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THE CRANFIELD HELIUM HYPersonic WIND TUNNEL -
TUNNEL, PLANT AND INSTRUMENTATION

- by -

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The philosophy behind the use of helium as a wind tunnel working fluid is discussed and its advantages over air for the simulation of flows of high Mach number and high Reynolds number are presented.

Much of the report is devoted to the design and construction of the Cranfield Helium Tunnel and the detailed operation of both plant and instrumentation. A brief outline is given of the tunnel operating range and the type of work which is projected for the future.

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LIST OF SYMBOLS

A  flow area
a  local speed of sound = $\sqrt{\gamma \frac{p}{\rho}}$
l  length
M  Mach number = $v/a$
p  pressure
R  Reynolds number = $\frac{v \ell \rho}{\mu}$
T  Temperature
v  flow velocity

$\gamma$  ratio of specific heats
$\rho$  density
$\mu$  viscosity

SUBSCRIPTS

T  Throat conditions
o  reservoir conditions
1. **Introduction**

As aircraft performance has advanced further up the corridor of continuous flight there has been a demand for test facilities in which to simulate flight in the atmosphere at high Mach numbers and extreme attitudes. However, the use of unheated air as a wind tunnel working fluid is limited to Mach numbers of about 4.5 to 5.5 since, by the time the gas has been expanded to these Mach numbers, the flow is approaching the equilibrium vapour pressure curve (fig. 2) where condensation of the flow should occur. Some supersaturation will be present, the amount depending on the scale of the nozzle, the rate of expansion of the flow, reservoir conditions and freedom of the gas from condensable impurities and dirt particles, but several workers have shown (refs. 1 to 6) that this effect is small and of doubtful utility.

This problem may be overcome by heating the air, but the mechanical and aerodynamic problems involved in heating to avoid condensation at Mach numbers up to 15 and beyond are considerable. The problem of adding sufficient heat to the stream has been overcome in facilities such as the hotshot and arc-heated wind tunnel and shock-tunnels, but stagnation temperatures are so high, in excess of To = 3000°K, that real-gas effects are significant in the working section. They have the advantage that it is possible to simulate full scale stagnation enthalpy but at the expense of Reynolds number, usable running time and, in the case of arc-heated and shock-tunnels, contamination of the flow by electrode and diaphragm fragments.

Another solution is to use a gas with a much lower condensation temperature and helium is the obvious choice. Not only can it be expanded to much lower temperatures and consequently higher Mach numbers before liquefaction occurs, temperatures of 10°K and a Mach number of 33 are theoretically possible expanding from room temperature, but it has several other advantages over air. Chief among these is that for any given Mach number above about M = 2.5 the Reynolds number is greater in helium than in air and is such that it is possible to achieve full scale Reynolds numbers of the order of 10⁶/in. at Mach numbers in excess of 10. Another advantage is that because of the difference in the ratio of specific heats the area ratio required to expand to a given Mach number is reduced (fig. 3). For example, to expand to a Mach number of 10 in air requires A/A₁ to be 535.9 whereas in helium the value is only 66.3. This obviously eases the problems of nozzle manufacture considerably. Several workers (refs. 7 and 8) have proved the equivalence of results obtained in air and helium both theoretically and experimentally.

Owing to the advantages listed above the design and construction of a facility to run at Mach numbers between 10 and 30 using helium as a working fluid presents few problems that have not already been met in the design of low Mach number tunnels using air. The main new problem is that of sealing the system completely and of preventing leakage first of helium out of the high pressure sections and secondly of air into the vacuum system. The former is important since the high cost of helium forces conservation on an operator and the latter since any contamination will result in early condensation of the contaminating gas in the nozzle and a consequent undesirable change in the flow properties. This means that helium purity must be carefully monitored and provision made for purification of the gas in any closed circuit installation.
Considerable experience has been build up in the United States of America on the operation of helium hypersonic wind tunnels, particularly at Princeton (refs. 9 and 10) and at Langley Field (refs. 11, 12 and 13). Because of the ready availability of helium in the United States the early tunnels were straight-through, blow-down ejector tunnels exhausting to the atmosphere (ref. 9) but the later, larger tunnels, particularly the 11 ins. and 22 ins. tunnels at Langley Field, operate on the intermittent, closed circuit principle.

