BIRLA INSTITUTE OF TECHNOLOGY
MESRA : RANCHI

## DEPARTMENT OF SPACE ENGINEERING & ROCKETRY

### M. E. PROGRAMME

### COURSE STRUCTURE

**I SEMESTER**

| Course No. | Title | L | T | P | C |
|---|---|---|---|---|---|
| MSR 1101 | Elements of Rocket Propulsion | 3 | 1 | 0 | 4 |
| MSR 1103 | Elements of Aerodynamics | 3 | 1 | 0 | 4 |
| MSR 1005 | Space Engineering & Space Flight | 3 | 0 | 0 | 3 |
| MMA1105 | Computational Mathematics | 3 | 0 | 0 | 3 |
| MSR 1002 | Rocket Propulsion Lab | 0 | 0 | 3 | 2 |
| MSR 1004 | Aerodynamics Lab I | 0 | 0 | 3 | 2 |
| **ELECTIVE – I** | (One Course to be selected) | | | | |
| MSR 1007 | Fundamentals of Combustion | 3 | 0 | 0 | 3 |
| MSR 1111 | Stability and Control | 3 | 0 | 0 | 3 |

**II SEMESTER (ROCKET PROPULSION)**

| | | | | | |
|---|---|---|---|---|---|
| MSR 2001 | Solid Rocket Propulsion | 3 | 0 | 0 | 3 |
| MSR 2103 | Liquid & Hybrid Rocket Propulsion | 3 | 0 | 0 | 3 |
| MSR 2105 | Rocket Combustion Processes | 3 | 0 | 0 | 3 |
| MSR 2002 | Solid Rocket Propulsion Lab | 0 | 0 | 3 | 2 |
| MSR 2004 | Liquid & Hybrid Propulsion Lab | 0 | 0 | 3 | 2 |
| **ELECTIVE – II** | (One Course to be selected) | | | | |
| MSR 2009 | Ignition and Ignition Devices | 3 | 0 | 0 | 3 |
| MSR 2111 | Propellant Technology | 3 | 0 | 0 | 3 |
| MSR 2013 | Special Topics in Chemical Propulsion | 3 | 0 | 0 | 3 |
| | Breadth Paper | 3 | 0 | 0 | 3 |

**II SEMESTER (AERODYNAMICS)**

| | | | | | |
|---|---|---|---|---|---|
| MSR 2021 | Missile Aerodynamics | 3 | 0 | 0 | 3 |
| MSR 2123 | Viscous Flows | 3 | 0 | 0 | 3 |
| MSR 2125 | High Speed Aerodynamics | 3 | 0 | 0 | 3 |
| MSR 2008 | Aerodynamics Lab II | 0 | 0 | 3 | 2 |
| MSR 2010 | Aerodynamics Lab III | 0 | 0 | 3 | 2 |
| **ELECTIVE – II** | (One Course to be selected) | | | | |
| MSR 2029 | Experimental Aerodynamics | 3 | 0 | 0 | 3 |
| MSR 2131 | Theory of Turbulence | 3 | 0 | 0 | 3 |
| MSR 2033 | Elements of Hypersonic Flight | 3 | 0 | 0 | 3 |
| | Breadth Paper | 3 | 0 | 0 | 3 |

**III SEMESTER**

| | | | | | |
|---|---|---|---|---|---|
| MSR 3001 | Thesis | 0 | 0 | 0 | 15 |

**IV SEMESTER**

| | | | | | |
|---|---|---|---|---|---|
| MSR 4001 | Thesis | 0 | 0 | 0 | 20 |

**Total Credits : 75**

Breadth Papers offered by the Department :

| | | | | | |
|---|---|---|---|---|---|
| **MSR 2007** | **Advanced Propulsion Systems** | 3 | 0 | 0 | 3 |
| **MSR 2127** | **Computational Aerodynamics** | 3 | 0 | 0 | 3 |

## MSR 1101 : ELEMENTS OF ROCKET PROPULSION

**Propulsion Systems:** Jet Propulsion and Rocket Propulsion – Definition, Principle, Classification, Description and Application; Electrical, Nuclear and other Advanced Propulsion Systems.

**Nozzle Theory:** Ideal Rocket; Isentropic Flow through Nozzles; Exhaust Velocity; Choking; Nozzle Types; Nozzle Shape; Nozzle Area Expansion Ratio; Underexpansion and Overexpansion; Nozzle Configurations; Real Nozzles; Performance Correction Factors; Multiphase Flow.

**Thrust and Thrust Chambers:** Thrust Equation; Specific Impulse, Thrust Coefficient, Characteristic Velocity and other Performance Parameters; Thrust Chambers; Methods of Cooling of Thrust Chambers; Steady State and Transient Heat Transfer; Heat Transfer Distribution; Steady State Heat Transfer to Liquids in Cooling Jackets; Uncooled Thrust Chambers; Thermal insulation; Radiation; Exhaust Plumes.

**Solid Propellant Rocket Motors:** Application and Classification of Solid Propellant Rocket Motors; Propellants and Characteristics; Composite, Double Base and Composite Modified Double Base Propellants; Metallized Propellants; Ingredients and Processing; Propellant Burning Rate; Erosive Burning; Propellant Grains and Grain Configurations; Propellant Grains Stress and Strain.

**Liquid Propellant Rocket Engines :** Propellant and their Properties; Monopropellants and Bipropellants; Storable, Cryogenic and Gelled Propellants; Fuels and Oxidizers; Metals; Propellant Tanks; Liquid Propellant Feed Systems; Injectors; Thrust Chamber Shapes and Characteristic Length; Hybrid Propellant Rocket Motors; Gaseous Propellant Rocket Motors and Reaction Control Systems.

**Rocket Testing:** Types of Tests; Test Facilities and Safeguards; Safety and Environmental Concerns; Facilities and Safeguards; Monitoring and Control of Toxic Materials and Exhaust Gases; Instrumentation and Data Management; Reliability and Quality Control; Flight Testing.

**Books Recommended :**


1. Rocket Propulsion Elements – Sutton, George P. and Biblarz, Oscar, 7th Edition, John Willey and Sons
2. Rocket Propulsion – Barrere, M., Elsevier Publication
3. Rocket and Spacecraft Propulsion: Principle, Practice and New Developments – Turner, Martin J. L., Springer Verlag

## MSR 1103 : ELEMENTS OF AERODYNAMICS

**Some Fundamental Principles**: Models of Fluid; Control Volume and Fluid Elements; Continuity and Momentum Equations; Application of Momentum Equation for the Estimation of Drag of a Two- dimensional Body; Energy Equation, Substantive Derivatives; Fundamental Equations in Substantive Derivatives; Pathlines and Streamlines of a Flow; Angular Velocity, Vorticity and Strain; Circulation; Stream Function; Velocity Potential.

