INVITED PAPER

DESIGN AND DEVELOPMENT OF A NEW 0.5m HYPERSONIC WIND TUNNEL FACILITY AT INDIAN INSTITUTE OF SCIENCE

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Abstract

This paper describes the realization of a 0.5m hypersonic wind tunnel, second largest of its kind in India, at the High Speed Wind Tunnel Complex at Indian Institute of Science (IISc), Bangalore. The project was fully funded by the Aerodynamics Panel of AR & DB. There were two major activities associated with the project. One of them pertains to the ***"Strengthening of the existing 0.3m Hypersonic Wind Tunnel*** *"(originally built in 1985) by adding a new high pressure air compressor, a cascade of high pressure air storage tanks, vacuum pumps and vacuum tanks and another related to establishing* ***"an Additional 0.5m Hypersonic Wind Tunnel Leg"****. Preliminary commissioning trials of the new facility at low stagnation pressures were conducted in October 2013. Subsequently several hypersonic blow downs were carried out on a variety of models at Mach 8.0. Pitot probe measurements performed in the test section confirmed that the flow Mach number was close to Mach 8.0. The total run time measured was around 10 seconds. Thus, a large 0.5m hypersonic wind tunnel was indigenously designed, developed and commissioned in about 30 months at a cost of Rs.6 Crores. The facility was inaugurated by Prof. R. Narasimha in the presence of a large gathering of leading aerospace scientists in the country, on 8^{th} April 2014.*

Introduction

The high speed wind tunnel complex has evolved over seven decades, starting in the year 1942, when the department of aeronautical engineering was established. During the 1950's, a high speed aerodynamics laboratory, first of its kind in India was set up in the department. Several open-circuit and closed-circuit wind tunnels working in the Mach number range of 1.15 to 4 were set up under the leadership of Prof. S. Dhawan [1]. The major open-circuit supersonic tunnels had test section sizes of 2" x 1", 3" x 1" and 5" x 7" while the closed circuit tunnel had a test section size of 4" x 1". All these facilities were using a common high pressure air storage vessel (35m^3) pressurized to 300psi using a multi-stage, water-cooled reciprocating air compressor and a de-humidifier. These facilities were effectively used by over two generations of doctoral and masters students at the department of aerospace engineering. Out of all the supersonic wind tunnel facilities built those days, only the 5" x 7" facility is still functional and presently used with color Schlieren, ESP scanners and miniature strain gauge balances. The facility is currently working on the "Induction" mode with a run time of about 60 seconds. This is the first and the only supersonic wind tunnel in India working on the induction mode.

In the mid-seventies, work on a pilot hypersonic wind tunnel of size 200 mm diameter was started by Prof. R. Narasimha [2] with funding from AR & DB. The facility became functional in 1985 and has been continuously generating hypersonic aerodynamic design data for several national programs. So far, a total of about 80 aerodynamic research and testing projects have been completed with close to 30,000 blow downs being conducted in the facility. In the early 90's, the tunnel was upgraded to 300 mm dia, enclosed free-jet facility. The major equipment in the facility included a pair of Norwalk (USA), 5 stage, water-cooled, 140bar reciprocating air compressors and a set of two multi-layered air storage vessels with a total volume of 20m^3. There was also a high pressure (70bar), high temperature (800K) pebble bed heat exchanger built by ISGEC Thomson, Yamunanagar, Haryana. Four large cylindrical vacuum tanks (~ 100m^3) with associated Rotary vane pumps were part of the wind tunnel.

Recently in 2011, AR & DB funded a major program to augment [3] the above facility with additional compressors, high pressure air storage vessels and new vacuum systems. Development of a 0.5m hypersonic wind tunnel leg was part of this program. This large facility was built with a clear mandate to carry out novel research programs in the area of hypersonic aerodynamics. This program saw the addition of a new 75bar, 850 K pebble bed heater and a 1MW LPG based auxiliary heating system. All these wind tunnels are now conveniently housed in a large 40m x 35m industrial shed with adequate space for control room and instrumentation. The complete view of the facility is shown in Fig.1. A close up view of the test section, nozzle and diffuser are shown in Fig.2.

