Proceedings of the XVth Bi-Annual Symposium on Measuring Techniques in transonic and Supersonic Flows in Cascades and Turbomachines. 21-22 September 2000, Firenze/Italy

Operation and Preliminary Measurements from a New Transonic Wind Tunnel

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Abstract:

A transonic blow down wind tunnel has been designed and constructed at the University of Limerick. The tunnel operates as a controlled blow down facility to give constant conditions during the time necessary for the acquisition of data from fast response transducers. The facility is to be used for aerodynamic testing of turbine blading with the primary aim at present being entropy measurements in the boundary layer of a two dimensional cascade. At the design point the exit Reynolds and Mach numbers are $0.94*10^6$ *and 0.92 respectively on the present cascade. The tunnel has a running time of 0.4-0.8 seconds, which means that an inexpensive compressor plant is sufficient to supply the facility with compressed air. The pressure is regulated by the use of a digital computer combined with two pneumatically controlled valves and one manual valve. The operation and control of the facility and preliminary measurements from it are presented in this paper.*

Introduction:

The continuing increases in efficiency and power to weight ratio of the already highly developed gas turbine engine is achieved at least partly by reducing the entropy generated in the boundary layers. This reduction has the direct effect of increasing the efficiency of the machine as may be seen from the classical entropy-enthalpy diagrams. The successful prediction of entropy in the boundary layer and indeed in the entire engine requires a detailed knowledge of the flow regime. The primary design tool of industry for the gas turbine is CFD and many commercial and private in house CFD codes rely heavily on empirical correlations, (Denton 1993). A reason for the unsuccessful prediction with these codes is that they are in some cases based on relatively old measurements where the geometry and flow conditions do not represent the problem being analyzed sufficiently well to produce an accurate prediction. In addition, the state of the boundary layer is usually assumed turbulent over the entire blade or vane surface, which is never the case. It is therefore necessary to provide measurements at realistic engine Mach and Reynolds numbers to both verify and help in CFD advancements. Ideally, such measurements would be obtained from a full-scale engine, however this is usually not economically viable and detailed measurement is very difficult under operating engine conditions. Thus simpler more economical methods are used. These methods are primarily cascade testing and rotating facilities, perhaps with only one stage and lower temperatures than during engine operation. This testing requires the design and construction of wind tunnels in which conditions as close as possible to operating conditions may be achieved.

The authors have for several years been operating a medium speed wind tunnel in the incompressible range from which very detailed entropy measurements have been obtained from the boundary layer of a two dimensional cascade, Davies (1998, 2000) and O'Donnell (1999, 2000). It has become apparent that there is a need for a high-speed wind tunnel in which realistic engine Mach and Reynolds numbers can be reached.

The construction of such a facility would also complete the aerodynamic wind tunnel facilities at the university where a low speed wind tunnel <30m/s and a medium speed wind tunnel <110m/s have been present for a number of years. Therefore, the design and construction of a transonic facility, which would complement measurements from the medium speed facility, was undertaken.

Design considerations:

The vast majority of aerodynamic testing in the past being has been carried out in continuous running wind tunnels. These facilities offer the advantage of steady state aerodynamic conditions for long periods of time. This in turn allows the use of low frequency response measuring techniques. However continuous running test facilities encounter both high capital costs and high running costs. The closed loop wind tunnel at DFVLR Braunschweig which has a working section capable of testing 7 passages of 300 mm span and 100mm chord at a maximum exit Mach and Reynolds number of 1.05 and 10^7 respectively uses an axial compressor driven by a 1.3MW electric motor, Hoheisel (1974). The blow-down wind tunnel at oxford which has a working section of equal size to that of DFVLR Braunschweig and maximum Reynolds and Mach numbers of $6*10^7$ and1.45 respectively was estimated to require a 7MW motor if it was to be a continuous running wind tunnel, Baines (1982). It was decided that the design exit Mach and Reynolds numbers for this facility would be 0.92 and $0.49*10^6$ respectively. These design parameters are the same as that of the rotating rig at DLR, Tiedemann (1997) and VKI, Denos (1998) in which the mid span of the rotating blades is geometrically identical to the intended cascade of this facility.