Due to the high cost of helium in the United Kingdom and the natural wish to conserve gas the Cranfield Helium Hypersonic Wind Tunnel operates on the closed circuit, intermittent principle, being a combination of blow-down, suck-down types. The general layout of the tunnel and plant is shown in fig. 4. The gas is stored in a high pressure manifold and, after passing through a control valve into the settling chamber, expands down the nozzle to the working section. It then passes through the second diffuser and into the vacuum system. This is pumped out with a Kinney type mechanical vacuum pump which exhausts into the inlet of a 4 stage reciprocating compressor that raises the gas back to the storage pressure. Provision exists for purification of the working fluid in a cooled and activated filter bed either continuously, while the plant is in operation, or in a special purification cycle.

Figure 5 shows the operating envelope of the tunnel giving a Mach number range from 10 to 30 with Reynolds numbers up to $10^7$/ft. at the higher driving pressures. Static pressures obtained range from a maximum of 10 mm Hg. at $M = 10$ to a minimum of 10 microns Hg. at $M = 30$ (fig. 6). Static temperatures range from $80^\circ$K down to less than $10^\circ$K at $M = 30$ (fig. 7). The running times of the tunnel vary little with Mach number and are between 20 and 30 seconds depending on the initial conditions in the vacuum receiver.

These extreme conditions together with the comparatively short running times have meant that special instrumentation has had to be developed. These are miniature Pirani type vacuum gauges in three basic forms with very short response times and a range from 10 mm Hg. down to 10 microns Hg. and, together with more normal diaphragm pressure transducers and thermo couples, they make up the bulk of the instrumentation.

2. Wind tunnel and associated plant

The tunnel is of the intermittent type operating on the blow-down-suck-down principle. Interchangeable throat sections give a Mach number range from 10 to 30 and special precautions are taken to monitor and control the contamination level of the helium.

2.1 Working section and second diffuser

Figure 1 gives a general view of the control valve, settling chamber and working section. High pressure gas enters the settling chamber through the pneumatic diaphragm control and shut-off valve (fig. 4). This will control the pressure in the settling chamber to within 5% of any set value during a run and may also be made to open quickly, to shorten tunnel starting times, by dumping control air from above the diaphragm by means of a solenoid valve. The settling chamber is filled with polished pebbles to cut down filling times by reducing the volume and also to act as an effective screen.
The interchangeable nozzle throat sections, to change tunnel Mach number, screw directly into the settling chamber (fig. 8). The present nozzle, which is straight conical with a raduised throat, has a semi-angle of $5\frac{1}{2}^\circ$ and is approximately 22 in. long from the throat to the end of the working section, the precise dimension depending on the Mach number of the tunnel and the throat insert used. The maximum diameter is 4\(\frac{1}{2}\) in. but this is restricted to 2\(\frac{1}{4}\) in. by 4\(\frac{1}{4}\) in. (fig. 8) when the windows are fitted for optical work. Shaped blocks are available to replace the windows when the full circular working section is desired. The nozzle block is drilled to facilitate static pressure measurement and the replacement blocks have provision for measuring both static pressure and surface temperature.

The second diffuser follows directly after the short parallel portion of the nozzle. It is a fixed geometry aluminium insert designed to operate always with a 1 in. diameter sting down its axis. It was thought that a fixed geometry diffuser would be adequate for the full operating range, since the area ratio for satisfactory starting and running varies little with Mach number above a Mach number of 10.

### 2.2 Model support and control mechanism

Models and probes may be mounted on a centrally held sting which can be moved along or rotated about the tunnel axis. The sting is 1 in. external diameter and extends through the second diffuser to the end of the working section, a total of 40 ins. in length. It is held in two three-arm spiders at the ends of the support section (fig. 9) and is moved in an axial direction by a pivoted lever arm and electrically driven lead screw mounted outside the diffuser tube. Rotation about the axis is achieved by means of a worm wheel turned by a crank, operating through o-ring seals, from outside the tunnel. Counters attached to the drives give a digital output of the position of the sting in the working section. Terminal blocks in the control box are used to carry electrical outputs and reference pressures into the tunnel pressure vessel.

### 2.3 Dump tank and vacuum system

At the end of the model support section the main 12 in. diameter dump line is entered through a large baffle valve by which the working section may be isolated from the rest of the system for work on models. There is a by-pass round this valve fitted with an emergency blow-out diaphragm in case the working section is inadvertently pressurised whilst the vacuum valve is closed.

The main vacuum dump tank is of 3000 cubic ft. capacity and this may be increased to 3500 cubic ft. by use of a supplementary tank.

The whole system is evacuated by means of a GKD780 Kinney type mechanical vacuum pump (fig. 4) which is capable of pumping the whole system down to pressures of less than 50 microns Hg. at rates up to 780 litres/min. This is necessary when purging the system of air before charging with helium and is rarely used in practice, the usual minimum pressure being about 0.1 m.m.Hg.