High Pressure Systems

Compressors

The high speed wind tunnel complex is equipped with three large high pressure compressors. Two of them were manufactured by Norwalk (USA make) in 1970's. They are both reciprocating type, 5-stage, water-cooled, powered by a 3 phase, 415 V, 125 HP AC motor drive operating at 720 RPM. Each one of the 5 stages has thermal and pressure switches with pressure relief valves at the outlet of each stage giving full safety to the operating personnel in the laboratory. The suction capacity of each compressor is around 450Nm^3/hr. At the end of 5th stage, air is discharged at 140 bar into a pair of Lambda make silica gel driers to give moisture free dry air (at a dew point of 228 K or better). Fig.3 shows a view of Norwalk compressors.

In 2013, the laboratory acquired a large compressor which serves to replace the ageing Norwalk compressors. While this new compressor system retains all the mechanical safety systems of the previous generation compressors, there are many additional features. The new Burckhardt compressor runs on a 5-stage air-cooled system, driven by a 132 KW, 3-phase electrical motor. Complete assembly is mounted inside an acoustic canopy giving a noise-free system (less than 75 dB at a distance of 1m from the compressor) as shown in Fig.4. While the suction capacity and discharge pressures are identical to Norwalk compressors, Burckhardt compressor is equipped with micro-controllers and has state of the art twin tower silica gel driers with a dew point of 180 K or better. Additionally, this compressor has a variable frequency drive which limits the starting current to less than 250 Amps which substantially brings down the connected load and power consumption related expenses.

Pressure Vessels

The complex has two large (1m dia and 12m long) multi-layered pressure vessels built in the late 1970's. These were the first such vessels built in India for 140 bar pressure and the technology for the same was provided by M/s. Nooker of USA. These vessels are periodically tested at a hydraulic pressure of 210 bars. This technology assures a very high standard of safety that in case of a material failure; the vessels do not explode, but allows release of the high pressure air through several small holes leading to an extremely safe working condition for the personnel in and around the laboratory. Recently, a cascade of 40 cylinders, each having a volume of 250 liters, was added to the complex which gives a total volume of about 35m^3 of 140 bar dry air storage. Also, the outlet pipes are so designed to release up to about 60 Kg/sec of high pressure air into the several wind tunnels placed in the laboratory. These vessels are also provided with adequate safety relief valves in the circuit. Fig.5 shows the bird's eye view of the high pressure vessels.

Vacuum Systems

Vacuum Tanks

The wind tunnel complex requires a large vacuum volume to provide for large pressure ratios that are required for running high Mach number flows. At about Mach 4.0, pressure ratio needed to run the wind tunnel is about 10, allowing the air to be discharged in to the atmosphere. However, as one approaches a Mach number of 10.0, this ratio increases to several hundred [4] , leading to the necessity of having very low pressures on the discharge side of the hypersonic wind tunnel circuit. Conventionally, one could run large ejectors to obtain this pressure ratio or one goes for large vacuum volumes to obtain the needed test durations at high Mach numbers in such facilities. At the IISc complex, there are several vacuum tanks built over the last 30 years giving a total volume of close to 300 m^3. Essentially, there are about 12 cylindrical tanks with each one of them having a diameter of 2m and height of about 7 to 8 m. Many of the tanks built in the last decade have a cylindrical wall thickness of 6mm while the one procured 3 decades ago had a thickness of 20mm. Thus, the usage of steel in the recently procured vessels has been reduced by a factor of 3 to 4, thereby reducing the overall weight and cost of vacuum tanks. These tanks are generally evacuated to a vacuum level of a few mm of Hg though they are designed for zero pressure inside. A general view of these vacuum tanks is shown in Fig.6.

Vacuum Pumps

The vacuum tanks in the complex are evacuated using several combination vacuum pumps. Currently, there are two sets of vacuum pumps consisting of two rotary vane and two Roots pumping systems. These pumps are manufactured by "Varian" of Italy and they are capable of evacuating the vacuum tanks to a level of milli-bars. There is also a pair of older vacuum pumps supplied by Hind Hi Vacuum Systems of Bangalore consisting of a pair of rotary piston and Roots pumps. All the eight pumps are powered by 7.5 to 10 HP, 3-phase electrical motors. It takes about 90 minutes to completely evacuate the 300 m^3 volume to a few mm of Hg. All these pumps have control panels situated very close to the pumps. Fig.7 presents a photograph of the "Varian" brand pumps.