**Fundamentals of Inviscid Flow:** Incompressible Flow; Derivation of Bernoulli's Equation from Euler's Momentum Equation; Pressure Coefficient; Incompressible Flow in a Low Speed Wind Tunnel; Flow Measuring Device – Pitot Tube; Governing Equation for Incompressible, Irrotational Flow; Laplace's Equation; Elementary Inviscid Flows, like Source Flow, Source- Sink Flows, Doublet Flow, Non- lifting Flow over a Circular Cylinder; Vortex Flow; Lifting Flow over a Cylinder; Kutta – Joukowski Theorem and the Generation of Lift; Non- lifting Flows over Arbitrary Bodies; Numerical Source Panel Method; D' Alembert's Paradox; Kutta- Joukowski Transformation of Flow past Circular Cylinder into a Flow past Flat Plate and Aerofoils.

**Incompressible Flow over Aerofoils:** Aerofoil Nomenclature and Aerofoil Characteristics; Theoretical Solution for Low Speed Flow over Aerofoils; Vortex Sheet Method; Kutta's Conditions; Kelvin`s Circulation Theorem and Starting Vortex; Classical Thin Aerofoil Theory; Symmetrical and Cambered Aerofoils; Lifting Flows over Arbitrary Bodies; Vortex Panel Methods Outline; Modern Low Speed Aerofoils; Aerodynamic Forces and Moments; Estimation from Pressure distribution; Types of Drag; Centre of Pressure and Aerodynamic Centre.

**Incompressible Flow over Finite Wings**: Introduction; Downwash and Induced Drag; The Vortex Filament, Biot- Savart Law, Helmholtz`s Vortex Theorem; Prandtl's Classical Lifting Line Theory; Numerical Nonlinear Lifting Line Method; Lifting Surface Theory; Vortex Lattice; Numerical Method.

**Viscous Flows**: Newton's Law of Viscosity; Generalised Hooke`s Law, Stoke's Law of Friction; Navier- Stokes Equation; Solutions of the Navier- Stokes Equations– Steady Parallel Flow, Couette Flow, Hagen – Poiseuille Flow, Flow between Concentric Rotating Cylinders; Stagnation Flow.

**Basic Flows**: Laminar and Turbulent Flows; Boundary Layer and Boundary Layer Thickness; Displacement Thickness; Momentum Thickness and Energy Thickness; Estimation of Skin Friction Drag from Momentum Thickness over a Flat Plate; Derivation of Prandtl`s Boundary Layer Equation from Navier- Stokes Equation; Properties of Boundary Layer Equation.

**Books Recommended:**


1. Fundamentals of Aerodynamics – Anderson, J. D.
2. Aerodynamics for Engineering Students – Houghton, E. L. and Carpenter, P. W.
3. Boundary Layer Theory – Schlichting, H.

## MSR 1005 : SPACE ENGINEERING & SPACE FLIGHT

**Earth and Atmosphere:** The Planet Earth; Earth's Gravitational Field; Earth as an Ellipsoid; Peer- shaped Earth; Ellipticity of the Earth; The Geoid and Its Importance; Thermal Structure of the Atmosphere; Atmospheric Density Variation; Van-Allen Radiation Belt; The Ionosphere.

**Solar System:** Motion and Rotation of the Planets; Geocentric and Heliocentric Systems; Sidereal and Synodic Periods; Ecliptic Plane and the Zodiac; Direct and Retrograde Motions; Configuration and Phases of Interior Planets; Configurations of Exterior Planets; Asteroids; Comets; Meteors, Meteorites and Tektites; Micrometeorites; The Milky Way, the Galaxies and the Universe.

**Trajectory of a Rocket:** Mass Ratio and Propellant Mass Fraction; Equation of Motion of an Ideal Rocket; Motion of a Rocket in a Gravitational Field; Simplified Vertical Trajectory; Burn- out Velocity and Burn- out Height; Step- Rockets; Ideal Mission Velocity and Losses; Effect of Launch Angle; Factors Causing Dispersion of Rockets in Flight; Dispersion of Finned Rockets; Stability of Flight.

**Satellite Launch and Satellite Orbits:** Orbits and Trajectories; Conic Sections; Kepler's Laws of Satellite Motion; Orbital Velocity of Satellites; Orbital Periods; Eccentric Elliptical Orbits; Effect of Injection Conditions; Perturbation of Orbits; Effect of Earth's Rotation; Low Earth Orbits; Geostationary Satellites; Sun- synchronous Satellites.

**Satellite Applications:** Satellite for Meteorological, Communication, Navigational and Geodetic Applications; Atmospheric Sounding; Satellites for Geophysical and Interplanetary Studies.

**Interplanetary Mission:** Parking Orbit; Transfer Trajectory; Impulsive Shot; Launching of Interplanetary Spacecraft.

**Books Recommended:**


1. Source book on the Space Science – Glasstone, S.
2. Space Science & Engineering – Stuhlinger, E. and Mesmer, G.
3. Space Science – Hess, W. N.
4. Rocket Propulsion and Spacecraft Dynamics –
   Cornelisse, J. W. Schoyer, H. F. R. and Wakkar, K. F.

## MSR 1007 : FUNDAMENTALS OF COMBUSTION

**Thermochemistry :** Stoichiometry; Absolute Enthalpy and Enthalpy of Formation; Enthalpy of Combustion and Heating Value; Laws of Thermochemistry; Pressure and Temperature Effect on Enthalpy of Formation; Adiabatic Flame Temperature; Chemical and Equilibrium Products of Combustion; Some Applications; Sample Calculations.

**Flame :** Concept of Flame; Definition, Classification and Properties of Premixed Flames; Properties of Diffusion Flames; Measurement of Burning Velocity; Flame Stabilization; Quenching; Flame Temperature Measurement Techniques; Ionisation in Rocket Exhaust.

**Detonation :** Detonation Wave and their Characteristics; Deflagration to Detonation Transition; Derivation of Rankine- Hugoniot equation; Chapman- Jouguet States and their Properties; Computation of Detonation Velocity.