### 2.4 Pressure regulator

The vacuum pump is at its most efficient working condition when delivering to a back pressure of 1 atmosphere and, similarly, the compressor has been designed to operate with atmospheric pressure at its inlet. In order to maintain this pressure
in the connecting line the Reavell pressure regulator is used (fig. 4). This senses the pressure in the connecting line and if it is too high operates a butterfly valve in the vacuum line, cutting down the mass flow through the pump and consequently reducing the back pressure. Conversely, if the pressure is low it bleeds gas back from the high-pressure side into the connecting line until the correct level is reached.

2.5 Compressor and high pressure storage

The gas is compressed to the storage pressure with an Esslingen 4 stage compressor (fig. 4) capable of pumping up to 3000 p.s.i. at rates up to $2.83 \times 10^3$ litres/min. This full capacity is never used in practice since the maximum storage pressure is 2000 p.s.i. and the vacuum pump is limited to a rate of 780 litres/min.

After the compressor the gas passes through an oil separator and charcoal filter before entering the storage cylinders. These are simply a total of up to 45 helium battles connected to a manifold. The driving pressure may be increased beyond the normal operating maximum of 1200 p.s.i.a. simply by cutting down the high pressure storage volume, by turning off some bottles, before pumping up the system.

During a run gas leaving the manifold passes through temperature recovery vessels, pressure vessels filled with pebble screening, to stabilise the stagnation temperature before passing on to the control valve and settling chamber.

2.6 Purity analysis and purification plant

Owing to the possibility of contamination of the working gas by air leakage into the vacuum system and subsequent condensation of the contaminant in the working section (ref. 12), close control has to be kept on the purity of the helium. This is monitored (fig. 4) with a Perkin Elmer Gas Chromatograph using a synthetic zeolite filter to separate the oxygen and nitrogen of the air from the helium working gas. The instrument will detect impurity levels of a few parts per million and consequently is ideal for the present purpose where a maximum limit of 1.0% (by weight) contamination may be tolerated before errors due to condensation of air are significant (ref. 12). When contamination reaches the critical level the gas must be purified.

The purifier as originally designed was a large stainless steel pressure vessel filled with activated charcoal and immersed in a liquid nitrogen bath. The contaminated gas was passed through the filter bed and the oxygen and nitrogen preferentially adsorbed. This would of course only adsorb a certain volume of contaminant, up to 170 cubic ft./cubic ft. of filter at S.T.P. (ref. 14), before it was saturated and had to be reactivated. This meant removing the vessel from the bath and heating to reactivate the filter whilst purging the filter bed with a stream of pure gas.

Experience of the National Physical Laboratory, Teddington, operating a similar installation, showed great difficulty in sealing the vessel at high pressures, used for greater filter efficiency, and low temperature and on the basis of this the design has been completely changed.

The purifier in its new form is a long stainless steel coil, of equivalent
internal volume to the old system, but one tenth the thermal mass. This means that not only are the sealing problems greatly reduced, by having very much smaller ends, but there is a considerable saving in liquid nitrogen for cooling and electricity used for heating in the reactivating cycle.

The purifier may be used in any one of three ways. It may be run in series with the compressor, the gas simply passing continuously through the purifier and into the manifold. Since the contamination levels will not be high this method of continuous purification will be rather wasteful. A more normal process would be to have a purification cycle once every few days. Here, the gas would be drawn from the vacuum tank and simply cycled once through the pumps and purifier before being passed to the manifold. The third alternative is to use the pressure in the manifold to drive the gas in a reverse direction, through the purifier and into the vacuum storage line. In all cases the gas passes through a heater after coming out of the cooled purifier and before going back into the system.

2.7 General running

The sequence of operations for a series of runs is normally as follows. After checking that the pneumatic control air is on and that all valves are in the correct position as indicated by a system of microswitches and lights, the vacuum pump and the compressor are started. When the vacuum tank and working section have been evacuated to the desired level the tunnel is ready to be run.

The stagnation pressure is set on the control unit and the tunnel started by simply dumping the high pressure air from above the diaphragm and opening the control valve quickly. Supersonic flow is established almost immediately but the settling chamber takes some time to fill, up to 3 or 4 seconds for the higher pressures. The normal running time of 20 to 30 seconds is virtually independent of Mach number and depends more on the tunnel starting conditions.

The flow may be shut down simply by reversing the starting sequence or by waiting until the flow breaks down of its own accord with the diffuser shock moving into the working section. The pumping time between runs varies from 15 to 30 minutes depending on conditions used.

After a series of runs have been completed and the pumps shut down, high pressure gas is normally bled into the vacuum line until the pressure throughout the system is as near atmospheric pressure as possible. This is in an effort to minimise leakage into and out of the system.

