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Design & Operation of an Intermittent 1" X 3" Supersonic Wind Tunnel
Satish Dhawan

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by **SATISH DHAWAN***

Introduction

A BLOW-DOWN Supersonic Wind Tunnel utilizes stored pressure energy from a high pressure air storage tank for its operation. For equal size and range such an installation is, in general, considerably more economical when compared to a continuously operating type especially with regard to the power plant requirements. There are, however, some penalties involved for the lowered cost. The operation of a blow-down tunnel is intermittent and the duration of a run seldom exceeds a few minutes. This calls for special instrumentation and techniques for obtaining reliable measurements. In recent years considerable attention has been devoted to this type of installation, principally on account of the simplicity of operation and the attractive economic features. The development of technique and instrumentation has gradually overcome the handicaps due to intermittent operation until now, for most high speed aerodynamics research the blow-down tunnel is almost at par with the continuously operating type. This paper describes the design and development of one such installation together with some new control techniques. This installation is the first of a series of high speed wind tunnels now under construction at the Department of Aeronautical Engineering, Indian Institute of Science, Bangalore. The design and construction of the wind tunnel described here follows more or less conventional lines except that low-cost materials and easily available commercial equipment have been fully utilized in the interest of economy and simplicity. These considerations led the design to avoid the use of expensive heating equipment for the purpose of achieving Reynolds number control in the tunnel. A study of the operation of blow-down supersonic tunnels showed that a simple solution of the heating problem is possible and practical. The resulting tunnel has proved to be highly satisfactory and, being the first supersonic wind tunnel in India, a somewhat detailed description may prove to be of some help in the development of other installations in this country.

Symbols

A	Area of test section
A^*	Area at throat where Mach number $=1{\cdot}0$
P_o	Absolute pressure in storage tank
T_o	Absolute temperature in storage tank
P_b	Absolute pressure in settling chamber
T_b	Absolute temperature in settling chamber
P_e	Absolute pressure at discharge end of diffuser
μ	Viscosity coefficient
ρ	Density of air
M	Mach number
u	Velocity of the air in the test section
R.No.	Reynolds number
d	Length entering into Reynolds number

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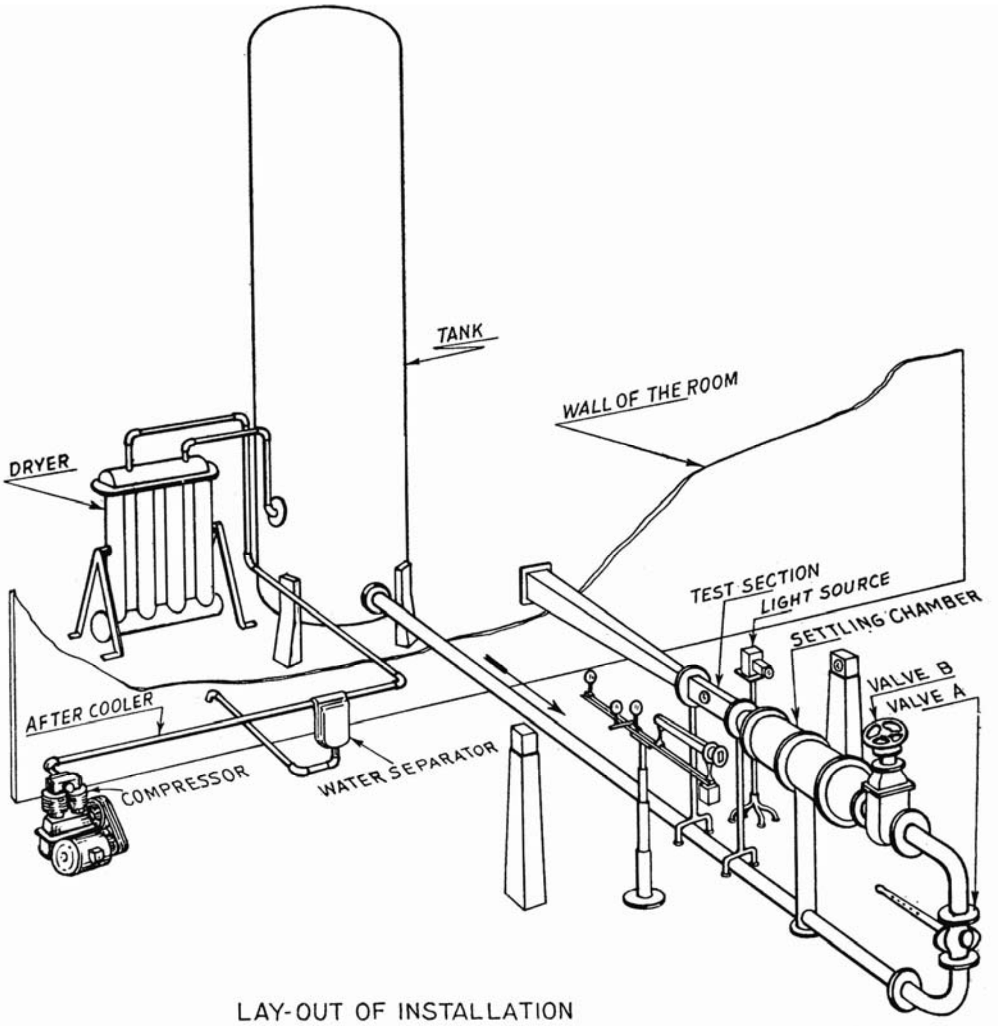


LAY-OUT OF INSTALLATION

FIG. 1

γ	Isentropic expansion index
n	Polytropic expansion index
m	Viscosity index
α, β	Constants in pressure law
t	Time
R	Gas constant for air
a	Velocity of sound

Subscripts

o	Refers to conditions in tank
b	Refers to conditions in settling chamber
i	Refers to conditions at start of a run
MIN.	Refers to minimum
MAX.	Refers to maximum
OPT.	Refers to optimum conditions

Wind Tunnel Size & Mach Number Range

The main factors determining the size of this wind tunnel were those of cost and availability of the compressor and pressure storage tank. The available compressor was a Broomwade 8·5 h.p. reciprocating type delivering 30 cubic feet of free air per minute at a delivery pressure of 100 p.s.i.g. Considerations of a reasonably short charge-up time between tunnel runs (about one hour) fixed the volume of the air storage vessel to approximately 300 cubic feet. The storage tank was constructed by Messrs Mazagon Docks of Bombay and is 17 ft. high, 5 ft. in diameter and made of $\frac{1}{2}$ in. boiler plate. With this size of tank and with the requirement of minimum running times to be at least of the order of 30 seconds, the tunnel test section size would be approximately 3 sq. inches over a range of Mach numbers of 1·25 to 3·0. Throttling of the air between the tank and the settling chamber would increase the running time to approximately 60 seconds. The final choice of a 1 in. × 3 in.

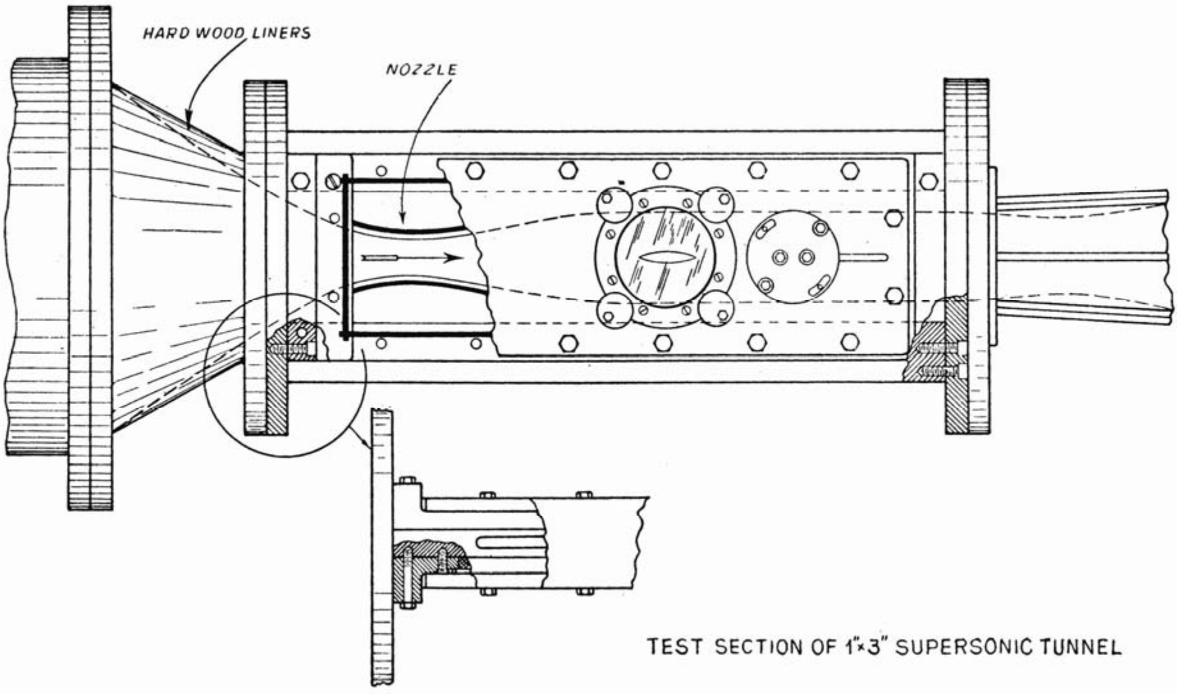
test section was chosen as being conservative. This consideration was specially important to avoid the necessity of having to use expensive fast response and automatic recording electronic instrumentation for measurements. The aspect ratio of 3 was chosen as a compromise since the tunnel would be used both for 2- and 3-dimensional tests.

