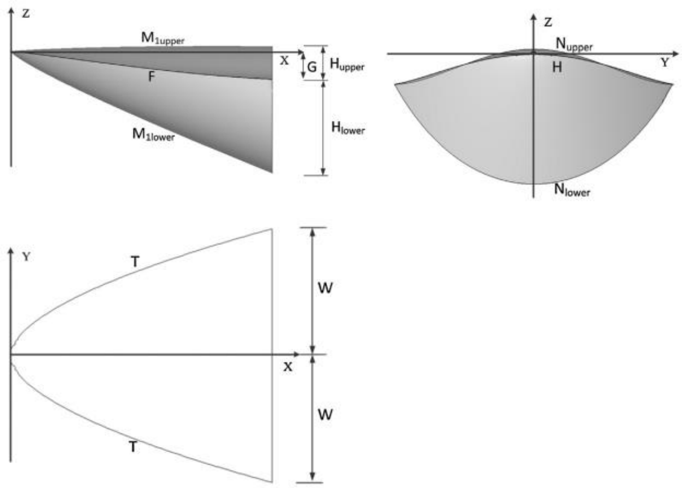

Fig. 2.7: HGV Geometry

The subsequent code validation can be done through CFD studies, where we study the characteristics of this slender body shape used for the Glide Vehicle and compare it with the available Experimental Data. The graph below shows, the CFD and Experimental Result in one Plot.

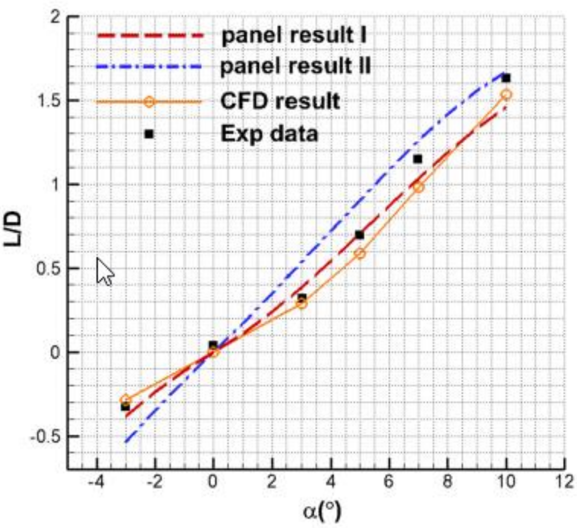

Fig. 2.8: HGV Performance

2.3 Hypersonic Vehicles

2.3.1 Boeing X-51A

The Boeing X-51A ‘Wave Rider’ is an unmanned, research, scramjet, and experimental aircraft designed for hypersonic flight at Mach 5 (3,300 mph: 5,300 km/hour) at an altitude of about 70,000 feet (21,000 m). It was named ‘X-51’ in the year 2005. The first powered hypersonic flight by X-51 was completed on May 26th, 2010. The X-51 completed a flight of over 6 minutes and reached a velocity of over Mach 5 for a total of 210 seconds on May 1 st, 2013. This was achieved after two unsuccessful flights. It is also the longest duration powered hypersonic flight. The aircraft is referred as a ‘Wave Rider’ as it effectively uses its own compression lift produced by its own shock waves. It was a joint effort of United States Air Force, DARPA, NASA, Boeing and Pratt & Whitney Rocketdyne. This program was headed by the Aerospace Systems Directorate in the US Air Force Research Laboratory (AFRL). The X-51 technology has been posited to be used in the High-Speed Strike Weapon (HSSW) which is a Mach 5+ missile that is expected to enter service by mid-2020s [2].

The X-51 was able to complete its first powered flight on May 26th, 2010. It reached a velocity of Mach 5 (3,300 mph; 5,300 km/hour) at an altitude of about 70,000 feet (21,000 m) and flew for over 200 seconds. The test had the longest hypersonic flight time, at 140 seconds using its scramjet power. After two seemingly unsuccessful flight tests, a third flight test took place on May 1st, 2013. The X-51 and its booster attached from a B-52H was flown and hence powered to Mach 4.8 (3,200 mph: 5,100 km/hour) by its booster rocket. It separated and ignited its engine [2].

The test aircraft accelerated to Mach 5.1 (3,400 mph; 5,400km/hour) and flew for 210 seconds until running out of fuel and falling in the Pacific Ocean, for a total flight time of over 6 minutes. This test was the longest air-breathing hypersonic flight. The Air Force Research Laboratory believes that it will serve as research for practical applications of hypersonic flight, such as: missile reconnaissance, transport, and as an air-breathing first stage for space vehicle system.

