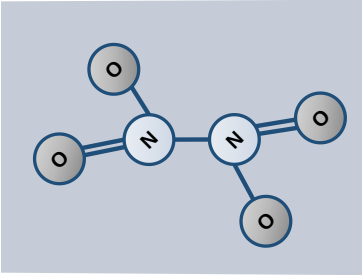
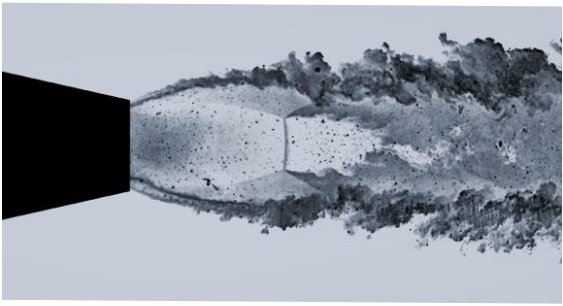
LABORATORY FOR HYPERSONIC AND SHOCK WAVE RESEARCH

LHSR

LAB BROCHURE





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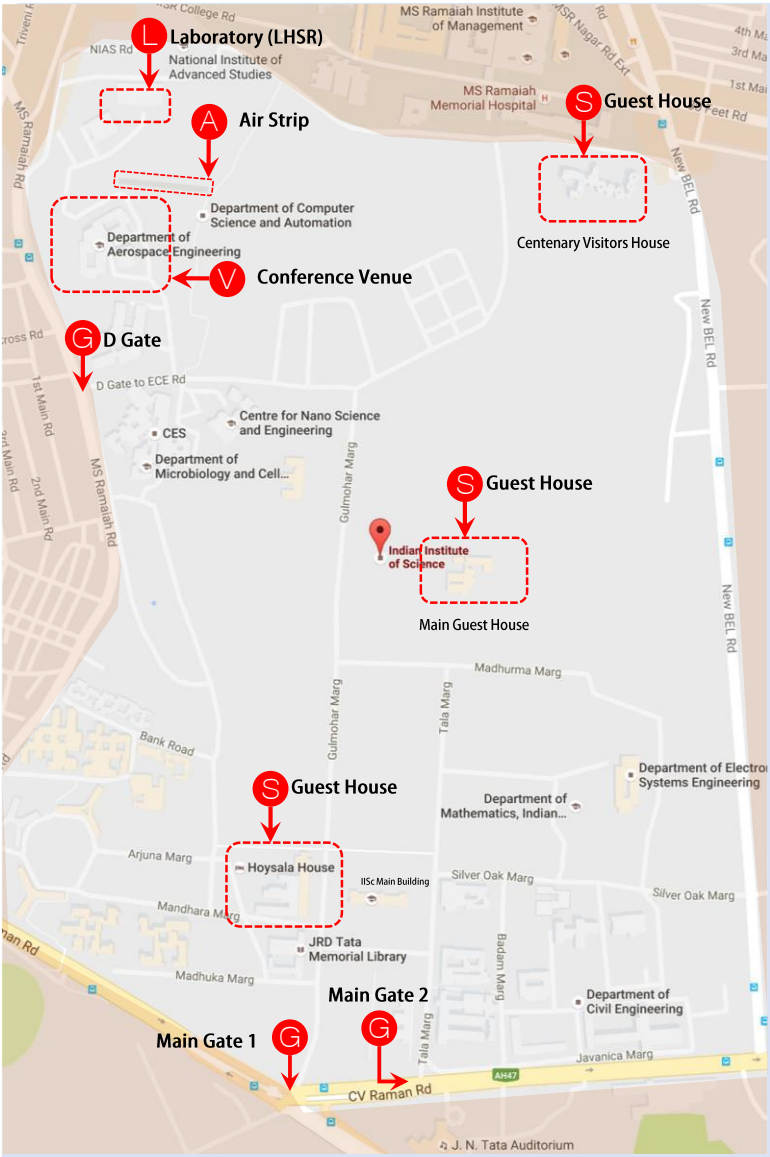

Navigate @ IISc

The app helps one navigate inside the serene and green campus of the Indian Institute of Science (IISc), Bengaluru. The interface has categories of all key points of interest allowing the user to choose her/his desired location. The map interface also allows for routing. |An initiative of DIGITS Office, IISc|

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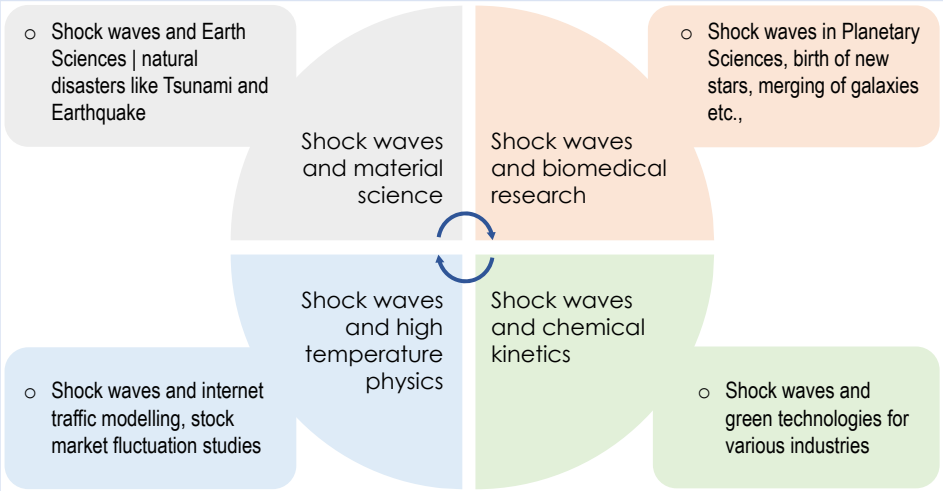
LAB BROCHURE

General Information

INTRODUCTION

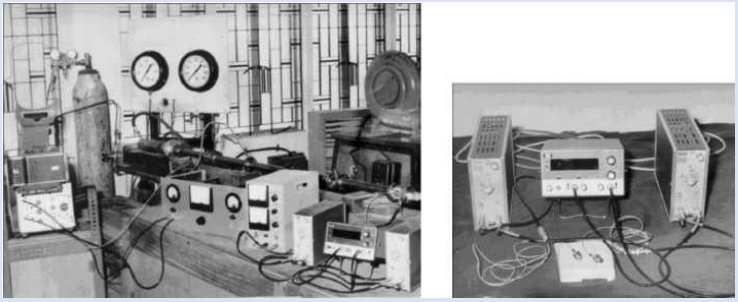
Laboratory for Hypersonic and Shock wave Research (LHSR) was started in early 1970's by Prof. N M Reddy with the primary goal of carrying out research in the field of hypersonics that helps the ongoing aerospace activities in the country. Presently, LHSR has been involved in the research work on High speed aerodynamics, Chemical kinetics, Shock wave phenomena and its related applications. LHSR is equipped with a wide range of test facilities. The details of these facilities along with their performance capabilities and typical results of recent research studies are described in this brochure.

RESEARCH FOCUS



HISTORY

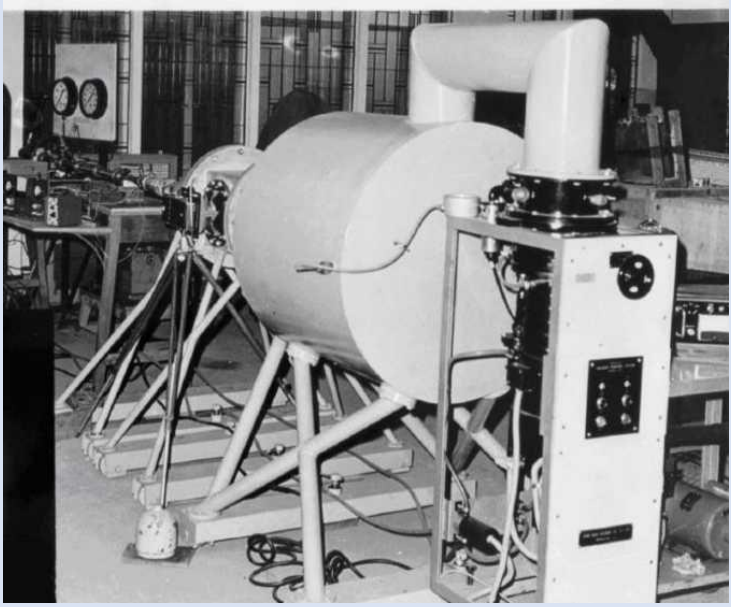
The present LHSR has its origin in the High Enthalpy Aerodynamics Laboratory (HEAL) started in the early 1970's by Prof. N. M. Reddy, a student of Prof. I. I. Glass who was one of the pioneers in shock wave research. The first working shock tube consisting of 32 mm diameter brass tube with metallic diaphragm separating the driver and driven sections was established in HEAL in 1972. Instrumentation for measuring the shock speed using a pair of platinum



HEAL's first Shock Tube and instrumentation for Shock speed measurement

thin film gauges mounted 300 mm apart on the driven tube, pressure measurement using flush mounted PCB pressure sensor and heat flux using platinum thin film sensors with analogue networks, were employed in the shock tube. Subsequently, the country's first Hypersonic Shock Tunnel (HST1) was built in 1973 using aluminum shock tube of 50mm diameter with a conical nozzle and variable throats capable of producing Mach numbers in the range of 4 and 13.