Design Features of the Installation

General Layout — Fig. 1 shows the complete installation. Air from the 8·5 h.p. compressor passes through a water cooled after cooler and moisture separator before circulating through a silica gel adsorption dryer and is then stored in the 324 cubic feet storage tank. The tank is connected to the tunnel proper through a 4 in. dia. steel pipe. The diameter of this pipe is such that during a run the flow never exceeds a Mach number of 0·1, thus keeping friction losses quite low. Air from the tank is controlled by the two valves shown and passing through the settling chamber and contraction it enters the supersonic nozzle in the test section. After passing through the supersonic diffuser just downstream of the test section, the air is gradually slowed down by the subsonic diffuser to approximately a speed of 20 ft. per second before emerging from its end which is open to the atmosphere.

Control Valves — Of the two valves shown in Fig. 1, valve A is of a quick-acting type. A commercial 4 in. dia. quarter turn plug type boiler blow-off cock fitted with a 21 in. lever has proved very satisfactory for this purpose. The opening or closing times are of the order of $\frac{1}{2}$ second and the operation extremely simple, since it involves only the movement of a single lever. Valve B is a standard wheel gate valve with a round 4 in. dia. opening. This valve is the principal control which affects the running of the tunnel. A typical operating procedure consists of pre-setting valve B at some value depending on the starting blowing pressure required in the settling chamber. The tunnel is then started by operation of valve A and simultaneously valve B is regulated according to the type of operation desired.

Settling Chamber — The settling chamber is 12 in. dia. and 24 in. long. It is of welded construction and is made out of $\frac{1}{4}$ in. M.S. sheet with external ribs for additional strength. The chamber is made in two halves with provision for flush mounting of two $\frac{1}{16}$ in. mesh screens at the joint. A coarser $\frac{1}{4}$ in. mesh screen is fixed at the entrance end. Provision is made in the walls of the settling chamber for pressure taps and for the mounting of temperature probes, etc. The entire assembly is supported from the floor by a 6 in. dia. pipe with flanged ends.



TEST SECTION OF 1"×3" SUPERSONIC TUNNEL

FIG. 2

Contraction — The contraction is in the form of a conical welded steel shell inside of which there are shaped hardwood liners. These liners smoothly change the 12 in. dia. circular shape of the settling chamber into a rectangular opening 1 in. × 5 in. at the exit end of the contraction. While a more gradual transition would be aerodynamically preferable, constructional difficulties forced the above method to be adopted. The inside of the contraction was made exceptionally smooth by filling up all corners and crevices, smooth sanding and, finally, spray painting several coats of Duco cellulose paint on the prepared surface. This procedure resulted in a smooth mirror-like finish and the performance of the contraction has proved to be satisfactory in all respects.

Test Section — The test section proper, Fig. 2, was designed in the form of a built-up steel frame in which welding was completely replaced by bolts and screws. Such a procedure is desirable on account of the high degree of dimensional accuracy required in the test section and the difficulty of avoiding distortions introduced by welding. The principal feature in the structural design of supersonic wind tunnel test sections is the limitation on deflection of the members rather than structural strength as such. The present installation uses 1 in. thick steel plate for the tunnel side walls. These limit the maximum distortion due to deflection under the worst loading conditions to less than 10^{-4} inches. The entire test section was fabricated to overall dimensional tolerances of $\pm 0{\cdot}002$ in. The nozzle blocks bolt down on the test section floor and ceiling while the side walls exactly fit the sides. Either is easily removed and installed. A nozzle change (for Mach number change) being easily accomplished within approximately 15 minutes. Schlieren observation is through two $3\frac{1}{2}$ in. dia. glass windows and downstream of these two 2 in. dia. circular ports are provided for installation of a model support system or alternatively for the insertion of measuring probes, etc. The floor and ceiling of the test section are slotted longitudinally for later incorporation of instrument traverse mechanisms.

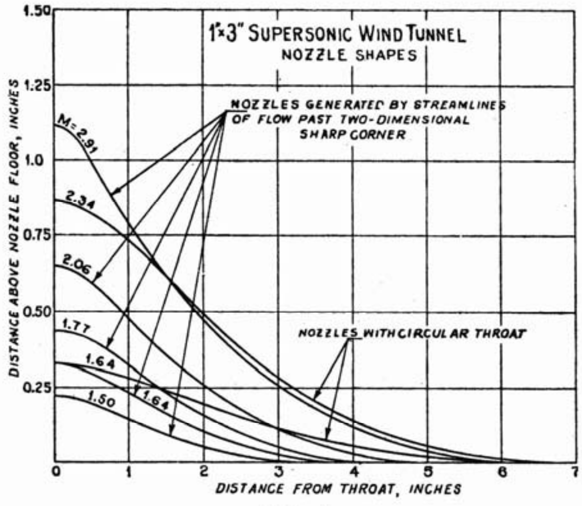
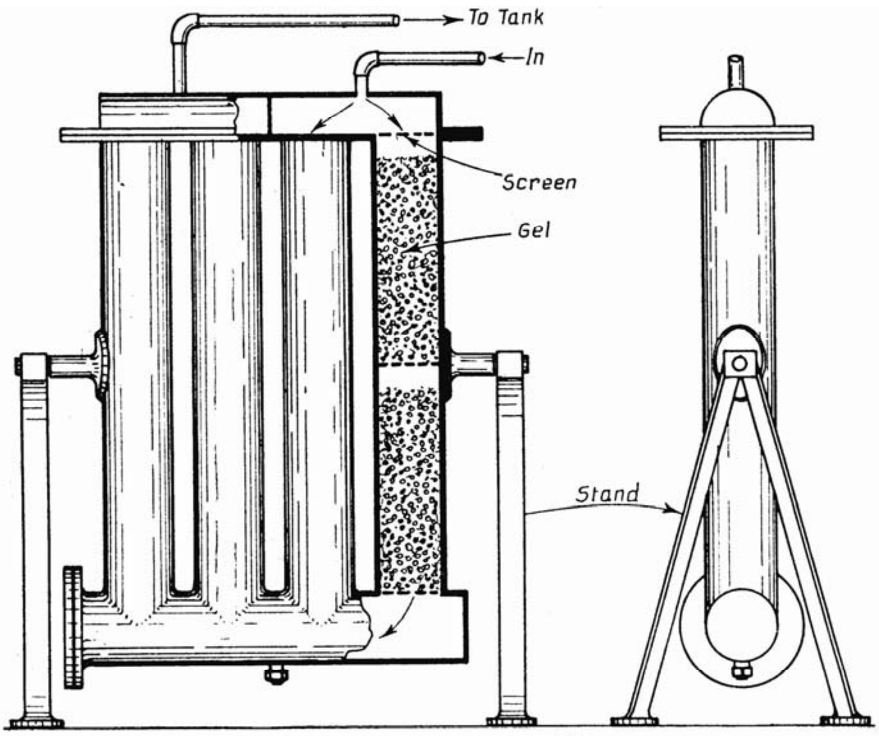


FIG. 3

Supersonic Nozzles — All the supersonic nozzle blocks have a straight 30° converging portion which fairs smoothly on one side with the inlet contraction and with the throat section on the other. The divergent portion of the supersonic nozzles was designed by the method of characteristics to give shock-free uniform flow in the test region. Typical nozzle shapes are shown in Fig. 3.

Diffuser — The diffuser section consists of two parts. The supersonic portion is made of steel with provision for interchangeable wooden liners for giving the various second throat areas at various Mach numbers and having provision for total head and static pressure probes for pressure-recovery measurements. The subsonic diffuser is constructed out of $\frac{3}{4}$ in. waterproof plywood with reinforcing ribs on the outside. It has a rectangular cross-section with a total average divergence of 5°. The exit area of the diffuser is such that the emergent flow has a velocity of approximately 20 ft./sec.

Air Dryer — Removal of moisture from the air in a supersonic wind tunnel is essential to avoid condensation effects. In this installation the moisture removal is accomplished by passing all the air delivered by the compressor through a silica gel adsorption dryer before storage. The dryer was constructed out of 6 in. dia. steel pipes. The capacity of the dryer is dependent on the moisture content of the air. A study was made of the local humidity conditions, and the capacity of the dryer is such as to reduce the moisture content of the dry air to approximately −20°C. dew point for all weather conditions, except during the monsoon season when the air is almost saturated. The dryer is diagrammatically shown in Fig. 4. Its capacity of 120 lb. gel is sufficient to provide approximately 20 tunnel runs. For reactivation the gel is removed and heated to approximately 250°C. and cooled before recharging the dryer. To facilitate removal of the gel the dryer is mounted on a stand so that it can be tilted and the gel poured out.