In the past, long measurement periods may have been a necessity as fast response transducers and digital computers were not readily available. However, with the advancements in fast response transducers and the digital computer long measurement periods are no longer a necessity. Therefore, it was decided to design and manufacture a blowdown wind tunnel at the University of Limerick as the capital and running costs would be much lower than a continuous running facility. The most prominent unrealistic feature of such a facility is the gas to wall temperature ratio. For the gas to wall temperature ratio to match that of a gas turbine, external heating would be required in such a facility. This is however not as important in an aerodynamic facility as in a heat transfer facility and the primary use of this facility would be detailed aerodynamic measurements.

Wind tunnel description:

The UL transonic wind tunnel is an open circuit, blow-down wind tunnel that operates from a reservoir of compressed air. The air reservoir has a volume of $4m^3$ and is pressurised by using a combination of a screw compressor, (Kaeser SM11), and two booster compressors, (Kaeser N60-G), the pressurised air enters an after-cooler which removes heat from the air after compression. A desiccant drier dries the air to a dew point of -70^0C. Air filtration is performed at the inlet to the screw compressor and at the inlet to the desiccant drier to remove any dust or oil, this set-up is shown as a schematic in figure 1.

The main features of the facility are labelled in figure 2. These are

1. An air reservoir which is used as the supply for the facility. This reservoir is pressurised to a certain pressure depending on the conditions required in the working section; this process may take up to 3 hours. After a test is completed the reservoir remains partly pressurised and requires approximately 25 minutes before the next test may commence. Thus a test can be performed every 30 minutes. These times vary depending on the operating conditions required.
2. Two pneumatically controlled valves that are used in combination with a digital computer system and a manual valve control the operation of the facility. It is the sequencing of these valves that creates

a steady state period for measurements to be taken.

3. A blow off stack which has a 5 bar bursting disk inserted into it; this is a safety feature on the wind tunnel
4. The settling chamber which consists of an inlet diffuser and 4 sets of wire meshes which are used to remove swirl and turbulence from the flow.
5. The working section which has an area of 0.014448 m^2.
6. Various locations for instrumentation to be inserted for measurement of aerodynamic properties. The flanges in the settling chamber and the inlet and outlet from the cascade are tapped with holes for the measurement of pressure and temperature. There are also facilities for hot wire and hot film anemometry.
7. Diffuser, a throat will be inserted between the exit of the cascade and the diffuser. This will make it possible to vary the Mach and Reynolds numbers independently.

Downstream of the reservoir tank the entire tunnel is manufactured from stainless steel.

Description of cascade

The cascade consists of 8 blades with dimensions as shown in figure 3. The cascade blades are scaled models of the mid-span of a high pressure turbine rotor blade designed by Santoriello et al (1993), now operational in two single stage turbine facilities at VKI, Brussels, Belgium and DLR, Göttingen, Germany. The main parameters of the cascade blade from Santoriello and Colella (1993) are given in table 1.

Pitch/Chord Ratio	0.752
Throat width/Chord	0.301
Pitch/Axial Chord	0.916
Blade inlet flow angle	45.4^0
Blade exit flow angle	117^0

Table 1. Main parameters of cascade blade from Santoriello and Colella (1993)

Fitzgerald et al (1998) and O'Donnell et al (1999) at the University of Limerick have previously studied a scaled cascade in the incompressible range. Further investigations of the blade profile in a turbine stage have been reported by among others, Tiedemann (1997) and Denos et al (1998) in the transonic regime. During design it was attempted to have the cascade Mach and Reynolds numbers similar to that of the DLR rotating facility. However, it was estimated that the required chord length would be in the region of 18mm to achieve a similar Reynolds number. This in turn would have lead to both machining and instrumentation difficulties so it was decided to use a chord length to 35mm.

Data acquisition system and instrumentation

The data acquisition and control system comprises of a 6 channel Entran signal conditioning unit and a DSPACE (*Digital Signal Processing and Control Engineering)* system used in combination with a 200MHz PC. The DSPACE system has a 5-channel data acquisition card (DS2001). Each channel has it's own A/D converter, thus the five channels may sample simultaneously, with up to 16 bit resolution, over the range ± 5 or ± 10 volts at a frequency of 50kHz per channel. A 96-channel TTL card (DS4003) is used to control the pneumatic valves and the stepper motor.