Since inception, HEAL has pioneered in the development of accelerometer based force balance system for measuring aerodynamic forces for various model configurations, platinum thin film gauges for measuring aerodynamic heat transfer rates and optical techniques for visualization of high speed flows in shock tunnels. In recent times there has been a paradigm shift towards interdisciplinary research steered by the core team consisting of Prof. K P J Reddy, Prof. G. Jagadeesh, Prof. E. Arunan (IPC Dept.) and Dr. S. Saravanan with the active participation of large number of researchers from within the campus and outside. The research activities aimed at understanding the shock wave phenomenon gave birth to Shock waves laboratory. Subsequently, shock waves found applications in chemical kinetics and bio-sciences research, giving birth to High Temperature Chemical Kinetics Laboratory and Bio-Sciences Laboratory. In the year 2010 all these laboratories were amalgamated under the name of Laboratory for Hypersonic and Shock wave Research (LHSR) located in the new building.



India's first Hypersonic Shock Tunnel - HST1

First photograph of the flow over the model taken in Hypersonic Shock Tunnel - HST1

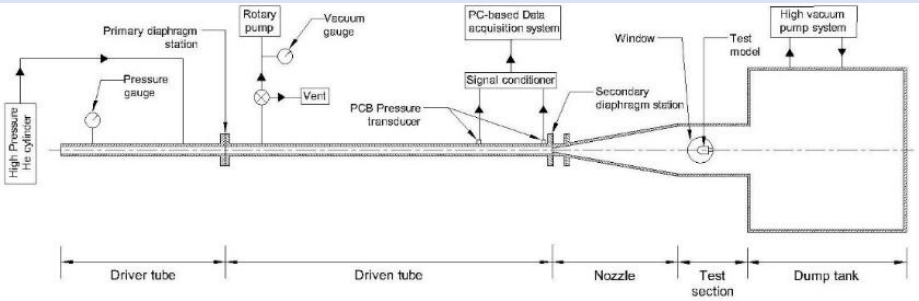
Facilities

SHOCK TUNNELS

Shock tunnel is an impulse facility which has the ability to produce high stagnation pressures and temperatures, with minimum power requirements and with reduced contaminant of test gas. Presently, LHSR owns five shock tunnels used for different purposes are described below.

HYPERSONIC SHOCK TUNNEL 1 (HST1)

HST1, shown schematically below, consists of a shock tube portion attached to wind tunnel portion which is a hypersonic nozzle - test section - dump tank - high vacuum system assembly. The shock tube portion is a constant area cylindrical duct whose inner diameter is 50 mm for a length of 7 m. The shock tube which is made up of aluminium, is divided into 2 m long driver section and 5 m long driven section by placing a metal diaphragm in-between the sections. A thin paper diaphragm separates the shock tube portion from the wind tunnel portion. The HST1 generally operates at Mach 6 in the straight through mode by using a conical nozzle whose entry diameter is 50 mm and exit diameter is 300 mm. However the flow Mach number could be varied by attaching a throat portion between the shock tube and the nozzle. The test section whose length is 450 mm and cross section is 300 mm x 300 mm, is attached to a 1.5 m long cylindrical dump tank whose diameter is 1m.



Schematic sketch of HST1

HYPERSONIC SHOCK TUNNEL 2 (HST2)

HST2 is built to overcome the limitations on performance capabilities of HST1. Since the shock tube in the HST1 is made of aluminium, the range of operating pressure levels are limited and hence the tunnel could not produce high enthalpy flows suitable for testing at flow velocities beyond 1.5 km/s. In addition, the test-section-dump tank assembly in the HST1 is made of cast iron which contaminates the hypersonic flow due to the rusting. In order to overcome the above limitations, the shock tube, nozzle, test section and dump tank in HST2 is made of stainless steel material. HST2 can operate in the Mach number range of 6-14 with the help of appropriate nozzle throat inserts and can produce specific flow enthalpies up to 5 MJ/kg. The photographs of HST2 shock tunnel along with the throat inserts are shown below.

(a) Photograph of HST2 hypersonic shock tunnel (b) nozzle with a convergent divergent (CD) throat (c) different throat inserts for changing the free stream Mach number

FREE PISTON DRIVEN HYPERSONIC SHOCK TUNNEL 3 (HST3)

HST3 is a free-piston driven hypersonic shock tunnel built to operate at very high enthalpy flow conditions which is limited in the conventional hypersonic shock tunnels because of the limitation on the driver gas pressure required for producing shock waves of higher strength. One way to produce high enthalpy flow conditions is by heating the driver gas temperature which helps to increase the strength of the shock waves in the shock tube, and this is achieved in HST3. HST3 consists of compression tube whose length is 10 m and inner diameter is 165 mm, and shock tube whose length is 4.5 m and inner diameter is 50 mm attached to a convergent-divergent conical nozzle whose exit diame-

ter is 300 mm opens into the dump tank containing the test section. The compression tube is separated from shock tube by a metal diaphragm, and the shock tube is separated from nozzle by a paper diaphragm. The compression tube is filled with helium gas at 1 atm and the high pressure air in the reservoir which is attached to the other end of the compression tube drives a 20 kg piston to a speed of about 150 m/s in the compression tube. This process adiabatically compresses the helium gas to about 10 MPa and heated to about 4500 K. This gas ruptures the diaphragm producing a strong shock wave of Mach numbers exceeding 10 into the driven section. The stagnated test gas behind the reflected shock expands through the nozzle to produce hypersonic flow of Mach 8 with enthalpy exceeding 5 MJ/kg. Different codes such as ESTC, STN, L1D and MBCNS are used to evaluate the tunnel performance.

Photograph of Free Piston Driven Hypersonic Shock Tunnel - HST3

HYPERSONIC SHOCK TUNNEL 4 (HST4)

HST4 is built to accommodate large size test models of about 100 mm in diameter and up to a meter in length, which is unlikely in HST1, HST2 and HST3 shock tunnels. It consists of a shock tube with an inner diameter of 165 mm and a length of 17 m, attached to hypersonic conical nozzle whose half-angle is 10O, entry diameter is 165 mm and exit diameter is 1000 mm, opens into the dump tank containing the test section. The dump tank/test section assembly is 2.85 m long cylindrical tank of 1.50 m diameter. BK 7 optical glass view ports with a window diameter of 367 mm are mounted on the test section to facilitate flow visualization. Test times up to 4ms can be obtained in this facility. The schematic diagram and photographs of HST4 tunnel are shown below:

Photograph of HST4 hypersonic shock tunnel

COMBUSTION DRIVEN HYPERSONIC SHOCK TUNNEL 5 (HST5)

Photograph of combustion driven hypersonic shock tunnel HST5

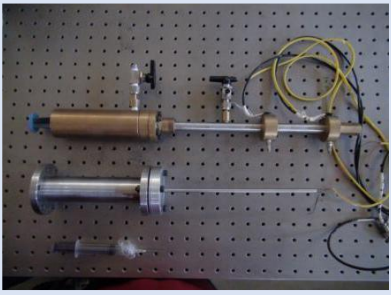
HST5 is a combustion driven hypersonic shock tunnel built to operate at high enthalpy conditions using minimum amount of driver gas. It consists of shock tube of inner diameter 105 mm with driver and driven lengths of 3.5m and 9m respectively and attached to a hypersonic nozzle-test section-sump tank-high vacuum system assembly. A mixture of hydrogen, helium and oxygen gas is combusted in the driver section of shock tube using four spark plugs mounted circumferentially at right angles close to the diaphragm station in the driver

tube. The pressure and temperature increases due to combustion and ruptures the diaphragm creating a shock wave in the driven tube, producing a reservoir of high pressure and temperature test gas behind the reflected shock wave which is further expanded through convergent-divergent conical nozzle to produce a hypersonic Mach flow. The free-stream conditions of HST5 depend on driver gas pressure, driver gas temperature, specific heat ratio of driver gas and driven gas pressure unlike free-stream conditions of conventional shock tunnel which depend only on driver gas pressure and driven gas pressure.

REDDY TUBES & TUNNEL

Reddy tubes are hand operated shock tubes, where the high pressure required for rupturing the diaphragm is generated inside the driver tube by pushing a hand-held piston. Available in varying diameters these tubes find application in diverse areas like artificial insemination of cattle, investigation of brain injuries in accidents, removal of brain tumour, water purification, oil extraction etc. Reddy tunnel, another facility developed in-house, is aimed at bringing the field of shock waves to every educational institution. It is capable of producing hypersonic flow for test times of the order of 300 µs, with stagnation enthalpy up to 2 MJ/Kg. The shock tube portion is of 29 mm inner diameter, with driver and driven lengths of 0.4 m and 0.6 m respectively. The wind tunnel portion consist of a CD-nozzle of 75 mm exit diameter, a rectangular test section and a cylindrical dump tank where models up to 50 mm (cross-wise dimension) can be mounted.

Super bull-Reddy tube developed for artificial insemination



1 mm, 4mm and 8 mm diameter Reddy tubes

Reddy tunnel

The ease of operation and low cost (compared to conventional shock tunnels) being the most significant aspects of this facility, the reddy tube and tunnel are incorporated into the under-graduate syllabus in various prestigious institutes across India. Also Super bull,a reddy tube developed for artificial insemination is currently under trails and is shown to have increased the conception rate in cows by atleast 15%.

