AN INTERMITTENT HIGH REYNOLDS NUMBER WIND TUNNEL

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Abstract

The paper suggests a simple method of generating intermittent reservoir conditions for an intermittent, cryogenic wind tunnel. This can be done by operating some existing types of short-duration tunnels 'in reverse'. Two examples are considered (a) a modification of the Ludwieg Tube (b) the Isentropic Light Piston Tunnel.

The sizes of tunnels required to meet the European and American specifications for a high Reynolds number tunnel with a 10 second running time are given together with proposals for a more modest National or University facility with a one second test time.

1. Introduction

The specification for the new European transonic high Reynolds number wind tunnel includes the following test conditions:

Reynolds number (see notation)	=	40×10^6
Mach number	=	0.9
Running time	$\geqslant$	10 seconds

In addition an upper limit of 6 atmospheres of pressurisation was chosen on the grounds of cost and structural integrity.

For tunnels operating at ambient temperature and the maximum pressure of 6 bars this specification fixes the test section area at 21 square metres and the dimensions suggested were 5 metres wide and 4.2 metres high.

The four competing designs were:

(i) the Ludwieg Tube (LT)
(ii) the Evans Clean Tube (ECT)
(iii) the Injector Driven Tunnel (IDT) and
(iv) the Cryogenic Tunnel (CT)

Papers describing these various facilities can be found in Ref.1.

The European Working Party made an extensive study of the merits and drawbacks of the various proposed facilities and hired a well-known firm of international consultants to give an independent assessment of the total cost (capital plus operating) of each of the four tunnels.

The comparison (Ref.2) shows that the cryogenic tunnel has significant advantages. By operating at 120^0K the specification can be met by a much smaller tunnel. At 6 atmospheres the tunnel test section need only be 1.4m x 1.2m but to ease the manufacture of detailed models the size suggested has been increased to 1.95m x 1.65m and the tunnel pressure dropped to 4.4 bars. The influence of size on cost is so great that the cryogenic principle is the least expensive, even when applied to a fully continuous tunnel as the design submitted implied. Coupled with the unique ability to vary Mach number, Reynolds number and the dynamic pressure totally independently, the merits of the cryogenic tunnel become irresistible.

The decision has now been taken that the European Countries should at some time and place build a continuous cryogenic tunnel. It is noteworthy that the USA is currently building such a tunnel to meet the even more demanding specification of $R_e = 120 \times 10^6$, $M_\infty = 0.9$, $p_o = 8.8$ bar, with a test section of 8ft. (2.4m) square.

Notation

A	cross sectional area of the tunnel test section
M_∞	test section Mach number
p_o	reservoir pressure
R_e	Reynolds number based on a length of $0.1\sqrt{A}$
Re_c	Reynolds number based on turbine blade chord
T_a	ambient temperature, taken as 300^0K here
T_o	reservoir temperature

2. An Intermittent Cryogenic Tunnel

Of course the cryogenic principle can be applied to any type of tunnel whether it be continuous or intermittent in action. Indeed the proponents of the Ludwieg Tube showed how the pump tube could be refrigerated and shortened for cryogenic operation, (Ref.1). However it seems fundamentally incompatible to use a 'continuous' cooling principle with an intermittent facility particularly since hypersonic intermittent tunnels have long since shown how to obtain almost any desired reservoir condition. A number of such intermittent facilities, e.g. shock tubes, shock tunnels, gun tunnels and light or heavy-piston tubes, have been developed over the years.

Shock tunnels have a very short running time but gun tunnels have achieved test times of tens of milli-seconds. The Ludwieg tube can generate any desired test time but only at the expense of great length (Fig.1). The ECT can be much shorter than the Ludwieg Tube because it uses a moving wall (piston) to cancel the reflection of the expansion fan (Fig.2). In this way the whole of the driving chamber volume can be used for test gas instead of the driving chamber length determining the running time. A group at Oxford University have used these ideas to develop two intermittent facilities which give extended running times.

The purpose of this note is to point out that by operating a number of already well developed tunnel drive techniques 'in reverse', the cryogenic reservoir conditions required for a High Reynolds number Transonic Tunnel can be achieved.

2.1 The Ludwieg Tube with Light Piston Isentropic Compression Heating

The LICH tube (Ref.3) was specifically developed to provide elevated stagnation temperatures without preheating the test gas. The mode of operation is shown schematically in Fig. 3. Obviously if the light piston is used to expand the gas isentropically rather than compress it then cryogenic reservoir conditions can be achieved. (Fig.4). The final position of the piston would be at or near the end furthest from the test section and so waves reflected from the piston would be of less importance compared with the compressive mode developed at Oxford.

