THE EUROPEAN TRANSONIC WINDTUNNEL (ETW) FOR HIGH-REYNOLDS-NUMBER TESTING

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Abstract

A joint project of four nations (France, Germany, The Netherlands and U.K.) to define, and later to construct, a new European high-Reynolds-number transonic windtunnel using cold nitrogen gas as the test medium is described.

The concept of windtunnel testing at cryogenic temperatures is discussed and a brief description of the proposed tunnel, as it is envisaged at present, is given.

Introduction

The need for a new transonic windtunnel in Europe to achieve high Reynolds numbers has been well established by studies under the auspices of NATO going back to 1968. Existing tunnels in Europe and USA, mostly built two decades ago, do not provide Reynolds numbers sufficiently large for results to be extrapolated reliably to flight conditions. The penalties of consequent errors in design are formidable because of the large cost of present-day aircraft programmes.

The basic functional specification of a suitable tunnel was drafted by the Large Windtunnels Working Group (LaWs) of the Fluid Dynamics Panel of AGARD in 1972 [1] and 1974 [4].

In 1975 an important decision was made by NASA in USA to build a transonic windtunnel (test section 2.5 m x 2.5 m) using cold nitrogen as the test gas and to be called the National Transonic Facility (NTF) [3]. This cryogenic windtunnel concept was selected after a number of other possible systems had been considered. The feasibility of testing in nitrogen gas at cryogenic conditions had been demonstrated in a pilot facility [4] operating since 1974 at NASA Langley Research Center. The group responsible for studying the matter in Europe soon concluded that substantial savings might be possible with a cryogenic tunnel compared with other options they had considered up to that time. An engineering study [5] was commissioned to establish relative capital and operating costs.

Eventually four nations (France, Germany, The Netherlands and UK) signed a Memorandum of Understanding in early 1978 covering the Preliminary Design Phase of the proposed European High-Reynolds-Number Transonic Windtunnel (now known as ETW). The participating Governments will, on the basis of the information from the Preliminary Design Phase, consider their position and consult amongst themselves before entering a Final Design Phase. The Preliminary Design Phase, to last two years, includes preliminary design and specification, design and construction of a small pilot tunnel, studies on model design and instrumentation, and estimates of investment and operating costs.

A technical group, consisting of two engineers each from France, Germany and UK and one from the Netherlands, is based at the National Aerospace Laboratory NLR in Amsterdam. It reports to a Steering Committee comprised of one member from each country, accompanied by specialist advisers if desired, which meets from time to time in Amsterdam.

An annex to the Memorandum of Understanding envisages the total project: a Final Design Phase in 1980 and a Construction Phase in 1981 to 1984, subject to decisions to proceed at each Phase.

The concept of windtunnel testing at cryogenic temperatures

The Reynolds number is defined as:

$$Re = \frac{\rho V L}{\mu} \qquad (1)$$

where ρ = density
V = velocity
L = reference length
μ = viscosity

There are three ways to obtain high Reynolds numbers:

(a) to test with a large model (ℓ), which results in a large and costly facility;

(b) to increase pressure (and thus ρ). A limit arises here because of the high loads on models, balances, stings and sting supports and because of the aeroelastic deformation of the model wings, resulting in a non-representative shape in comparison to the actual aircraft;

(c) to lower the stagnation temperature (higher ρ and lower μ).

As early as 1945 Smelt(6) indicated the advantages of testing at cryogenic temperatures which included a considerable gain in Reynolds number and a reduction in drive power.

The idea was taken up in 1971 at NASA, by which time considerable development in low temperature engineering had made it reasonable to consider a windtunnel operating with a test gas at cryogenic temperatures.

The advantage of testing at lower temperatures than ambient is well illustrated in Figure 1, taken from Ref. 7. At a given tunnel size and constant stagnation pressure, the Reynolds number is increased by a factor of 6 when the stagnation temperature is determined by saturation of the test medium.

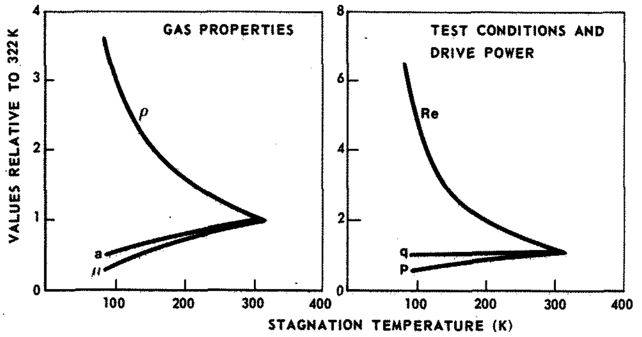

Fig. 1 Effect of temperature reduction on gas properties, test conditions and drive power (for M = 1 and constant stagnation pressure and tunnel size).

