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# Design and Development of a Gas Dynamics Facility and a Supersonic Wind Tunnel

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Additional information is available at the end of the chapter

## 1. Introduction

The design of a Supersonic Wind Tunnel is complex, expensive and time consuming. One of the pre-requisites of such a facility is the availability of compressed air necessary to generate the required speed.
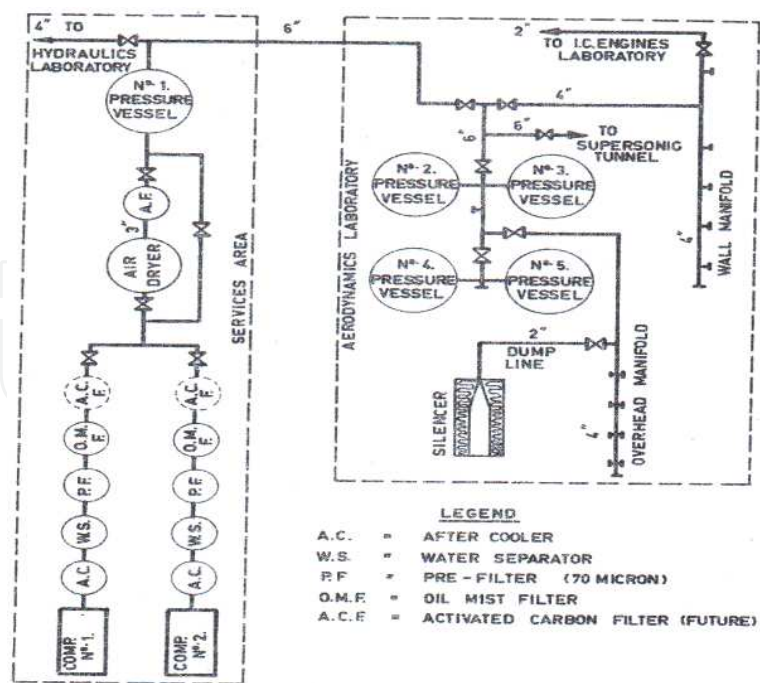


**Figure 1.** A Schematic of the arrangement of the Gas Dynamics Facility

In this Chapter, the design and construction of the basic gas dynamics facility (Fig. 1) is described first in Part I followed by that of a blow down type supersonic wind tunnel (Fig. 2) in Part II. The two facilities are currently in operation at the School of Mechanical and Manufacturing Engineering of the University of New South Wale.
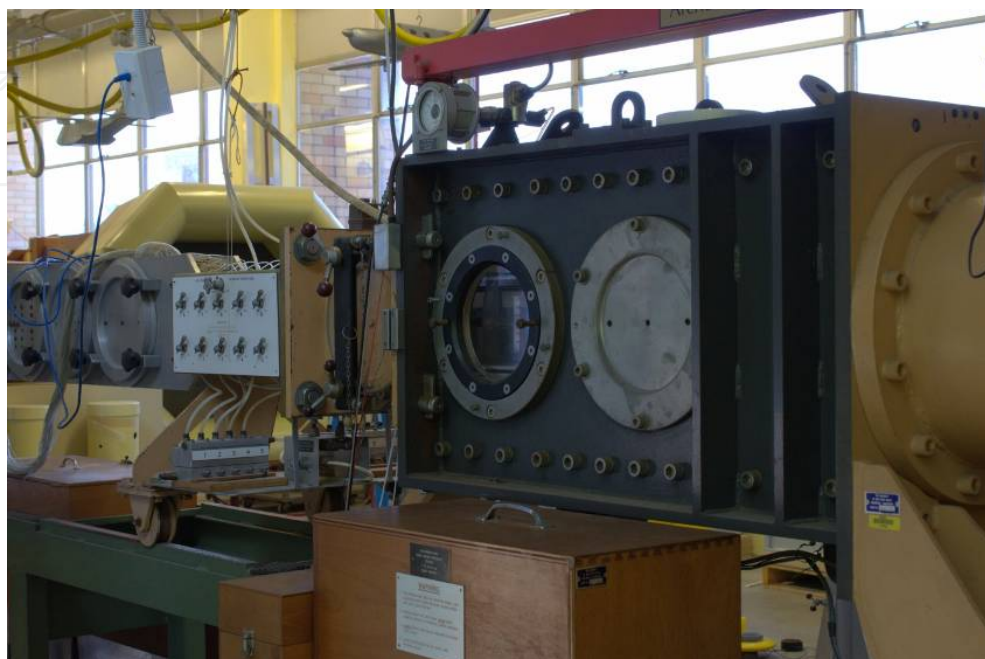


**Figure 2.** A side view of the 5 ½ inch x 4 inch Supersonic Wind Tunnel

## 1.2. The design and construction of a Gas Dynamics facility

The Gas Dynamics facility consists of a large capacity compressed air plant that involved the installation in the Aerodynamics Laboratory of the University of New South Wales of a compressed air plant on the floor and the construction of an overhead structure of four identical 200 cubic feet capacity storage pressure vessels.