2.2 The Isentropic Light Piston Tunnel (ILPT) (Ref.4.)

The tunnel described in section 2.1 still behaves finally as a Ludwieg Tube with the running time limited by charge tube length. One method of increasing the test time is to make the far end of the LT movable in such a way as to 'cancel' the expansion fan generated by starting the flow to the nozzle and test section. This is done in the ECT by 'tuning' the motion of a piston (see figs.1 and 2). In the ILPT the charge tube is short and 'fat' and the running time is far greater than the wave transit time along the tube. Initially the piston is used to heat the test gas by compression and subsequently moves so as to compensate for the volumetric outflow through the test section and steady conditions are achieved as shown in fig.5. Because the working section area is small in comparison with the charge tube cross sectional area the expansion waves formed when the nozzle opens are of small amplitude. The piston does produce compression waves which cancel these rarefactions overall but due to their small magnitude it is not necessary to programme the piston to achieve exact cancellation as is done in the ECT.

Currently the Oxford ILPT facility is being used for 'high' temperature, 'low' Reynolds number tests to simulate gas turbine blade flow conditions (e.g. $T_0 = 430^0$K $R_{ec} = 1.2 \times 10^6$). The compression and test times are typically 0.6 and 0.3 seconds. If the operation of such a tunnel was to be altered with the initial piston motion reversed, as shown in fig.6, then the facility could become a simple cryogenic high Reynolds number tunnel.

3. Some Approximate Performance Estimates

3.1 The European Specification

Given the reservoir conditions, $p_0 = 4.4$ bar and $T_0 = 120^0$K, a test Mach number $M_\infty = 0.9$ and a working section area of 1.95m x 1.65m, the total test mass required for a 10 second running time is 53 tonnes (3600 slugs). The corresponding volume is 4,060m^3 (143,000 ft^3) which means for example a 4m diameter cylinder over 300m long; a considerable size. The pressure ratio through which the test gas must expand is given by

$$\left(\frac{T_a}{T_o}\right)^{\gamma/\gamma-1} = \left(\frac{300}{120}\right)^{3.5} = 25$$

where T_a is the ambient temperature (taken here as 300^0K).

Thus part of the charge tube must be stressed to withstand a pressure of 25 x 4.4 = 110 bars. Alternatively a separate high pressure drive vessel could be used as shown in Fig.7.

Although this facility is quite large it is extremely simple and in comparison with the alternative proposals it may be far cheaper. The important questions which remain concern the quality of the flow and the variation of the cold reservoir temperature (initially 120^0K) during the run due to heat transfer from the tube walls.

3.2 The American Specification

If the more ambitious Reynolds number of 120 x 10^6 is required in an 8' x 8' tunnel stressed for a reservoir pressure of 8.8 bars then the corresponding figures are:

Test mass = 194 tonnes (13,300 slugs)

Volume of charge tube = 7,400m^3 (260,000 ft^3)

Drive pressure = 25 x 8.8 = 220 bars

3.3 A National or University Facility

For individual nations or individual laboratories much more modest facilities are inevitable. Nevertheless the use of the intermittent cryogenic principle can increase the Reynolds number range significantly. Taking the somewhat arbitrary structural limit of 6 bars and a 0.6m x 0.6m (2ft square) test section designed for $M_\infty = 0.9$, the charge tube volume required for a one second run is 47m^3 (1650ft^3) e.g. a 2m cylinder 15m long. The Reynolds number that could be achieved would be nearly 19 x 10^6 compared with a straight blowdown figure ($p_0 = 6$ bars, $T_0 = 300^0$K) of 5.2 x 10^6.

4. Final Remarks

If the cryogenic principle is to be applied to an intermittent facility then it seems sensible to apply it intermittently.

Two existing, operational, light-piston tunnels are considered as examples. It is shown that cryogenic reservoir conditions can be obtained by reversing the initial piston motion.

The cryogenic intermittent tunnel described here is extremely simple and should be relatively inexpensive. However it is unlikely to be able to match the flow quality that would be achieved in the equivalent continuous facility.

Further studies of intermittent cryogenic tunnels should be made for they may increase the opportunities for high Reynolds number research. It would be interesting to cost an intermittent European facility with a running time of say 1 second capable of exploring the Reynolds number range $40 \times 10^6 \leqslant R_e \leqslant 120 \times 10^6$