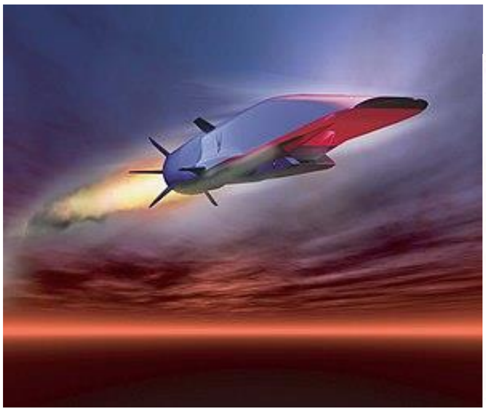

Fig. 2.9: X-51 Render

Fig. 2.10: X-51 Launcher

2.3.2 Reusable Launch Vehicle Technology Demonstrator Program (RLV-TD)

Reusable Launch Vehicle-Technology Demonstrator (RLV-TD) is India's first uncrewed, flying testbed (a platform for conducting rigorous transparent and replicable testing for scientific theories, computational tools and new technologies) It is one of India's most technologically challenging endeavours of ISRO (Indian Space Research Organization) toward developing essential technologies for a fully reusable launch vehicle in order to enable low-cost access to space.

It is a scaled down prototype of an eventual two-stage-to-orbit (TSTO) reusable launch vehicle. The RLV-TD successfully completed its first atmospheric test flight on May 23rd, 2016, at 01:30 UTC from Shashi Dhawan Space Centre for 770 seconds and reached a maximum altitude of 65 km. (40 miles) The final version of this vehicle is expected to be ready by the year 2030.

The fully developed RLV is expected to take off vertically like a rocket, deploy a satellite into orbit and return to earth landing on a runway like an airplane.

The dimensions of RLV include a height of approximately 16m (52 ft.) Length 6.5 m which is approximately 21 ft. for orbiter. RLV-TD has mass of 1.75 tonnes, (orbiter: 1.75 tonnes) wingspan of 3.6 meters and overall length of 6.5 meters (excluding the rocket). The vehicle had 600 heat-resistant tiles on its undercarriage, and it features delta wings and angled tail fins.

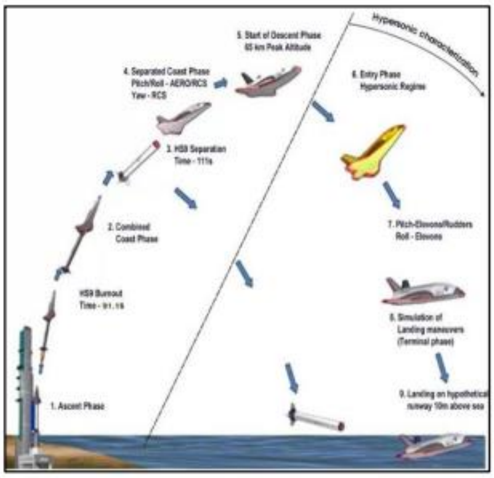

Fig. 2.11: RLV-TD Mission Profile   Fig. 2.12: RLV-TD Assembly

2.3.3 Hypersonic Technology Demonstrator Vehicle (HSTDV)

HSTDV is unmanned scramjet demonstrator aircraft for hypersonic speed flight. The HSTDV` program is run by the Indian Defence Research and Development Organization. (DRDO)

The long-term objective of this program is to develop a successful hypersonic missile program as the HSTDV can be used as a launcher for hypersonic cruise missiles as well as a launcher for satellites at a low cost. It is being developed as a carrier vehicle for hypersonic as well as long range cruise missiles and will also have multiple civilian applications. The objectives of the DRDO are to develop a ground and flight test hardware as a part of a plan for hypersonic cruise missile development [2].

The DRDO's HSTDV was intended to attain an autonomous scramjet flight for 20 seconds, using a solid rocket booster. This research will also bolster India's attempts in developing a Reusable Launch Vehicle (RLV) for future space missions. The target was to reach Mach 6 at an altitude 32.5 km. (20 miles) The initial testing was meant to validate the aerodynamics of the vehicle, as well as the thermal properties and the performance of the scramjet engine. The design for airframe attachment with the engine was completed by 2004 [2].

On June 12th, 2019, the first flight test was performed. The cruise vehicle was mounted on Agni-I solid rocket motor, ballistic carrier vehicle to take it to the required altitude. After achieving the required altitude and the Mach, the cruise vehicle was ejected out of the launch vehicle. Mid- air scramjet engine auto ignited and was able to propel the cruise vehicle at Mach 6 [2].

On September 7 the, 2020 the Scramjet Powered Hypersonic Technology

Demonstrator Vehicle (HSTDV) was successfully tested by DRDO. The cruise vehicle was launched at 11:03 IST from Dr. APJ Abdul Kalam Launch Complex at Wheeler Island atop a solid booster. At 30 km altitude, the payload fairing separated, the HSTDV cruise vehicle separated after that, followed by air intake opening, fuel injection and auto-ignition. After sustaining hypersonic combustion for 20 seconds, the cruise vehicle achieved a velocity of nearly 2km/sec [2].