SILICA GEL DRYER

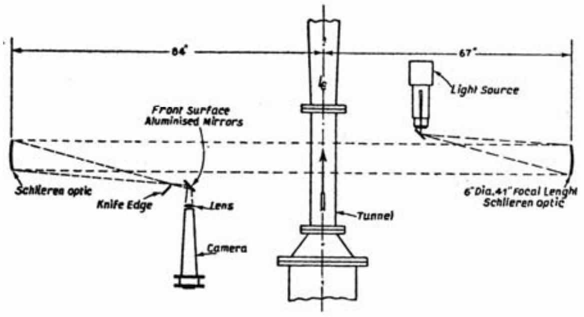
FIG. 4

Schlieren System — A conventional off-axis two-mirror Schlieren system was designed utilizing 6 in. dia. spherical front surface mirrors of 42 in. focal length. The mirror surfaces are not optically first rate, but were readily available at low cost and hence were used. The light source is a 220-volt 150 c.p. Point-O-Lite lamp or alternatively an AH-4 General Electric mercury vapour lamp. Light from the source is focussed by a pair of condensers on to an adjustable knife edge slit and transmitted to the 6 in. dia. optic by reflection from a small plane mirror. The optical components and the light path are shown in Fig. 5. The 6 in. dia. optics are mounted on stands constructed out of hard seasoned wood with metal inserts and have provision for fine tangent screw adjustment of the mirror about two mutually perpendicular axes. This type of optical stand, Fig. 6, has been found to be very satisfactory as well as cheap and easily constructed. The cut-off knife edge, screen and camera are all mounted on a pedestal type optical stand allowing adjustments along the optical path for sharp focussing. The camera was designed to give as large an image as could be accommodated on $2\frac{1}{4}$ in. × $3\frac{1}{4}$ in. cut film and it has a diaphragm type shutter. The image can be viewed on a ground glass screen or photographed by replacing the screen with a film holder.

Other Instrumentation

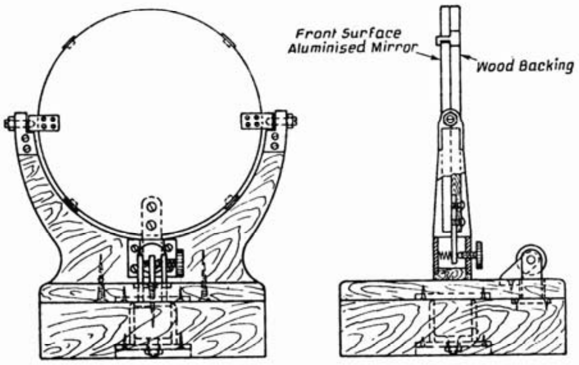
Pressure — Calibrated pressure gauges of the Bourdon type are mounted on a panel on the settling chamber and indicate simultaneously the total pressure in the settling chamber, the pressure in the tank and the static pressure at one undisturbed location in the test section. These three pressures are recorded for all routine measurements, simultaneously with the reading of a stop watch mounted on the same panel. Simultaneity is ensured by instantaneously photographing the dials of all four instruments. In addition to the pressure gauges, a 14-channel manometer of 48 in. tube length is available for measurement of pressures at various points in the test section or model under study. This manometer was designed with a quick-acting valve which freezes simultaneously the readings of all fourteen channels so that they can conveniently be read after a run (*see* FIG. 7). The time required for stabilization of the readings of this manometer is of the order of 5 seconds.

Temperature — The temperature of the air in the tank and in the settling chamber of



SCHLIEREN ARRANGEMENT
1"x3" SUPERSONIC WIND TUNNEL

FIG. 5



SCHLIEREN OPTIC STAND

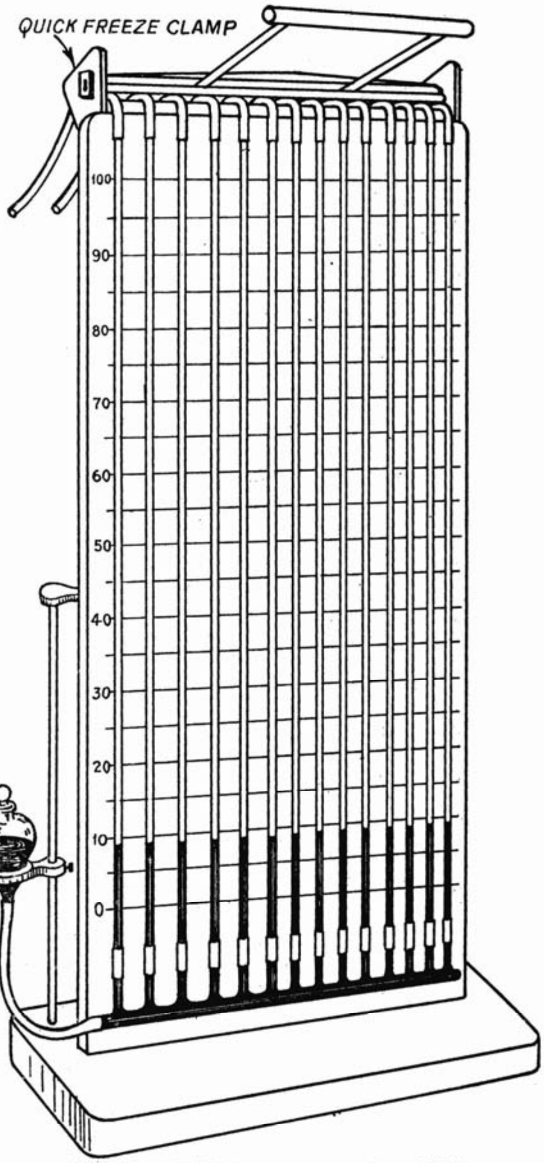
FIG. 6

the tunnel is measured by means of calibrated copper-constantan thermocouples installed in the two locations. The thermo-junctions were constructed from 1 mil. dia. wires so that they have very small thermal lag. The thermocouple output is indicated on a sensitive Leeds and Northrup suspension galvanometer equipped with a lamp and scale arrangement — the scale directly indicating the temperature in degrees centigrade.

Dew Point — Since normally the moisture content of the air stored in the tank is quite low, the dew point cannot be reliably measured by the usual hygrometric techniques. So a dew point meter of the type described by Liepmann, Ref. 1, was designed. This instrument uses CO_2 expansion for cooling a small polished mirror on which the moisture condenses, the temperature of condensation being measured. The principal difference in the instrument designed here is the use of an extremely thin polished metallic mirror surface insulated from the surroundings and having the thermocouple elements directly embedded on the surface of the mirror. This resulted in an instrument with very small thermal capacity and therefore with very fast response. Details of the dew point meter are shown in Fig. 8. In actual use it is mounted directly on a CO_2 bottle fitted with a pressure regulator valve. A dew point measurement usually takes approximately 30 seconds and is usually made at the beginning, before the start of a tunnel run.

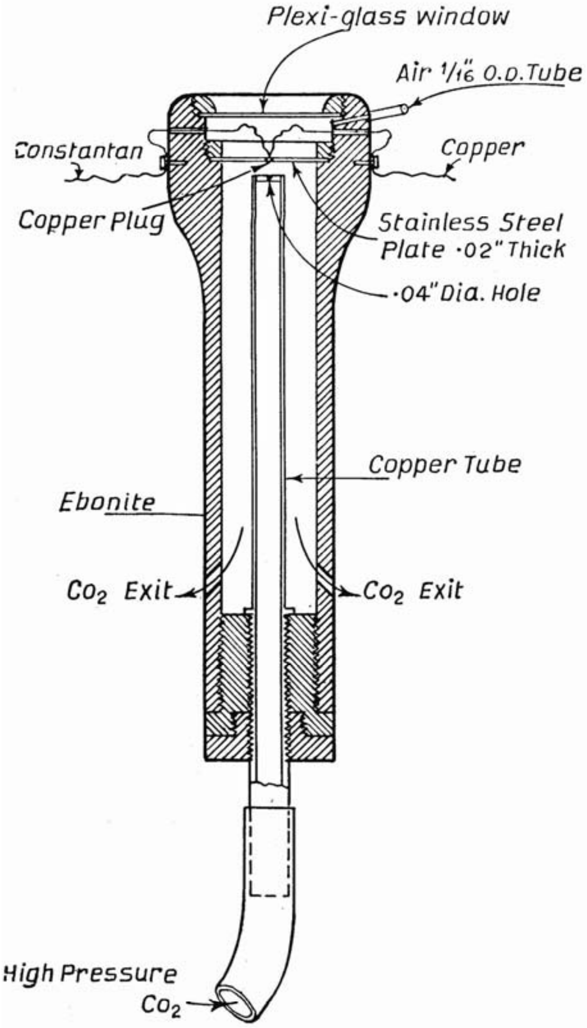
Operating Procedures for a Blow-down Wind Tunnel

Blow-down wind tunnels utilizing a compressed air storage suffer inherently from the disadvantage that the pressure, temperature and density of the air in the storage vessel decrease during a run. For some simple



14 CHANNEL MULTIMANOMETER

FIG. 7



DEW POINT METER

FIG. 8

types of tests these changes may be tolerated, but for most quantitative research one or the other variation is not permissible. The pressure variation can be eliminated by controlled throttling during a run, but the temperature variation is more serious and usually is not handled in a simple manner. The mass flow through the tunnel being of the order of several pounds of air per second, the problem of heating the air becomes rather complex and costly. These factors of cost and mechanical complexity would seem to reduce the advantages of low cost and simplicity, which are the principal features to recommend a blow-down supersonic wind tunnel.