5. Acknowledgements

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6. References

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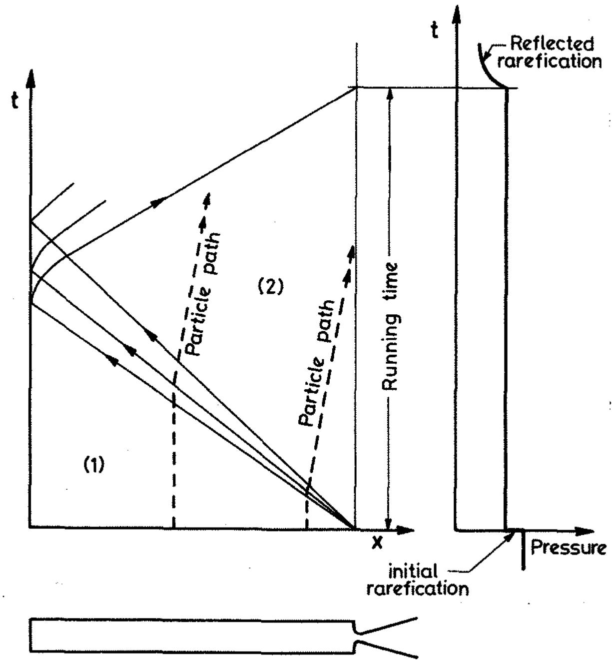

Fig.1. A conventional Ludwieg Tube

Only part of the test gas (region (2)) is used during the running time.

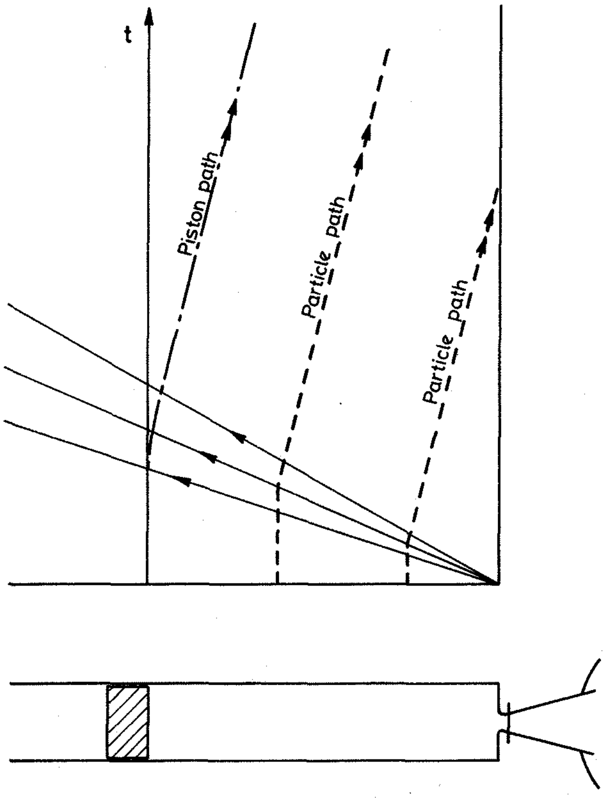

Fig.2. Principle of the ECT.

A solid piston is 'tuned' to the initial rarefication fan. There is no reflected wave, the piston motion maintains a constant pressure reservoir of gas, all of which can be used for test purposes.

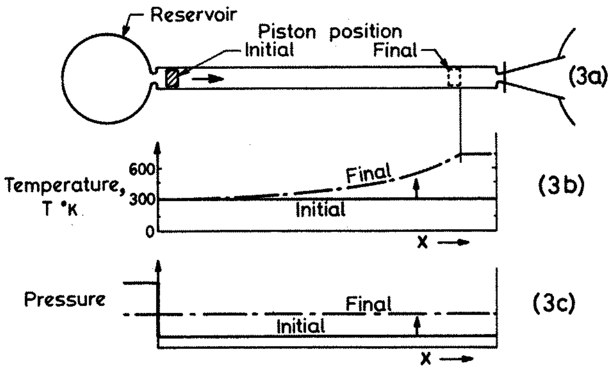

Fig. 3. Conventional Lich Tube operation to generate a hot test gas.

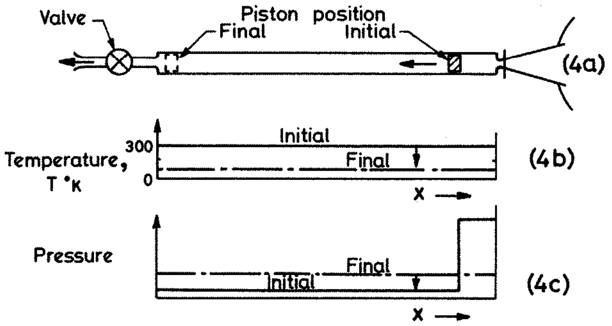

Fig. 4. Reverse Lich Tube operation to generate cryogenic test conditions.

In both cases the tunnel subsequently operates as a Ludwieg tube. In conventional operation (Fig.3) the flow is complicated by reflections from (i) the piston and (ii) from the temperature gradient along the charge tube generated during the compression process. Neither of these complications should occur in 'reverse operation' - Fig.4.