**Internal Ballistics :** Burning Rate Laws and Pressure Quotient; Parameters Controlling Burning Rate; Fundamental Relations of Internal Ballistics; Equation of Continuity; Equilibrium Pressure; Transient Operation; Pressure and Temperature Limits; Temperature Sensitivity; Resonance Burning.

**Liquid Propellant Combustion :** Physico- chemical Description of Combustion in a Liquid Propellant Rocket Motor; Droplet Combustion.

**Propellant Performance Evaluation :** Dissociation and Reassociation Phenomenon in Rocket Motors; Specific Formula of Simple Compounds and Mixtures; Mixture Ratio; Equivalence Ratio; Theoretical Computation of Stoichiometry; Thermodynamic Properties of Gas Mixtures; Computation of Adiabatic Flame Temperature and Specific Impulse for Reaction or Simple System Like $H_2$-$O_2$; Theoretical Performance Valuation of Solid Rocket Propellants.

**Books Recommended :**


1. Fundamentals of Combustion – Turn, S. R.
2. Principles of Combustion – Kuo, K. K.
3. Flames, Combustion and Explosion Phenomenon – Von Elbe and Lewis
4. Flames: Their Structure, Radiation and Temperature – Gaydon, A. G. & Wolfhard, H. D.
5. Theoretical Evaluation of Propellants – Wilkins, R. L.

## MSR 1111 : STABILITY AND CONTROL

**Introduction :** Basic Fluid Dynamic Equations; Incompressible and Compressible Flows; Pressure Coefficients; Two- dimensional and Three- dimensional Aerofoil Theory; Viscous Forces.

**Forces & Moments :** Different Types of Missile & Rockets; Major Components of Aircraft and Missiles; Trajectories; Aerodynamics Forces and Moments on Aerospace Vehicles; Thrust; Drag; Normal and Side Forces; Pitch; Yaw and Rolling Moments; Centre of Pressure; Static Margin.

**Longitudinal, Directional, Lateral Static Stability :** Introduction to Six Degrees of Freedom; Forces and Moments for Two Degrees of Freedom; Derivation of Static Margin; Behaviour with different Control Surfaces. Introduction to Angles of Attack; Estimation of Forces and Moments due to Control Surfaces; Induced Rolling; Roll Moments and Controls.

**Dynamic Stability** : Necessity and Approximate Analysis; Damping; Time- to- half Response Characteristics, Oscillatory and Non- Oscillatory Motion; Effect of Various Control Surfaces.

**Controls :** Different Types of Disturbances, Time- to- Half; Time- to- Double; Active and Passive Controls; Open Loop and Closed Loop Controls; Feed back, Types of Feed back, Time Domain Analysis, Frequency Domain Analysis, Nyquist criterion, Response, Attitude control of aircraft, Staging of Missile and rockets, it's advantages and disadvantages.

**Performance :** Introduction to Reliability; Theories of Reliability, Estimation of reliability and it's importance, Accuracy; Safety of Aircraft, Missiles, Rockets, Description and necessity of Launcher & launch complex, Safety aspects for different launchers and Associated Problems.

**Books Recommended:**


1. Aerodynamics for Engineering Students – Houghton, E. L. and Carruthers, N. B.
2. Airplane Performance, Stability & Control – Perkins, C. D. and Hege, R. E.
3. Missile Aerodynamics – Chin, S. S.
4. Automatic Control system – B. C. Kuo

## MSR 2001 : SOLID ROCKET PROPULSION

**Structural Analysis:** Major Section of Rocket and their Structure; Flight Loads; Forces and Moments acting on the Missile; Missile Loading Concepts; Structural Analysis; Hardware Design.

**Design Criteria:** Basic Preflight and Flight Loads; Rigidity Requirements; Distribution of Weight and Stability; Allowable Safety Margins Environmental Conditions.

**Rocket Engine Design :** Design Criteria; Principal Parameters Governing Rocket Engine Design; System Analysis and Design Layout; Stress Analysis; Selection of Material; System Optimization; Design of Proof Motor and Flight Motor; Engine -to -vehicle Interface; Clustering of Rocket Engines; Reliability Concept; Quality Control; Static and Flight Tests; Environmental Test; Scaling of Rocket Motors.

**Nozzle :** Isentropic Flow through Nozzles, Nozzle Configuration; Convergent- Divergent Nozzles, Bell Nozzles, Annular Nozzles, Adopted Nozzles, Submerged Nozzles; Nozzle Flow and Design Optimization; Nozzle Construction; Throat Inserts.

**Associated Systems :** Ignition and Ignition Delay; Selection Criteria of Igniter Composition, Quantity and Location; Design of Igniters; Sample Calculation; Igniters for Solid Rocket Motor; Igniter Hardware; Igniter Pellets; Pyrogen Igniters; Extinction of Solid Rocket Motors; Restart of Solid Rocket Motors; Inhibition and Inhibitors; Insulation and Liners; Thrust Vector Control; Mechanism and Methods of TVC; Testing and Integration with Vehicle.

**Combustion Instability:** Types of Instability – Bulk Mode, Transverse Mode and Axial Mode Instabilities; Causes of Instability in Solid Rocket Motors; Analysis of Instability in Solid Rocket Motors; Remedial Methods.

**Books Recommended:**


1. Solid Rocket Propulsion – Barrere, M., et. al
2. Rocket Propulsion Elements – Sutton, G. P. and Biblarz, O., 7th Ed.
3. Solid Rocket Technology – Shorr, M. and Zaehringer, A. J.

## MSR 2103 : LIQUID & HYBRID ROCKET PROPULSION

**Liquid Propellants and LPR Engine:** Basic Elements of an LPR Engine; Performance Parameters of Selected Existing Liquid Rocket Engines.

**Pressure Feed Systems :** Purpose; Types of Pressure Feed Systems; Methods of Tank-pressure Control; Types of Pressurization Systems; Desirable Characteristics of Pressurants; Tank Pressurant Requirements and Its Determination; Pressurized Gas Systems.

**Pump- Feed Systems**: Elements of Pump Feed Systems; Centrifugal Pumps and Axial Flow Pumps; Turbines; Design Layout of Turbopump Assemblies; Control Valves and their Selection; Transient Pressures due to Valve Closure and Valve Opening; Design for the Wall Thickness of Propellant Line; Frictional Losses in Propellant Feed Lines.