Reddy tube in Operation at Centre for Nano-sciences, IISc

Blast induced trauma model, National Institute of Mental Health and Neurosciences

UNDERWATER SHOCK WAVE GENERATOR

An underwater electric discharge device has been designed, fabricated and successfully used for creating spherical micro shock waves. The below figure shows the photograph of an underwater shock wave generator. Spherical micro shock waves (few millimetres radius) are generated in water, by instantaneously depositing electrical energy (100 J) between two stainless steel electrodes (1 mm apart) for about 0.35 ms. Peak overpressures up to 100 MPa can be generated for about 10 ms. The water between the electrodes is instantaneously vaporized, creating a tiny vapour bubble. This bubble grows in size and

subsequently bursts creating the spherical micro shock wave. The high voltage applied between the electrodes can be varied to generate shock waves of requisite strength. A high-precision mechanical traverse system is used to hold the eppendorf tubes containing any biological samples such as bacterial cells with naked plasmid DNA above the electrodes. The distance between the bottom of the tube and electrodes can be accurately adjusted (least count 0.01 mm) and monitored using a digital encoder. In most of the ongoing experiments, the distance between the sample tube and the electrodes is maintained at ~ 3 mm and the corresponding pressure measured (PVDF Needle Hydrophone, Ms Muller, Germany) inside the test tube was ~ 13.0 MPa.

Photograph of underwater shock wave generator

Photograph of the diaphragmless shock tube

VERTICAL SHOCK TUBE

Shock tubes are also used to simulate and understand the interaction of a blast wave with a structure. A test plate may be placed at the end of the shock

tube and this may then be subjected to blast loading. In order to vary the loading pulse duration, we need to have a provision to vary the driver and driven tube lengths. At LHSR, we have two vertical shock tubes for this purpose, each of 136 mm inner diameter, opening into a safety tank on which these tubes are supported. These tubes have been designed to handle a shock pressure of 100 bar. Two shock tubes were made with an intention to study the effect of multiple point loading on wider samples such as concrete blocks. This facility has the provision to vary the lengths of the driver section (3 tubes of 0.5 m each) and the driven section (one tube of 1.5 m, 3 tubes of 0.6m, 1 tube of 0.5 m, and one tube of 0.39 m). We also have a driver section tube whose length may be varied from 80 mm to 200 mm. The safety tank has provisions to view the deformation of the test plate through five 350 mm viewing windows. To test plates that will be subjected to under-water blast loading, we need to have an easy way to handle liquids and so the tubes were designed to be vertically placed.

Photograph of vertical shock tube

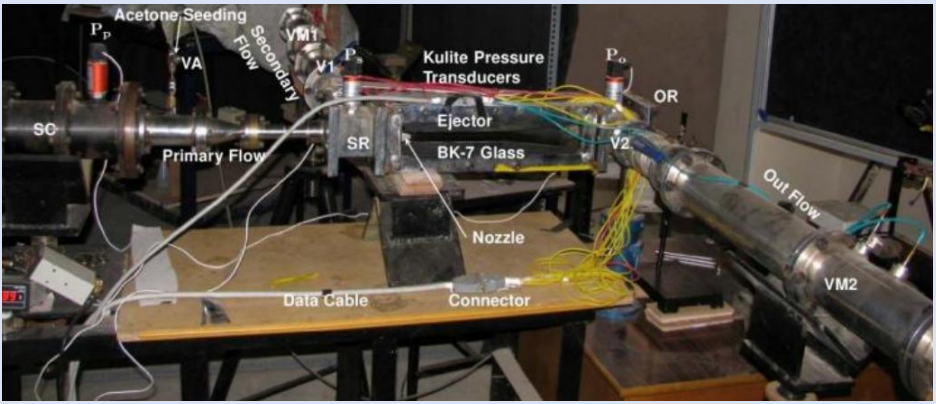
SUPERSONIC JET FACILITY

A Supersonic Jet facility has been established at LHSR to study the fluid dynamic phenomena of mixing layers which helps in improving the devices such as aero-engines, injection of fuel into combustor, supersonic ejector, RAMJET/SCRAMJET and noise reduction in aero-engines. It consists of two compressed air tanks of 3 cubic meter capacity and one compressed air tank of 2 cubic meter capacity at 12 bar pressure. The tanks are filled by an Elgi E22-13 GS screw compressor system delivering compressed dry air at 12 bars, 95 CFM. The flow from the tanks is regulated by a pressure regulator-solenoid valve assembly that allows control over the flow rates and stagnation pressures delivered to the downstream. The facility has flexibility to conduct various experi-

mental configurations involving supersonic flows in general and jets in particular. Currently experiments are being conducted in supersonic ejectors and wall jets. A supersonic ejector uses a primary motive fluid expanding from high pressure to entrain a secondary flow into a mixing duct where by augmentation of momentum and energy and the secondary flow is pumped to higher pressures. A purely aerodynamic device, it finds numerous applications in vacuum generation, thrust augmentation, alternate refrigeration, gas dynamic lasers, wind tunnels, and noise suppression from jets, RAM/SCRAMJET, recirculation in fuel cells. A two dimensional ejector with a primary nozzle of Mach number 2.5 and a mixing duct of 20mm has been established. Studies are being conducted to understand the mixing phenomena of co-flowing supersonic jet within confined ducts using optical tools like Schlieren, LASER scattering, pressure measurements. The facility can be interchangeably used with an axi-symmetric configuration which allows for use of different secondary fluids, nozzle geometries and a range of mass flow ratios. The photograph of the facility is shown above.

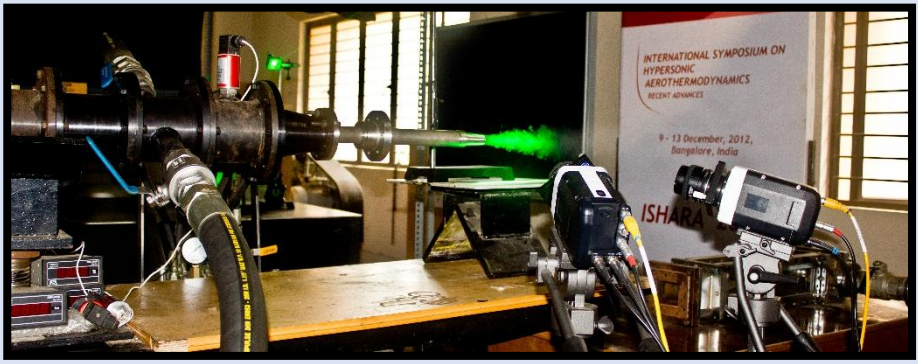
The jet facility has been modified to study a supersonic wall/free jet, which within the same flow topology has interactions of shock with boundary layer and mixing layer. This flow scenario is found in various aerospace applications, especially in futuristic SCRAMJET applications. The flow features and its response to local thermal and momentum bumps have been investigated with Schlieren, pressure measurements, and oil-flow visualizations. The photograph of the facility is shown below.

Photograph of the screw compressor with controller, refrigerant type air drier and the storage tanks of the blow-down facility



Photograph of the supersonic ejector facility

Photograph of the supersonic wall jet facility

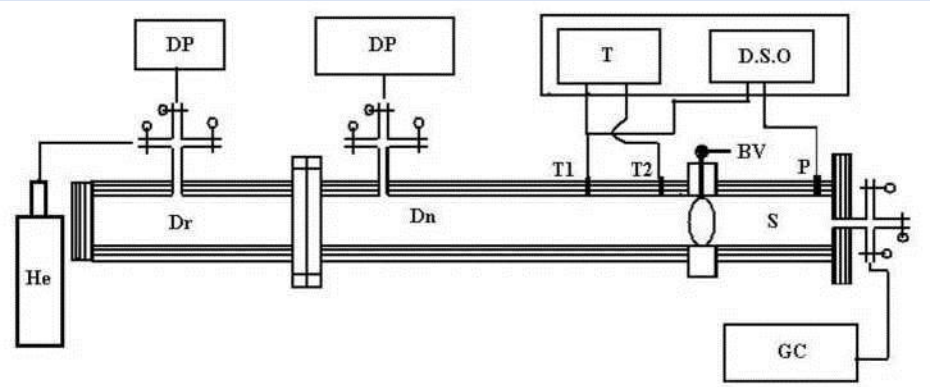


Photograph of the supersonic free jet facility

The blow-down facility can also be operated in the supersonic free jet mode. Photograph of the supersonic free jet facility is shown above. Supersonic jet coming out of exotic nozzle shapes are studied in this facility for accessing the mixing enhancement capabilities which are important in reducing the thermal and acoustic signature in supersonic jet exhaust.

SHOCK TUBES FOR CHEMICAL KINETICS

We have established three shock tubes CST1, CST2 AND CST3, shown schematically in the following figure for measuring chemical kinetic rates at high temperatures. The chemical shock tube 1(CST1) is an aluminium tube with inner diameter 50.8 mm and other 2 are stainless steel tubes with inner diameter 39 mm and 50.8 mm respectively. CST 1 and CST 2 are single pulse shock tubes while CST 3 is designed to work for online measurements such as ignition delay and Atomic Resonance Absorption Spectroscopy (ARAS) studies. CST2 and CST3 are provided with optical ports to facilitate absorption and emission spectroscopic studies.



