Module 1: Hypersonic Atmosphere

Lecture1: Characteristics of Hypersonic Atmosphere

1.1 Introduction

Hypersonic flight has special traits, some of which are seen in every hypersonic flight. Presence of these particular features during a flight is highly dependant on type of trajectory, configuration etc. In short it is the mission requirement which decides the nature of hypersonic atmosphere encountered by the flight vehicle. Some missions are designed for high deceleration in outer atmosphere during reentry. Hence, those flight vehicles experience longer flight duration at high angle of attacks due to which blunt nosed configuration are generally preferred for such aircrafts. On the contrary, some missions are centered on low flight duration with major deceleration closer to earth surface hence these vehicles have sharp nose and low angle of attack flights. Reentry flight path of hypersonic vehicle is thus governed by the parameters called as ballistic parameter and lifting parameter. These parameters are obtained by applying momentum conservation equation in the direction of the flight path and normal to it. Velocity-altitude map of the flight is thus made from the knowledge of these governing flight parameters, weight and surface area. Ballistic parameter is considered for non lifting reentry flights like flight path of Apollo capsule, however lifting parameter is considered for lifting reentry trajectories like that of space shuttle.

Therefore hypersonic flight vehicles are classified in four different types based on the design constraints imposed from mission specifications.

1. **Reentry Vehicles (RV):** These vehicles are typically launched using rocket propulsion system. Reentry of these vehicles is controlled by control surfaces. Large angle of attack flight of blunt nosed configurations is the need of these flights. Space shuttle (US), BURAN (Russian), HOPE (Japan) and HERMES (European) are some examples of these kind vehicles.

2. **Cruise and Acceleration Vehicle (CAV):** Slender configurations with low angle of attack flights are main features of these flights. These vehicles are prepared for high heating loads with ablative cooling system. Air breathing propulsion system of ram or scramjet type is generally preferred for these vehicles. Sanger, which is a two stage (TSTO) hypersonic vehicle, has first stage with air breathing propulsion and second stage is propelled with rocket. Hence first stage of Sanger falls in CAV category for which separation takes place at Mach 7.
3. **Ascent and Reentry Vehicles (ARV):** These vehicles have opposing requirements of their design due to dual duty of ascent, which is dominated by fuel requirements, and reentry by aero-braking. Rocket or air breathing propulsion systems can be preferred for these flights. NASP or National Aerospace Plane of US, Space Plane by Japan and HOTOL are some examples of these vehicles.
4. **Aeroassisted Orbit Transfer Vehicle (AOTV):** This is one more class in which hypersonic vehicles are classified. Ionisation and hence presence of plasma in the vicinity of the spacecraft is the major concern of these vehicles.

Each of these vehicles faces different flight challenges based on their missions and flight configurations. These challenges form the topic of research in the field of hypersonic aerodynamics.

1.2. Definition of hypersonic flow regime:

Definition of flow regime is based on the Mach number of the flow. If Mach number is below unity then the flow is called as subsonic. Sonic flow has Mach number exactly equal to one however flow in the narrow range of Mach number between 0.8-1.2 is called as transonic flow. When the flow Mach number exceeds beyond 1 then flow is called as supersonic flow. As per the thumb rules, when flow speed exceeds five times the sound speed, it is treated as hypersonic flow. However hypersonic flow has certain characteristics which when experienced in the flow, should then only be termed as hypersonic. These characteristics of hypersonic flow are mentioned below.

a. Thin Shock Layers

Region between shock and the body (flight vehicle) is named as shock layer. From the relations between shock angle, Mach number and flow deflection angle or wedge angle commonly known as θ-β-M relation, it would be clear that, for same flow deflection angle, shock angle decreases with increase in Mach number. Hence the thickness of the shock layer decreases with increase in Mach number for the same flow deflection angle. Therefore hypersonic flows have thin shock layer. This interpretation of shock layer thinness for calorically perfect gas is also applicable for thermally perfect gas and chemically reacting flow. However, complexity of flow field increases due to thin shock layer where the boundary layer thickness and shock layer thickness become comparable.

b. Entropy Layer

One of the main properties of the curved shock waves in that, each streamline passing through the shock faces differential entropy rise where stronger portion of shock leads to higher entropy rise than the weaker portion. Therefore, a layer of entropy variation getting formed downstream of the shock is termed as entropy layer. Analysis of hypersonic flow becomes further troublesome with consideration of this entropy layer since according to Croco's principle the entropy layer leads to vorticity. As it was evident that the shock layer thickness decreases with increase in Mach number and shock comes closer to the sharp leading edge configurations like wedge or cone, it is also obvious that shock detachment distance decreases with increase in Mach number for blunt bodies. Hence the entropy layer exhibits strong gradient of entropy which leads to higher vorticity at higher magnitudes of Mach numbers. Due to presence of entropy layer it becomes difficult to predict the boundary layer properties and properties at the edge of the boundary layer of hypersonic flow due to interaction of boundary layer vorticity and entropy layer vorticity. This interaction is termed as vorticity interaction.