3. Instrumentation

In the Cranfield Helium Hypersonic Tunnel several different techniques are used for the measurement of the flow variables pressure and temperature. Pressure is measured with a selection of vacuum gauges and the more standard strain gauge diaphragm transducers, whilst temperatures are measured with flush mounted or shielded thermocouples and a combination of hot and cold wire anemometric techniques.

3.1 Pressure measurement

In a tunnel of this type where running times are comparatively short,
20 to 30 seconds, and pressures range from the lowest static pressure of 10 microns Hg. at \( M = 30 \) to impact pressures of over 1000 mm. at \( M = 10 \) and stagnation pressures in excess of 1000 p.s.i.a., it is obvious that several different methods of measurement must be employed.

**Stagnation pressure**

Stagnation pressure is measured with a standard Langham Thompson strain gauged diaphragm transducer having a range of 0 to 1000 p.s.i. with better than 1% accuracy over the range. This is sensed in the centre of the settling chamber at the same point as that at which the reading for the pressure controller is taken.

**Impact pressure**

Centre line impact pressures which range from 10 mm. Hg. to 1000 mm. Hg. are sensed by one of two sting mounted probes. The first of these is a large (3mm. o.d.) impact tube (fig. 10) for use in conjunction with the centreline static measurements. The second is a rake array of seven smaller (1.6 mm. o.d.) impact tubes for general tunnel survey work.

The pressures from the sting mounted probes are led down the sting, through PVC or copper tubing, to a Solartron Pressure Switch, with a capacity for up to 24 pressure inputs, and a Solartron 0 to 10 p.s.i. (\( \pm 0.5\% \)) differential transducer. Owing to the long lengths of tubing between probes and transducer and the consequent increase in the response times with falling pressure, this system is restricted to one measurement per run in the low pressure, high Mach number region. At higher pressures, however, several measurements may be made in one run and the response time of the single large tube is such that it may be traversed down the nozzle during a test. Reference pressure for the transducer is supplied by a tube run down the sting from the entry part on the Model Control unit. The reference is either read with a mercury manometer or a Langham Thompson 0 to \( \pm 15 \) p.s.i. (\( \pm 0.5\% \)) transducer mounted outside the tunnel.

Impact pressures close to the wall approach very low values at the higher Mach numbers and require techniques other than those described above since the lowest pressure measurable by a standard transducer even with amplification is only about 10 mm. Hg. The ideal instrument would be a vacuum gauge with a range from 10 mm. Hg. to 10 microns Hg. Unfortunately most vacuum gauges, because of their bulk, must be mounted outside the tunnel and the necessary long lengths of connecting tubing introduce prohibitive response times at the low pressures.

This has led to the development of a family of impact and static measuring probes using a miniature Pirani type vacuum gauge (ref. 15). The gauge may be made so small that it may be fitted in the open end of a flattened 2 mm. hypodermic tube and the very small gauge volume results in good response characteristics and the ability to traverse the probes continuously during a run. This is useful in boundary layer survey work.

Due to the wide range of pressures met in a boundary layer traverse in hypersonic flow (e.g. from 60 microns Hg. at the wall to 60 mm. Hg. in the free stream for a stagnation pressure of 400 p.s.i.a. at \( M = 20 \)), a special double probe has been developed (fig. 11) which combines a vacuum gauge near the wall and a tube leading to a standard Solartron 0 to 10 p.s.i. differential transducer mounted
outside the tunnel (fig. 13).

Static pressures

Wall static pressures near the throat of the nozzle are measured with a Langham Thompson 0 to \( \pm 15 \) p.s.i. (\( \pm 0.5\% \)) transducer. The lower pressures in the working section are measured by a set of miniature Pirani gauges, mounted in 0.25 in. external diameter stainless steel tubes and slid down into parts along the tunnel walls (fig. 8). This keeps the effective gauge volume down to a reasonable value with a maximum response time of about 1\( \frac{1}{2} \) sec. at the lowest pressures.

Centre-line static pressure is also measured with a miniature Pirani gauge mounted just inside the probe cavity (fig. 10).

Power supplies and outputs

All the strain-gauge diaphragm transducers are driven by constant voltage power supplies at 5 volts. Their outputs are fed into individual low drift D.C. amplifiers that amplify the transducer output for input to the Ultra Violet Galvorometer Recorder (figs. 14 and 15).

The Pirani vacuum gauges are connected to a simple bridge unit which is fed by very stable constant-current power supplies and the outputs are again fed to the U.V. Recorder.