Schematic diagram of the shock tube: DP - diffusion pump; Dr - driver section; DSO-digital storage oscilloscope Tektronix; Dn - driven section; T1/ T2 - thermal sensors; T- counter; P - pressure transducer, GC-Gas Chromatograph

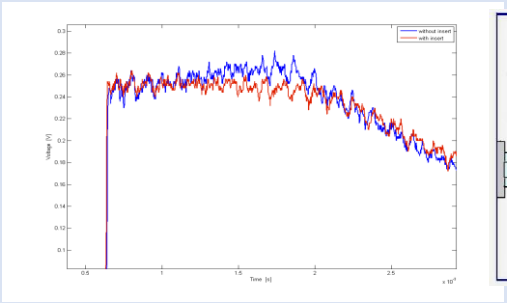
INCORPORATION OF DRIVER INSERT IN CHEMICAL SHOCK TUBE

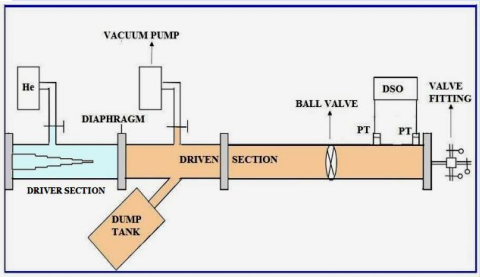
(A Strategy to achieve the near constant pressure behind Reflected shock)

Shock tube is an ideal tool to study chemical kinetics at elevated temperature and pressure. It provides near ideal behavior behind reflected shock wave which helps in the measurements of ignition delay times and determination of

reaction rates. Any non-ideal effects such as incident shock wave attenuation, boundary layer growth etc. will cause gradual rise in pressure behind reflected shock region in turn result in change in temperature behind reflected shock wave. In order to overcome such problem we have also employed the methodology of putting “driver insert” in driver section in our chemical shock tubes which thereby can counterpart non ideal rise in pressure behind reflected shock. The driver insert acts as sources of expansion waves and provides near-ideal behaviour behind reflected shock waves. When the driver insert is employed in shock tube, near ideal performance in reflected shock wave experiment can be achieved.

Photograph of the CST1, CST2, and CST3 shock tubes





(Left) Highly uniform temperature profile obtained when pressure is precisely maintained constant using a driver insert. (Right) Schematic diagram of the chemical shock tube (CST3) with driver insert. DSO, Digital storage oscilloscope; PT, Pressure transducer

Measurement techniques and flow diagnostics

The laboratory is equipped with different kind of measurement techniques and advanced flow diagnostics that were used to understand the flow physics.

PRESSURE MEASUREMENT

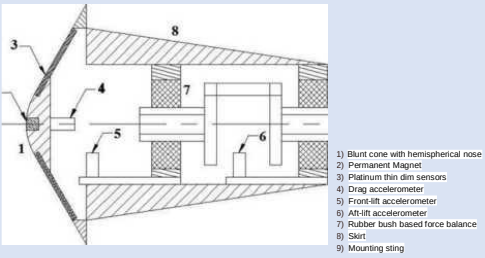
Piezo-electric sensors are used to measure pressure behind the incident shock waves in the shock tubes which help to calculate the shock speed, and the total pressure of the free-stream flow in the shock tunnels. We have many Piezo-electric and Piezo-resistive sensors which are also used for measuring pressures on the model, and its specifications are given below:

	Piezo-electric pressure transducers	*Piezo-resistive pressure sensors*
Make	PCB	Kulite
Available Ranges	5 - 5000 PSI	5 - 500 PSI
Available Sensitivities	1 - 93 mV/PSI	0.2 - 20 mV/PSI

BALANCE SYSTEM FOR MEASURING AERODYNAMIC FORCES

Aerodynamic forces acting on the model are measured using Accelerometer based force balance measurement technique and it is capable of measuring small forces within the test duration of milliseconds in hypersonic shock tunnels. This measurement technique was proposed by American researchers and developed by our group. It is designed in such a way that the model is freely-floating during the flow in the tunnel and uses the commercially available miniature accelerometers to measure the acceleration experienced by the model. The forces are then computed from these measured accelerations. We have developed single component balance system for measuring the drag force, a three component balance system for measuring the drag, lift and pitching moment and also a six component balance system to measure drag, lift, pitching

moment, rolling moment and yawing moment coefficients for different shape and size models in the shock tunnel. The balance system has been analyzed using FEM technique and compared with the stress wave balance developed by the Australian researchers.



Schematic diagram of the accelerometer balance system used for measuring the aerodynamic forces over a blunt-cone model

Photograph of the force balance system used in the model

THIN FILM GAUGES FOR MEASURING HEAT TRANSFER RATES

Measuring the heat transfer rates is essential to understand the phenomenon of shock-shock, shock-boundary layer interaction, flow separation, aerodynamic heating and transition in hypersonic flow over the models. Measuring the heat transfer rates is also essential for the development of thermal protection system for reentry vehicles traveling at hypersonic Mach numbers. Since the flow duration in typical high speed tunnels such as shock tunnel is of the order of a millisecond it is essential to develop thermal sensors with response time of a microsecond. We use conventional platinum thin film gauges

Sputtering unit for making platinum thin film gauges (left) and furnace unit for making Large Carbon Clusters thin film gauges (right)

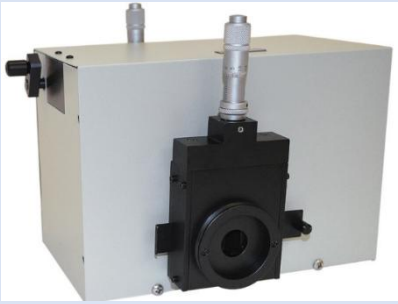
deposited on insulating material such as Pyrex glass or machinable glass MA-COR for measuring the heat transfer rates for different model configurations tested in the shock tunnels. These film gauges are developed either by using the platinum particles suspended in a liquid chemical or by magnetic sputtering using platinum target. Platinum thin film sensors and sputtering machines available in lab are shown below.

The lab has also developed in-house sensors using Large Carbon Clusters as sensing element deposited onto same substrate as platinum. These sensor have much higher sensitivity than platinum and have a high absorptivity that make them ideal for radiative heat flux measurement which is very challenging using platinum thin film. LCC heat flux sensors and furnace required to chemically deposit these sensors is shown below.

Platinum and LCC heat flux

MONOCHROMATORS AND SPECTROMETERS

A grating monochromator from Acton that uses a photo-multiplier tube as the detector and has a resolution of 0.1 nm is used in the chemical shock tube facility to monitor the formation of chemical products during the operation of the tunnel. They help to study the evolution of chemical reactions. Additionally, two fiber-coupled grating micro spectrometers from Ocean Optics - STS-UV and STS-NIR - are also available in the lab. Together these two spectrometers can cover a range of wavelength from 190 nm to 1100 nm with a resolution of 1.5 nm. We also have a 1/8 m hand-operated monochromator with micrometer driven slit assemblies at the entrance and the exit. Although this monochromator has a low-resolution, it can be used with a calibration source available in the lab to characterize the spectral sensitivity of cameras and detectors.



Monochromators

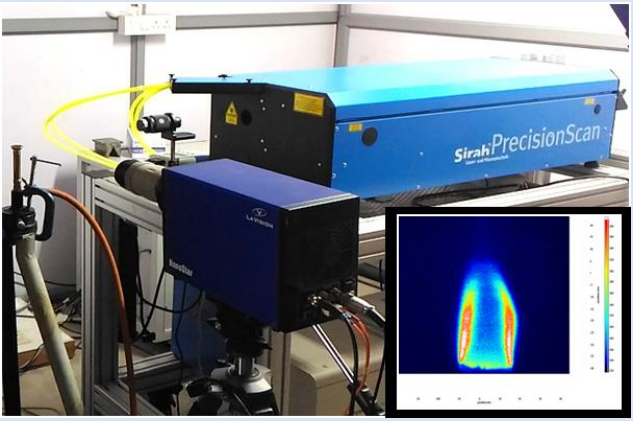
Fiber-coupled micro-spectrometers

calibration lamp

PLANAR LASER INDUCED FLUORESCENCE SPECTROSCOPY

Planar laser induced fluorescence (PLIF) is an optical diagnostic technique that targets minor combustion species such as OH, NO, and CH to measure temperature, velocity and species concentration. This technique extends the laser induced fluorescence spectroscopy to two dimensions by expanding an excitation laser beam into a laser sheet and passing through the sample. In our lab, a Sirah pulsed dye laser system is used to excite fluorescence in the flow studied. The laser is tuneable from a range of 350 nm to 610 nm. Typical pulse energies are above 10 mJ, pulse duration is around 10 nanoseconds and the typical repetition rate is 10 Hz. A high energy pulsed Nd:YAG laser is used to optically pump the dye laser. The Nd:YAG laser has excellent beam quality and stability, and can be used to produce high intensity pulses at 532 nm, 355 or 266 nm. The output wavelength of the system depends on the dye used. For example, when Rhodamine 6G dye is used as the dye, 685875875. An intensified CCD camera is used to capture the emitted fluorescence with the help of a band-pass filter designed for the required fluorescence wavelength range.

The camera is equipped with an image intensifier system that gives the ultimate sensitivity. It also acts as an extremely fast optical shutter and can be gated down to 10 ns. It covers the wavelength range from 190 nm to 800 nm, and has a resolution of 1280 X 1024. The entire unit is controlled through the Davis software module of LaVision. PLIF provides qualitative as well as quantitative measurement of flow properties in regions where the conditions are extreme. The stagnation point on a blunt model in a hypersonic flow and turbulent reacting flows are typical examples. An image of the laser and high speed camera is shown in figure below, along with a PLIF image of OH radicals captured in a flame.