The design was initiated by setting a requirement of continuous mass flow rate of about 1 lb/sec. For continuous operation, the system pressure was set to about 100 psig. The gas dynamics facility was also required to provide air supply to a 3.5 inch x 4 inch supersonic wind tunnel, capable of operation of up to Mach 3.5.

A brief description of the gas dynamic facility is given next.

### 1.2.1. Compressed air plant

Compressors

From a consideration of vibration and intake resonance of the machines and also to provide significantly larger outputs per unit cost, it was decided to use rotary compressors. Two Holman RO600S screw type compressors, each rated at 600 cubic feet per minute of free air each

and capable of operation separately to provide a mass flow of 0.75 lb/sec or in parallel for an output of 1.5 lb/sec were acquired. Each compressor maximum pressure ratings is 100 psig for continuous operation and 115 psig for intermittent operation such as that required for use with supersonic wind tunnels. Each unit is driven by a 150 HP 1440 RPM induction motor controlled by an auto-transformer started capable of up to 15 starts per hour. Each compressor unit was installed on 'Vulcascot' anti-vibration matting and was isolated from the discharge pipe work by means of a flexible pipe work connector. As an additional precaution, the first length of outlet pipe work to the after coolers was supported on anti-vibration matting. The result is that with both compressor operating, virtually no vibration is transmitted to the Laboratory building. A schematic of the compressed air plant is shown in Fig 1.

Control of the compressor output pressure is by either an automatic stop-start system or a constant speed uploading system operating between pre-set pressure limits. In operation, the constant speed uploading mode has been most frequently used but the original pneumatic system supplied with the compressors for this purpose proved to be unreliable. Subsequently, this was replaced with an electrical system utilising an electric control pressure gauges. This system has proved to be very satisfactory in operation and enables repeatable and readily varied settings of cut-in and cut-out pressure to be obtained with differentials as small as 2 psi.

The compressors are cooled by oil injection and lubricated by the same oil pressurised from a small pump. The cooling/lubricating oil is stored in a 40 gallon tank and cooled by an oil/ water heat exchanger. The air, after compression, passes through a multi-stage reverse flow oil separator with absorbent filters so as to remove most of the oil present. Claimed oil consumption is one gallon per compressor per 400 hours of operation. Fig. 3 shows the Compressor of the gas dynamics facility.



**Figure 3.** The Compressor of the Gas Dynamics Facility

### 1.2.2. Filtration system

After compression, air from each compressor is passed through individual shell and tube af-
ter coolers, centrifugal action water separators, pre-filters and oil-mist filters. The pre-filters
consist of a centrifugal action separator combined with a 70 micron porosity, sintered
bronze filter element. The oil mist filters are a proprietary design of Daltech Engineering In-
corporated, USA, and consist of a stainless wire wool pre-filter and a chemical absorption
type main element. These filter units are claimed to have a 99.4% filtration efficiency for all
oil particulates down to 0.5 microns. Both pre-filters and oil-mist filters operate with a 'col-
our change' principle in that, as the element becomes saturated with oil, its colour changes
from light pink to bright red. All filters, after coolers and water separators are fitted with
automatic water drains.

### 1.2.3. Air drier

The air drier (Fig. 4) is a proprietary designed manufactured in Australia by B.C. Johnson
Ltd. It is designed for inlet air conditions of 1.5 ib/sec at a pressure of 115 psig, a maximum
temperature of $105^0$ F and an ambient relative humidity at compressor inlet of 100%. The
dryer is required to provide an outlet humidity equivalent to -50 $^0$ F at atmospheric pressure
after a two hour drying cycle.



**Figure 4.** Air Drier System

The air dryer is of the single tower at a larger stage. Regeneration is accomplished by air pre-heated in an 80 kW electrical heater and forced through the dryer stack in a counter-flow direction by a centrifugal blower. The desiccant employed is 800 lb of activated alumina in a 2 ft diameter by 4.5 ft high bed, preceded by 80lb of buffer desiccant whose purpose is to prevent damage to the main desiccant by liquid carry over from filtration equipment. The dryer is fitted with a water coil for cooling the desiccant bed after regeneration and a felt pad and fibreglass after-filter is installed to prevent any carryover of desiccant dust into the storage vessels.

In operation, dew points of as low as -80$^0$ F have been obtained after regeneration. With one compressor in operation, drying times of up to six hours have been achieved, although a higher final dew points than -50$^0$ F regeneration time is about four hours for heating and four hours for cooling.

