TRAINING CENTER FOR EXPERIMENTAL AERODYNAMICS

TECHNICAL MEMORANDUM 7

THE T.C.E.A.

CONTINUOUS SUPersonic WIND TUNNEL S-1

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This memorandum has been produced primarily for the information of students at the Centre. It describes the essential physical features of the continuous supersonic wind tunnel S-1 but does not include such details of performance as the distribution of Mach number in the test section or of measured values of humidity in the tunnel during operation.
INTRODUCTION

The (S-1) 40 cm x 40 cm (16" x 16") supersonic wind tunnel, built in 1950 is a copy, with some changes in detail, of the continuous variable-density supersonic tunnel installed at Zurich E.T.H. and designed by Professor Ackeret.

The driving unit is a 13-stage axial-flow compressor powered by a d.c. motor having a maximum continuous rating of 615 Kwatts at 4,000 r.p.m. This power is such that the stagnation pressure of the tunnel is limited to 0.3 ata at a test Mach number of 2.25. Thus the maximum Reynolds number at this speed is about $3.5 \times 10^5$ per meter ($1.1 \times 10^6$ per foot).

A silicagel dryer, located in a by-pass and designed to reduce the humidity level of the tunnel to $2 \times 10^{-4}$ at a pressure of 0.1 ata, was installed in 1958.

For supersonic operation, the tunnel is fitted with a fixed-geometry metallic nozzle coated with araldite and designed for a Mach number of 2.25. The test section is followed by a variable geometry diffuser incorporating a sting support rig allowing for change of model incidence and also for displacement of probes in three directions.

An alternative transonic test section (also 40 cm x 40 cm) comprising two slotted (horizontal) walls and two plain (vertical) walls, designed by NASA, was built by T.C.E.A. in 1959. The available power limits the Reynolds number to about $4.7 \times 10^6$ per metre ($1.5 \times 10^6$ per foot) at $M = 1$. 
Figure 1 is a vertical cross-section of the tunnel. The 13-stage axial flow compressor (3) is driven through a step-up gear (2) (ratio 3.4/1) by a D.C. motor (1). A variable voltage is supplied by an MG set working on 6,000 volts A.C. The maximum continuous power is 615 kwatts, but 800 kwatts can be used for 15 minutes.

The circuit, made of steel, is sealed; it has a total volume of about 60 m$^3$ and can be evacuated with a vacuum pump (9) down to 0.1 ata in about 30 minutes. This pump is connected through a pipe (a) to the high-pressure side of the main compressor and is used both for reducing the tunnel pressure for starting and also for modifying the stagnation pressure while the tunnel is running. The pressure is maintained at a constant and adjustable value by a regulating valve (13) fed with air passing through the auxiliary dryer (7). The pressure level in the circuit can be rapidly raised to atmospheric by means of the hydraulic valve (12).

A by-pass line (11) is used to match the compressor and nozzle mass-flows in order to avoid surging of the compressor. The surplus air is drawn from the space, vented to the settling chamber, between the circular outer-wall of the tunnel and an inner shell of rectangular cross-section. The cooler (3) is located in the settling chamber. It is followed by antiturbulence screens: three 13-mesh screens (0.5 mm diameter) plus two 55-mesh screens (0.2 mm diameter).

The main silicagel dryer (8) is located in a by-pass line. The working section is formed by a nozzle with fixed blocks (4) followed by a variable-throat diffuser. Inside lighting (b) is provided at the top surface of the test section. Models are held either by a sting support rig located in the diffuser or by supports fixed to the lower surface of
the test chamber.

A safety screen (6) is located downstream of the test section. Access to the return circuit is obtained by a man-hole (10).

The whole circuit is rigidly fixed to the ground only at the compressor and the cooler, the rest of the circuit being mounted on springs and sliding supports.