If a blow-down supersonic tunnel were allowed to run without regard to the variation of parameters such as pressure, etc., due to expansion, one may summarize the important changes as follows:

(1) Total and static pressure changes
(2) Total and static temperature changes
(3) Reynolds number changes due to (1) and (2)
(4) Mach number changes due to (3)

Effects of Changes in the Flow during Uncontrolled Operation

Pressure — The pressure change in the storage tank, due to the expansion of air, causes the tunnel stagnation and proportionately the static pressure to fall. For the 1 in. × 3 in. tunnel installation this amounts to a stagnation pressure decrease of approximately 55 per cent in the worst case and about 15 per cent under the most favourable conditions. One effect of such a pressure change is to subject the tunnel structure to dynamic loading conditions. These must be allowed for in the structural design of the components — especially in the region of the test section. Another effect of the change in pressure level during a run is reflected in a corresponding change in the dynamic pressure. The principal effect of this would be on the force experienced by models of airfoils, etc., under test in the tunnel. The fact that the force is a continuously varying one does not in itself constitute a very serious drawback as far as force determination is concerned. Standard electronic equipment used for the recording of dynamic phenomenon

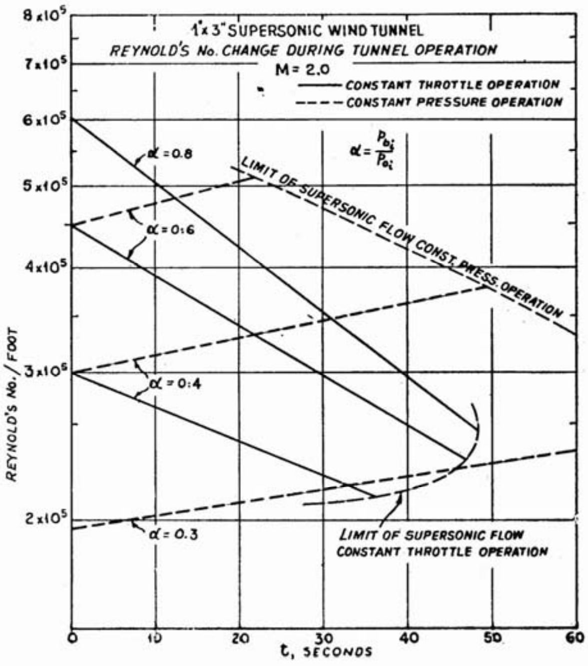


FIG. 9

such as vibrations can adequately handle this problem (*see* Ref. 2). Such equipment, of course, introduces additional questions of increased cost and complexity. On the other hand, the fact that the force on the model is quite large at the beginning of a run and decreases appreciably towards the end calls for the supporting system of the model to be designed for the starting conditions. Questions of tunnel blockage by the support system would have considerable importance specially in the low Mach number region. The adverse effects of the pressure changes can be eliminated to a large extent by adopting the constant pressure method of throttle operation and the starting loads can be decreased by starting the tunnel at low stagnation pressure values. Another important effect of the pressure changes is on the Reynolds number.

Temperature — Unless the air flowing through the tunnel settling chamber is continuously heated, its temperature must fall due to the effect of expansion in the tank. The adiabatic temperature drop, due to expansion from an initial pressure of 100 p.s.i.a. and an initial temperature of 30°C. during a tunnel run at $M = 2{\cdot}3$, would be of the order of 90°C. Actually due to heat transfer effects this drop is reduced considerably. For the 1 in. × 3 in. tunnel it is of the order of only 30°C. at $M = 2{\cdot}3$. As far as the structural design of the tunnel is concerned, this does not pose any additional problem since it is the usual practice to allow for such temperature changes in piping and ducting installation. Also the drop of temperature has no deleterious effect on any of the materials of construction that are used in the tunnel construction. The major effect of the temperature change is on the Reynolds number and hence on boundary layer phenomenon associated with it. Temperature changes would, of course, render the study of heat transfer phenomenon practically very difficult.

Reynolds Number and Mach Number — Due to the pressure and temperature changes the Reynolds number and hence all effects dependent on the Reynolds number would be subject to change during the tunnel operation. If no control whatsoever is exercised on the air flow from the storage tank then the Reynolds number would decrease during a run. The magnitude of this decrease can be seen from Fig. 9 for a representative case at $M = 2{\cdot}0$. The same figure also shows the Reynolds number increase if the pressure is maintained constant during a tunnel run. The effects of such Reynolds number changes would be twofold. Firstly, on the flow in the tunnel test section and, secondly, on the model under study. A Reynolds number change is intimately associated with boundary layer changes which in turn modify the actual

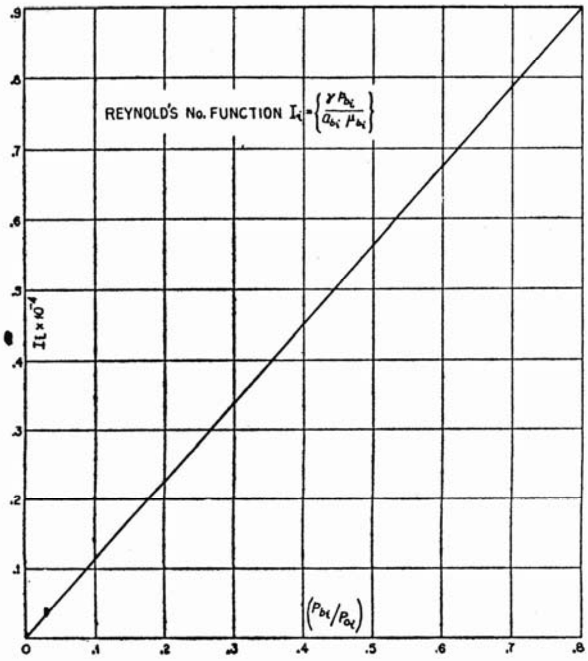


FIG. 10

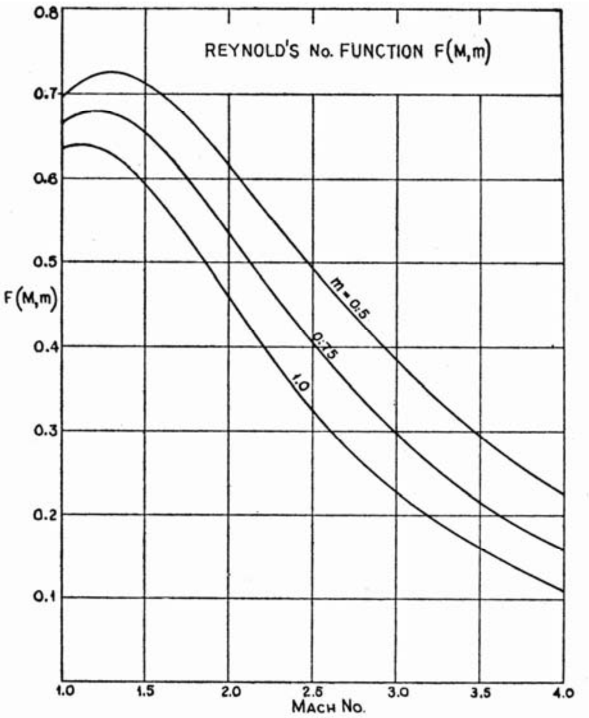


FIG. 11

uniform flow, to maintain which is always the aim of a good design. On the assumption that at the start of a tunnel run the flow was uniform, a Reynolds number change, due to the combined changes in pressure and temperature, would induce changes in the thickness of the boundary layer on the tunnel walls, thus causing an effective area change in the tunnel cross-section. This area change would, generally speaking, be reflected in a Mach number change as well as a departure from the original uniformity of flow. Such changes in Mach number are relatively small (being usually less than 2 per cent for the 1 in. × 3 in. tunnel), but they may become important in certain types of work. Boundary layer changes produced on the model or a surface under study can be much more serious, since shifts in transition and thickening or thinning of the boundary layer under study would render the measurements of doubtful value. The importance of this for controlled study of complex phenomenon, such as boundary layer shock wave interactions or the mechanism of transition from laminar to turbulent flow, is obvious.

Reynolds Number Control

The above discussion shows the importance of controlling the Reynolds number during a run. Fortunately, this is possible by a rather simple method without resorting to the expense and complexity of heating the air. This method is based on the possibility of controlling the blowing pressure in the settling chamber of the tunnel independently of the temperature drop due to expansion. In a blow-down type installation with a throttle valve between the settling chamber and the pressure storage vessel (*see* FIG. 1), the tunnel stagnation may be varied within a very wide variety of ways. Since the tunnel running times are relatively short, the manner of temperature fall in the storage vessel is not seriously affected by the manner of pressure control. (For an experimental confirmation of this see section below.)