Thermal Management Systems

Heat Exchanger

High speed wind tunnels that operate above Mach 4.0 need additional heating systems to avoid liquefaction of air as it expands to high Mach numbers in the divergent section of the nozzles. The operating temperatures in these heating systems increase with flow Mach numbers. Typically, Mach 12 simulation in a blow down wind tunnel requires stagnation temperatures of about 1500 K. There are two major types of heat exchangers used in such wind tunnels depending on how the heat exchange takes place. One of them is "core brick" technology while the other system uses "pebble bed" technology. Both core brick and the pebbles are made of refractory materials and chosen, based on the operating temperatures of the flow medium. Fig.8 gives a view of the pebble bed heater used for the 0.5 M hypersonic wind tunnel along with the trolley support system. The heat exchanger is filled with high alumina spheres of mean diameter of 27 mm and weighs over 6 tonnes. The heat addition could be done through electrical means or using combustion of fuels like "LPG".

Auxiliary Heating System

Figure 9 shows a view of the 1.0 MW LPG based auxiliary heating system. There are two high velocity burners rated at 500 KW each. There are also two pilot burners in the system. The burner management system uses Honeywell electronics like flame detectors, ignition controllers for pilot flame and pressure controller for LPG. Additionally, there are safety systems like flash back arrestors. The construction of LPG storage room and burner room are done as given in relevant Indian Standards. The combustion chamber operates at less than ambient pressures and this is achieved with a blower based ejector system. There is also an exhaust blower to facilitate the ejection of the combustion products after it passes through the pebble bed heater.

Other Wind Tunnel Systems

Model Incidence System

The models in the hypersonic wind tunnel are generally injected into the hypersonic stream after the flow gets started. This is done to ensure that the starting aerodynamic loads on the models are not transferred to the sensitive strain gauge balances placed inside the models. At Indian Institute of Science, electro-servo-hydraulic systems are used for model injection and incidence control. Fig.10 shows the model incidence system housed within the test section. The models are supported by means of a sting or strut depending on the type of tests carried out in the facility. Models are injected into the jet in less than a second using hydraulic actuators. These systems are connected to a 10 turn, 10K potentiometer to obtain feedback. The angle of attack varies from -6° to +24° with angular accuracy of 0.1°. Hydraulic actuators are activated by using a power pack which uses 7.5/10 HP vane pumps providing 12 litres/min oil flow at 70bar.

Plenum Chamber

The settling chamber is usually a cylindrical shell capable of taking the high pressures and high temperatures of the flow media where the flow velocities are also very small. There are wide angle diffusers, thermal mixers and several fine meshes to control and minimize fluctuations in the flow. The settling chamber at IISc is a 12" cylindrical pressure vessel, 2.0 m long, with instrumentation ports capable of taking a high stagnation pressure (140 bar) and temperature (850 K). Fig.11 shows the settling chamber of 0.5 m hypersonic wind tunnel with four instrumentation ports (two for pressures and another two for temperatures).

Nozzle

At high Mach number flows, axi-symmetric nozzles are preferred to two-dimensional nozzles due to the inherent difficulties in the latter. Nozzle is designed using method of characteristics with boundary layer corrections accounting for boundary layer growth [5]. All nozzles are contoured, axi-symmetric and un-cooled and are made using CNC machines. Throat is made of 17-4-Ph material (some form of stainless steel). Currently, Mach 8.0 nozzle has been designed and developed. Two additional nozzles are planned for Mach 6 and 9.5. The length of the nozzle is about 3.4m and is held by a hanging support system. Due to manufacturing and handling difficulty the entire nozzle is divided into 6 parts as shown in Fig.12 and are sealed using appropriate O-rings.

Instrumentation

The facility complex is equipped with calibration equipment such as 6 1/2 digit fluke multimeters, current/voltage calibrators, dead weight testers and vacuum leak detector units. There are several special equipment such as color-video Schlieren imaging systems, Infra-red thermography systems from FLIR and powerful La Vision high speed, time-resolved PIV system (Fig.13) for high speed flows in the complex. The instrumentation systems consist of several high speed digital data acquisition cards/books with over 1 MHz sampling rate with about 64 channels of Analog to Digital, 16 channels of Digital to Analog, 96 channels of Digital input/outputs, counter-timers etc working with GUI software like DASYLAB and LABVIEW modules (Fig.14). The complex has several electronic pressure scanners (Fig.15) in the range of +/- 10" Hg to +/- 100psi, besides several individual pressure transducers in the range of 1.0psi to several hundreds of psi. Highly accurate conventional piezo-resistive and capacitive transducers are available for precision measurement of pressures. There are several conventional strain gauge balances for force and moment measurements, designed and developed at the facility and are shown in Fig.16. For calibration of these balances a single axis portable calibration rig and a multi-component automatic balance calibration rig have been designed, developed and built at IISc.