 SUPersonic nozzle

The tunnel is equipped with a nozzle designed for a Mach number of 2.25, using the Friedrichs methods. The coordinates of the contoured top and bottom walls were taken from reference 1 and corrections were made for a laminar boundary-layer using the theory derived in reference 2. The test section is 40 cm x 40 cm (16" x 16").

The blocks, made of light alloy steel, were cast and coated with araldite using the technique developed in L.R.B.A. (Vernon, France); i.e. two accurately machine brass templates, were fastened to the sides of each block leaving a gap at the contoured surface which was then filled with a mixture of araldite and fine metallic powder, the surface profile being obtained by a straight-edge supported on either side by the templates and moved over the contour at a constant, low speed. The nozzle surface was then polished.

The entrance portion of the nozzle is formed by small auxiliary blocks and flexible plates as shown in figure 2. The exit section is followed by flat surfaces. The top one includes inside lighting of the tunnel and the bottom one can be used to support large models as shown in the same figure.
Each block, weighing approximately 125 kilogrammes, is fixed to the tunnel walls by adjustable supports. The supports were calculated for an average pressure of 1500 kg/m² acting on the 0.5 m² nozzle surface. Later tests showed that a local pressure of 400 kg/m² existed at a stagnation pressure of 0.1 ata, during starting and stopping operations of the nozzle. Fluctuations of ± 100 kg/m² around this value were recorded having a frequency of about 20 c/sec. The supports can thus withstand the loads which would arise in an emergency stopping of the tunnel at a relatively high stagnation pressure (i.e. 0.3 ata).

The nozzle is mounted in the tunnel by means of a circular steel bar inserted in a hole drilled through the center of gravity of each block as shown in figure 2. Also seen in the figure are the plastic tubes connected to the pressure orifices on the nozzle surfaces; these were used for calibration purposes.

TRANSONIC TEST SECTION

The alternative test section for transonic operation is also 40 cm x 40 cm (16" x 16"). It employs the principle of diffuser suction to generate supersonic speed which is varied by changing the rotational speed of the compressor. The test section incorporates the two vertical (side) walls (with replaceable observation windows) of the supersonic test section and replaces the top and bottom nozzle blocks by slotted walls, each wall having 10 slots. The parallel portion of the slot profile is 30 cm long and the slot width in this portion is 4.5 mm thus giving an open-area ratio of 11.25 % on each of the two walls or 5.6 % overall. The slots are tapered to zero at the upstream end and open up to merge together at the entrance to
There is a gap of 17 cm between the slotted walls and the inner surface of the tunnel structure; thus the "plenum chamber" consists of two halves (each 40 cm x 17 cm) which are connected together by a specially constructed duct to equalize the pressures in the two halves.

**DIFFUSER**

Figures 2, 3, and 4 show the diffuser. It can be used for supersonic as well as transonic operation because of its variable throat; its opening can be varied between 28 and 48 cm.

The aft section of the diffuser consists of aluminium plates, hinged at their downstream ends, and slightly curved at their upstream ends which are supported by adjustable jacks. The forward section of the diffuser consists of smaller plates hinged to the back end of the test section and spring-loaded to bear against the curved portion of the rear plates (fig. 3). The jacks are manually controlled from outside the tunnel so that the second throat can be varied while the tunnel is running.

The large plates are 3 mm thick and reinforced by three U stiffeners; they weigh approximately 50 kilogrammes each. An average load of 400 kg/m², acting on the 0.6 m² plate surface, was assumed for the strength computation. Later tests showed that local oscillatory loads of ± 100 kg/m² existed at a stagnation pressure of 0.1 ata even after the supersonic flow is established; the frequency being a few cycles per second.
A sting support rig, allowing for change of model incidence and also for displacement of probes in three-directions, is incorporated in the diffuser. It consists in an axial tube (1.1 m long) supported by two vertical screws (having a 2 mm pitch), the axes of which pass through the upper wall of the tunnel. Their motion is controlled by reversible electrical motors (fig. 4). The revolutions are recorded on counters (one revolution of both counters corresponds to a probe displacement of 0.054 mm). Both screws can be rotated independently so that vertical translation of the sting along a 40 cm range, can be obtained as well as a rotation around the center of the test section (± 7 degrees).