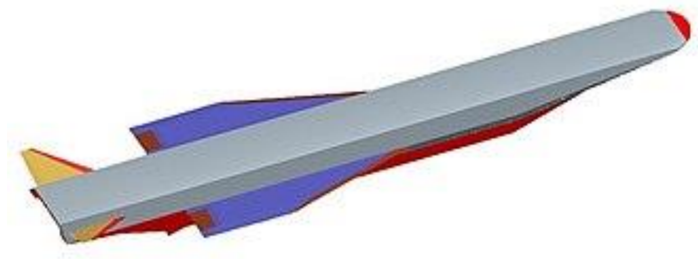

Fig. 2.13: HSTDV Render

Fig. 2.14: HSTDV Scaled Down Model

2.3.4 Avangard(Russia)

In 2015, a claim was made that the Avangard manoeuvrable hypersonic vehicle can work as an option for the "Samrat" missile, which would have the capacity to carry three of such missiles. As the glide vehicle will approach its target, the surface temperature rises sharply to 2000 °C and because of this reason composite materials which can withstand such temperatures have been developed, to protect it not only from aerodynamic heating but also from potential laser radiation. "Avangard" is a real system which is at an advanced stage of development, and it is believed that it will be deployable within next 3 to 5 years

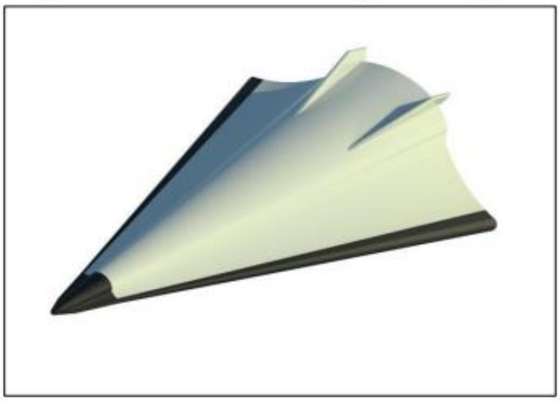

Fig. 2.15: Avangard

2.3.5 Dongfeng-17 (DF-17), (China)

The DF-ZF, designated by Pentagon as the WU-14, is a hypersonic missile delivery vehicle that has been flight-tested by China seven times, on 9 January, 7 August and 2 December 2014; 7 June and 27 November 2015; in April 2016 and twice in November 2017. The system is operational as of 2019.

Hypersonic glider vehicles are less susceptible to anti-ballistic missile countermeasures than conventional re-entry vehicles (RVs). Normal RVs descend through the atmosphere on a predictable ballistic trajectory a hypersonic glider like the HGV can pull-up after re-entering the atmosphere and approach its target in a relatively flat glide, lessening the time it can be detected, fired at, or reengaged if an initial attack fails. Gliding makes it more manoeuvrable and extends its range. Although gliding creates more drag, it flies further than it would on a higher trajectory through space, and is too low to be intercepted by exo-atmospheric kill vehicles.

Fig. 2.16: DF-17

CHAPTER 3

RESULTS

The Hypersonic Flow Regime occurs beyond Mach 5. Here we observe extensive aerodynamic heating on the surface of the body which eventually leads to the formation of Plasma around them.

This aerodynamic Heating is observed in Atmospheric Reentry Vehicles like Space Capsules and Ballistic Missiles.

The 4 shapes were analyzed in the Hypersonic regime, and the one with the lowest drag coefficient is found to be observed for the elliptical nosecone, meanwhile, the rectangular nosecone has the highest.

The Slender shape is preferred for Hypersonic Glide Vehicles as there is less occurrence of flow separation.

The review also discussed 5 Hypersonic Vehicles.

The Avangard and DF-17 are the only 2 operational Hypersonic Glide Vehicle.

CHAPTER 4

CONCLUSION

Hypersonic Flows are not a new phenomenon, it has been extensively explored and scientifically one of the niche areas of Research.

Apart from its application for defense use, Hypersonic Flows are studied to design a Hypersonic Civilian Aircraft, which can cut travel time by an impressive margin.

The Slenderer the Body, the lesser the drag, the better the maneuverability of the Glide Vehicle. Mostly Elliptical Nosecones are preferred in order to reduce Flow separation as much as possible.

Moreover, the study of Hypersonic Flows is important in the designing of Heatshields for Atmospheric Reentry Vehicles. In the field of understanding Turbulence and Turbulence Modeling, Hypersonic Flow offers a vast area to be researched which can give more insights to compressible flow research.

The different types of Hypersonic Vehicles as discussed in this review shows the wide range of application of these Vehicles.

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