The tunnel is instrumented with Kulite pressure transducers in the settling chamber to measure stagnation pressure and at the inlet and exit of the cascade to measure static pressures as shown in figure 2. Type-T thermocouples and hot-wires running in constant current mode are used to measure temperature. The turbulence intensity at the inlet to the cascade was measured using a hot wire at a constant over-heat temperature of 250^0C. Other measuring techniques including hot film anemometry and PIV are available and will be setup for this facility in the future.

Operation and Control of facility

The control of the wind tunnel to produce a steady state period for data acquisition from fast response transducers was achieved by regulating the valves labeled in figure 2 using the dspace computer system described above. It was required that the computer system control several processes, these processes and the flow of information to and from the computer system may be seen in figure 4. The processes may be grouped and listed as

1. Control of pneumatic valves to regulate the air supply to obtain steady state conditions
2. Control of a stepper motor to allow traverses to be accomplished
3. Data acquisition from the various transducers

The air requirements in the working section result in a substantial drop in air pressure in the reservoir tank, thus steady conditions will not be achieved with the pressure in the reservoir tank continually changing. A pressure regulator was developed to compensate for this and give constant conditions in the settling chamber for enough time to acquire data and perform traverses, the full details of which are given by Mulcaire (1997). It would be difficult to regulate the entire flow due to the large volume of air passing through the system. Thus it was decided to regulate only part of the air supply and this was done in the form of a gate way valve in a by-pass line called the control valve in figure 2. The pneumatic valves opening and closing sequence is controlled by the pressure in the settling chamber. The pressure parameters to control the valves are defined by the user in the dspace program.

Figure 5 shows a timing diagram of all the processes for an entire test. Figure 5a shows the main valve from the reservoir opening at the start of a test using the DS4003 TTL dspace board. The pressure in the settling chamber is monitored using the DS2001 board and begins to rise as shown in figure 5e. When a preset pressure (set point 1 in figure 5e) is reached in the settling chamber the control valve is opened by the DS4003 TTL board as shown in figure 5b. This results in steady state conditions in the settling chamber as shown in figure 5e. At a preset time delay after the pressure in the settling chamber has reached steady state conditions the DS2001 data acquisition card is initiated to acquire data from the transducers and the DS4003 board is initiated for the stepper motor to start a traverse. This is shown in figure 5c with the DS4003 board producing a TTL signal for the stepper motor and in figure 5d with the data acquisition window. After the steady state period the pressure will rise in the settling chamber due to the control valve continuing to open, and at a preset pressure (set point 2 in figure 5e) both valves will close, thus ending the test. During the run the pressure in the reservoir drops by approximately 20%, the reservoir may then be re-pressurized for the next test in approximately 25 minutes. These figures change depending on the operating conditions required in the working section. The Dspace program used to control the facility was a custom designed program, written firstly in Simulink but then changed to C-code to allow higher turnaround times of the program and thus high sampling rates to be achieved.

Results:

The results presented are typical preliminary results from the facility. Figure 6 shows the measurement of pressure at various locations and the valve sequencing for an entire test. The steady state period for data acquisition may be seen in this figure.

The turbulence intensity was measured at the inlet using hot wire anemometry. The hot wire was calibrated in a medium speed facility in steps of 10m/s up to a maximum velocity of 110m/s. This calibration was then extended into the required range. The accuracy of this method was demonstrated by the velocity measurement with the hot wire being within 1.5% of the velocity measured with the pressure transducers. A turbulence intensity of approximately 4.5% was calculated. A spectrum analysis was performed on the hot wire signal and no peaks were seen thus indicating that the measurement was turbulence and not some cyclic event.

Flow visualisation was carried out on the cascade to ensure that the secondary flows will not effect the measurement transducers to be placed at the midspan of the cascade. Figure 7 shows the flow visualisation results after a test at design conditions. It is clear that the secondary flows do not have an effect on the midspan of the blade.