The sting can slide inside the axial tube; its motion is controlled by a reversible electrical motor located in the air-stream at the back end of the tube (fig. 4). It has a total range of displacement of 500 mm, one revolution on the counter corresponding to a 1/20 mm displacement of the sting.

In addition, the test section can be traversed horizontally along a 150 mm length by fixing a special head on the sting (figures 5 and 6). This consists of a horizontal slotted wedge having a 180 mm span in which a carriage can slide. The manual control is made from outside the tunnel through a flexible drive fitted with a revolution counter.

**DRYER**

The absolute humidity in the tunnel is kept below $2 \times 10^{-4}$ at a stagnation pressure of 0.1 ata by a silicagel dryer. The dryer must be in continuous operation while the tunnel is running because of air leaks. They represent about 180 gr of air entering the tunnel per minute. Thus if the dryer were stopped at the desired level of humidity ($2 \times 10^{-4}$) the amount
of water would double in one minute.

The dryer is located in a by-pass in which 10% of the main flow circulates, i.e. about 10 kg/minute at a stagnation pressure of 0.1 ata. The air passes firstly through an oil filter (activated carbon), then through the silicagel bed and finally through a dust filter. The circuit is shown in fig. 7 (from left to right: the dryer, the oil filter, the vacuum pump - at the back, behind the oil filter, is the dust filter). A small amount of a special type of silicagel (400 kg) is used in the system in spite of the low operating pressure; this is made possible by the high efficiency of the reacting cycle described below.

An auxiliary silicagel dryer (figure 8 - at the back) is used to feed the regulating valve of the tunnel with dry air (see following section) at a maximum rate of about 2 kg per minute; 400 kg of silicagel are used in the system.

Both dryers have to be reactivated after 4 runs of the tunnel of 2 1/2 hours at low pressure. The reactivation, which takes about 3 hours, can be made at night; it includes successive operations that take place automatically. First, the auxiliary dryer is reactivated with atmospheric air heated to approximately 150°C. Then, reactivation of the main dryer takes place in a closed circuit. For this operation, the air passes through the auxiliary dryer, is heated before it passes through the main dryer, and is then cooled down before it re-enters the auxiliary dryer. With this system the reactivation of the main dryer is extremely good.
The vacuum pump which is used to evacuate the circuit is a constant volume pump; it operates continuously while the tunnel is running. It compensates for the tunnel leaks and also allows the adjustment of the inside pressure level. The latter is maintained constant at any desired value between 0.05 ata and 0.3 ata by introducing an artificial leak with a regulating piston-valve fed with dry air. A beam-balance system with rider provides a variable load on the piston (figure 9), remotely controlled from the control room.

With this arrangement the tunnel pressure remains constant within a few tenths of millimetre of mercury for several hours.

**AUXILIARY CIRCUITS**

The auxiliary circuits are shown in figure 10. Circled numbers are used to ease the starting operation of the tunnel by students.

**Water circuits**

The water circulation in the tunnel heat exchanger is provided by a centrifugal pump (82). The water passes through a cooling tower (81) located on the roof of the building. During hot weather, forced convection is obtained in the tower by means of four fans.

The same water supply is used for cooling the vacuum pump (9) and the oil-cooler (17).
Oil-circuits

Oil circuits are provided for the lubrication of the compressor bearings (3) and of the step-up gear (2). (19) is the reservoir. The oil is pumped into the hydraulic circuits by the auxiliary pump (15) when the compressor is at rest. That pump automatically stops when the main pump (14) driven by the compressor itself, gives sufficient oil pressure.