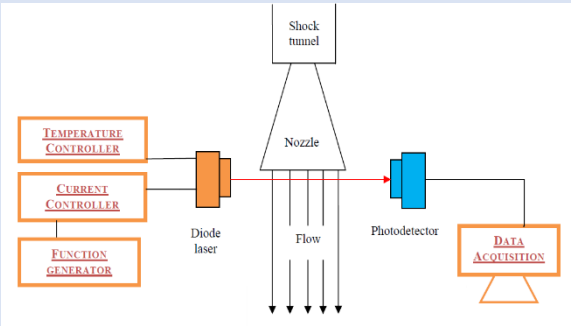


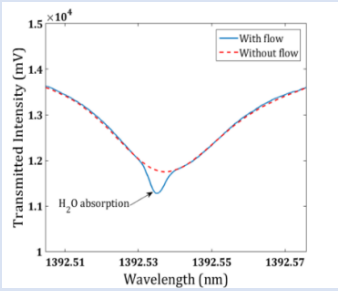
The dye laser, sheet optics and intensified CCD camera used for the PLIF spectroscopy. OH PLIF image obtained in a Bunsen burner is also shown in the inset.

TUNABLE DIODE LASER ABSORPTION SPECTROSCOPY

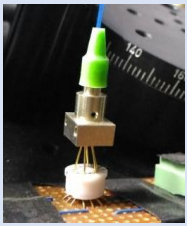
In tunable diode laser absorption spectroscopy (TDLAS), the wavelength of a monochromatic diode laser is scanned across the absorption feature of a target species in the flow and the laser beam is passed through the flow. The transmitted intensity is detected using a high speed photodetector and compared to the incident intensity to obtain the absorption spectrum of the target species. This spectrum can be used to retrieve the temperature, velocity and concentration of the target species in the sample (gas flow in our case). The TDLAS system is being used to measure flow parameters in the freestream flow of various shock tunnels in the lab. The laser currently in use is a fiber-coupled vertical-cavity surface-emitting laser that emits near 1392 nm. Other than the

laser, the important components of the system include a VCSEL current controller, temperature controller, digital function generator, collimating optics, high-bandwidth photodetector (150 MHz) and a high speed data acquisition system (250 MS/s). The schematic diagram of the system is given in the figure below. Currently a diode laser system targeting water vapor absorption lines is used in the lab. However, other lasers that target species such as carbon dioxide, oxygen and carbon monoxide can also be used in the system with modifications in the detection system.





The schematic diagram of the TDLAS system with a sample transmitted intensity spectrum of water vapour obtained in a shock tunnel flow



Diode laser

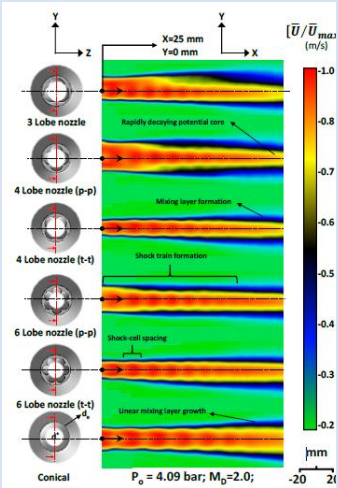
Laser controllers

Photodiode

High-speed data acquisition system

PARTICLE IMAGE VELOCIMETRY

Particle Image Velocimetry (PIV) is an excellent method to measure velocity profile in high speed flows. In PIV, two images of the flow at very close time instants are captured and these images are processed using autocorrelation or cross-correlation technique to obtain local velocity. High speed PIV experiments in ejector facilities are about to mature in this lab. A high speed Nd-YLF laser from Litron with dual cavity is procured. Each cavity has a capability to fire at 0.1-10 KHz. The pulse width of the 527 nm laser is 100 ns. Experiments are performed at 1 kHz with an energy of 22.5 mJ. LaVision's laser guiding arm and collimated sheet optics are used to transport the beam from the laser to the interrogation area. The entire experimentation area is calibrated properly for spatial dimensions using in-house calibration board with image correction module. Phantom Miro 110 PIV (20 micrometer/pixel) camera is used in double frame – shutter off PIV mode. A Schimpflug adapter is used to correct the errors in viewing the image perpendicular to the sensor. Di-ethylene Glycol is used as the seeding agent in the fore-said seeding generator. A double-pulsed timing of 0.5 micro second is maintained. The certainty of the pulse spacing is properly monitored using an oscilloscope. Nearly 800 double-frame images are acquired for processing. After proper back-ground subtraction the images are processed for PIV vectors. The entire unit is controlled through the Davis 8 module of LaVision. The figure below displays time-averaged 2D-PIV images in the XY plane obtained in a supersonic Elliptic Sharp Tipped Shallow (ESTS) lobed nozzle.



Time-averaged 2D-PIV images in the XY plane obtained in a supersonic Elliptic Sharp Tipped Shallow (ESTS) lobed nozzle that show the normalized velocity contours with key flow features. Flow is from left to right.

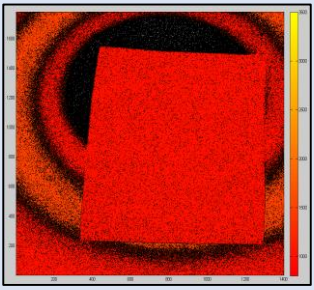
TWO COLOUR RATIO PYROMETRY (TCRP)

A pyrometer is a device that determines the temperature of a surface from a distance, using the spectrum of thermal radiation it emits. This temperature

is dependent on the emissivity of the subject, which often changes drastically, with surface roughness, bulk and surface composition and even the temperature itself. To get around these difficulties, TCRP was developed. Instead of requiring an absolute intensity measurement, TCRP relies on ratio of intensities at two known wavelengths. TCRP can provide measurements of high surface temperatures with the help of a commercially available cameras such as Digital Single Lens Reflex (DSLR) cameras. A DSLR camera comes in handy for this purpose, in that it provides red, green and blue (RGB) intensities at each pixel of the sensor, over a wavelength range that lies in the visible region of the spectrum, typically 400-700 nm. These intensity data may be used to ascertain two color ratios and each ratio can be connected to a temperature, via a calibration of the camera. The method assumes that the emissivity of the subject does not vary with the wavelength in the visible region, and hence gets cancelled out in the two color ratio. This is known as the grey body assumption. Most metals and refractory materials fulfil this assumption, as has been shown from past research. This being a non-contact method, with the camera placed at a considerable distance from the high temperature subject, the potential for damage is minimized.

An example of TCRP measurement is shown below. Stainless steel sheet was placed in a tube furnace and heated to temperatures as high as 1426 K. TCRP was used to measure a 2-D surface temperature of the sheet. The result has been presented below. The mean temperature over the sheet was calculated and compared with emission spectroscopy and analytical calculations. The results were found to be within 8% of each other.

A commercial DSLR camera Used for TCRP. The camera has effectively 18 MP resolution.



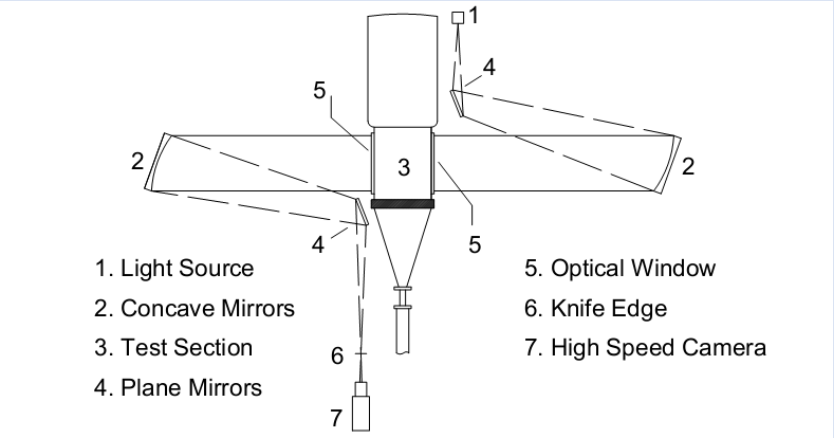
2-D surface temperature plot for furnace wall temperature at 1426