Automatic Balance Calibration Rig

A fully automatic, low-cost, multi-component balance calibration rig has been set up at the facility complex for obtaining linear and non-linear calibration co-efficients of internal strain gauge balances. These balances are used in the 14’ x 9’ low speed wind tunnel, 300 mm hypersonic wind tunnel and also in newly commissioned 500mm hypersonic wind tunnel of the Institute. The advanced "Automatic Balance Calibration Rig" is capable of applying loads of up to 250 kg, with a unique feature like nullifying the balance deflections under loads by operating a "Motion Control System" and bringing the balance to null position, for each step load. In commercially available rigs, the above said procedure is not done. Instead, the deflections of the balance are measured and correspondingly the applied loads are computed. Thus the measuring accuracies are compromised at low loads, in commercial rigs, as the deflections are very small. The Automatic Balance Calibration Rig at IISc nullifies the balance deflections by operating a series of motors in a sequential way, under each loaded condition. This makes it possible for application of pure loads which is generally not possible in commercial rigs and also increases the overall accuracy of calibration [6]. Fig.17 shows the complete view of the automatic balance calibration rig.

Major R & D Work: Past and Future

The IISc wind tunnel was the only major hypersonic facility in the country during the last 3 decades and has been extensively used for DRDO projects including testing of re-entry vehicles, several missile configurations, HSTDV, HRV, stage separation studies etc., The IISc group has been very active in the area of wind tunnel balance design and development and has also pioneered the work on the use of fiber-optic sensors for fluid flow research [7,8]. The first fiber-optic wind tunnel balance in the world was built at IISc. Also, the facility contributed significantly to academic programs leading to several doctoral and masters degree students performing original research in this field. Pioneering work in the design of miniaturized balances led to outstanding contribution to the understanding of Aerodynamics of Slab delta wings at high Mach numbers [9,10]. More recently, extensive work was carried out on Aerospike Engine research leading to important publications in this area [11,12,13]. The successful addition of the new facility to the wind tunnel complex has created tremendous interest in the user community. This has resulted in a rush of projects from HSTDV, missile programs, BrahMos management and others. The addition of this facility opens new avenues to flow through intake studies at high Mach numbers which was very difficult in the earlier smaller facility. The commercial value of the programs under discussion in financial terms exceeds the cost of this new facility which is very encouraging. Many fundamental programs like the "Hypersonic Transition Research" which requires improving the quality of flow, cutting down the noise levels and thus developing a "Quiet" hypersonic wind tunnel are the focus of attention of the scientific community at IISc.

Conclusion

The new 0.5m hypersonic wind tunnel, the second largest facility in India was successfully designed, developed, assembled and commissioned as planned at High

Speed Wind Tunnel complex at IISc. Preliminary commissioning trials at low stagnation pressures were conducted to gain confidence. Tests at higher stagnation pressures and temperatures are being carried out and the entire Mach number - Reynolds number envelope will be completed in the next 2 months. Fig.18 shows the tunnel operating envelope of the 0.5 m hypersonic wind tunnel facility. Pitot probe measurements carried out in the test section indicated that the flow Mach number was close to Mach 8.0. The total run time measured was around 10 seconds. Fig.19 shows data from a typical wind tunnel blow down. It is seen that the total pressure at the plenum chamber is around 350 psi (~24 kg/cm^2) and the total temperature at the same location is around ~600 K. Electronic Pressure Scanner was connected to the probe which measured the total pressure behind the normal shock (Pt_2) and is shown in Fig.20 (Pt_2 is given here in electrical units). The Schlieren images of flow over a 30° cone and a cone-cylinder model are shown in Figs.21 and 22. Further tests are being done to evaluate the quality of flow in the 0.5m Hypersonic Wind Tunnel.

References

1. Satish Dhawan., "Design and Operation of an Intermittent 1" x 3"Supersonic Wind Tunnel", Journal of the Aeronautical Society of India, Vol.7, pp.1-17, 1955.