c. Viscous Interaction

As we know, formation of boundary layer takes place near the wall due to no-slip property of the viscous fluid flow. Formation of this boundary layer takes place across enourmous loss of kinetic energy at hypersonic speeds. This kinetic energy necessarily gets converted in to thermal energy which leads to increase in temperature of the flow in the vicinity of the wall. This phenomenon is called as viscous dissipation. Viscous dissipation leads to increase in boundary layer thickness due to increase in viscosity coefficient with temperature. This situation can also be interpreted from boundary layer theory where pressure is considered to be constant across the boundary layer. This thickened boundary layer displaces outer inviscid flow hence freestream hypersonic flow encounters an inflated object which changes the shock shape and intren boundary layer parameters along with surface pressure, wall heat flux, skin friction etc. This interaction or communication loop between viscous boundary layer and outer inviscid flow is called as viscous interaction. As a result of this interaction aerodynamic parameters such as lift, drag etc deviate a lot from their base value without interaction. Hence it becomes mandatory to treat viscous interaction for hypersonic flights since whole shock layer tends to become viscous due to this interaction.

d. High-Temperature Flows

As we know, viscous dissipation leads to higher boundary layer thickness and temperature of the boundary layer fluid. Therefore any hypersonic flight expreiences presence of high temperature fluid in the vicinity of the flight vehicle. Apart from this, blunt nosed configurations encounter very high temperatures due to normal shock present at the stagnation point. Therefore at these elevated temperaturess, treatment of fluid as calorically perfect or with constant thermodynamic properties leads to unrealistic estimations. Hence it becomes essential to take in to account the dependence of specific heats and their ratio as function of temperature for rational estimates.

The dependence of thermodynamic properties on temperature mainly comes from microscopic changes in the fluid due to increase in internal energy of the fluid by the virtue of loss of kinetic energy. Increased internal energy leads initially to vibrational excitation followed by dissociation and finally ionization according to the extent of increase in internal energy. As per the order of magnitude estimate, vibrational excitation of air takes place at around 800K. Oxygen dissociation starts at around 2000 K and completes at 4000 K. At around 4000 K nitrogen dissociation commences and completes at 9000 K. Ionization of this high temperature air or mixture of gases starts from 9000 K temperature. Hence the initil air with atmosheric composition becomes plasma after 9000 K. As a result of all these reactions, hypersonic vehicle gets engulfed by reacting boundary layer and high temperature plasma. Therefore treatment of air or any fluid flowing with hypersonic speed over any configuration should be done properly by incorporating all the microscopic changes which essentially leads to change in thermodynamic properties with temperature. This dependence is highly non-linear, hence analysis or prediction of flowfield becomes tougher in this flow regime. Therefore two types of assumptions are generally made about the flow conditions for high temperature fluid as equilibrium flow and non-equilibrium flow. If the microscopic changes or reactions are at faster rate than the movement of the fluid, then it is treated as equilibrium flow otherwise it is treated as non-equilibrium flow which is difficult to analyze. All these difficulties are collectively termed as ‘real gas effects'.

Some consequences of presence of high temperature reacting fluid or plasma in the vicinity of the flight vehicle include, influence on aerodynamic parameters, aerodynamic heating and communication block-out. Flight parameters like pitch, roll, drag, lift, defection of control surfaces get largely deviated from their usual estimate of calorically perfect gas. Presence of hot fluid near the cold vehicle surface induces heat transfer not only through convection but also through radiation. Communication waves which are necessarily radio waves get absorbed by free electrons formed from ionization of atmospheric fluid. This phenomenon is called as communication block-out where on board and ground communication gets terminated

e. Low-Density Flow

Hypersonic flights at higher altitudes experience very low density flows. The governing non-dimensional parameter for these regimes is called as Knudsen number which is defined as the ratio of mean free path to the characteristic length of the object. Here mean free path is termed as the mean distance traveled by the fluid molecule between two successive collisions with other molecules. Since density of air is very high on the earth's surface, therefore Knudsen number is close to zero for standard dimensions of hypersonic flights. However if we consider any standard hypersonic flight taking off from earth surface, it becomes clear that, the flight vehicle is going to encounter change in density with increase in altitude. Validation of continuum assumption and in turn the usage of usual governing equations remains intact till the altitude of around 90 km from earth surface where Knudsen number is below 0.3. Above this altitude, till 150 km from earth surface, density becomes lower as a effect of which fluid velocity and temperature at the surface do not remain in equilibrium with the surface. Therefore flow for Knudsen number in range 0.3 to 1 is treated in the transitional regime where slip wall boundary conditions should be used along with the usual governing equations based on continuum assumption. However above 150 km from earth's surface, density of air becomes very low therefore this region is called as free molecular flow where Knudsen number becomes more than or equal to unity. Thus need for change in governing equations arise in this regime. Hence kinetic theory of gases finds its application for hypersonic flights at such altitudes.

From these specifications of hypersonic flow regime, it is clear that Mach number to be very much greater than one is the formal definition of hypersonic flow. Higher density ratio is also one of the definitions of hypersonic flow. Density ratio across normal shock would reach 6 for calorically perfect gas (air or diatomic gas) at very high Mach numbers. If concerned fluid is chemically reacting mixture or even thermally perfect then this ratio increases to value more than 20, which was reached in Apollo flight. For density ratio to reach more than 20, the specific heat ratio should decrease and reach a value close to one for air. In actual flight conditions, hypersonic flow field can be reached with increasing the flight velocity without altering thermal properties of surrounding fluid. However, it is difficult to achieve this flow in ground testing with very high kinetic energy and high Mach number without change in thermal properties the fluid. Therefore there are many challenges for experimental simulation of hypersonic flow. One solution for this problem is the use of different gases to simulate the low specific heat ratio condition. Tetrafluoroethane is used for specific heat ratio of 1.2 and hexafluoroethane for 1.1. Understanding the challenges faced by hypersonic flight and derived solutions for some of those problems are the themes of this subject.