**Thrust Chambers and Auxiliary Combustion Devices:** Basic Thrust Chamber Elements; Combustion Chamber Design and Characteristic Length; Combustion Process; Performance Parameters; Engine Design and Control; Configuration Layout; Materials and Selection; Types of Injectors; Injector Design and Performance; Ignition Devices; Heat Transfer; Regenerative Cooling; Uncooled Chambers; Combustion Instability; Nozzle Flow; Supersonic Aerodynamics; Nozzle Design; Thrust Vector Control.

**Cryogenic Propulsion:** Cryogenic Loading Problems; Temperature and Pressure Effects on Loading; Tank Collapse; Phenomenon of Thermal Stratification; Effect of Thermal Stratification on Rocket Engine Performance; Prediction and Methods of Elimination of Thermal Stratification.

**Hybrid Rocket Propulsion**: Introduction; Classification; System Arrangement and Components; Typical Fuels and Oxidizers; Advantages and Disadvantages; Application Areas; Performance and Limitations; Performance Parameters of Selected Existing Hybrid Rocket Engines; System Integration; Manufacturing Methods for Low- and High- Thrust Engines.

**Books Recommended:**


1. Design of Liquid Propellant Rocket Engine – Huzel, D. K. & Huang, D. H., NASA SP-125
2. Heterogeneous Combustion – Wolfhard,H. G., Progress in Aeronautics & Astronautics, Vol. 15, AIAA
3. Rocket Propellant and Pressurization Systems – Ring, E.
4. Liquid Rocket and Propellants – Bollinger, L. E., Progress in Aeronautics & Astronautics, Vol. AIAA
5. Cryogenic Systems – Barron, R.

## MSR 2105 : ROCKET COMBUSTION PROCESSES

**Solid Propellant Combustion** : Combustion of Double Base Propellants; Mechanism of Combustion –Temperature and Concentration Profile across the Burning Surface; Combustion Mechanisms in Condensed Phase and Gas Phase; Theories of Combustion of D. B. Propellants – Boys & Corner Theory, Rice- Ginell and Crawford & Parr Theories; Mechanisms of Super Rate and Plateau Effects; Pyrolysis of Composite Propellant Ingredients and Two- temperature Postulate; Deflagration of Ammonium Perchlorate; Degradation of Fuel Binders; Combustion Mechanism of Composite Propellants; Theories of Combustion – Outline of Thermal Theory, GDF Model and Multiple Flame (BDP) Combustion Model.

**Combustion of Metals** : Physical Considerations; Description and Classification of Various Burning Metals; Experimental Nature of Metal Powder Combustion; Theories of Combustion of Metal powders; Metal Combustion in deflagrating propellants; Effect of Aluminum on Propellant Burning Rate; Equilibrium Composition of Combustion Products of Metallized Propellants.

**Erosive Burning** : Introduction; Threshold Velocity; Laboratory Methods for Determination of the Erosion Function; Theories of Erosive Burning– Levoneir and Robillard's Theory; Vandenkerckhove Theory; Effect of Erosion on Geometry of Central Port; Effect of Cross- Flow Velocity, Free Stream Gas Composition, Propellant Characteristics and Combustion Chamber Pressure on Erosive Burning; Negative Erosion Phenomenon.

**Liquid Propellant Combustion** : Physico- Chemical Description of Combustion in a Liquid Propellant Rocket Motor; Atomization and Droplet Size Distribution in Injection Sprays; Spherico- symmetric Model of Fuel Burning in Oxidizing Atmosphere; Correlation for Non- spherical Model; Effect of Drag on Combustion; Effect of Pressure on Combustion; Droplet Burning Rate Measurement; Combustion Models for Monopropellants.

**Hybrid Propellant Combustion** : Introduction; Combustion Model for a Hybrid Fuel Burning in an Oxidizer Stream; Theories of Hybrid combustion – Laminar Boundary Layer Theories, Turbulent Boundary Layer Theories, Theories Based on Chemical Kinetics; Effect of Pressure and Mass Flow Rate on Hybrid Combustion; Transient Behaviour of Hybrid Regression Rate; Temperature Profile Inside the Regressing Solid Fuel; Combustion of Metallized Hybrid Fuel; Effect of Radiation, Burning Time, Length and Port Size on Fuel Regression Rate.

**Combustion Instability:** Combustion Instability and Classification; Types of Instability in Solid Rocket and Liquid Rocket Motors ; Low Frequency, Medium Frequency and High Frequency Instability in Liquid Rocket Motors – Causes, Analysis, Effects and Remedial Methods.

**Books Recommended :**


1. Fundamentals of Solid Propellant Combustion – Kuo, K. K.& Summerefied, M., Progress in Astronautics & Aeronautics, Vol. 90, AIAA.
2. Heterogeneous Combustion – Wolfhard, H. G., Progress in Astronautics & Aeronautics, Vol. 15, AIAA.
3. Liquid Propellant Rockets – Altman, D. and Penner, S. S.

## MSR 2007 : ADVANCED PROPULSION SYSTEMS

**Advanced Chemical Propulsion System :** High Performance Chemical Propulsion Systems, Tripropellants; Metalized Propellants; Free Radical Propulsion; Flight Hybrid Rocket Propulsion Systems.

**Hypersonic Propulsion :** Introduction to Hypersonic Propulsion; Developments in High Speed Vehicle Propulsion System; Aerodynamic Shape of a Hypersonic Vehicle with an Air Breathing Engine; Engine Cycle; Diffusion Flame Combustion and Supersonic Combustion; Supersonic Flow Combustors; Dual-mode Combustion System.

**Scramjet Propulsion :** Scramjet and Ram Rocket Propulsion System; Scramjet Inlets; Scramjet Performance.

**Nuclear Propulsion System :** Types of Nuclear Propulsion Systems; Heat Transfer Nuclear Rockets; Gaseous Core Nuclear Rockets; Pure Nuclear Propulsion System; Operation, Performance and Application Areas; Nuclear Hazards; Nuclear Power Generation in Space.

**Electric Propulsion System :** Overview of Application Areas; Ideal Flight Performance; Electrothermal Thrusters – Resistojets and Arcjets. Pure Electric Thrusters – Electrostatic, Electro Magnetic and Hall- effect Thrusters; Optimum Flight Performance; Electric Power Generation in Space.

**Micropropulsion System :** Recent Micro Spacecraft Developments; Micropropulsion Options; Primary Set of Micropropulsion Requirements; Chemical Propulsion Options; Review of Electric Propulsion Technologies for Micro and Nano- satellites; Emerging Technologies: MEMS and MEMS- Hybrid Propulsion System.