2. Roddam Narasimha., "Pilot Hypersonic Wind Tunnel Development at IISc", ARDB/RN/6, Aerodynamics Panel, 1971.

3. Vasudevan, B., "Augmentation of 0.3 m Hypersonic Wind Tunnel at IISc", ARDB/214, Aerodynamics Panel, 2011.

4. Alan Pope and Kennith L. Goin., "High Speed Wind Tunnel Testing", John Wiley and Sons, Inc, 1965.

5. Ying-Nien Yu., "A Summary of Design Techniques for Axisymmetric Hypersonic Wind Tunnels", Agardograph, November 1958.

6. Vasudevan, B., Shivashankar, B. M., Srikanth S. Padabidri and Tirumalai, N. C., "Development of a Low Cost Automatic Balance Calibration Rig" 8th International Symposium on Strain Gauge Balances, May 7-10, 2012, Switzerland.

7. Vasudevan, B., Srikanth S. Padbidri and Chandra Kishore, M., "Flow Diagnostics Using Fiber Optics A Review" 5th International Symposium on Strain-Gauge Balances, May 9-12, 2006, ONERA, France.

8. Vasudevan, B., Sharan, K.C. and Ashwin, K., "A Measurement Tool in Fluid Mechanics", Symposium on Advances in Fluid Mechanics, 2003, pp.76-85, February, 1998.

9. Ramesh. R., Ramaswamy, M. A., Vasudevan, B. and Prabhu, A., "On the Aerodynamic Characteristics of Thin Slab Delta Wings at Hypersonic Speed - Part 1: Interference of Lee-side Bodies", Aeronautical Journal of the Royal Aeronautical Society, November, 2000, 104 (1041), pp.561-567.

10. Ramesh, R, Ramaswamy, M. A., Vasudevan, B. and Prabhu, A.,"On the Aerodynamic Characteristics of Thin Slab Delta Wings at Hypersonic Speed - Part 2: Effect of Wing Geometry", Aeronautical Journal of the Royal Aeronautical Society, December, 2000, pp.597-614.

11. Chutkey, K., Vasudevan, B. and Balakrishnan, N., "Flowfield Analysis of Linear Plug Nozzle", Journal of Spacecrafts and Rockets, Vol.49, No.6, November-December, 2012, pp.1109-1119.

12. Chutkey, K., Vasudevan, B. and Balakrishnan, N., "Axially Symmetric Plug Nozzle Experimental Data", Department of Aerospace Engineering, Indian Institute of Science, CAdLab TN-2012:01, Bangalore, India, June, 2012.

13. Kiran Chutkey., Vasudevan, B. and Balakrishnan, N., Journal of Spacecraft and Rockets Vol. 51, No. 2, March-April 2014 "Analysis of Annular Plug Nozzle Flowfield", Indian Institute of Science, Bangalore, India, pp.478-490.

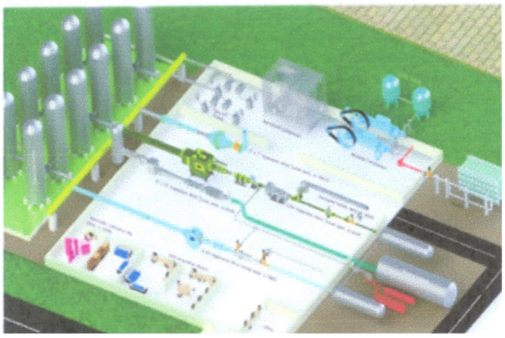

Fig.1 Shows the Pictorial Representation of High Speed Wind Tunnel Complex at IISc, Bangalore