Advantages of the cryogenic concept

The advantages of wind-tunnel testing at cryogenic temperature for the European transonic tunnel are:

(a) The size can be reduced in comparison with other known options, thus decreasing the total capital costs despite the extra costs due to cryogenic capability.

(b) The use of a test-section of similar size to existing major transonic windtunnels means that models are compatible in size.

(c) As mentioned above testing at cryogenic temperature requires much less fan drive power. For given tunnel dimensions and stagnation pressure the following relationship holds:

$$P \sim \mathrm{Re}\,T_o^{1.9} \qquad (2)$$

Thus, for this example, if stagnation temperature is lowered from ambient to 100 K the required fan drive power is reduced by a factor 0.12 for the same Reynolds number.

(d) The lower maximum stagnation pressure reduces model aeroelastic deformation and stress levels in the sting.

(e) In conventional windtunnels the Reynolds number can only be changed by variation of the stagnation pressure (keeping the Mach number constant). Model wing loads and deflections depend on dynamic pressure and this makes it difficult to separate Reynolds number effects from deformation effects.

Cryogenic testing gives a solution to this problem; the dynamic pressure can be kept constant for variable Reynolds number through variation in stagnation temperatures (at constant stagnation pressure). This method of testing is illustrated as "mode 1" in Figure 2.

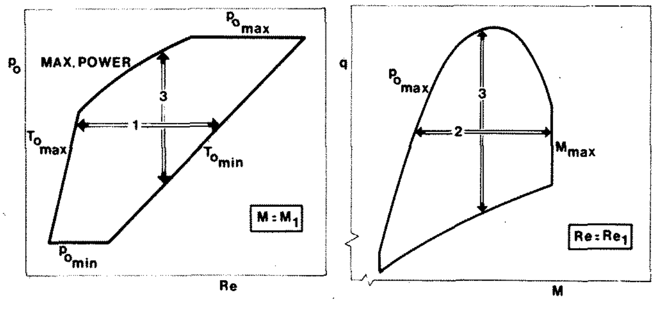

Fig. 2 The different modes of operation of a cryogenic windtunnel
Mode 1 : Reynolds number effects (constant q and M)
Mode 2 : Mach number effects (constant q and Re)
Mode 3 : Aeroelastic effects and flutter tests (constant M and Re)

(f) Stagnation pressure and stagnation temperature can also be adjusted in such a way that dynamic pressure and Reynolds number are kept constant when Mach number is varied. "Mode 2" in Figure 2 illustrates this type of operation. As the only test parameter which then varies is M, this mode of operation may be useful for the determination of "pure" Mach number effects (eg buffet boundaries).

(g) "Mode 3" in Figure 2 illustrates yet another way of operation; dynamic pressure can be varied when keeping Mach number and Reynolds number constant. This is of high interest for "pure" aeroelastic studies in determining the influence of model deformation on the aerodynamic behaviour. The wing deformation can possibly be better matched to that of the real aircraft.

(h) Flutter studies can now be made with variation of dynamic pressure only, without disturbing side effects from variations of Mach number and/or Reynolds number.

(i) For flutter tests complete scaling (Mach and Froude numbers) is possible (8), (9) for aircraft components at reduced scale, when the stagnation temperature can be varied as in a cryogenic facility. Apart from the gain in Reynolds number, this gives for the first time the possibility of performing flutter tests using the same model to simulate correctly a complete range of altitudes of practical interest (8).

Drawbacks of testing at cryogenic temperatures

(a) Although the fan power is much reduced, cryogenic conditions can only be obtained by means of cooling with large quantities of liquid nitrogen. The amount of liquid nitrogen is not only determined by the time required for data gathering. It is mainly needed to cope with other factors such as transitions between set-points, fan starting and stopping, and losses (insulation, distribution, and facility cool-down). Thus, for testing at cryogenic temperatures, there are large energy requirements for providing liquid nitrogen.

(b) Model design and manufacture will be more complicated and thus more costly than for present-day models in existing facilities. The cryogenic environment will necessitate the use of steels new to the model designer, thermal stresses will give problems and homogeneous materials will probably have to be used throughout the model. General opinion appears to be that these problems can be overcome in time by development.