From the flow visualization, a definite change in flow pattern at around 65% under design conditions was seen. It is thought that the sudden change in flow on the surface of the blade may be caused by a shock wave impinging on the suction surface of the blade. Further experimentation is required to verify this assumption.

Future Work

The next part of this work is to make detailed aerodynamic measurements from the cascades boundary layer. Hot wire traverses of the boundary layer will be performed and from these traverses, the entropy in the boundary layer will be computed. Hot film anemometry will be used in conjunction with the hot wire measurements to calibrate the hot films to measure entropy in the boundary layer.

A rotor stator simulator may be designed and constructed for use within this facility to determine the effect of wake interaction on the entropy in the boundary layer. A modern PIV system, which is readily available at the university, will be set up to take measurements from this facility in the future.

Acknowledgements:

The facility was developed with the aid of funding from GPA, whose support is greatly acknowledged.

References:

1. Baines, N.C., Oldfield, M.L.G., Jones, T.V., Schultz, D.L., King, P.I., Daniels, L.C., "A short-duration blowdown tunnel for aerodynamic studies on gas turbine blading", ASME Paper 82-GT-312.
2. Davies, M.R.D., Niven, A.J., O'Donnell, F.K. & Fitzgerald, J.E., "Measuring Entropy Generation in Turbomachinery Applications", presented at the Ariane International Conference on Spacecraft Propulsion, Dublin, Ireland, April, 1998.
3. Davies, M.R.D., O'Donnell, F. K. & Niven, A.J. "Turbine Blade Entropy Generation Rate Part I: The Boundary Layer defined", Presented at the *American Society of Mechanical Engineers Turbo Expo*, Munich 2000. Accepted for publication at ASME Int. Gas Turbine & Aeroengine Congress & Exhibition, Munich, Germany, May 2000.
4. Denos, R., Sieverding, C.H., Arts, T., Brouckaert, J.F., Paniagua, G., Michelassi, V. & Martelli, F., 1998, "Unsteady Investigation Of Rotor Aerodynamics Of A Transonic Turbine Stage" 43rd ASME Gas Turbine and Aeroengine Congress, Stockholm, Sweden.
5. Denton, J.D., 1993, "Loss mechanisms in turbomachines", ASME J. Turbomachinery, Vol.115, pp.621-656.
6. Fitzgerald, J.E., Niven, A.J. & Davies, M.R.D., (1998), "Turbine Blade Aerodynamic Wall Shear Stress Measurements And Predictions", ASME Paper Ref. 98-GT-562
7. Hoheisel, H., "The cascade wind tunnels of the Institut für aerodynamik – Short description", DFVLR Braunschweig, IB 151-74/13, 1974.
8. Mulcaire, T.G., 1997, "The design and manufacture of a transonic blowdown cascade wind tunnel", Masters Thesis, Mech. and Aero. Dept., University of Limerick.
9. O'Donnell, F. K. & Davies, M.R.D., 2000, "Turbine Blade Entropy Generation Rate Part II: The Measured Loss", Accepted for publication at ASME Int. Gas Turbine & Aeroengine Congress
10. O'Donnell, F., "The Measurement of Aerodynamic Entropy Generation in a Turbine Blade Boundary Layer" PhD Thesis, University of Limerick, 2000.
11. O'Donnell, F.K. and Davies, M.R.D., 1999, "Measurements of Turbine Blade Aerodynamic Entropy Generation Rate", 3rd European Conference on Turbomachinery, London, England. Also accepted for publication in the I.Mech.Eng. Journal of Power and Energy
12. Santoriello, G., Colella, A., and Colantuoni, S., 1993, "Investigation Of Aerodynamics And Cooling Of Advanced Engine Turbine Components:- Rotor Blade Aerodynamic Design" Brite/Euram Area 3 Aeronautics Technical Report, AER2-CT92-0044 IACA Package A.
13. Tiedemann, M., 1997, "Stator wake effects on the boundary layer transition on a transonic turbine rotor blade", "Eurotherm Seminar No. 55, Heat transfer in single phase flows 5" Sept 18-19, 1997 in Santorini, Greece.