The Reynolds number per unit length in the wind tunnel test section can be written as

$$\frac{\text{R.No.}}{\text{d}} = \frac{\rho \text{u}}{\mu}$$

where ρ = density of the air in the test section
u = velocity of the air in the test section
μ = coefficient of viscosity in the test section
d = length entering into the Reynolds number

The viscosity coefficient μ is independent of the pressure and depends only on the absolute temperature of the air. This dependence is very closely represented by a power law. Using this power law representation of the viscosity and the isentropic flow

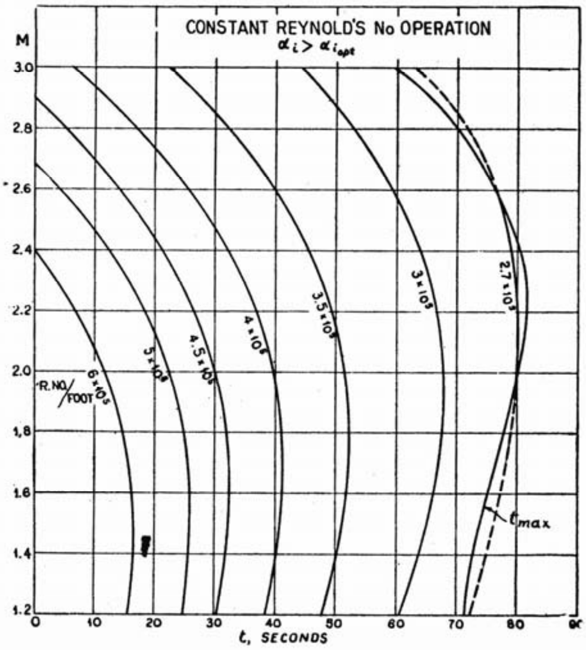


FIG. 12

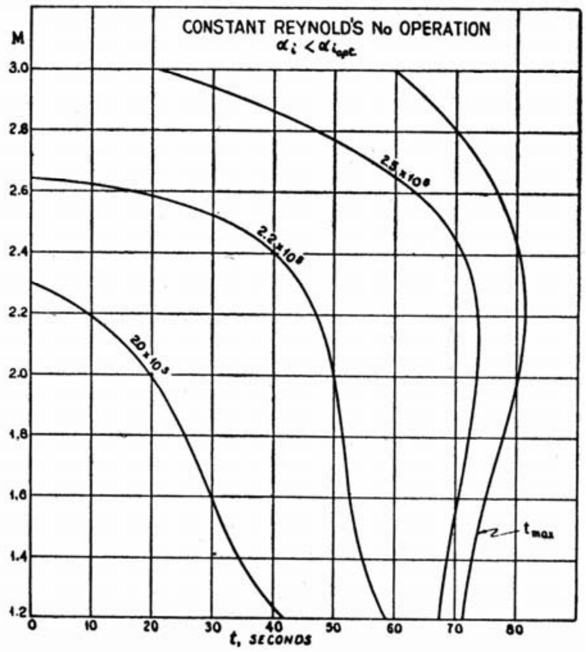


FIG. 13

relations governing the flow of air in the tunnel the Reynolds number can be expressed as

$$\frac{\text{R.No.}}{\text{d}} = \text{I}_\text{i}\,\text{F(M, m)} \left\{ \frac{\left(\frac{\text{P}_\text{b}}{\text{P}_{\text{b}_\text{i}}}\right)}{\left(\frac{\text{T}_\text{b}}{\text{T}_{\text{b}_\text{i}}}\right)^{\text{m}+\frac{1}{2}}} \right\}$$

where I_i = a function of initial starting conditions of the tunnel

F(M, m) = a function of Mach number and the viscosity index m

The function I_i determines the numerical value of the Reynolds number, but is independent of time. Similarly F(M, m) is independent of time for a given Mach number. The functions I_i and F(M, m) are shown graphically in Figs. 10 and 11 respectively. We thus see that in the expression for the Reynolds number the only time dependent quantities are the pressure and temperature in the settling chamber. It is clear from the expression that if the pressure variation can be arranged to compensate the effect of the temperature drop the Reynolds number will remain fixed during a tunnel run. This pressure control may readily be arranged with the wheel throttle valve. In general for a smooth, continuous operation of the throttle valve, the total pressures on its upstream and downstream side may be represented by a law of the form

$$\text{P}_\text{b} = \alpha \text{P}_\text{o}^{\beta}$$

where P_b = total pressure downstream of valve (stagnation in settling chamber)

P_o = total pressure upstream of valve (stagnation in storage tank)

α, β = constants

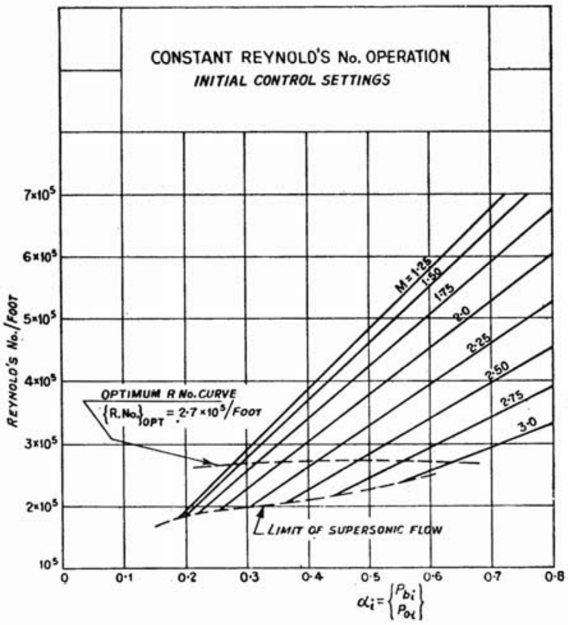


FIG. 14

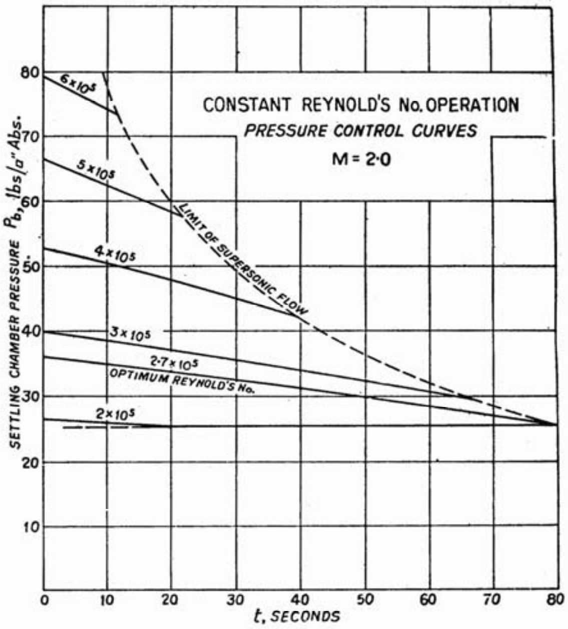


FIG. 15

With a pressure low of this form, the value of the constants α and β can be determined, to give any desired Reynolds number variation. In particular for maintaining constant Reynolds number α and β have the values

$$\alpha = \frac{\text{P}_{\text{b}_\text{i}}}{\text{P}_{\text{o}_\text{i}}^{\frac{(2\text{m}+1)(\text{n}-1)}{2\text{n}}}}$$

$$\beta = \frac{(2\text{m}+1)(\text{n}-1)}{2\text{n}}$$

Here n is the index governing the polytropic expansion of air during a run. The actual pressure drop in the settling chamber with time can now be worked out. This calculation shows the pressure variation to be

$$\frac{\text{P}_\text{b}}{\text{P}_{\text{b}_\text{i}}} = (1 - \text{A t})^{\text{B}}$$

where A = A (n, m, M)

B = B (n, m)

The parameters A and B are constant for a given Mach number and Reynolds number. It is thus possible to obtain the entire running characteristics of the tunnel over a range of Reynolds and Mach numbers giving the throttle setting, pressure variation and maximum operating times, etc. For the 1 in. × 3 in. supersonic tunnel, such calculations have been carried out for all the three types of operation, viz. constant Reynolds number, constant pressure and constant throttle setting.

Constant Reynolds Number Operation — Figs. 12 and 13 show the duration of tunnel runs at various Mach numbers and Reynolds numbers. These figures show that the $t_{MAX.}$ line is closely approximated by the Reynolds number/foot line of $2{\cdot}7 \times 10^5$. This is, therefore, an optimum value of the Reynolds number for the entire range of Mach numbers, since operation at this Reynolds number results in amximum time of supersonic operation. For the 1 in. × 3 in. tunnel $t_{MAX.}$ is seen to be 60 seconds or more over the entire Mach range. The throttle settings required to obtain any desired Reynolds number for a given Mach number are shown in Fig. 14. For a representative case of Mach number of 2·0 the corresponding pressure control curves are shown in Fig. 15. The pressure control curves for the optimum operation are given in Fig. 16 for the entire working range of the 1 in. × 3 in. tunnel. An interesting feature of the constant Reynolds number operation is revealed by cross plotting from Figs. 12 and 13 in the form shown in Fig. 17. Throttle settings below the optimum value affect the running times to a markedly different extent than those above the optimum. As shown by Fig. 17 the running times are much more sensitive to control setting below the optimum Reynolds number curve than above it. It would therefore appear that the range above the critical setting would prove more useful in actual operation. This was actually found to be the case. However, this consideration does not seriously limit the Reynolds number range of the tunnel which is approximately $2{\cdot}5 \times 10^5$ to 6×10^5 per foot.