**Books Recommended:**


1. Developments in High Speed- Vehicle Propulsion System – Paul, Z., Progress in Astronautics & Aeronautics, Vol.165, AIAA.
2. Scramjet Propulsion – Paul, Z., Progress in Astronautics & Aeronautics, Vol. 189, AIAA.
3. Micropropulsion for Small Spacecraft – Paul, Z., Progress in Astronautics & Aeronautics, Vol. 187, AIAA.

## MSR 2009 : IGNITION AND IGNITION DEVICES

**Ignition :** Introduction; Process of Self- ignition; Induction Period; Limits of Self-ignition; Forced ignition; Basic Idea of Ignition by Spark, Pilot Flames, Hot Gases and Shock Waves.

**Factors affecting Ignition Energy :** Effect of Composition, Type of Electrode, Spark Duration, Pressure, Temperature, Diluents, Mixture Velocity and Turbulence on Ignition Energy.

**Igniters for Chemical Rocket :** Igniters for Solid Rocket Motors – Role and Requirements; Classification of Igniters based on Mounting Locations and Energy Release Systems; Construction and Initiation Systems; Hardware Components; Design of Pyrotechnic and Pyrogen Igniters; Testing and Evaluation; Igniters for Liquid Propellant Engines, Hypergolic Ignition and Ignition Delay; Catalyst Induced Ignition; Igniters for Cryogenic Engines – Spark Torch, Pyrotechnic, Pyrogen and Plasma Igniters; Igniters for Hybrid Motors and Air Breathing Engines; Laser Induced Ignition and Its Applications.

**Ignition Mechanism :** Sequence of Ignition; Theories of Ignition – Thermal Ignition Theory, Gas- Phase Theory and Heterogeneous Theory; Pre- ignition Reactions; Effect of Catalyst on Ignition Process; Shock Tube and Ignition Experiments.

**Flame Spreading and Ignition Transient:** Physical Processes during Ignition Transient; Ignition Transient Models and Experiments; Flame Spreading over Solid Propellants, Fuels, Defects and Cracks.

**Extinction :** Controlled Termination of Thrust – Approaches; Energy Balance at Burning Surface; Dynamic Extinction by Fast Depressurization, Fast Deradiation and other Quenching Techniques, like Injection of Flame Inhibitors, Heat Sink, etc.; Theories and Experiments of Extinction.

**Books Recommended:**


1. Fuels & Combustion – Sharma,S. P. & Mohan, C., Tata- McGraw Hill
2. Advanced Chemical Rocket Propulsion Elements – Timnat,Y. M., Academic Press.
3. Fundamentals of Solid Propellant Combustion – Kuo, K. K. & Summerfield, M, Progress in Astronautics & Aeronautics, Vol.90, AIAA.

## MSR 2111 : PROPELLANT TECHNOLOGY

**Solid Propellant:** Classification – Double Base, Composite, Composite Modified Double Base, Fuel- rich and Metallized Propellants; Ingredients; Composition and Processing; Mechanical and Ballistic Properties; Ageing Characteristics.

**Grain Design Fundamentals:** Classification of Solid Propellant Grains; End Burning, Radial Burning and Non- cylindrical Burning Grains; Fundamental Characteristics; Various Configurations; Internal Burning Star Configuration; Segmented Grains; Grain Clustering; Burning Surface Area Evaluation; Design Criteria; Dual Thrust Grains; Free- standing and Case- bonded Grains; Inhibitors and Insulators.

**Grain Design:** Design Parameters; Performance Parameters; End Burning and Radial Burning Grain Design as applicable to Static Motors and Flight Rockets; Sample Calculations; Stress Analysis in Solid Propellant Grains.

**Liquid Propellant:** Classification – Mono-; Bi- and Tri- Propellants; Non Hypergolic and Hypergolic Systems; Gel Propellant Systems; Essential Characteristics of Liquid Propellants; Physical Properties; Ignition Characteristics; Ignition Delay; Ignition and Combustion Properties; Performance of Selected Bipropellant Systems; Factors affecting the Performance.

**Propellant Loading:** Various Tank Configuration; Design Considerations; Loading Concepts; Outage – Prediction and Control; Calibrated and Propellant Utilization Systems; Tank Ullage; Propellant Slosh; Estimation of Sloshing Mass; Frequency and Stiffness of an Equivalent System; Cavitation Drop- out and Vortexing; Design of Tank Outlet.

**Cryogenic Propellant:** Production, Storage and Handling; Thermo- physical Properties of Cryogenic Propellants; Geysering Phenomenon; Elimination of Geysering Effect in Missiles; Phenomenon of Thermal Stratification; Methods of Elimination of Thermal Stratification.

**Books Recommended :**


1. Fundamental Aspects of Solid Propellant Rocket – William, F. A., Barrere, M. & Huang, N. C.
2. Solid Rocket Technology – Shorr, M. & Zaehringer, A. J.
3. Rocket Propulsion – Barrere, M., Jaumotte, A. et. al.
4. Internal Ballistics of Solid Fuel Rockets – Wimpress, R. N. & Sage, B. H.

## MSR 2013 : SPECIAL TOPICS IN CHEMICAL PROPULSION

**Combustion Modeling:** Introduction; Theoretical Formulation – Solid Phase Region; Subsurface Multiphase Region and Gas Phase Region; Boundary Conditions; Numerical Methods; Effect of Chemical Additives on Burn Rate of Solid Propellants; Modeling of Liquid Propellant Combustion Phenomena – Basic Idea of Droplet and Spray Combustion Modeling.

**Green Propellants & Their Applications:** Introduction; Advantages of Green Propellants; Physico- chemical Properties; Performance, Design and Operational Requirements.

**Two- Phase Flow in Solid Rocket Motors:** Introduction; Aluminium Oxide Formation; Interactions between Droplet and Gas Flowfields; Slag Accumulation; Two- phase Flowfields; Effect of Droplet Coalescence; Effect of Vortices.

**Jet Injector Atomization:** Introduction; General Characteristics of Impinging Liquid Jets; Theoretical Models of Impinging Jet Atomization; Effect of Flow Conditions; Droplet Size Distribution; Orifice L/ D Ratio and Impingement Length Effects; Primary Atomization Mechanisms.

**Spray Characterization:** Introduction; Confined and Unconfined Sprays; Experimental Methods for Spray Characterization; Effect of Gas Velocity; Orifice Diameter; Flow Rate; Chamber Pressure on Spray Characteristics; Composite Mean Droplet Sizes.