Fig.2 0.5 m Hypersonic Wind Tunnel

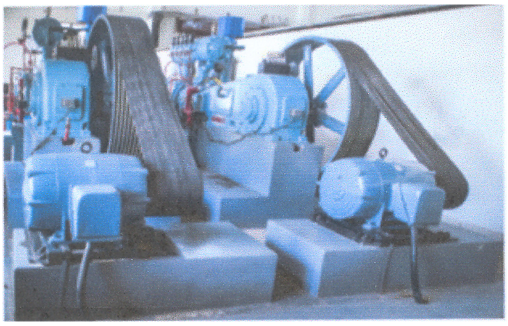

Fig.3 Norwalk Compressors

Fig.4 Burckhardt Compressor with Driers

Fig.5 Cascade Assembly and Multi-layered Pressure Vessels

Fig.6 Vacuum Tanks

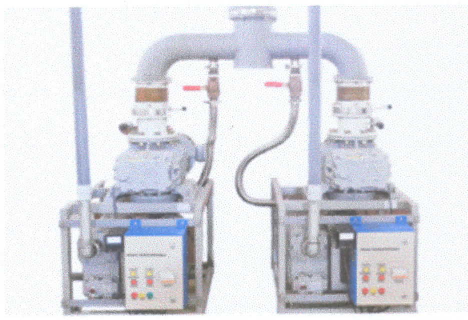

Fig.7 Vacuum Pumps

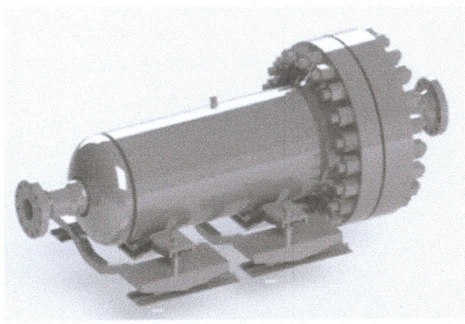

Fig.8 Pebble Bed Heater for 0.5 m HWT

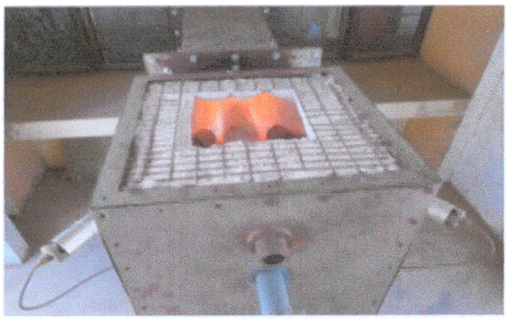

Fig.9 1 MW LPG Based Burner System

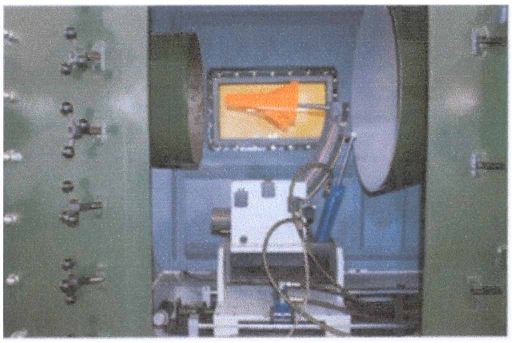

Fig.10 Model Incidence System in 0.5 m HWT

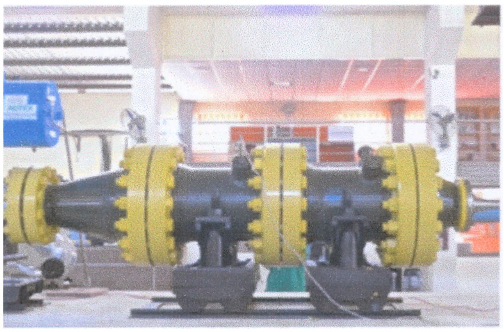

Fig.11 Plenum Chamber for 0.5 m HWT

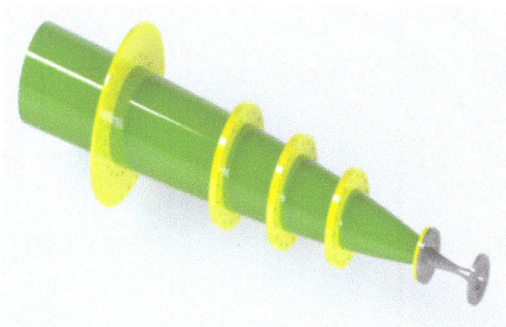

Fig.12 Mach 8.0 Nozzle for 0.5 m HWT

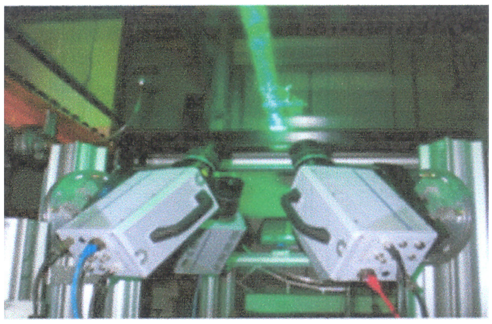

Fig.13 La Vision High Speed PIV System

Fig.14 Data Acquisition Systems

Fig.15 Pressure Scanners and Transducers

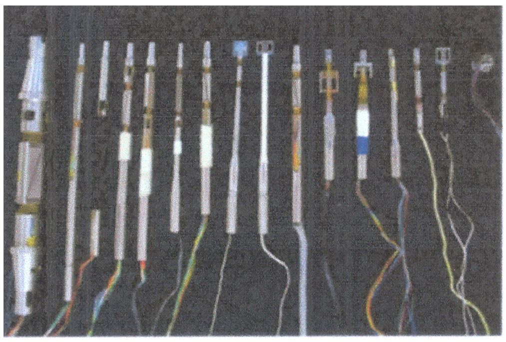

Fig.16 Various Strain Gauge Balances of the Facility Designed and Developed at IISc