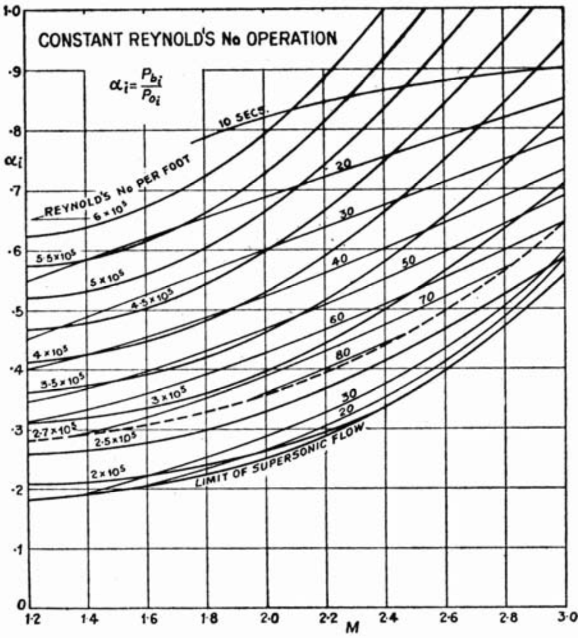


FIG. 17

Constant Pressure Operation — Such an operation is achieved by controlling the throttle valve to give constant pressure in the settling chamber. In most blow-down tunnel installations, the constant pressure is maintained by an automatic throttle valve operated by a servomotor which itself derives its controlling pressure from a feedback of the controlled settling chamber

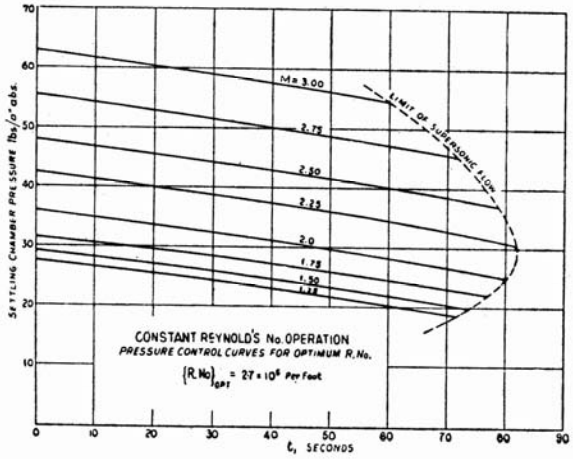


FIG. 16

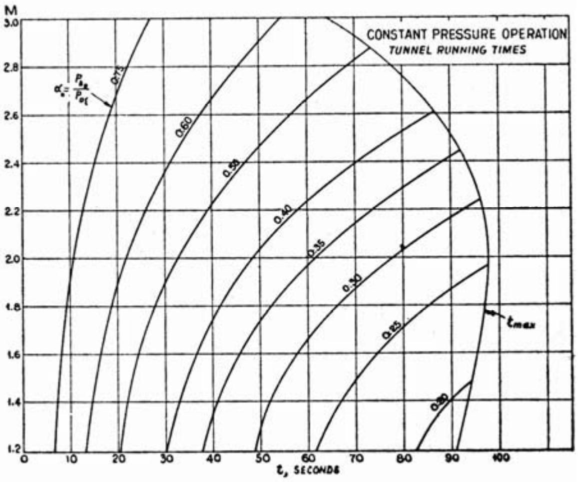


FIG. 18

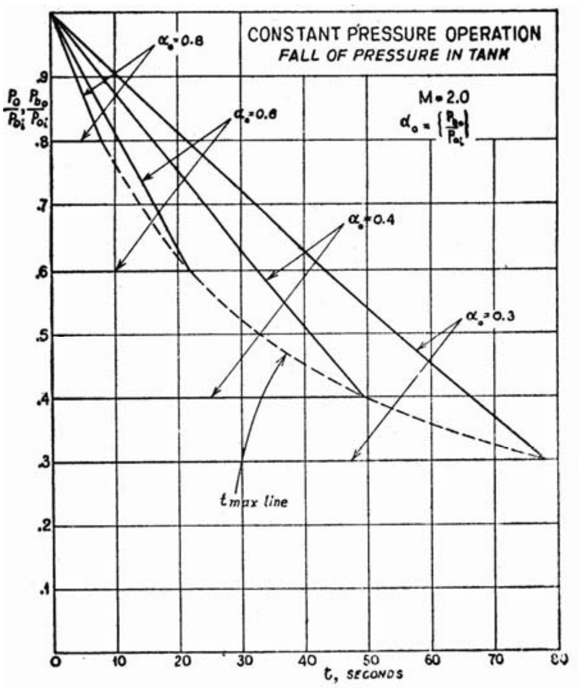


FIG. 19

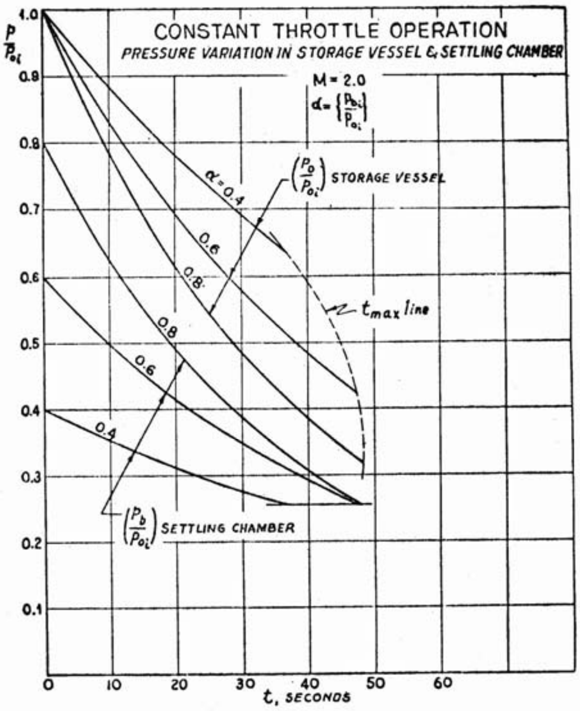


FIG. 21

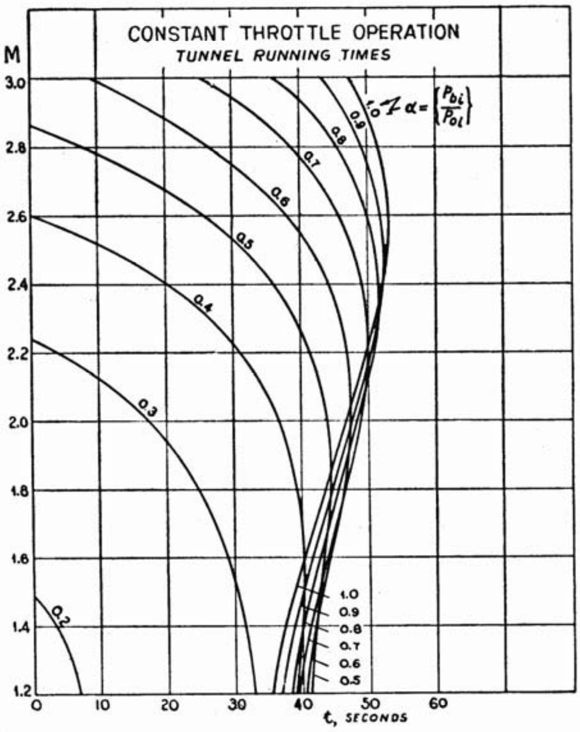


FIG. 20

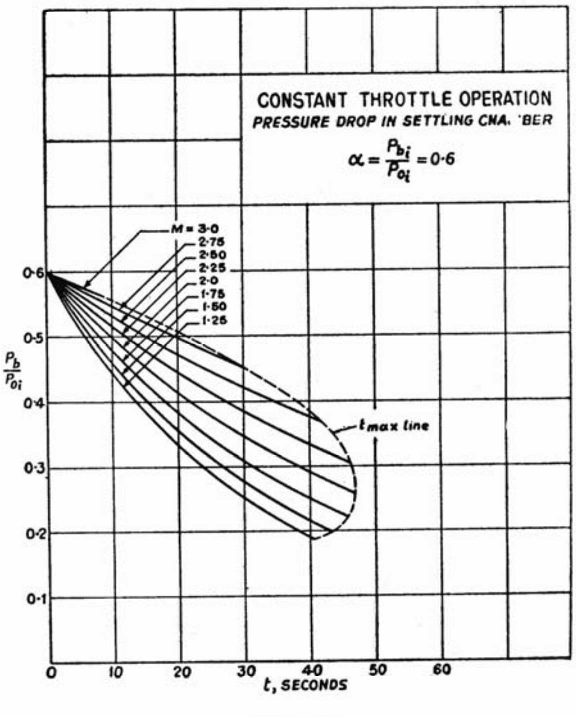


FIG. 22

pressure. This automatic method is being incorporated in the larger 5 in. × 7 in. supersonic tunnel installation under construction at the Indian Institute of Science, Bangalore. For the tunnel described in this paper the control is manual, but no difficulty has been experienced in maintaining the constant blowing pressure to within $\pm\frac{1}{2}$ p.s.i.a. Fig. 18 shows the running times of the 1 in. × 3 in. tunnel at various pressure levels. The value of β in the pressure law is $\beta = 0$ for such constant pressure operation. The fall of pressure in the storage tank under constant tunnel pressure conditions is shown in Fig. 19, for M=2·0. Of course, constant pressure operation is accompanied by a Reynolds number increase due to the uncompensated temperature drop. Fig. 9 indicates the magnitude of this increase, for M=2·0.

Constant Throttle Operation — This is the simplest mode of operation of a blow-down tunnel. It consists of setting the wheel throttle at some predetermined opening and then operating the quick-acting valve. Supersonic flow is established in the test section within approximately half a second and is maintained until the pressure in the settling chamber drops to a value equal to the minimum necessary for supersonic flow at the nozzle Mach number. With the throttle fixed, the settling chamber pressure is in a fixed proportion to the tank pressure. This corresponds to a β value of 1·0 and a pressure law of the form

$$P_b = \alpha P_o \quad \text{with} \quad \alpha = \text{constant}$$

Figs. 20, 21 and 22 are typical control charts for such operation. They give the initial settings, time of run and manner of pressure drop in both the settling chamber as well as the tank. The magnitude of Reynolds number changes during such run is indicated on Fig. 9. It will be noticed by a comparison of Figs. 12, 13, 18 and 20, that constant throttle operation affords the least running times among the three modes discussed, but nevertheless these times are of considerable duration being approximately 30 seconds or more over a major portion of the operating range of the tunnel.