**Rocket Plume:** Introduction; Chemical Origin of Smoke; Homogeneous and Heterogeneous Nucleation of Smoke; Plume Visibility; Ionization in Rocket Exhaust Plume; Smoke Measurements; Methods for Reducing Smoke.

**Books Recommended:**


1. Solid Propellant Chemistry, Combustion and Motor Interior Ballistics – Yang,V., Brill, T. B. and Ren, W., Progress in Astronautics & Aeronautics, Vol. 185, AIAA.
2. Modeling and Performance Prediction in Rockets and Guns – Chakravarthy, S. R. and S. Krishnan, Allied Publisher.
3. Advanced Propulsion Systems and Technologies, Today to 2020 – Bruno, C.and Accettura, A. G.,
4. Progress in Astronautics & Aeronautics, Vol. 223, AIAA.
5. Liquid Rocket Engine Combustion Instability – Yang, V. and Anderson, W. Progress in Astronautics & Aeronautics, Vol. 169, AIAA.
6. Fundamentals of Solid Propellant Combustion – Kuo, K. K. & Summerfield, M., Progress in Astronautics & Aeronautics, Vol. 90, AIAA.

## MSR 2021 : MISSILE AERODYNAMICS

**Missiles :** Different Types of Missiles and their Characteristics; Different Types of Controls and their Merits / Demerits; Overall Aerodynamics Forces and Moments; Major Components of Missiles and their Contributions; Effect of Aspect Ratio, and Shapes; Preliminary Estimates of Forces on Missiles.

**Longitudinal Stability :** Six Degree of Freedom; Forces and Moments for Two Degree of Freedom; Derivation of Forces, Moments and Static Margin; Load Factors for Complete Missile, Canard, Wing and Tail Controls; Interference Factors; Methods to Alter the Stability of Missile.

**Lateral and Directional Stability :** Assumptions; Relation between Angles in Pitch and Yaw Plane with Total Angle of Attack; Methods to Estimate the Stability of Missile in Yaw Plane; Effect of Different Control Surfaces; Induced Rolling; Roll Damping.

**Dynamic Stability :** Introduction; Equation of Motion for Six Degrees of Freedom, Oscillating and Non Oscillating Motion; Short and Long Period; Phugoid Motion; Longitudinal Dynamic Stability with Two and Three Degree of Freedom; Time- to-Half and Time- to- Double; Effect due to Angular Velocity; Lateral Dynamic Stability; Response Characteristics of Missile.

**Compressible flow :** Flow Through Passage of Varying Area; Nozzle with Different Back Pressures; Improper Expansion of Nozzles; Diffuser; Wind Tunnels; Different Types of Wind Tunnels; Major Components of Wind Tunnels; Measurement Technique for Various Aerodynamic Parameters; Simulation Parameters.

**Approximate Methods :** Derivation of Small Perturbation Equation; Assumptions for Linearised Perturbation Equation at Subsonic, Supersonic and Transonic Speed; Hodograph Method.

**Similarly Rules:** Prandtl- Glauert and Goethert Similarly Rules, Karman Similarity and Transonic Speed; Hypersonic Similarity Rule; Area Rule; Drag Divergence; Critical Mach Number; Flow Past Wedge and Cone at Subsonic and Supersonic Speed.

**Books Recommended:**


1. Missile Aerodynamics – Chin, S. S.
2. Gas Dynamics – Liepmann, H. & Roshko, A.
3. Fundamental of Aerodynamics – Anderson, John D.

## MSR 2123 : VISCOUS FLOWS

**Law of Viscosity :** Types of Fluids; Dependence of Boundary Layer at Different Reynolds Number, Blassius Solution and Its Series; Asymptotic Solutions; Theory of Similarity; Separation of Boundary Layer; Similar Solutions; Reduction of the Navier- Stokes Equation to the Boundary Layer Equations.

**Solution of Boundary Layer Equations** : Exact Solutions; Flow Past a Wedge; Flow Past a Cylinder; Flow in the Wake of Flat Plate at Zero Incidence; Momentum Integral and Energy Integral Equations; Approximate Solutions; Application of Momentum Equation to the Flat Plate; Karman- Pouhlsen Method; Approximate Methods for 2D Flows; Comparison of Exact and Approximate Methods for Flat Plate at Zero Incidence, Two- dimensional Stagnation Flow and Flow Past a Circular Cylinder.

**Thermal Boundary Layer :** Derivation of Energy Equation; Theory of Similarity in Heat Transfer; Non Dimensional Numbers – Grashoff's, Prandtl, Reynolds and Eckert Numbers; Analogy between Heat Transfer and Momentum Transfer; Exact Solution of Temperature Distribution in Viscous Flows; Couette Flow and Poiseuille Flow; Boundary Layer Simplification; Properties of Thermal Boundary Layer; Forced and Natural Flows; Adiabatic Wall; Analogy between Heat Transfer and Skin Friction; Effect of Prandlt's Number.

**Laminar Boundary Layer :** Introduction; Relation between Velocity and Temperature Fields – Adiabatic Wall and Heat Transfer; Flat Plate at Zero Incidence; IIlingworth - Stewartson Transformation; Approximate Solution; Introduction to Unsteady Boundary Layers; Transition and Origin of Turbulence; Interaction between Shockwave and Boundary Layer.

**Axially Symmetric and 3D Boundary Layers :** Introduction; Exact Solution for Axially-Symmetric Boundary Layer; Circular Jet; Axially- Symmetric Wake; Boundary Layer on a Body of Revolution; Approximate Solutions for Axially Symmetric Boundary Layer – Boundary Layers on Rotating Bodies of Revolution; Relation between Axially- Symmetric and Two- dimensional Boundary Layers; Mangler Transformation; Three Dimensional Boundary Layer; Boundary Layer on Yawed Cylinder and Swept Wings.

**Boundary Layer Control :** Introduction; Fundamental Equation with Suction/ Injection; Exact and Approximate Solutions with Suction and Injection; Solution of Pressure Gradient Cases; Prevention of Separation on Aerofoil; Control and Means to Increase Lift and to Reduce Drag; Some Experimental Results.