The oil passes through a filter (16), then through a cooler (17) which limits its temperature to 45°C; the pressure is regulated to about 4.5 kg/m² by the regulator (18).

As the tunnel is used under vacuum conditions the design of the compressor incorporates special features to avoid leakage of oil into the tunnel air circuit. After leaving the main shaft bearings the oil is passed into a separator (29, 30, 31) to extract the air which has entered the oil circuit; this air is returned to the tunnel circuit through the orifice A. The clean oil flows in the container (32) at low pressure from which it is extracted by a gear pump (34). The electrical connections are such that this pump must necessarily be started before the oil pump can be switched on. This is done to avoid the leakage of oil into the tunnel itself. For complete safety, a floating switch (33) will stop the tunnel when the oil level gets too high in the lower container.

An emergency oil supply is maintained in a reservoir (37) located near the roof of the building. The tunnel cannot be started unless this reservoir is full. In case of emergency, this oil flows under gravity and lubricates the compressor bearings.

Electrical circuits

The description of the electrical circuits will be limited to the arrangement of the main group (figure 11). The same MG set supplies the D.C. voltage to tunnel S-1 as well as to the low-speed wind tunnels (i.e.
both tunnels cannot be operated together).

The MG set is operated on 6,000 volts A.C. and is synchronized, after starting, by the auxiliary group (23a).

The compressor motor has a constant excitation given by the group (24). Speed variation of the blowers is obtained by varying the output voltage of the MG group by potentiometer (109).

OPTICAL SYSTEM

Tunnel S-1 is equipped with an optical system for shadow and schlieren pictures.

It is a conventional Z-type (i.e. off-axis) system with two parabolic mirrors (focal length: 213 cm; diameter: 30 cm). A mercury vapor lamp (500 watts) is used for visual observation; it is operated on A.C. voltage but can be supplied with direct current when movies are taken. Pictures are generally taken with a spark obtained by the discharge in the air of a condenser at 12,000 volts. A plane mirror rotates to select the desired light source (figure 12). The selection is made automatically from the control room of the tunnel.

The light sources and the first mirror are located in a dark room. The light beam passes through a duct connecting the dark room to the rear window of the test chamber. With this arrangement, shadowgraphs can be taken by mounting a plate holder on the front window.

The second mirror is in a dark box connected to the front window by another duct (removed in figure 13). The light falls on the
knife-edge as it goes out again from the box. By rotation of a prism, the image can be focused either on a screen in the control room or on the photographic film. An aerial camera (type Kodak K-24, U.S. Army surplus) is used giving pictures of 11.5 cm in diameter (figure 13). It contains a roll on which a maximum of about 150 pictures can be taken automatically from the control room.

The tunnel windows are of optical quality, having a diameter of 31 cm and a thickness of 20 mm.

REFERENCES


2. WALZ - Approximate Computation of Laminar Compressible Boundary-Layers
   L.R.B.A. Vernon (in German). Berichts N° 9 and 19/47 and 3.48.
Fig. 2 - Nozzle and Diffuser

Fig. 3 - Back End of Test Section

Fig. 4 - Nozzle and Diffuser
Fig. 5 - Surveying Mechanism

Fig. 6 - Surveying Mechanism
Fig. 7 - Circuit of the Main Dryer

Fig. 8 - Auxiliary Dryer and Part of the Reactivation System
Fig. 9 - Regulating Valve
Fig 10. AUXILIARY CIRCUITS
Fig. 11  MAIN ELECTRICAL CIRCUITS.
Fig. 12 - Light Sources

Fig. 13 - Knife and Camera
A description of the T.C.E.A.
40cm x 40cm continuous supersonic wind tunnel is given with details of the nozzle, diffuser, dryer and optical system.

A description de la soufflerie supersonique 40cm x 40cm du CFAE est donnée, comprenant principalement des détails sur la réalisation de la tuyère du diffuseur, du dessiccateur et du système optique.
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