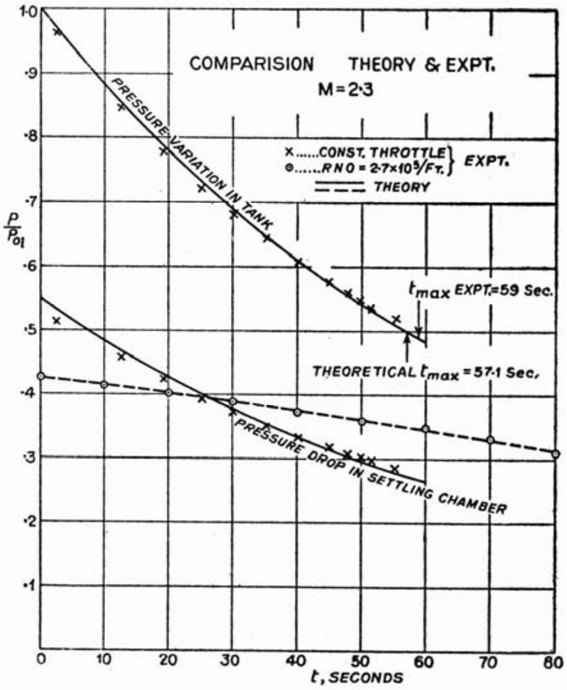


Fig. 25

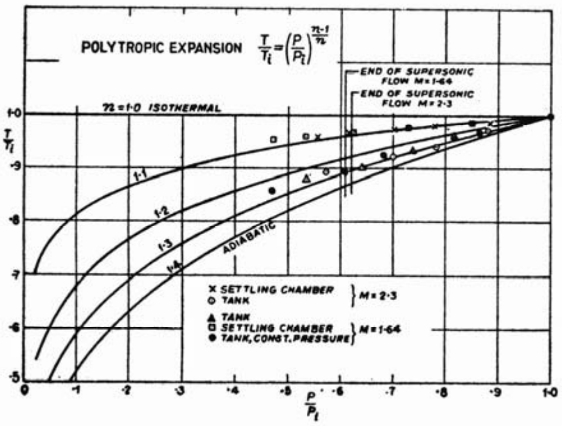


Fig. 23

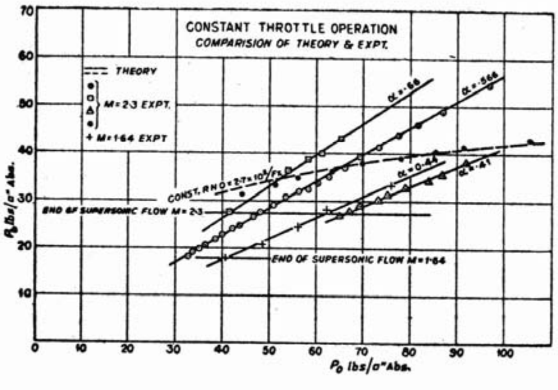


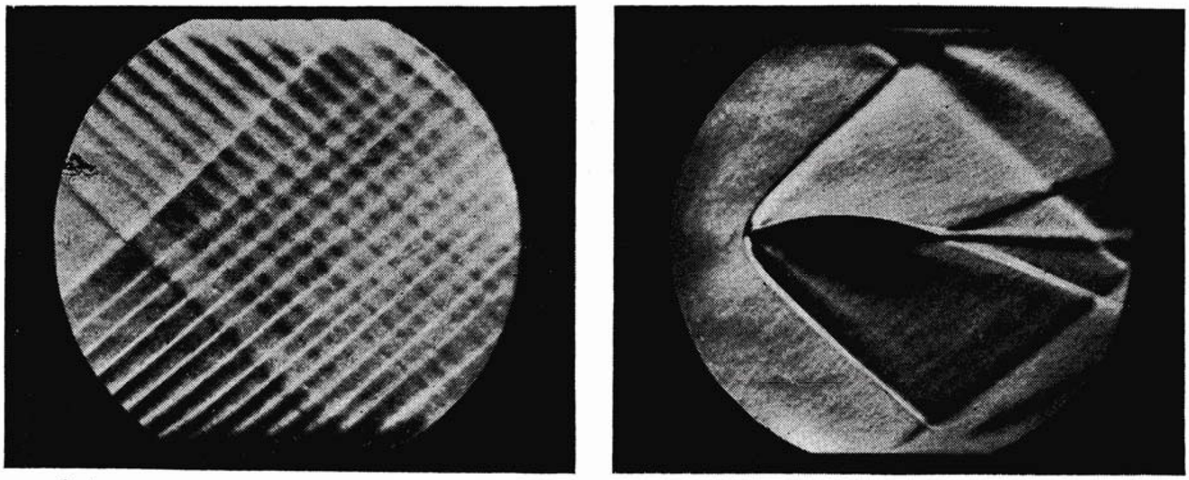
Fig. 24

Remarks on the Choice of the Method of Tunnel Operation

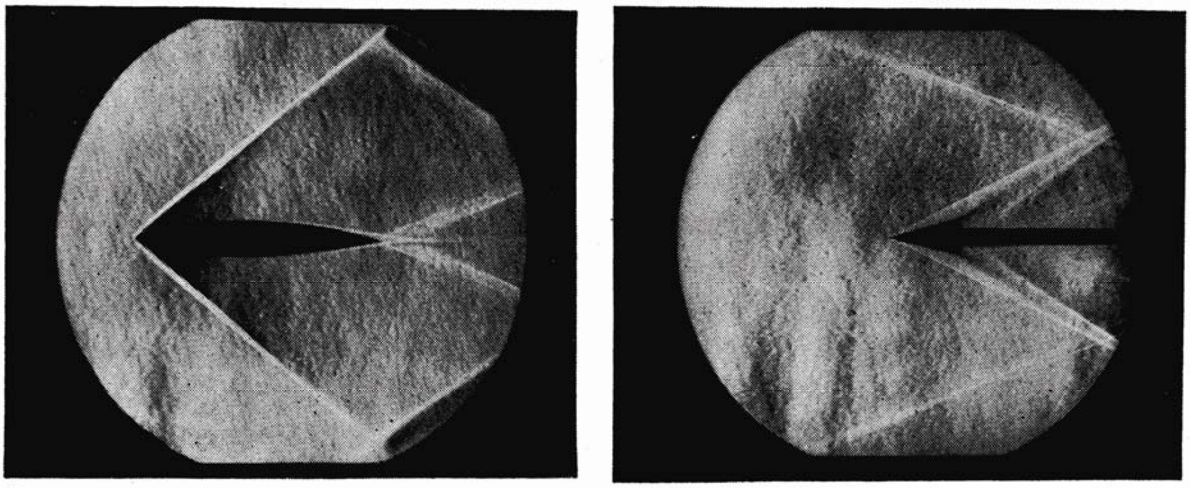
The choice of operating mode in any given investigation would be largely determined by the intrinsic requirements of that research, but a few general remarks may be of help in deciding the suitability. Most investigations into boundary layer phenomenon would generally require the constant Reynolds number method. It is conceivable, however, that some types of research into even viscous phenomenon would make use of the changing Reynolds number provided by the constant pressure and constant throttle methods. The intermittent blow-down tunnel with its Reynolds number control should provide a good possibility of investigations into boundary layer phenomenon on accelerating or decelerating bodies. The constant pressure method requires comparatively simple instrumentation, thus for experiments such as pressure distributions on wing surfaces, such a method would be adequate. Of course, care would have to be taken that the Reynolds number changes with their associated secondary effects can be tolerated. For qualitative work, such as study of shock wave patterns, the constant throttle mode is the simplest and most readily adopted. None of the three methods discussed here would be suitable for heat transfer research which requires a high degree of temperature stability. For such research the continuous type of wind tunnel would be superior.

Checks with Experiment

The theoretical analysis outlined above was checked against the operation of the 1 in. × 3 in. tunnel installation. Temperature drop measurements were made in the settling chamber and the storage tank in order to test the validity of the assumption that temperature drop due to expansion was independent of the method of pressure control. Fig. 23 shows the results of some of these measurements and shows that the nature of the temperature variation, as reflected in the value of the index n, is essentially independent of the type of operation or Mach number. It will be, however, seen that, although constant, n has a



(a) FLOW PAST WIRE TRIPS M=1·55 (b) ROUND NOSED 19% BICONVEX AIRFOIL M=2·3



(c) SHAP NOSED 15% BICONVEX AIRFOIL M=2·3 (d) 30° TOTAL ANGLE CONE M=2·62

SCHLIEREN PHOTOGRAPHS

FIG. 26

different value for the settling chamber and the tank. This is due to the difference in heat transfer at the two locations. The tank air gains additional heat from the surroundings during transit to the settling chamber so that the polytropic index for the air in the settling chamber is closer to the isothermal value. In calculating the tunnel running characteristics a value of n, average between that for the tank and the settling chamber, may be used. This procedure considerably simplifies the calculations and gives results very close to those obtained by using the separate indices. Fig. 24 shows the experimental values of the pressures in the tank and the settling chamber for some constant throttle runs. The experimental values confirm the straight line relationship between the two pressures for this type of operation. Fig. 25 shows a comparison of the observed and calculated values of the pressure drop and running times for a Mach number of 2·3. In calculating the theoretical values the measured value of n and the observed minimum pressure ratio for supersonic flow were used. Figs. 24 and 25 also show a representative case of the constant Reynolds number operation. The measured values compare very well with the predicted ones bearing out the theoretical reasoning underlying the method.