### 1.2.4. Air storage vessels

Four storage vessels (Fig.5 ), each 5 ft diameter by 11 ft 6 ins overall length and designed for a working pressure of 130 psig have been installed with a total storage capacity o f800 cubic feet as mentioned earlier were placed in an overhead structural steel support in the Aerodynamics laboratory near which a supersonic wind tunnel was built.



**Figure 5.** Air Storage Vessels

### 1.2.5. Air conditions 105$^0$ F at atmospheric pressure

Air conditions in the storage vessels are a volume of 800 cubic feet at ambient temperature and dried to a dew point the equivalent of at least -50$^0$ F at atmospheric pressure. For intermittent operation, maximum pressure is 125 psia. Maximum intermittent mass flow rates are in the region of 10 to 20 lb/sec to limit the system pressure loss to approximately 5 psi. Maximum continuous mass flow is 1.5 lb/sec with a pressure not exceeding 110 psia.

Because the pressure available for supersonic tunnel injection is comparatively low, care was taken in the design and piping and filtration equipment to reduce pressure losses. The overall pressure drop between compressor outlet and storage vessels has been kept between 3 and 5 psi depending upon filter condition.

### 1.2.6. Air distribution manifolds

The supply pipe work inter-connecting the five pressure vessels is of 6 inch inside pipe diameter pipe. There is a 6 inch branch to the supersonic tunnel. Gas dynamics rigs in the Aerodynamics Laboratory are supplied from two 4 inch pipe manifolds, one wall mounted and the other suspended from the ceiling. A four inch line, reducing to 3 inch, supply air to the Hydraulics Laboratory.

Maximum intermittent flow rates are about 10 lb/sec through the 6 inch branch supplying the supersonic tunnel and 4 lb/sec through the 4 inch manifolds. At these flow rates, the pressure drop between reservoirs and manifold outlets does not exceed about 3 psi. The hydraulics Laboratory supply system permits an intermittent flow rate of about 5 psi.

A 2 inch dump line is provided, together with a control valve and attenuating duct silencer to empty the storage vessel contents or to permit an adjustable air bled for stabilization purposes.

## 2. The design and construction of a blow down type supersonic wind tunnel

### 2.1. Design of supersonic tunnel components

Some of the details of the design of the various tunnel components are described in the following sections. The aerodynamic configuration finally selected for the tunnel is shown in Fig. 6.
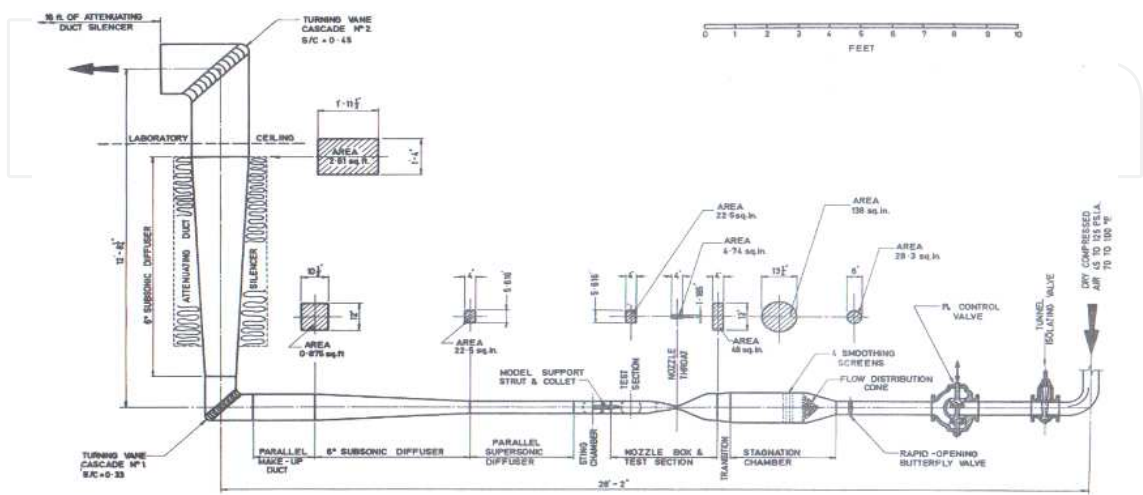


**Figure 6.** A Schematic of the 5 ½ inch x 4 inch Supersonic Wind Tunnel

*2.1.1. Intake piping and control valves*

The following requirements received attention:

• Reduction of pressure loss

• The need to supply a uniform airflow free of pulsation to the stagnation chamber

In addition to the selection of a 6 inch diameter for the tunnel intake pipe work, as mentioned in section 1.6, extra measures to reduce pressure losses and ensure flow uniformity were fitting of splitter vanes to all piping bends and tees in the final run to the tunnel. The design data of Ito (ref 29) was for this purpose.