**Books Recommended:**


1. Boundary Layer Theory – Schlichting, H.
2. Fundamental of Aerodynamics – Anderson, John D.

## MSR 2125 : HIGH SPEED AERODYNAMICS

**One-Dimensional Flow :** 1- D Flow Equations; Quasi 1- D Flow; Area- Velocity Relation; Isentropic Flow through Variable Area Ducts; Diffusers; Speed of Sound and Mach Number; Normal Shock; Pressure, Temperature, Density and Entropy Relations across a Normal Shock; Shock Strength; Rarefaction Shock an Impossibility; Hugoniot Equation; 1- D Flow with Heat Addition; 1- D Flow with Friction; Reyleigh and Fanno Lines; Unsteady Wave Motion; Moving Normal Shock Wave; Reflected Shock Wave; Physical Picture of Wave Propagation; Elements of Acoustic Theory; Finite Non- linear Waves; Incident and Reflected Expansion Waves; Shock Tube Relations; Finite Compression Waves.

**Oblique Shock and Expansion Wave :** Introduction and Source of Oblique Waves; Mach Wave; Mach Cone; Oblique Shock Relations for Pressure, Temperature and Mach Number; Supersonic Flow over Wedges and Cones; Weak Oblique Shock; Shock Polar; Pressure - Deflection Diagram; Reflection of Shock from a Solid Boundary; Intersection of Shocks of Opposite and Same Family; Detached Shock Wave; Prandtl-Meyer Expansion Wave; Shock Expansion Theory; Laminar and Turbulent Flow Separation Caused by the Interaction of Shock Waves with the Boundary Layer.

**Supersonic Flow in Diffusers and Ducts :** The Problem of Starting a Supersonic Flow in Diffusers; Supersonic Inlet – Internal, External and Mixed Compression, Total Pressure Recovery, Mass Flow Characteristics and Inlet Performance; Starting of Supersonic Inlets; Shock Wave Patterns in Ducts and Shock Train Behaviour.

**Conical Flow :** Physical Aspect of Conical Flow; Taylor and Maccoll Formulation; Numerical Procedure; Three- dimensional Flow over Cones and Blunt Nosed Bodies at Angle of Attack.

**Transonic Flow :** Physical and Theoretical Aspects of Transonic Flows; Solution of small Perturbation; Velocity Potential Equations (Murman and Cole Method); Solution of Full Velocity Potential Equations; Solution of Euler Equations.

**Method of Characteristics :** Philosophy; Characteristic Lines; Compatibility Equations; Unit Processes; Regions of Influence and Domain of Dependence; Supersonic Nozzle Design.

**Books Recommended:**


1. Modern Compressible Flow – Anderson, John D.
2. Elements of Aerodynamics of Supersonic Flows – Ferri, A.
3. Elements of Gas Dynamics – Liepmann, H. W. and Roshko, A.
4. Gas Dynamics – Becker, E.

# MSR 2127 : COMPUTATIONAL AERODYNAMICS

**Introduction**: Computational Fluid Dynamics; Classification of Partial Differential Equations; Linear and Non- linear Partial Differential Equations – Model Equation, Elliptic Equation, Parabolic Equation and Hyperbolic Equation; System of $1^{st}$ order Partial Differential Equations; System of $2^{nd}$ order Partial Difference Equations; Initial Conditions; Boundary Conditions.

**Finite Difference Formulations**: Introduction; Taylor Series Expansion; Finite Difference by Polynomial; Finite Difference Equations; Higher Order Derivatives; Multidimensional Finite Difference Formulas; Applications; Finite Difference Approximation of Mixed Partial Derivatives; Stability Analysis; Discrete Perturbation Stability Analysis; Von Neumann Stability Analysis; Multidimensional Problem; Error Analysis; Artificial Viscosity.

**Solution Methods of Finite Difference Equations**: Elliptic Equations – Finite Difference Formulations, Jacobi Iteration Method, Point Gauss Seidel Iteration Method, Line Gauss Seidel Iteration Method, Point Successive Over Relaxation Method, Line Successive Over Relaxation Method, Alternating Direction Implicit Method, Applications; Parabolic Equations – Finite Difference Formulations, Explicit Schemes, Implicit Schemes, Alternating Direction Implicit Schemes, Parabolic Equations in Two-space Dimensions, Approximate Factorization, Fractional Step Methods; Hyperbolic Equations – Explicit and Implicit Schemes, Splitting Methods, Multistep Methods, Application to Linear and Non-linear Problems, Flux Corrected Transport, Classification of Numerical Scheme, TVD Formulations; Application – Heat conduction, Couette Flow and Wave Motion.

**Incompressible Navier- Stokes Equations**: Introduction; Primitive Variable and Vorticity Stream Function Formulations; Poisson Equations for Pressure (Primitive Variable and Vorticity Stream Function Formulation); Numerical Algorithm (Primitive Variable); Artificial Compressibility; Solution on a Regular Grid; Crank Nicolson Implicit Method; Boundary Conditions (Body Surface, Far Field, Symmetry, Inflow, Outflow); Staggered Grid; Marker and Cell Method; Implementation of Boundary Conditions; DuFort Frankel Scheme; Use of the Poisson Equation for Pressure; Unsteady Incompressible Navier- Stokes Equation.

**Euler Equations**: Explicit Formulations – Steger and Warming Flux Vector Splitting, Van Leer Flux Vector Splitting, Runge Kutta Formulation, TVD Formulation; Implicit Formulations – Steger and Warming Flux Vector Splitting; Boundary Conditions; Global Time Step and Local Time Step; Application – Diverging Nozzle Configuration, Shock Tube or Reimann Problem, Supersonic Channel Flow.

**Finite Volume Method**: Approximation of Surface Integrals; Cell centered and Nodal Point Scheme; Interpolation and Differentiation Practices; Implementation of Boundary Conditions.

**Books Recommended:**


1. Computational Fluid Dynamics (Vol. I & II) – Hoffmann, K.A. and Chiang, S.T.
2. Numerical Computation of Internal and External Flows (Vol. I & II) – Hirsch, C.

## MSR 2029 : EXPERIMENTAL AERODYNAMICS

**Wind Tunnel:** Necessity of Wind Tunnels; Basic Principle; Types of Wind Tunnels; Components of Subsonic Tunnel, Supersonic Tunnel, Hypersonic Tunnel and Shock Tunnel; Special Purpose Wind Tunnel; Design Consideration of Subsonic Tunnel and Supersonic Tunnel; Calibration Methods of Different Wind Tunnels; Design of Wind Tunnel Models; Simulation Parameters; Accessories for Wind Tunnels.