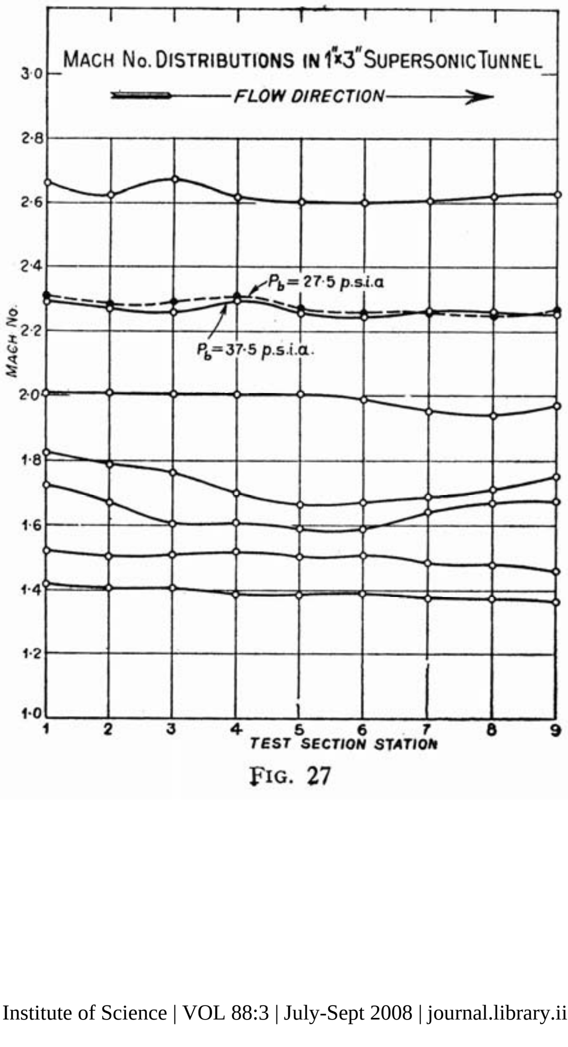


FIG. 27

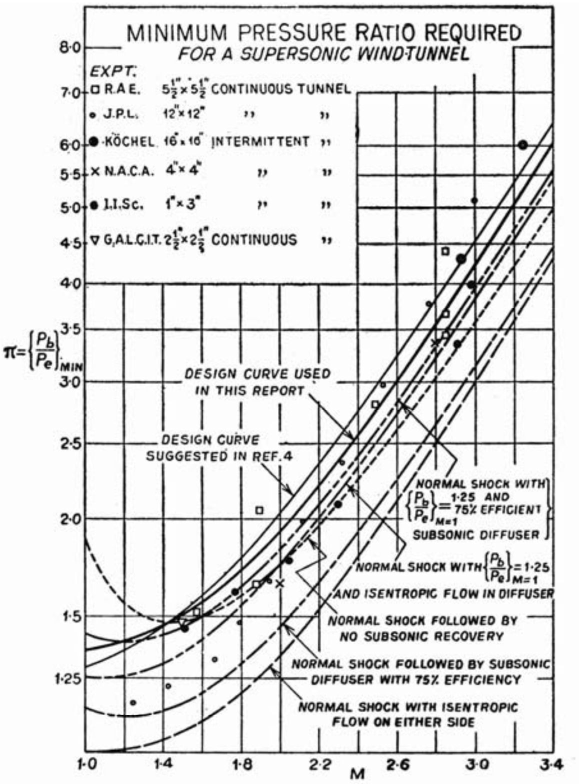


FIG. 28

Flow Photography

Since the window glass and the optical components of the Schlieren system are not of first quality, the resultant flow pictures are not completely free from extraneous striae. These imperfections, however, do not obscure any important details of the flow and do not impair the study of shock waves or friction layers, etc. The quality of the photographs can be seen from some representative samples shown in Fig. 26. Figs. 26(a) is a Schlieren photograph of supersonic flow at M = 1·55. The mesh-like wave pattern seen in this photograph is caused by a row of 0·006 in. dia. wires fixed to the nozzle walls. Figs. 26(b) and (c) show flow past biconvex airfoil profiles at M = 2·3. The boundary layer on the airfoils and the wakes are clearly visible. Fig. 26(d) shows a 30° total angle cone at M = 2·63.

Nozzle Pressure Distributions

Each set of supersonic nozzles has been calibrated for flow uniformity. The pressures were measured on the mercury multi-manometer equipped with quick-freeze arrangement. Fig. 27 shows some of the results over the working range of the 1 in. × 3 in. tunnel. In order to evaluate the effect of Reynolds number change on nozzle flow, some experiments were conducted using the constant throttle operation and recording the pressures at the start and at the end of a run. Fig. 27 shows the record of one such experiment at $M = 2{\cdot}3$. It shows that the Mach number distribution is changed but not to an intolerable extent.

Minimum Pressure Ratio for Supersonic Flow

The required pressure ratio for establishing and maintaining supersonic flow in a wind tunnel is that necessary to overcome the energy losses during flow. These losses include direct dissipation due to friction as well as those associated with other non-isentropic phenomenon such as shock waves and diffuser losses, etc. The exact computation of these losses has so far not been possible. Using simplified analysis (Refs. 3 and 4), it is possible to assess the important parameters involved and obtain qualitative information about the magnitude of the losses. The best procedure for practical design is to correlate the results of such simplified analyses with experimental data from wind tunnels and use numerical values with a certain margin of safety. A collection of the results of such a procedure are shown in Fig. 28, where several theoretical curves are given and the experimental data available in the literature are collected for comparison. On this basis a design curve for supersonic wind tunnels is developed. The pressure ratios given by this curve are conservative without being unrealistic. This curve is the basis of the calculation for maximum running times, etc., in this paper. Several experimental points obtained in the 1 in. × 3 in. blow-down tunnel are also shown in Fig. 28. In general, they show the tunnel to be an efficient one with somewhat better pressure recovery than indicated by the conservative design curve.

Acknowledgments

This project was initiated by Mr. K. Krishnamurty, but unfortunately he left the Indian Institute of Science before any of the tunnel components could be designed. Credit is due to the Hindustan Aircraft Ltd., Bangalore, for fabricating the test section. Special acknowledgment is made to the members of the Aeronautics Workshop of the Indian Institute of Science. The successful completion and operation of the installation is due, in no small measure, to their co-operation and efforts. The author wishes to thank Messrs R. Narasimha, B. V. Venkatesh, A. Das and M. A. Badrinarayanan, for their help at various stages.

References

1. LIEPMANN, K. & LIEPMANN, H. W., " A Dew-point Meter using cooling by Expansion of CO_2", *The Review of Scientific Instruments*, Vol. 16, No. 2, 1945.
2. LUKASIEWICZ, J., " Development of Intermittent Wind Tunnel Technique", *National Aeronautical Establishment Report* 1954, Ottawa, Canada.
3. CROCCO, L., " High Speed Wind Tunnels", *L'Aeronautica*, March 1935.
4. LUKASIEWICZ, J., "Supersonic Diffusers", *R. & M. No.* 2501.

APPENDIX I

Standard Conditions

In calculating the operating characteristics of the 1 in. × 3 in. supersonic wind tunnel, the following were adopted as the standard conditions. The temperatures assumed represent average values most likely to obtain throughout the year.

Volume of air storage tank (including volume of ducting up to valves) = 327·5 cu. ft.

Initial pressure of air in storage tank = 100 p.s.i.a.

Initial temperature of air in storage tank = 32°C.

Velocity of sound at 32°C. = 1150 ft./sec.

Coefficient of viscosity of air at 32°C. = $1{\cdot}247 \times 10^{-5}$ lb./ft. sec.

In the comparison between experimental values and theory, actual values obtaining at the time of the experiment have been used.

APPENDIX II

COST BREAK-DOWN OF 1 IN. × 3 IN. SUPERSONIC WIND TUNNEL

ITEM	COST Rs.	% OF TOTAL	SOURCE OF SUPPLY OR MANUFACTURER
Power Plant			
Air storage tank	5,285		Mazagon Docks, Bombay
Installation cost of tank	320		I.I.Sc., Bangalore
8·5 h.p. compressor	843		Broomwade, England
Motor and starter	1,048		Brown Boveri, Switzerland
After cooler and moisture separator	1,700		Consolidated Pneumatic Tool Co., England
Dryer construction cost	150		I.I.Sc., Bangalore
Dryer silica gel	570		National Industries, Bangalore
	9,916	59·6	
Tunnel Proper			
Test section	2,000		Hindustan Aircraft Ltd., Bangalore
Settling chamber and contraction	1,240		Steel Construction Co., Bangalore
Piping with fittings	796		Second hand, Bombay
Control valves	384		Commercial Equip., Bombay
Diffuser	200		I.I.Sc., Bangalore
	4,620	27·8	
Instrumentation			
Schlieren optics	120		Gowllands', England
Camera	95		I.I.Sc., Bangalore
Optical stands	150		I.I.Sc., Bangalore
Knife edge and slit	45		I.I.Sc., Bangalore
Light source AH-4 lamp	140		G.E., U.S.A.
Pressure gauges	120		Second hand, Bangalore
Multimanometer	40		I.I.Sc., Bangalore
5 sets supersonic nozzles	100		I.I.Sc., Bangalore
Dew point meter	30		I.I.Sc., Bangalore
	840	5·1	
Engineering Time	1,000	6·0	I.I.Sc., Bangalore
Miscellaneous	250	1·5	
TOTAL COST	16,626	100	