Three valves were fitted for the flow control (Fig. 6). The first, a 6 inch gate valve, serves merely as the tunnel isolation valve and a backup shut-off valve. The second valve, downstream of the gate valve, is the stagnation pressure control valve. This is followed by the quick opening valve which is located at the inlet to the tunnel stagnation chamber.

The stagnation pressure control valve is a 6 inch double seat Fisher Governor Company valve with pneumatic cylinder actuation. The valve is of the 'Vee-pup' type which has equal percentage flow characteristics. This characteristic restricts the rate of valve spindle movement which would otherwise be necessary when the pressure drop across the valve decreases towards the end of a tunnel run. Control of the valve opening is by means of a standard 3 to 15 psi regulator located at the tunnel control panel. This regulator, acting on the positioned, supplies air at up to 100 psi to the piston of the cylinder actuator. The 6 inch valve size was selected to limit the wide open pressure drop to less than 3 psi. Preliminary design estimates indicated that the pressure drop in a 4 inch diameter control valve would have been in the region of 15 to 20 psi. The double seat valve configuration ensures reasonable symmetry in the airstream approaching the stagnation chamber and assists in reducing pressure pulsations.

The quick-opening valve is a 6 inch diameter Fisher continental rubber seat butterfly valve with pneumatic cylinder actuation and a stroking time of less than one second. It is the last component in the 6 inch line before the stagnation chamber. The position gives the most rapid possible tunnel start using standard valves. Pressure loss is about 0.1 psi. An important advantage in operation of the tunnel is gained by locating the quick-opening valve downstream of the stagnation pressure control valve as the latter can then be correctly pre-set to the required starting pressure. The valve disc position when wide open ensures flow symmetry to the stagnation chamber. The quick opening valve is actuated by a solenoid operated air valves which are, in their turn, controlled by a push button solenoid circuit on the control panel. An electrical interlock is provided so that the tunnel cannot be started until the test section access facility has been securely closed. Tunnel operation may be stopped either at the control panel or from a wandering lead and control box operated by the tunnel engineer.

Maximum Mach number in the intake pipework, excluding 'jetting' from the stagnation control valve, is of the order of 0.1. The maximum calculated pressure loss from the pressure vessels to the stagnation chamber inlet is approximately 5 psi.

The Stagnation pressure control system was deliberately chosen to be manual in orer to simplify control although a hybrid system could be incorporated at a later stage if desired. This system would consist of manual start and initial stabilisation with switch over to automatic operation once the stagnation pressure has stabilised. Some of the problems of supersonic tunnel automatic stagnation pressure control have been discussed by Pugh and Ward [1] and Conolan [2].

### 2.1.2. Stagnation chamber

The stagnation chamber has an inside diameter of 13.5 inches and is connected to the 6 inch inlet pipe work by a 300 conical rapid expansion. Flow stabilisation and smoothing devices consist of a conical perforated plate and flow smoothing and turbulence reduction screens (Fig. 6). A parallel settling length is provided downstream of the screens and is fitted with stagnation temperature and pressure tappings.

The mean velocity at the screens is approximately 20 ft/sec for Mach 3 operation. The chamber is also sized to permit operation down to Mach 1.5 using the same test section area when the velocity at the screens could increase to about 70 ft/sec. This remains within the range of 10 to 80 ft/sec as recommended by Pope [3].

The perforated cone has an apex angle of 900 and is manufactured from a ¼ inch plate with 3/8 inch diameter holes on 9/6 inch centres. The perforations have an open area ratio of 40%. The mean Mach number through the perforations under the worst conditions, which occur at the lowest test section Mach number, is less than 0.1. The cone is welded into the wide angle expansion. In operation, it appears to have eliminated any pressure fluctuations generated by the stagnation pressure control valve as well as assisted in 'filling' the wide angle diffuser.

The four stainless steel flow smoothing screens are of 24 mesh by 34 gauge wire and have an open area ratio of 49.5%. The screens are fixed in individual aluminium retaining ring frames. These frames are clamped together by long bolts passing through large frames attached to the rapid expansion and settling length sections of the stagnation chamber. The individual frames are spigoted together to ensure internal surface alignment and are sealed by O rings at each joint.

The parallel settling length downstream of the screen is 1500 screen wire diameters long, or a length of approximately 18 inches.

A two dimensional contraction and section change transition region is provided at the downstream end of the settling chamber. This region has a rectangular outlet area of 12 inch x 4 inch and a circular 13.25 inch diameter inlet section. The area contraction ratio is 2.9:1. A further two-dimensional contraction, of ratio 10:1, is built into the nozzle blocks to contract the airstream to a sonic throat 1.185 inch high by 4 inches wide. The method of contraction design presented by Gibbings [4] is recommended. This method is also applicable to contractions in which there is an appreciable axial trigger between the plan and elevation profiles.