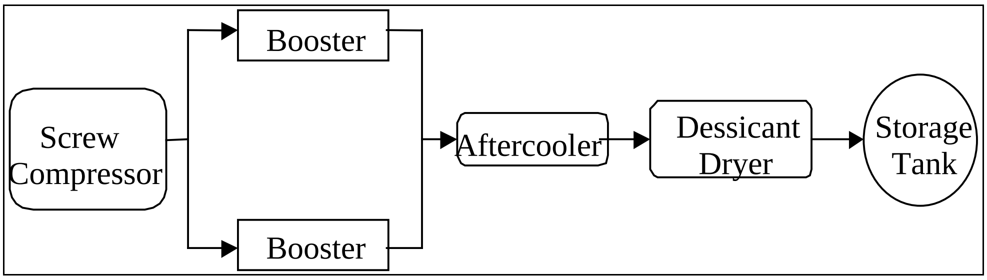

Figure 1: Storage tank compression method

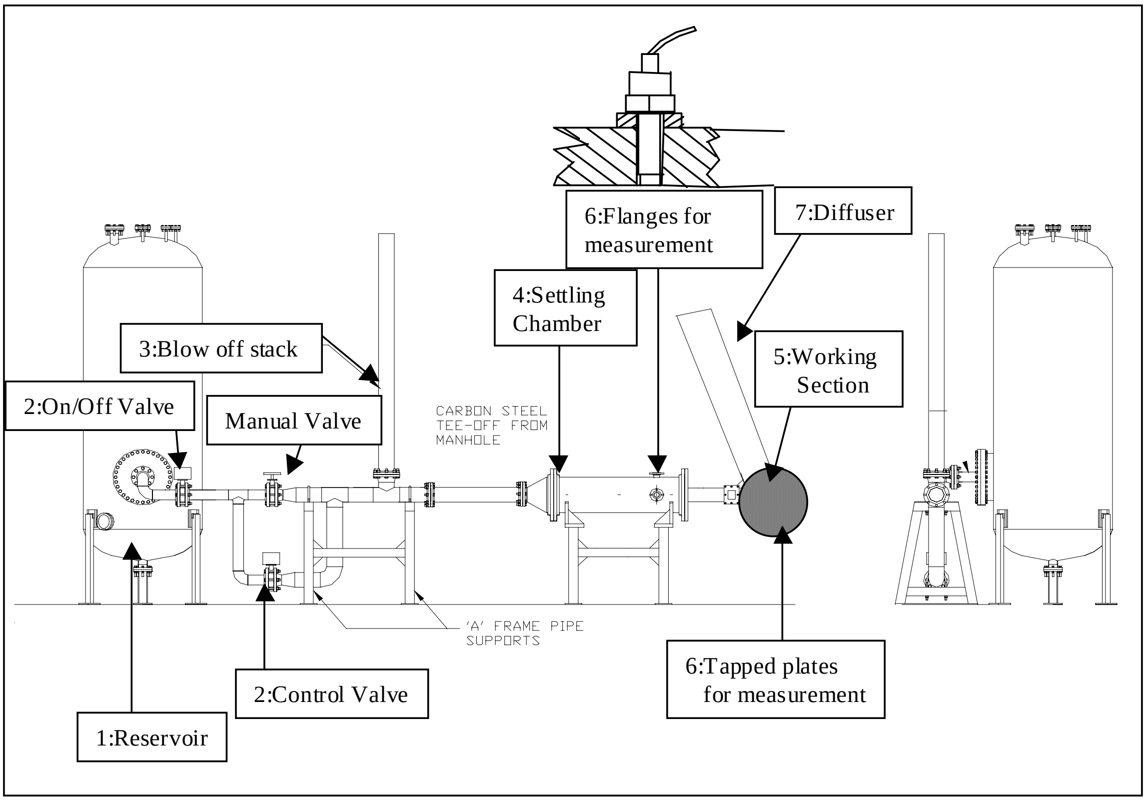

Figure 2: The UL transonic blow-down wind tunnel