3.2 Temperature measurement

Wall temperature is measured at four points in the window replacement blocks (fig. 8) by means of flush-mounted iron/constantan thermocouples with ice-point cold junctions.

Stagnation temperature is measured by means of a thermocouple immersed in the settling chamber whilst free stream stagnation recovery temperature is measured with a shielded thermocouple probe of 3 mm. o.d. as discussed in ref. 16. Since the tunnel boundary layer is of appreciable thickness, up to 1 in. total, the 3 mm. probe may be used to investigate the variation of recovery temperature towards the wall. Total temperature may also be obtained from a combination of impact pressure and hot wire anemometer measurements (ref. 17).

3.3 Traversing gear

Centre-line traverse

In addition to the movement of the sting along and about the tunnel axis (section 2.2 above) it was thought necessary to provide an additional movement to cover the rest of the working section. This is achieved with a traversing unit which may be plugged into the sting to replace fixed probes and will provide movement radially from the tunnel axis.

The probe motive power consists of a miniature D.C. servo motor operating through a 141:1 gear box and driving a rotating cam. A push rod rides on the cam and operates the spring-loaded traverse arm (fig. 12). Interchangeable probes for
different purposes may be fitted to the end of the moving arm and the pressure and electrical leads passed back through the sting. The position of the probe is given by a rotary precision potentiometer driven by the cam. The potentiometer, together with the motor, forms part of a feedback servo system which controls the probe position and speed from the panel outside the tunnel. The position of the probe can be determined to better than 1% of the full deflection of 1.5 ins., i.e. within 0.015 in., which is thought adequate for free stream work.

The whole unit, drive, position feedback potentiometer and sprung arm system is held in a unit which fits into the standard 1 in. diameter sting (fig. 12).

Wall Traverse

In order to carry out a detailed study of the boundary layer on the tunnel wall and to reinforce the free stream measurements in the horizontal plane arrangements have been made to survey the flow at four stations in the nozzle (fig. 8). Here, probes are driven normal to the wall by traversing gear mounted outside the tunnel.

The traverse (fig. 13) is driven by a D.C. electric motor and gear box. This operates a pinion and rack system which moves the probe tube through o-ring seals in the tunnel walls. Motor, and hence probe, speed is controlled by a variable power supply giving both forward and reverse movement. A system of interlocking safety switches prevents the probe from being run into the tunnel walls.

Positional output is obtained from a Schaevitz Linear Variable Differential Transformer (L.V.D.T.) mounted on the traverse. This gives an output which is recorded on the U.V. Recorder. Linearity of the L.V.D.T. is better than 0.3% over the full 2 in. traverse range and the resolution, depending on the sensitivity of the recording galvonometer, is theoretically infinite.

4. Discussion

Some preliminary work has been carried out on shockwave shapes around bodies of revolution of varying degrees of bluntness and pressure distributions around blunt cones at a Mach number of 10. This, together with full details of the tunnel calibration throughout the Mach number and pressure range, is presented in ref. 18.

The main bulk of work projected for the future is a thorough investigation, with all the means available, of boundary layers in hypersonic flows at Mach numbers between 10 and 30.

5. Conclusions

In the Helium Hypersonic Wind Tunnel we have a facility which enables the whole of the hypersonic field up to Mach numbers of 30 to be explored. Full scale Reynolds numbers may be attained on small models and results are free from any suspicions raised by real gas effects in the nozzle.

6. Acknowledgements

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FIG. 1. GENERAL VIEW OF TUNNEL
FIG. 2. ISENTROPIC EXPANSIONS OF AIR AND HELIUM AND SATURATION LINES FOR O₂, N₂ AND He.

FIG. 3. VARIATION OF NOZZLE AREA RATIO AND MACH NO. FOR \( \gamma = 1.4 \) AND 1.66
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FIG. 5. VARIATION OF REYNOLDS No. WITH MACH No. AND STAGNATION PRESSURE.

FIG. 6. TUNNEL STATIC PRESSURE FOR VARYING MACH No. AND RESERVOIR PRESSURE.

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FIG. 9. MODEL SUPPORT SYSTEM.
FIG. 10. CENTRE LINE PROBES

FIG. 11. WALL PROBES
FIG. 12a. CENTRE LINE TRAVERSE

FIG. 12b. CENTRE LINE TRAVERSE
Low Drift D.C. Amplifiers
Constant Voltage Power Supply
Pirani Bridge Units
Constant Current Power Supplies
Wall Traverse Drive and Indicators

L. V. D. T. Control  Pressure Switch  U. V. Recorder  Instrument Console
          Drive

FIG. 14

FIG. 15 INSTRUMENTATION LAYOUT