In operation, the stagnation chamber provides a steady pressure with accuracy of control of 1% or better. Estimated pressure loss for the stagnation chamber flow smoothing devices was 2 psi approximately, making a total estimated loss between pressure vessels and stagnation pressure measurement station of nearly 7 psi. In operation, this pressure loss varies between 7 -10 psi.

### 2.1.3. Nozzle box and test section

The nozzle box is of conventional construction and is manufactured from steel plate with internal surfaces ground after welding and stress relieving. Heavy stiffening ribs prevent deformation under pressure forces, particularly in the throat region. Dowels are fitted to ensure accurate and repeatable alignment of adjacent parts. Circumferential 'O' ring seals are provided at each end of the nozzle box. One side wall opens downwards on hinges to facilitate nozzle block changes. The complete assembly of nozzle box and settling length section of the stagnation chamber can be moved on rollers to permit easy screen removal. The rollers are brought into operation by four jack screws. An axial movement of 3 inches in the downstream direction is possible.

There are circular Schlieren window positions in the nozzle box walls, one pair at the throat and one pair at the test section. The windows have a clear diameter of 7.5 inches and thickness of 1 inch and are held in a sub-frame which is fixed to the tunnel by a clamping ring. This arrangement permits easy removal and rotation of each window. Rotation of the window assembly permits selection of the optimum orientation for optical characteristics of the glass fitted. This allows the use of cheap and comparatively low grade plate glass. The glass is sealed to the sub-frame with Dow Corning Silastic 732 RTV silicon rubber compound. A special jig has been developed for window assembly which ensures that the glass is completely 'floating' in Silastic and is also flush to within 0.001 inches with the frame edges. A set of high quality glass windows obtained from Optical Works, UK are also available for specially sensitive Schlieren applications.

The supersonic nozzle blocks are manufactured from extruded AA28S aluminium alloy. The contours were generated by a programmed 'Hydroptic jig borer and were finally hand finished to remove machining marks. Each block is fitted with a continuous, circular cross section rubber seal which runs as close to the contoured surface as is possible using straight line approximations. The nozzle blocks are held in the nozzle box with the bolts passing through the top and bottom walls of the box into barrel nuts inside each block. Location is by integral machined pads on the basis of each block. It is now realised that the provision of separate ground pads on the base of each nozzle block configuration would have permitted the fitting of permanent shims clamped between pad and block, thereby simplifying the fitting and accurate setting up of each nozzle block configuration within the nozzle box.

The nozzle block co-ordinates are those derived by McCabe [5] for operation at Mach 3 in a nominal 5.5 inch x 5.5 inch test section. The design method used by McCabe divides the nozzle inviscid core flow into five main regions, as follows:

- A subsonic contraction

- The high subsonic, low supersonic throat region
- An initial expansion region wherein the contour slope increases to its maximum value
- The straightening or 'Busemann Region'
- The parallel flow or test section region

McCabe also divides each of the 3rd and 4th regions into further regions so as to take advantage of more precise computational methods and eliminate discontinuities in nozzle curvature. The nozzle contour boundary layer corrections are based on the data of Sibulkin [6] for the throat region, with corrections on the contoured and flat side walls obtained from the data of Rogers and Davis [6]. Because the nozzle contours so derived did not have zero slope at the test section location, a cubic curve was fitted to permit smooth transition to the parallel block region downstream of the test rhombus. The boundary conditions were continuity of ordinate, slope and second derivative at the upstream and zero slope at the downstream end. Before feeding to the jig borer, the complete set of nozzle block co-ordinates was smoothed by computer using a 6th order polynomial. Data on nozzle profile design may be obtained from Refs 8-15.

### 2.1.4. Diffusers and model support system

Downstream of the nozzle box are a string chamber, supersonic diffuser, first stage subsonic diffuser, parallel make up duct and a set of cascade turning vanes. The complete assembly downstream of the nozzle box to the corner cascade is mounted on a flanged wheel and rail system and may be moved 18 inches in the downstream direction away from the test section. This allows easy access for model changes. The face of the sting chamber is aligned with, and closed against, the nozzle box pressure seal by four dowel pins and tapered locking wedges. Four cam clamps are used to close the pressure seal between the cascade corner and the vertical second stage subsonic diffuser.

The sting chamber can be removed entirely, if required. It is fitted with a pair of circular openings of the same diameter as those in the nozzle box side walls and, can, therefore, accept the interchangeable Schlieren windows or metal window blanks. A side mounted sting may be fitted to either of the side window blanks. A vertical, full span, wedge nose strut is also in use as a model sting support.

The optimum design of a supersonic diffuser for a small wind tunnel presents a difficult problem as it must operate over a wide range of inlet flow conditions and Reynolds numbers. Moreover, at Mach numbers in excess of 2, optimum starting and running diffuser geometries diverge significantly. It is assumed in the following discussion that the supersonic diffuser is followed by a subsonic diffuser of small divergence angle.