**Flow Visualisation:** Different Types of Flow Visualization Techniques for Subsonic, Supersonic and Hypersonic Tunnels; Basics of Schlieren, Shadowgraph and Interferometers; Laser Based Flow Visualization Technique.

**Pressure and Velocity Measurement:** Pitot Static Probe; Cup Anemometer; Basic Principle of Hot Wire Anemometer; Constant Current and Constant Temperature Anemometer; Laser Doppler Velocimeter; Backward and Forward Scattering; Merits and Demerits of Different Methods; Major Components of Hot Wire and Laser Doppler Anemometers; Mechanical System for Pressure Measurement; Water and Mercury Manometers; Principle of Pressure Transducer; Different Types of Pressure Transducers; Mechanical Pressure Scanner, Electronic Pressure Scanner; Pressure Sensitive Paint; Calibration of Pressure Measuring Units.

**Force and Moment Measurement:** Definition of Forces and Moments on Aerospace Vehicles; Basic Principle of Mechanical Balance and Strain Gage Balance; Interaction between Different Components of Forces and Moments; Major Components for Force and Moment Measuring Systems.

**Unsteady Measurement:** Introduction to Unsteady Pressure, Velocity and Temperature; Introduction to Turbulent Velocities and Turbulent Stresses; Measurement of Unsteady Velocities Using Hot Wire Anemometers; Measurement of Turbulent Stresses; Single and Multiple Hot Wire Probes; Basic Principles of Unsteady Pressure Transducers; Calibration of Steady and Unsteady Pressure Transducers.

**Data Acquisition System:** Analog and Digital Signals; Mean and Fluctuating Signals; ADC Cards; Amplifiers; Signal Conditioners; P C Based Data Acquisition System; Data Acquisition Software; Error Analysis.

**Books Recommended:**


1. High Speed Wind Tunnel Testing – Roe, W. H. and Pope, A.
2. Low Speed Wind Tunnel Testing – Pope, A. and Goin, L.

# MSR 2131 : THEORY OF TURBULENCE

**Introduction:** Laminar and Turbulent Flows; Origin of Turbulence; Characteristics of Turbulent Flow; Mean and Turbulent Quantities; Averaging Rules; Derivation of Continuity and Momentum Equations for Turbulent Flow; Compressibility and Incompressibility Effect; Reynolds Averaged Navier- Stokes Equation for Turbulent Flow; Reynolds Stress; Closure Problem.

**Turbulence Modeling:** Derivation of Energy Equation for Mean and Turbulent Quantities; Importance of Different Terms and Physical Significance; Boussinesq and Prandtl-Karman Hypothesis for Turbulence Modeling; Prandtl Mixing Length Theory; Introduction to Different Turbulence Modeling; Log Law; Law of Friction; Velocity Defect Law; Universal Velocity Profile for Ducts and Pipes; Friction Factors for Turbulent Flow.

**Boundary layer:** Momentum Integral Equation for Laminar Flow; Turbulent Boundary Layer on Flat Plate; Skin Friction; Boundary Layer on Rough Surface; Admissible and Critical Roughness; Boundary Layer with Pressure Gradient; Analogy with Laminar Boundary Layer; Momentum- Energy Integral Equation; Method of Truckenbort and Advantages.

**Hot Wire Anemometer:** Measurement of Turbulent Quantities; Basic Principle of Hot Wire Anemometer; Kings Law; Constant Temperature and Constant Current Anemometer; Measurement of Mean and Turbulent Quantities; Major Components of Hot Wire Anemometer; Measurement of Reynolds Stress; Different Types of Hot Wire Probes and Applications.

**Laser Doppler Anemometer:** Basic Principle of LDA; Different Types of LDA and Application; Reference Beam, Dual Beam and Dual Scattering LDA; Forward and Backward Scattering; Major Components of Two- Component LDA; Merits and Demerits in Comparison to Hot Wire Anemometer.

**Isotropic and Non Isotropic Turbulence:** Introduction to Isotropic and Non Isotropic Turbulence; Double Velocity Correlation, Triple Correlation, Different Types of Correlation Coefficients; Microscale and Integral Scale; Energy Spectrum; Dynamic Equation of Energy Spectrum; Grid Turbulence; Decay of Isotropic Turbulence; Free and Wall Turbulence; Behavior of Turbulent Flow behind Cylinder and Jet Flow.

**Books Recommended:**


1. Theory of Turbulence – Hinze, J. O.
2. Boundary Layer Theory – Schlichting, H.

## MSR 2033 : ELEMENTS OF HYPERSONIC FLIGHT

**Introduction:** Hypersonic Flow; Shock Layer; Entropy Layer; Viscous Interaction; High Temperature Flows; Low Density Flows; Velocity Altitude Map.

**Hypersonic Shock- Expansion Theory:** Shock Relation ; Hypersonic Shock Relations in Terms of the Hypersonic Similarity Parameter; Expansion Relation; Newtonian Flow; Modified Newtonian Law; Centrifugal Force Corrections to Newtonian Theory; Tangent- Wedge/ Tangent- Cone Methods; Shock- Expansion Method.

**Hypersonic Inviscid Flowfields (Approximate Methods):** Introduction; The Governing Equations; Mach Number Independence; The Hypersonic Small- Disturbance Equations; Hypersonic Similarity; Hypersonic Small- Disturbance Theory; The Hypersonic Equivalence Principle and Blast Wave Theory; Thin Shock- Layer Theory.

**Hypersonic Inviscid Flowfields (Exact Methods):** General Thoughts; Method of Characteristics; The Hypersonic Blunt- Body Problem; Correlations for Hypersonic Shock- Wave Shapes; Modern Computational Hypersonics.

**Viscous Hypersonic Flow:** Governing Equations for Viscous Flow; The Navier- Stokes Equations; Similarity Parameters and Boundary Conditions; The Boundary Layer Equations for Hypersonic Flow; Hypersonic Boundary Layer Theory; Self- Similar Solutions, Flat Plate Case, Stagnation Point Case; Hypersonic Transition; Hypersonic Turbulent Boundary Layer; Hypersonic Aerodynamic Heating; Entropy Layer Effects on Aerodynamic Heating.

**CFD Solutions of Hypersonic Viscous Flows:** Introduction; Viscous Shock- Layer Technique; Parabolized Navier- Stokes Solutions; Full Navier- Stokes Solutions.

**Books Recommended:**

1. Hypersonic and High Temperature Gas Dynamics – Anderson, John D.