Phantom V310

Photron FASTCAM SA4

HIGH SPEED VIDEO CAMERA

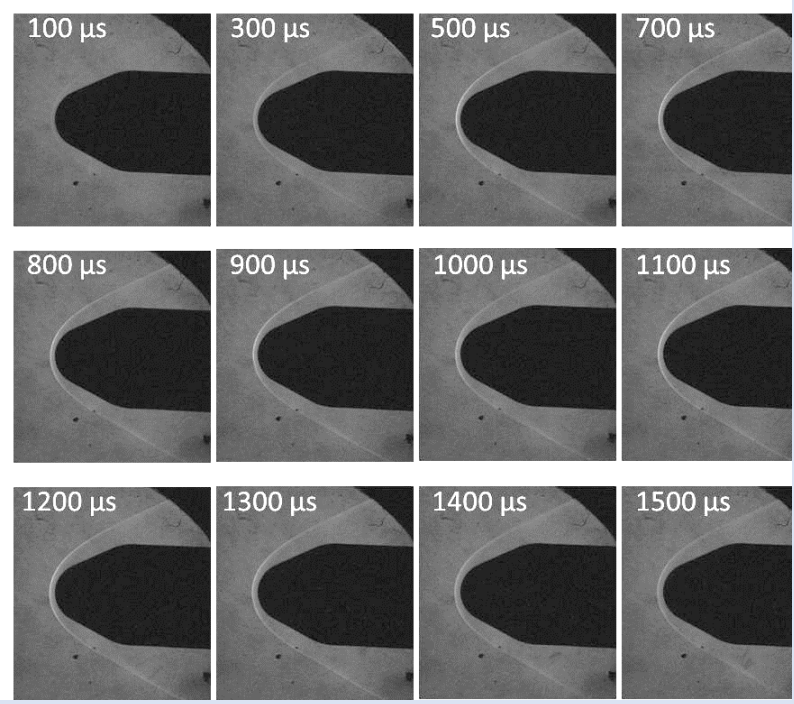
We have Phantom V310 and Photron FASTCAM SA4 model high speed digital camera with 1 microsecond exposure time. The Phantom V310 camera has optional 12 bit CMOS 1280 x 800 pixel sensor with an active pixel size of 20 microns, 3140 fps full frame and can be increased up to 500,000 fps maximum. The Photron FASTCAM SA4 camera has 12 bit CMOS 1024 x 1024 pixel sensor with an active pixel size of 20 microns, 3600 fps full frame and can be increased up to 500,000 fps maximum. These cameras have been integrated with the Schlieren system to visualize the hypersonic flows over the test models inside the shock tunnels which have run times in the order of a millisecond. Photograph of the high speed camera is shown in the below.



Schematic diagram of the high speed Schlieren system for visualization of hypersonic flow over the models in hypersonic shock tunnels

HIGH SPEED SCHLIEREN FACILITY

Single shot flow visualization is not adequate for understanding the flow starting and establishing processes in the shock tunnel. It is essential to have a dynamic visualization technique to record these processes which are of about one millisecond duration. For this purpose we have established a high speed Schlieren facility, as shown schematically in the above figure. This facility consists of a light source and optical system to pass an 8 inch diameter parallel beam of light through the shock tunnel test section. The parallel beam after passing through the test section is focused using a high quality mirror and the



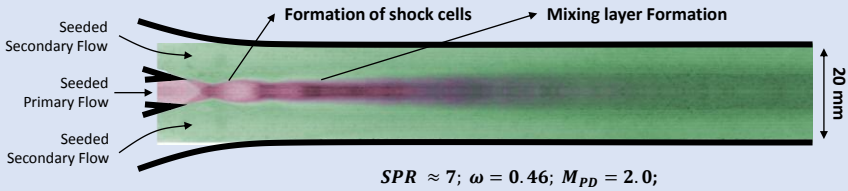
Schlieren images of the blunt body in Mach 8 flow.

shadow of the model with the information of the hypersonic flow over the model is recorded by high speed camera capable of taking 500,000 frames per second. The light rays bent by the high density regions in the test section are cut off using a knife edge at the focal point of the focusing mirror. Thus the

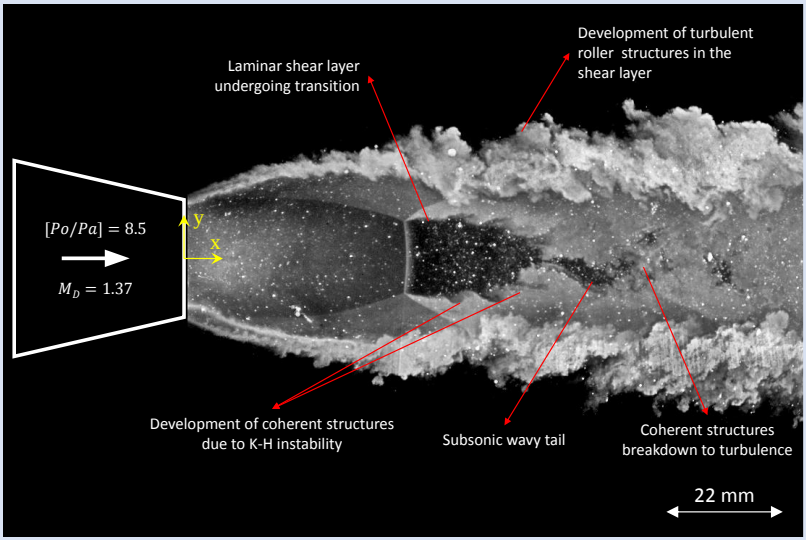
recorded images will show all the waves around the test model generated during the hypersonic flow in the test section. It is possible to record the flow starting, establishment and ending process as well as the model movement as a movie using this technique. The shock stand-off distance can be easily measured from the recorded Schlieren images.

LASER SCATTERING FLOW VISUALIZATIONS

Scattering of Laser light by particles seeded in the flow is used to capture the flow features. A Spectra Physics Nd-YAG laser Quanta-Ray, giving three wavelengths 1064nm, 532nm and 266nm, having a pulse rate of 10Hz and a pulse width of 7ns is used as the laser source. The 532 nm wavelength laser beam of 10mm diameter is rendered into a sheet using suitable cylindrical lens and optics. The sheet cuts through the mid-plane of the flow and the scattered light



Typical time-averaged laser scattering image captured in the supersonic ejector facility.



Typical instantaneous laser scattering image of an under-expanded axisymmetric free jet.

is collected using the Phantom Camera, as shown in the below figure. The laser scattering visualization has been used to study the mixing phenomena in the supersonic ejector/free jet facility. The primary flow has been seeded with acetone vapours that condense during expansion through the nozzle into tiny droplets. These droplets scatter the laser light. The figure below shows a crisp image of the flow in the supersonic ejector/free jet.

ELECTRICAL DISCHARGE SYSTEM FOR FLOW VISUALIZATION

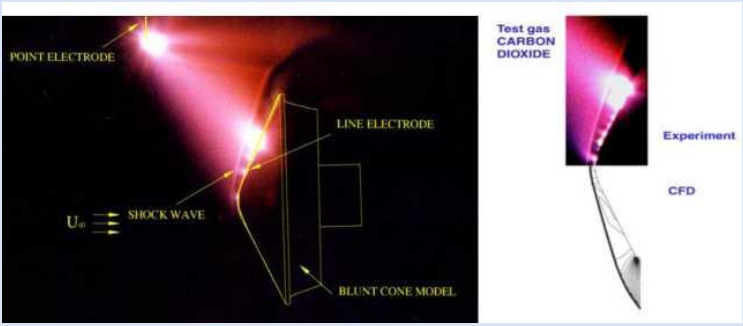
Visualizing the flow fields in the hypersonic shock tunnel is a challenging task since the flow duration is very short and the density levels are very low. However, flow visualization is essential for better understanding of the hypersonic flow around the models and the recorded wave structures will be useful for validating the computational fluid dynamics codes.

We developed a novel electrical discharge based flow visualization technique for visualizing the flow structure in hypersonic shock tunnel. The technique involves striking a discharge between a point electrode suspended from the top of the test section and a line electrode mounted flush with the external surface of the test model for 3-5 microseconds during the steady hypersonic flow in the test section. Since the intensity of spontaneous light emitted by the gas molecules in the discharge region is a function of the local gas density, the density gradients around the model due to the presence of a shock wave can be seen as the change in the intensity distribution. Thus if the light emitted by the discharge is recorded on a film, the shock wave can be seen as discontinuity. Because of the short duration and low intensity we have photographed the light using a 6400ASA speed film in a Nikon camera in B exposure mode. This technique is very inexpensive and has been successfully used to visualize the shock shapes around many test models at different flow Mach numbers. Some of the shock shapes visualized using this technique for different configurations are shown in below figure along with comparison with the predicted shock shape using CFD code.

DIAGNOSTICS FOR HIGH TEMPERATURE CHEMICAL KINETICS

We have a range of diagnostic facilities for studying the kinetics of chemical reaction at high temperatures using shock tubes. Gas chromatography (GC) with mass detector and GC with flame ionizing detector can be used to analyze

and quantify the equilibrated compounds after the chemical reactions. A new Gas chromatography (GC) whose method is based on capillary flow technology (CFT) Dean-switching (heart-cutting) has also been procured. The dean-switching feature allows for an extended hydrocarbon analyses enabling separation of the light hydrocarbon fractions as well as heavy hydrocarbon fractions with good resolution. Time resolved Fourier Transform Infrared Spectrometer and Mass spectrometer are used to identify the products presents in the mixture of equilibrated gas after reactant is subjected to reflected shock wave. The dynamic reaction process behind the shock wave can be monitored using online techniques such as Laser Schlieren System and Atomic Resonance Absorption. The schematic of the Laser Schlieren which has been developed in-house is shown below. A vacuum-UV monochromator has been procured to carry out ARAS studied and this facility is currently being set-up.