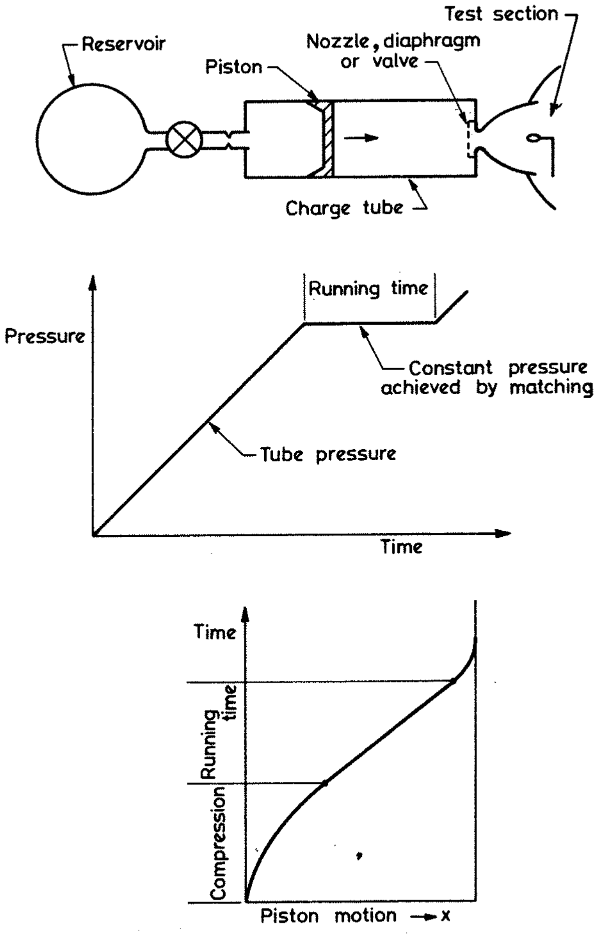

Fig. 5. The conventional ILPT. (from Ref. 4)

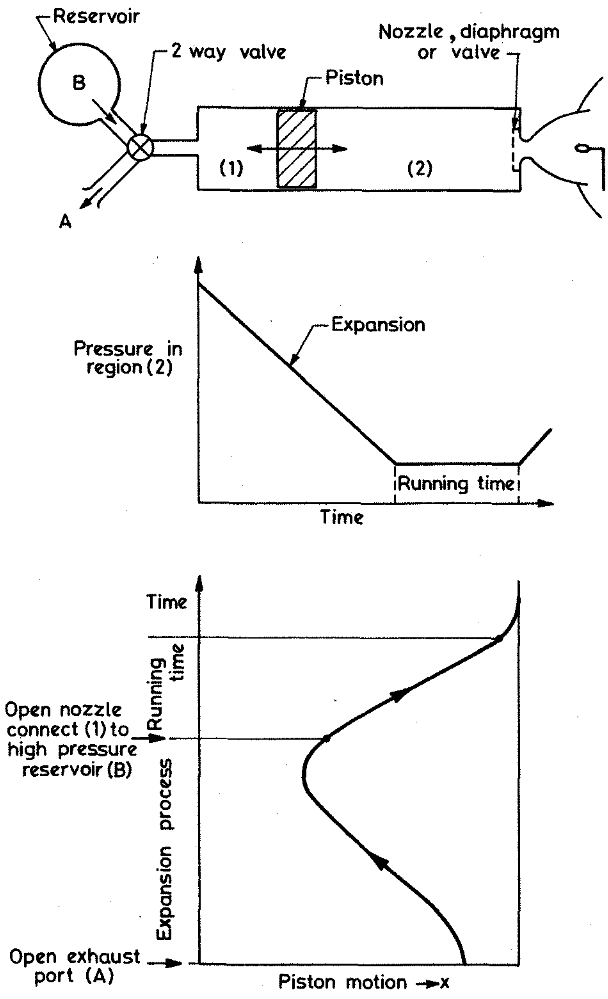

Fig. 6. The cryogenic ILPT.

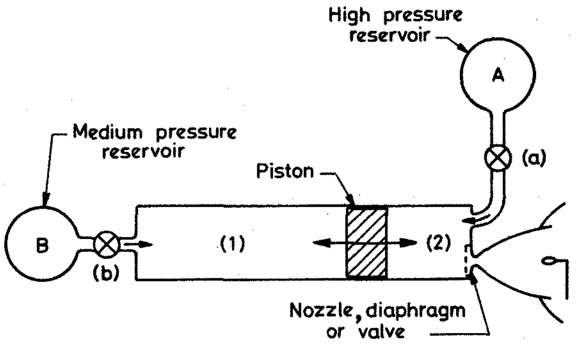

Fig. 7. The cryogenic tube with separate reservoir (A).

The method of operation is similar to that shown in Fig.6. Valve (a) is opened to allow the high pressure air in A to enter region (2) and, in doing work against the piston, cool to the desired conditions. The nozzle is then opened, together with valve (b), and the piston motion tuned to match the outflow of test gas. A single reservoir (with suitable piping) could probably be used for both functions A and B.