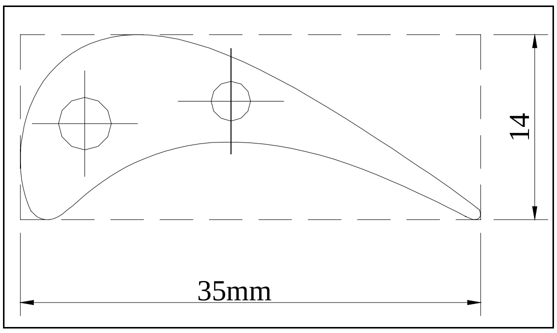

Figure 3: Dimensions of transonic blade in the blow-down wind tunnel

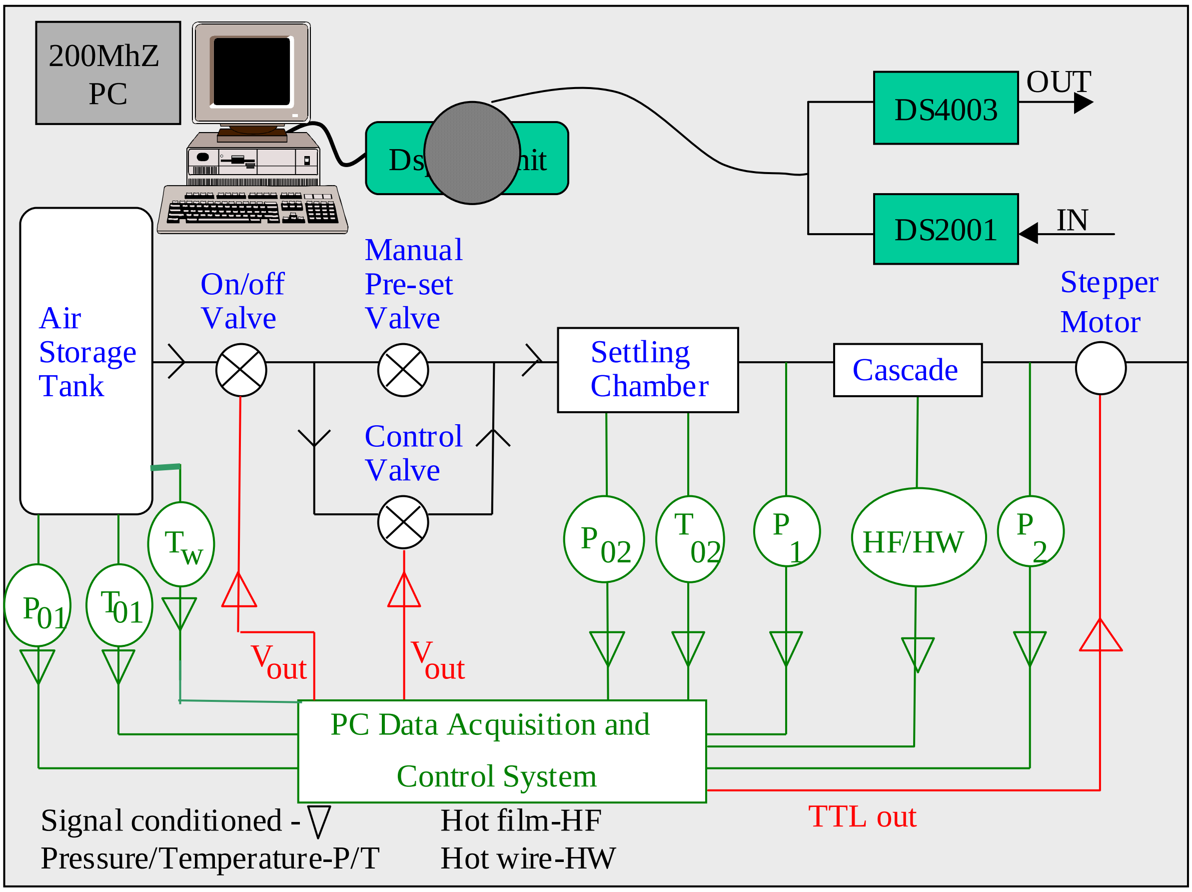

Figure 4:Computer system requirements for the facility