In general, the airstream entering the diffuser is highly turbulent because it contains the wake flow from the test section model and its support system. Moreover, diffuser performance is influenced by boundary layer effects which are a function of tunnel Reynolds number.

Supersonic diffusers for small wind tunnels may be one, or a combination of the following types:

- Fixed contraction with constant area second throat

- Variable contraction with variable area second throat

- Constant area duct

- Oblique shock diffuser with centre body

The diffuser throat must be sized must be to 'swallow' a normal shock when starting at the design Mach number in a second throat type of diffuser. Faro [11] obtained the theoretical minimum starting contraction ration required, together with experimental points from several sources. For Mach numbers in excess of 2, the experimental values are lower than the theoretical values. It is suspected that this is due the starting shock passing through the second throat before the design Mach number has been reached. The experimental data of Lukasiewicz [16] indicates that at the area ratio of $A_2/A_1 = 0.7$, which is required for stating at Mach 3, the starting pressure ratio requirement of a fixed geometry second throat diffuser, might be 0 to 30% less than that required by an optimum length constant area diffuser. If a variable geometry second throat diffuser is used, significant reductions in optimum running contraction ratio may be obtained particularly at Mach numbers in excess of 2.

Variable geometry diffusers, set at optimum running contraction ratios after starting, enable reductions in running pressure ratio of up to about 45% when compared with optimum length constant area ducts [17]. This reduction is achieved, however, at a considerable increase in complexity of construction and operation when compared with the simple constant area diffuser.

The advantages of the fixed and variable area second throat diffusers over the constant area diffuser are less certain when allowance is made for the presence of the model and its support system within the test section. Faro [11] states that in nearly all cases the presence of a model reduces supersonic diffuser efficiency. This is confirmed by De Leo and Huerta [17] who found that a 5% blockage model increased starting and running pressure ratios by approximately 7 and 13 % respectively for optimum empty tunnel diffuser geometry and Mach numbers of 2.5 and 3.4. However, experiments have also shown that the presence of a model tends to reduce tunnel instability through stabilisation of the diffuser shock system. This appears to be due to interaction between the wall reflections of the model bow wave and the diffuser shock system. In summary, therefore, it seems that the second throat diffuser types do not offer significant advantages over the constant area duct for small supersonic tunnels. This conclusion does not apply to very large intermittent type tunnels, however, as then a reduction in running pressure ratio could lead to significant increases in tunnel run time for a given pressure storage capacity or reduction in capital cost of the storage system for a given run time.

The supersonic diffuser of the University of New South Wales is a constant area duct system although the sting strut, when used probably acts as a centre body with oblique shock diffusion. Although such a constant diffuser is a dissipative system, it does have the considerable advantage of being stable over a wide range of inlet flow conditions and of being simple to construct and maintain.

The only design decision required for a constant area supersonic diffuser is the optimum length of duct. In such a diffuser the normal shock appears as a shock system which is strongly affected by the state of the boundary layer. Experimental dat quoted by Lukasiewcz [16] confirms that for best efficiency the shock compression process should be completed in the constant area duct and not in the divergent subsonic diffuser downstream of the supersonic diffuser. Faro [11] illustrates the gain in isentropic efficiency with increasing length to height ratio for a constant area duct at Mach 2. The significant reduction in operating pressure ratio with increasing length of parallel duct may be seen in curves plotted for length to height ratios of 0, 2 and 7. Further design data for constant area diffusers is demonstrated by Faro [11]. Two points are noted in connection with his work:

• The Mach number $M_{av}$ is the average Mach number at the supersonic diffuser inlet and would be less than the test section Mach number because of the presence of the model and its support system and boundary layer growth between test section and diffuser.

• The effect of the free stream Reynolds number is not accounted for. Some indication of the reduction in the length of the shock compression system at high Reynolds numbers may be obtained from [16]. This data is applicable to a Mach number of approximately 2.

Faro [26] indicates that a single wedge such as the leading edge of a sting support strut may be used to provide an oblique shock system which will improve diffuser efficiency over the simple normal shock case. The benefits for this type of device are limited, however, is that high efficiency can only be obtained with a large number of oblique shocks which in turn implies design for a specific Mach number and thus a narrow range of off-design conditions. The simple strut type oblique shock generator gives moderate efficiency gains over a wider range of Mach numbers.

To summarise, little data for the design of constant area supersonic diffusers or for the effect of a model and strut system on diffuser efficiency can be found. The available information suggests that:

• The shock system compression process should be completed within the parallel diffuser duct for best efficiency

• The optimum length of parallel duct required to complete the compression process is a strong function of Mach number and Reynolds number. This length is probably within the 5 to 12 diffuser heights of Mach numbers of 1.5 to 3.5 and Reynolds numbers of $2 \times 10^5$ to $6 \times 10^6$. Design data for supersonic diffusers may be obtained from Refs 16-22].