Electrical discharge flow visualization for the blunt cone model (left) and Comparison with the CFD results (right)

Gas Chromatography with flame ionization detector

Fourier transformed infra-red spectrometer

Gas Chromatography with mass spectrometer

Gas Chromatography with CFT-Dean Switch

COMPUTER HARDWARE AND SOFTWARE

We have four workstation class systems and the details are given below:

- Flink: Master node: 1 X Intel E5-2450 (2.1 GHz, 8 core) RAM: 16 GB
  Computer node (8 nos.): 2 X Intel E5-2650 v2
  (2.6 GHz, 8 core) RAM: 128 GB
- Blitz: Processors: 2 x Intel X5690 (3.46 GHz, 6 core) RAM: 48 GB
- Zephyr: Processors: 2 x Intel X5690 (3.46 GHz, 6 core) RAM: 40 GB
- Stark: Processors: 2 x Intel E5-2680v3 (2.5 GHz, 10 core) RAM: 96 GB

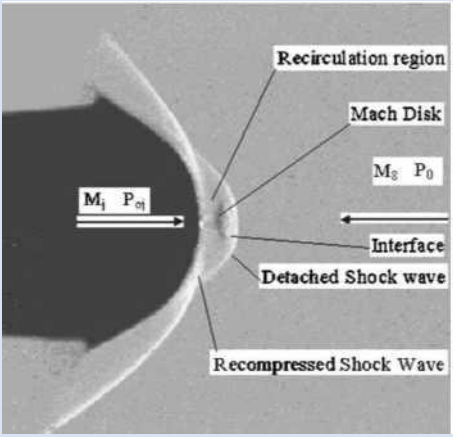
We have licensed version of the following softwares: ANSYS Fluent 13.0, ANSYS CFX, ICEMCFD, Autodyn, LS-DYNA, Abaqus, Tecplot, CATIA, CHEMKIN, GUASSIAN-09.

Research activities

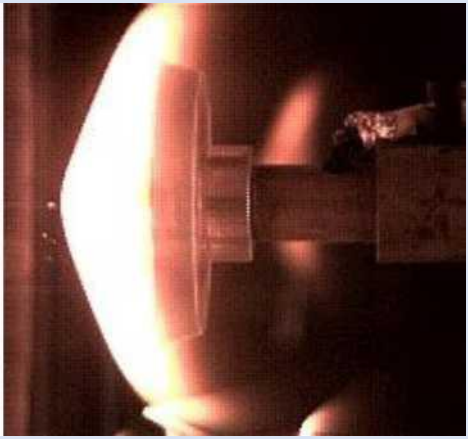
The Laboratory for Hypersonic and Shock Wave Research (LHSR) was started with the primary goal of carrying out research in the field of hypersonics that helps the ongoing aerospace activities in the country. Because of the complex interdisciplinary nature of the field of hypersonics it was decided to initiate research work in all the allied areas of specialization with the help of collaboration with various experts both inside the campus as well as outside institutions in India and abroad. The additional areas of specialization included physics of shock wave phenomenon, application of shock waves in biology, agriculture, wood and oil industries, High Temperature Chemical Kinetics and advanced materials research. Major contributions made in these fields are described briefly in the following sections:

HYPERSONICS

Hypersonic research provides useful aerodynamic data by measuring aerodynamic forces and surface heat transfer rates on various model configurations in hypersonic flight flow regimes, simulated in Hypersonic Shock Tunnels, for better aerodynamic design. Various drag reduction techniques such as forward facing aerospike, counter-flowing supersonic jet, energy deposition, multi-step aft-body, and counter-flowing plasma jet for re-entry and missile-shaped models have been investigated and published.

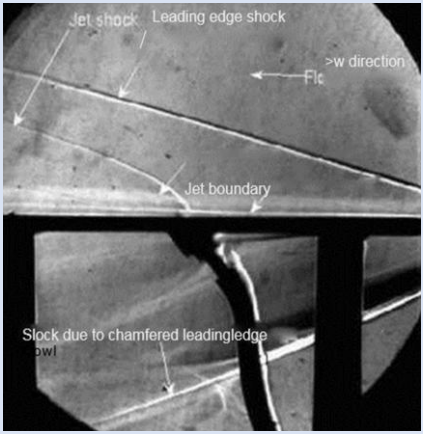


Schlieren image of the hypersonic wave drag reduction using counter



High enthalpy flow over blunt-cone model in Free-piston shock tunnel

Similarly reduction in heat-transfer rates to the models such as film cooling have also been investigated and published. Besides, different fundamental aspects of hypersonic flow are also studied on simple as well as complex geometries that enhance our understanding for better application to real problems. Some of these are hypersonic boundary layer, shock-boundary layer interaction, gas injection at supersonic speeds, radiating shock layer and high temperature real gas effects.



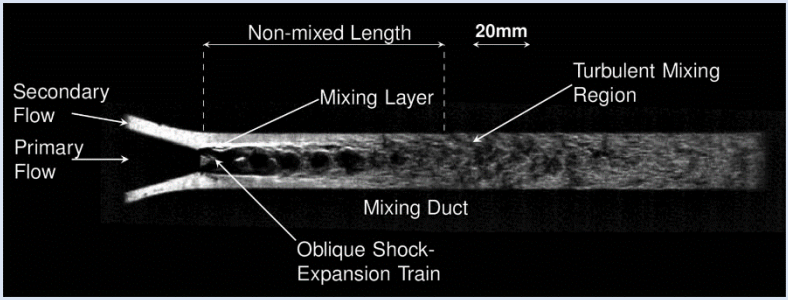
Schlieren images of the flow fields of the oblique injection at supersonic speed in supersonic flow

Schlieren images showing the shock-shock interactions in a multi-body configuration

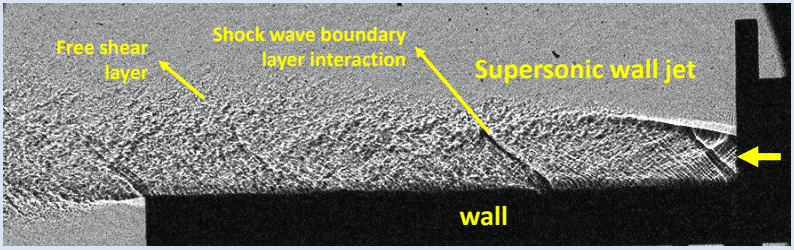
SHOCK WAVES

Shock waves research provides better insight in understanding the shock wave phenomenon that enhances our understanding of the fundamentals of shock wave physics. One primary aspect of research in this field is supersonic jets. Currently studies on supersonic ejector - an enclosed ducting involving a supersonic jet and a co-flow, wall jets - a supersonic jet having a wall on one side and open to ambient on the other are being carried out. The facility can also be used for study of open supersonic jets, and with appropriate additions can be converted to a small scale blow-down supersonic wind tunnel. Some of the research problems studied in the facility are - measurement and Schlieren flow visualization of the operation of a supersonic ejector, wall pressure measurement, surface flow patterns and Schlieren flow visualizations of a Mach 1.6 wall jet with and without boundary layer perturbing devices. The flow through a supersonic ejector, showing the supersonic jet entraining a co flow, the shock

structure within the supersonic jet (Mach 2.5) and the shear layers are clearly demarcated and the eventual mixed turbulent flow is shown below. Also shown below is the Schlieren of a wall jet (Mach 1.6) showing the interactions of the shock and expansions with a wall at the bottom and a free shear layer at the top. Laser Schlieren System and Atomic Resonance Absorption. The schematic of the Laser Schlieren which has been developed in-house is shown below. A vacuum-UV monochromator has been procured to carry out ARAS studied and this facility is currently being set-up.



Schlieren of the flow through the ejector

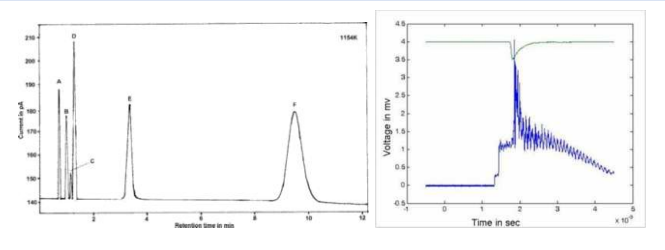


Schlieren photograph of the supersonic wall jet

CHEMICAL KINETICS

Uni-molecular dissociation rates for molecules of atmospheric interest such as 2-Fluoroethanol, Propargyl alcohol and 2-choloroethanol have been carried out using single pulse shock tubes CST1 and CST2. The typical pressure signal for single pulse operation is as shown in the below figure. The post-shock mixtures were analysed using gas chromatography quantifying its concentration. One of the post-shock chromatograms of 2-Fluoroethanol is shown below. The variation of ignition delay with temperature for JP-10 and carene has been studied using CST2. The typical pressure signal indicating ignition delay is

shown below. Currently, similar studies are carried on different molecules which help in understanding combustion processes and formation of inter-stellar molecules.

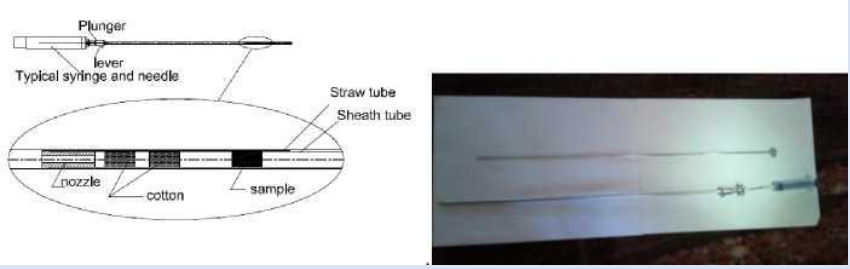


(Left) Gas chromatogram of a post shock mixture of 2-fluoroethanol in argon heated to 1154 K obtained on a 2-m Porapak Q column using FID. (Right) Typical ignition delay signal

BIOLOGICAL EFFECTS AND APPLICATIONS OF SHOCK WAVES

One of the important aspects of our shock wave research is the development of small size devises for producing shock waves of different strengths suitable for biological and other applications. The devises include the Nonel tube capable of producing Mach 2 shock waves, Manually operated piston driven shock tube named as Reddy Tube capable of producing up to Mach 2 shock waves inside medical syringe needles of mm diameter, modified Reddy Tube for chemical kinetics studies, Micro size Reddy Tube driven light gas gun capable of firing a 4mm diameter bullet at 100 m/s speed by hand operation and more than 450 m/s speed by operating using high pressure gas.