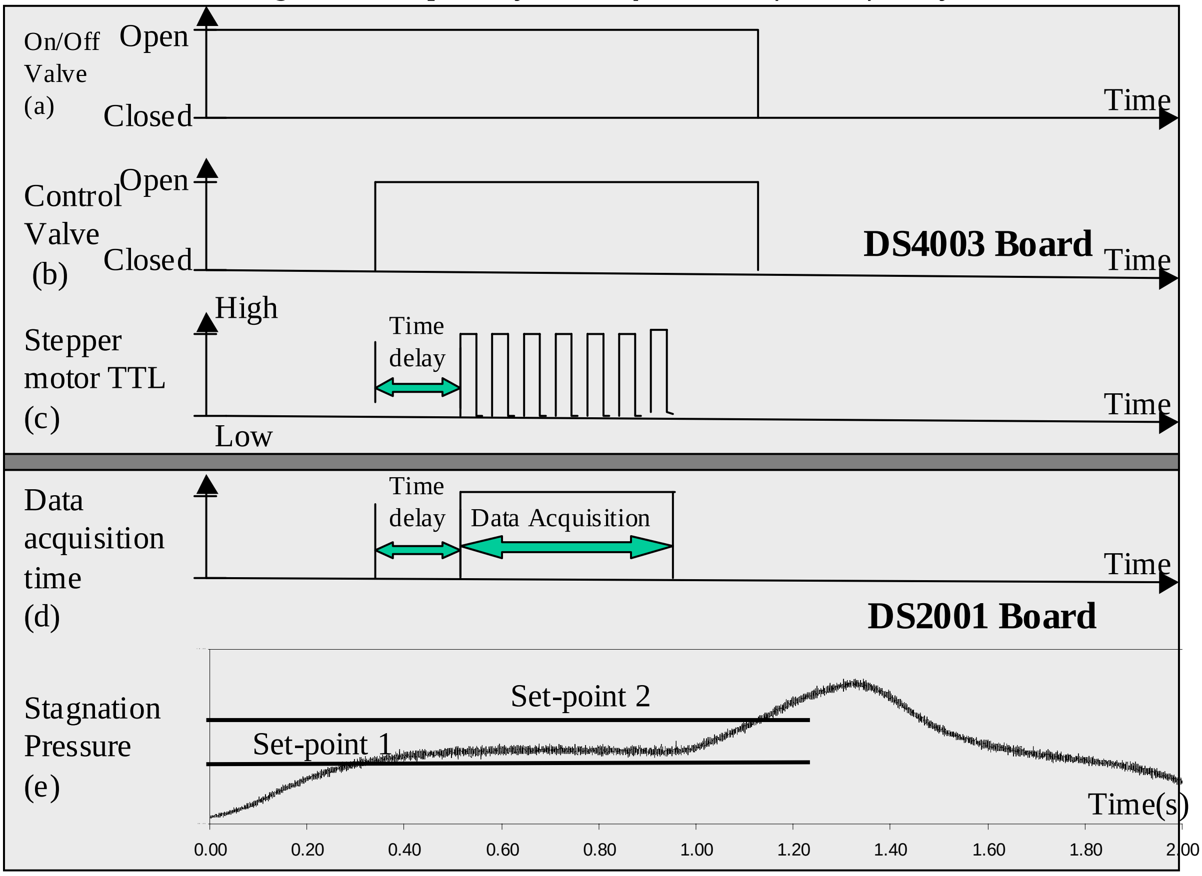

Figure 5: DS4003 and DS2001 board timing sequence

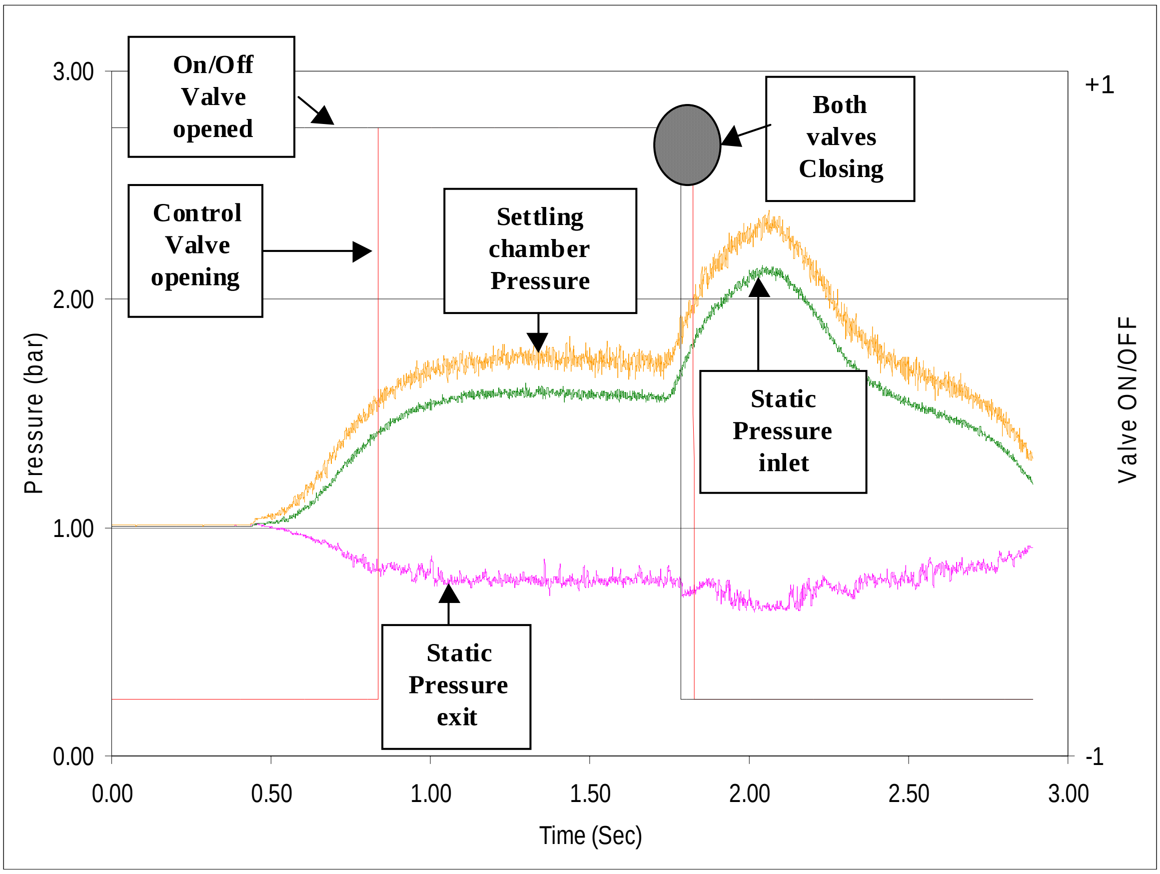

Figure 6: Measurements taken from transonic wind tunnel showing the steady state period.