The supersonic diffuser of the University of New South Wales tunnel is a parallel wall rectangular duct fabricated from 4 inch x 1 inch extruded aluminium bar top and bottom walls and 0.5 inch aluminium plate side walls. The top and bottom walls may be easily replaced with a set of contoured blocks so as to provide a fixed area second throat, if so desired. The parallel diffuser length is 8.4 diffuser heights from the rear of the model support strut and 11.4 heights from the end of the supersonic nozzle with model support system removed. A removable parallel subsonic make-up duct permits the fitting of an additional 4.3 diffuser

heights. The window blanks alongside the model support strut also allow for experiments involving 'de-blocking' of the area around the strut.

The design of the subsonic diffuser was straightforward. The data of Lukasiewicz [16] indicates that, in the Mach number range 0.4 to 0.9, total pressure recovery is virtually constant at about 0.88 for open ducts without models and that the diffuser divergence angle should be less than $7^0$. Data on subsonic diffuser design is available from Refs 14 and 16.

There are two stages of subsonic diffusion separated by the corner cascade (Fig. 6). The first stage of subsonic diffusion is separated by the corner cascade (Fig. 6). The first stage has an area ratio of 5.6 and divergence angle of 60. Maximum Mach number at the subsonic diffuser exit is approximately 0.13. The diffuser is constructed from 3/16 inch steel plate reinforced at 6 inch x 3 inch centres with 1 x 0.25 inch flat bars on edge.

The second stage subsonic diffuser has a 60 divergence angle and 3:1 area ratio. Maximum Mach number at exist to this diffuser is approximately 0.04. The diffuser is manufactured from plywood and incorporates part of the tunnel silencing system. The corner cascade utilises sheet metal circular arc turning vanes.

### 2.1.5. Silencer

Preliminary investigations on an existing M3.5, 4 inch diameter conical nozzle indicated that the noise level for an unsilenced tunnel would be unacceptably high at about 120 db in the frequency band of 100 to 2000 Hz. Accordingly, a silencer was designed for the supersonic tunnel to the following requirements:

• Noise reduction to about 80 dB in the 100 to 2000 Hz band

• Low pressure loss

• Ease of construction and low cost

After investigation, an attenuating duct design was chosen as best fulfilling these requirements. This type of silencer requires an absorbent material as dense as possible with a thickness of 2 inch to 12 inches to absorb the low frequency noise below 500 Hz. Attenuation at the lower frequencies is increased considerably by the use of a perforated duct facing material having about 3 to 10% open area perforations. Low frequency attenuation is further assisted by providing airspace behind the absorbent material and increasing the amount of absorbent around the duct periphery. When compared with splitter type duct attenuators, low frequency attenuation can be improved by arranging a given amount of attenuation material such that it forms thick layers. This latter arrangement gives a lower peak but better average attenuation over the 100 to 1000 Hz frequency band. Design information can be found in the literature [23-29].

The silencer for the University of New South Wales tunnel is constructed in two sections: the first of which is built around the second stage subsonic diffuser. The first section comprises 6 to 12 inch thickness of polythene wrapped rockwool batts and loose rockwool fill around around all four sides of the diffuser. The rockwool density varies from 4 to 6 lb/cubic

feet for the loose fill. The duct interline is surfaced with 3/16 inch thick perforated plywood and the outside of the silencer is sealed with 1 inch thick, exterior quality waterproof plywood. Both internal and external surfacing materials are heavily glued, screwed and nailed to substantial connecting framing. The second section of the silencer, which is 16 ft long is a rectangular duct lined on two sides with 6 inch thickness of rockwool batts backed by a 3 inch airspace. The remaining two sides of this duct are 1 inch thick exterior plywood. Other constructional details are similar to those of the first section silencer. The second diffuser section is run in the laboratory ceiling space and is supported from the roof structure on 'Silentbloc' vibration isolators.

Initial tests on completion of the tunnel indicated a large direct sound transmission through the walls of the first stage subsonic diffuser. This was found to be caused by high frequency resonance of the 3/16 inch thick flat steel plate walls. The vibration was almost completely eliminated and the noise level reduced by decreasing the spacing of the existing 1 inch x 0.25 inch stiffening bars from approximately 12 inch x 6 inch to 6 inch x 3 inch centres as described in section 4.4.

In the final form, the silencer has reduced the noise level in the vicinity of the tunnel to about 75 to 90 dB, for the 100 to 2000 Hz band, depending to some extent upon the operating stagnation pressure. It is estimated that the duct silencer provides an attenuation of about 2 to 3 dB per foot of length in the frequency range 100 to 1000 Hz.