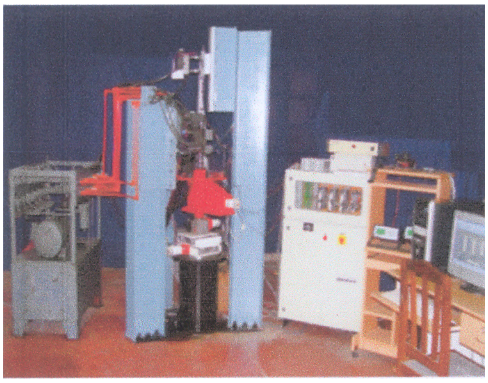

Fig.17 Overall View of the Automatic Balance Calibration Rig

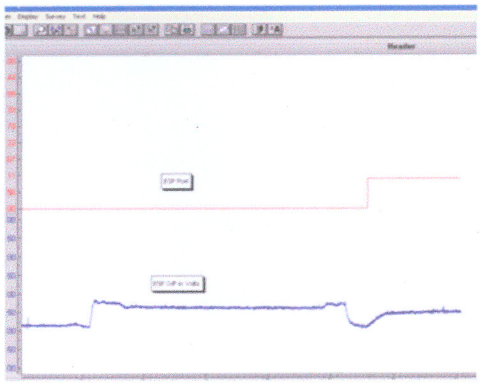

Fig.20 View of ESP O/P (Pt_2) : Run Data

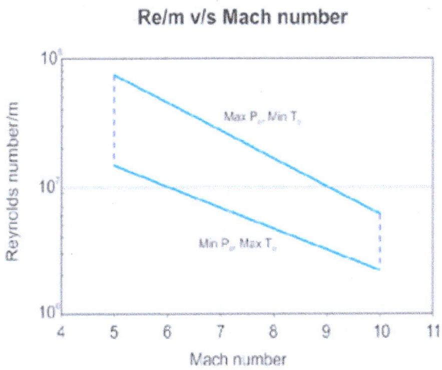

Fig.18 Performance Chart of Hypersonic Wind Tunnel (Mach No. Vs Reynolds No.)

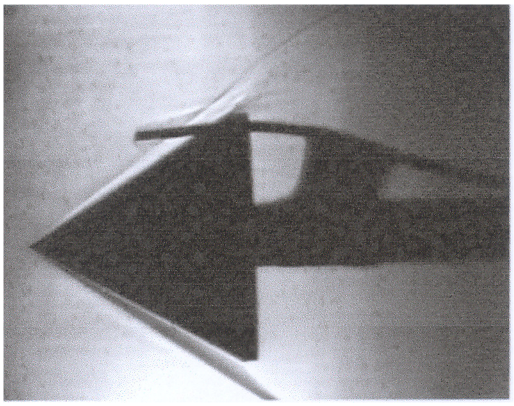

Fig.21 Schlieren Picture of 30 deg Cone with Pitot Probe in Mach 8.0 Flow

Fig.19 View of Po and To Run Data

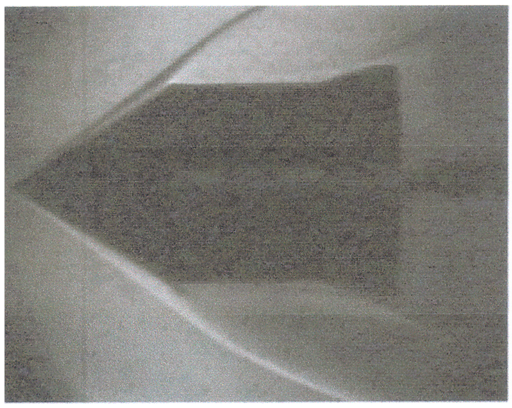

Fig.22 Schlieren Picture of Cone-cylindrical Model in Mach 8.0 Flow