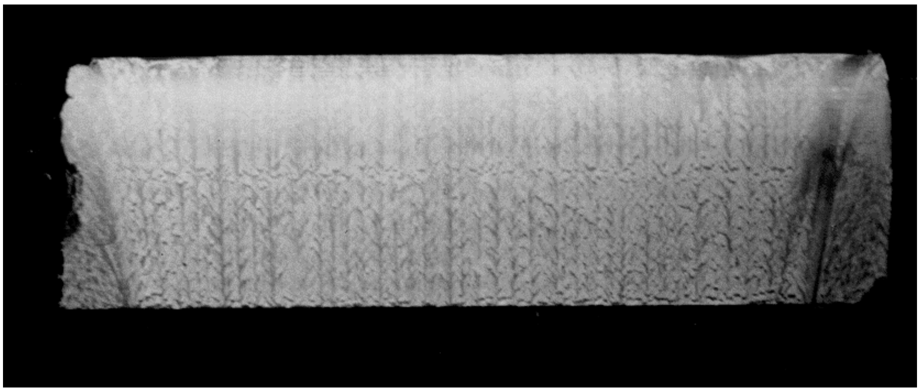

Figure 7: Flow visualisation from transonic cascade blade at exit Mach and Reynolds numbers of 0.92 and $0.94*10^6$ respectively.