### 2.1.6. Instrumentation

The tunnel stop-start system has been briefly described in section 2.1.4.

Tunnel stagnation pressure is read on 0.15% accuracy, temperature compensated, absolute pressure 'Heise' test gauge and recorded by a pressure transducer having 0.1% combined non-linearity and hysteresis. The transducer output can be displayed directly in psia on an 11 inch 'Honewell' strip chart recorder. The control panel is provided with an electrically actuated pneumatic calibration circuit which connects the stagnation pressure transducer and test gauge in a closed system. This circuit has an electrical override if the tunnel is started.

Stagnation temperature instrumentation consists of an exposed-junction 'BLH' micro-miniature thermocouple connected to an 11 inch strip chart recorder and reading directly in 0F. Bothe stagnation temperature and pressure recorders contain electrically operated chart speed-up facilities which automatically increase the chart speed by a factor of 60:1 when the tunnel run is started. A typical speed change is from 10 inches per hour to 10 inches per minute. Both chart recorders are provided with event markers which are connected into the tunnel timing circuit. The circuit operates an electrically actuated second timer which is controlled from a timer switch in the remote control box on a wandering lead. The box also contains the tunnel stop switch and a pressure clamp switch. The event markers are automatically actuated at the start and stop of a timing run. The wandering lead control box enables one man to control the run and monitor Schlieren and instrument read out.

Data acquisition is by conventional multi-manometers, pressure gauges or a range of flush diaphragm transducers. For calibration, the data transducers can be connected into a closed system with a 'heise' stagnation pressure gauge. This only requires operation of a control panel push-button. Read out equipment for the transducers are EAI and Solartron multi-channel data loggers and a 6 channel pen recorder.

Tunnel air flow calibration equipment has been designed and built in accordance with the data published by Anderson [16]. Air humidity is measured with a Casella-Alnor dew point meter which can measure dew points to $-80^0$F with an accuracy of $3^0$F.

A two-mirror, parallel path, 96 inch focal length, 7.5 inch aperture Schlieren system is currently in use with the tunnel and associated gas dynamics rigs. A second 60 inch focal length system is being assembled. Both systems are portable, freely adjustable and provided with heavy bases. Photographic facilities include a 5 inch x 4 inch plate camera specially adapted for daylight use with the Schlieren system along with a high speed drum camera and a cine camera oprating at framing speeds up to 20,000 frames per second.

## 2.2. Operational problems

The gas dynamics and supersonic tunnel facilities have proved to be simple to operate, reliable and comparatively trouble-free. However, there have been two operational problems which may of interest, and they are described below.

• Oil mist carry over: A slight oil deposition occurs on the tunnel test section windows after several runs indicating that the oil filtration is not completely effective. It is likely that this results from the fact that the oil mist filters have their highest removal efficiency for aerosol having particulate sizes down to 0.5 micron. It is possible that a very fine oil aerosol is passing through the filters with particulates in the size range 0.1 to 0.001 micron. A solution to the problem would be the use of a hydrocarbon selective absorbent which has a high removal efficiency in the size range where Brownonian motion predominates. For this reason, a set of activated carbon filters was manufactured and installed.

• Water Condensation in Pipelines: Operation of the gas dynamics facility without the air dryer is currently necessary for certain types of tests. As a result, liquid water condenses in the pipelines and pressure vessels and ultimately results in small rust flakes periodically discharging into a stagnation chamber. The solution to this problem appears to be use only dry air for all operations. The existing single dryer tower does not have sufficient drying capacity for some rig work where run durations of up to eight hours are required. Consequently, installation of the second dryer tower appears to be necessary, although much of this type of running can be done at higher outlet dew points than the supersonic tunnel operation, thus permitting longer run times before regeneration. It also appears desirable to introduce some form of direct reading humidity meter which could also be used to operate a warning system. As an interim measure to combat water collecting in the pipelines and fittings, all low points of the system have been provided with water drain valves.

## 3. Conclusion

A compressed air plant, providing 1.5 lb/sec of dry air at 100 to 115 psig and having a storage capacity of 1000 cubic feet, has been engineered and built. The system has been operating satisfactorily apart from an oil mist problem for which corrective measures are being investigated.

A supersonic blowdown wind tunnel, using air from the compressed air plant and exhausting to atmosphere, has also been built to simple, conventional design principles. Nozzle blocks for Mach 3 and parallel duct supersonic diffuser has been installed. Although stagnation pressure control is manual, the tunnel is designed for operation by only one man. Run time varies from 20 to 60 seconds and test section Reynolds numbers of about $10^6$ per inch may be obtained.

These facilities along with subsonic wind tunnel facilities form the basis of aerodynamic, research and development works at the University of New South Wales [31-89]

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