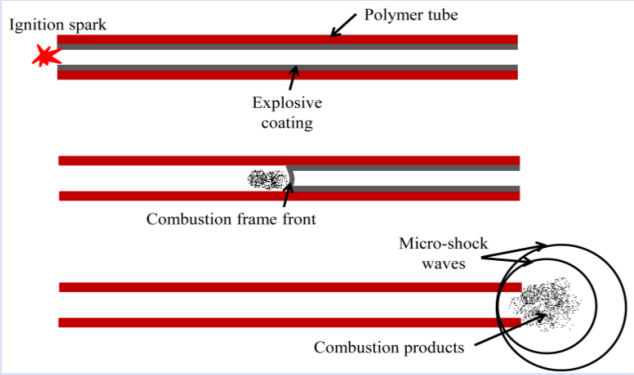
Modified Nonel tube for needleless drug delivery



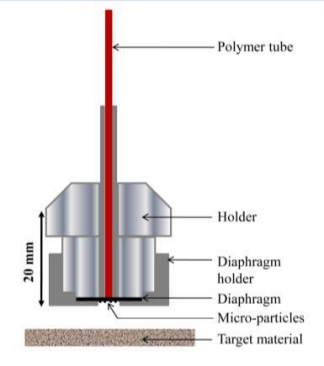
Schematic (left) and photograph (right) of Reddy tube used for artificial insemination

SuperBull, shown in the above figure, is a modified Artificial Insemination Gun where the steel rod used to inject the semen into the uterus of cattle is replaced by a hand operated shock tube called Reddy Tube. The shock wave produced by the Reddy tube injects the semen from the straw tube as a fast jet which makes it to penetrate deeper into the uterus which enhances the probability of conception.

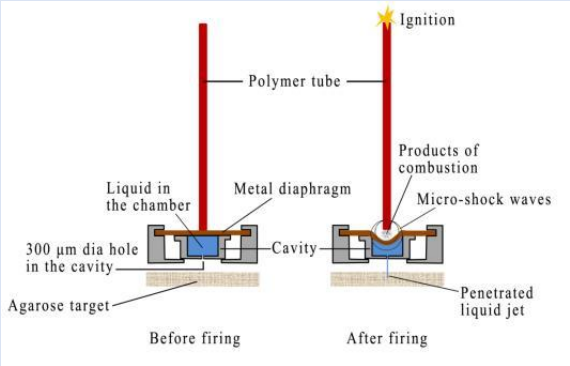
We have developed a novel device to generate controlled micro-shock waves using an explosive-coated polymer tube. Needleless vaccine delivery system that uses the micro-shock waves was developed. The system involves a cleverly designed device that uses a micro-explosion to generate the shock waves that fire the drug through into the subject. We have shown that vaccination using our device to mice against Salmonella obtained superior protection with 1/10 the normal dose of vaccine.



Generation of micro-shock waves in laboratory

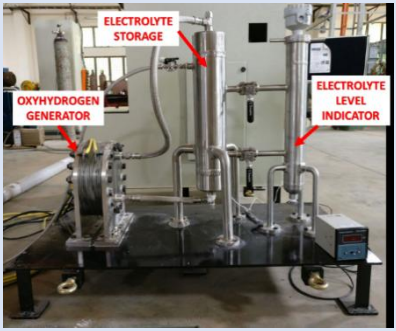


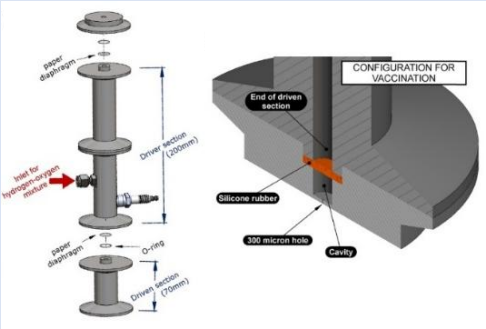
Needle-free vaccine delivery system



Dry particle delivery system

We also harnessed these controlled micro-shock waves to develop a unique bacterial transformation method. The conditions were optimized for the maximum transformation efficiency in *Escherichia coli*. The highest transformation efficiency achieved (1 x 10^5 transformants/cell) was at least 10 times greater than the previously reported ultrasound-mediated transformation (1x10^6 transformants/cell). This method was also successfully employed for the efficient and reproducible transformation of *Pseudomonas aeruginosa* and *Salmonella* Typhimurium. This novel method of transformation was shown to be as efficient as electroporation with the added advantage of better recovery of cells, reduced cost and growth phase independent transformation.





Experimental setup to generate oxyhydrogen mixture in-situ (top left); Miniature shock tube setup with internal diameter of 6mm for needleless drug delivery (top right); Blast wave evolution from the open end of miniature shock tube assembly (bottom left)

Needle-free, painless and localized drug delivery is a coveted technology in the area of biotechnological research. Here, we present a new method for delivering drugs using shockwaves generated by a miniature oxyhydrogen detonation-driven shock tube. An oxyhydrogen generator that is connected to the shock tube produces oxyhydrogen mixture using alkaline electrolysis. The desired drug is placed in a cavity at the end of the shock tube and isolated from the shock tube by means of a biocompatible silicone rubber membrane. This 3mm thick membrane also performs the function of effective energy transfer

from the shockwave to the drug. Upon shockwave loading, the drug in the cavity is ejected at high speeds enough to penetrate skin tissues. A fill pressure of 2.5 bar of oxyhydrogen mixture is sufficient to obtain liquid jets of about 100m/s and penetration depth of about 120µm in polyacrylamide targets. This configuration is ideal for needle-free and painless vaccination. Higher fill pressures of oxyhydrogen mixture have resulted in achieving greater penetration depths. This method has a great potential to overcome issues of existing techniques for needle-free drug delivery.

Biological effect of shock waves on infection studies are also being carried out. Human beings are constantly exposed to blast waves and more so the army personnel in the battle front. The immune status of the individual after successive exposure to shock wave is not known. From previous reports it is known that the immune system is also altered when mice were exposed to extracorporeal shock waves. But the role of shock waves on infection is not understood completely. In our current research mice were exposed to shock waves and infected with Salmonella to understand the role of shock waves on infection.

Spin-offs from LHSR

CENTRE OF EXCELLENCE IN HYPERSONICS

BrahMos Aerospace, a Joint Venture company between India and Russia and the producer of world class BRAHMOS supersonic cruise missiles, had signed a Memorandum of Understanding with IISc in to establish a Centre of Excellence in Hypersonics with the mission to promote development of world class systems and technology, which is a significant step towards national development.

SOCIETY FOR SHOCK WAVE RESEARCH (SSWR)

The Society for Shock Wave Research (SSWR) located at the Department of Aerospace Engineering, Indian Institute of Science, Bangalore was the first registered society in the area of shock waves in the world. Following the successful growth of the SSWR many such societies have been registered in different countries and subsequently an International Shock Wave Institute (ISWI) was established at Tohoku University in Sendai, Japan with Prof. K. Takayama as the Founder President (http://iswi.nuae.nagoya-u.ac.jp/). Prof. K. P. J. Reddy was elected as the President of ISWI at the recently held 28th International Symposium on Shock Waves at the University of Manchester, UK. The ISWI essentially acts as an umbrella organization and all the shock wave societies are affiliated to this Institute.

SUPER-WAVE TECHNOLOGY PRIVATE LIMITED (SWTPL)

Super-Wave Technology Private Limited (SWTPL) is an Indian Institute of Science initiative, promoted and managed by its Directors Prof. K. P. J. Reddy and Prof. G. Jagadeesh, both professors of Department of Aerospace Engineering, Indian Institute of Science (IISc), Bengaluru, India. The company is engaged in research in the area of shockwaves and its applications in various fields and has several patents to its credit. The research work of Prof. K P J Reddy and Prof. G. Jagadeesh in the area of shock waves for the past two decades has resulted in many inventions which have high commercial, educational and social value in the country. Some of these inventions which have evolved as marketable

products include Needleless drug delivery system, Shock wave assisted bamboo treatment plant, Hand operated shock tube for university education (Reddy tube), Reddy tube driven table-top hypersonic shock tunnel and Artificial insemination gun for animals (SuperBull). These inventions have been protected under patents. In addition to high commercial potential these inventions will contribute significantly to the improvement of quality of life and education in the country as well as abroad.

Memorandum of Understanding signed between ONGC and M/s Super Wave Technology Pvt Ltd, in the presence of the Honorable Prime Minister Narendra Modi.

Patents

1. Yan C, Reddy K.P.J, Jain R.K, and McInerney, J.G, "Regenerative optical pulse generator," U.S. Patent No. 5,390,202.
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This plant is the sapling of the Peepul Tree (Ficus religiosa, Family: Moracea) under which Prince Siddhartha Gautama attained enlightenment and became Bhagawan Buddha about 2500 years ago at Bodha Gaya.

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