(c) Model handling will be much more complicated and more time-consuming. It will not be possible to make even small adjustments or changes to the model surrounded in cryogenic nitrogen. So special measures have to be taken to bring the model into a tolerable environment. Elaborate and expensive systems have been conceived (see below). Checking of models and on-board instrumentation at low temperatures will be required before installation in the tunnel and additional cold chambers will be required.

(d) The design of force balances, pressure transducers, scanners, etc. for accurate measurements will require intensive development. Experts agree that no insoluble problems are expected.

Fundamental aspects of cryogenic aerodynamics

Minimum operating temperatures

Due to the sensitivity of both Reynolds number and fan drive power to stagnation temperature it is extremely important to know the minimum temperatures for operation of a cryogenic facility. At low temperatures condensation effects could have adverse effects on the measurements. Condensation is expected first in the regions on the model with lowest pressure; however, time and length considerations are also of importance.

Great caution in the assignment of minimum operating temperature is appropriate for ETW, as in the event of it proving necessary to use higher minimum temperatures than originally supposed the required Reynolds number will not be reached. Since the functional specification for the tunnel is based on the concept of reliable extrapolation of data to flight Reynolds numbers, a maximum useable Reynolds number less than 40×10^6 would materially degrade the effectiveness of the whole facility. Experiments on the lowest possible temperatures for testing have been made at NASA (10),(11),(12) indicating that one can go possibly as low as free-streams saturation temperatures. However, more data is needed before general conclusions can be drawn. Pending additional data, the minimum stagnation temperature for ETW has been conversatively taken as that corresponding to saturation at local Mach numbers of 1.7 on the model. However, the windtunnel structure is being designed for temperatures corresponding to saturation at stagnation conditions.

Real-gas effects

Cryogenic nitrogen departs from ideal-gas behaviour because of thermal ($p\rho^{-1} \neq RT$) and caloric ($\gamma \neq 1.4$) imperfections (γ can be as high as 1.5 under the pressure and temperature conditions of interest to cryogenic windtunnel testing).

Relating to this problem a number of theoretical studies have been performed on isentropic expansions, shock waves, airfoil pressure distributions, flow over wings, shock wave boundary layer interaction, etc. These studies have been reviewed (13), and the conclusion is that the cold nitrogen gas behaves almost like an ideal gas. The pressure-density relationship can be written as:

$$p = C\rho^{\alpha} \qquad (3)$$

α is very near to 1.4, the value for an ideal diatomic gas.

Also the Bernoulli equation takes an identical form to that for an ideal gas.

The conclusion from these theoretical studies is that real-gas effects in cryogenic nitrogen are very small, and that they are of similar magnitude to those at ambient temperature and at a stagnation pressure of, say, 6 bars.

The insignificance of real-gas effects has also been demonstrated by experiments on an airfoil in the NASA 0.3 - m cryogenic windtunnel(7). Also experiments(7) on boundary layers in the same facility indicated the absence of real-gas effects.

The European Transonic Windtunnel ETW

The LaWs functional specification

For economic reasons the LaWs Group (1),(2) adopted the philosophy of extrapolation of data obtained in the windtunnel to full-scale Reynolds numbers in flight. Reliable extrapolation is possible only when the flow over the model is representative of that of flight and it was concluded that the Reynolds number based on model mean aerodynamic chord should be variable between 25×10^6 and 40×10^6 at $M = 0.9$. At the time, the LaWs Group only considered ambient stagnation temperature facilities and it defined a maximum stagnation pressure of 6 bars, determined by model and model support considerations. These Reynolds number and stagnation pressure requirements led to a test-section size of 5 m x 4.2 m for ambient temperature operation.

The cryogenic concept introduces a new parameter into the consideration: the stagnation temperature. Keeping the Reynolds number requirements as defined by the LaWs Group a choice had to be made either on test-section size or on maximum stagnation pressure.

The test-section dimensions chosen are 1.95 m x 1.65 m, this being the minimum size and, hence, lowest cost compatible with the representation of adequate detail in models for project development tests. Together with the assumption of a minimum stagnation temperature determined by local saturation of flow on the model this leads to a maximum stagnation pressure of 4.4 bars.

Description of the facility

An artist's conception of the facility as presently envisaged is presented in Figure 3. As mentioned above, the test section size proposed is 1.95 m x 1.65 m, but the cost of a somewhat larger tunnel at lower pressure giving the same Reynolds number is being considered. The circuit is conventional, with a sonic throat aft of the test section to regulate Mach number and to prevent disturbances from downstream entering the test section.

Cooling is by liquid nitrogen sprayed into the circuit at two locations, the first ahead of the fan and the second one in the second cross-leg to obtain quick temperature response during transients.

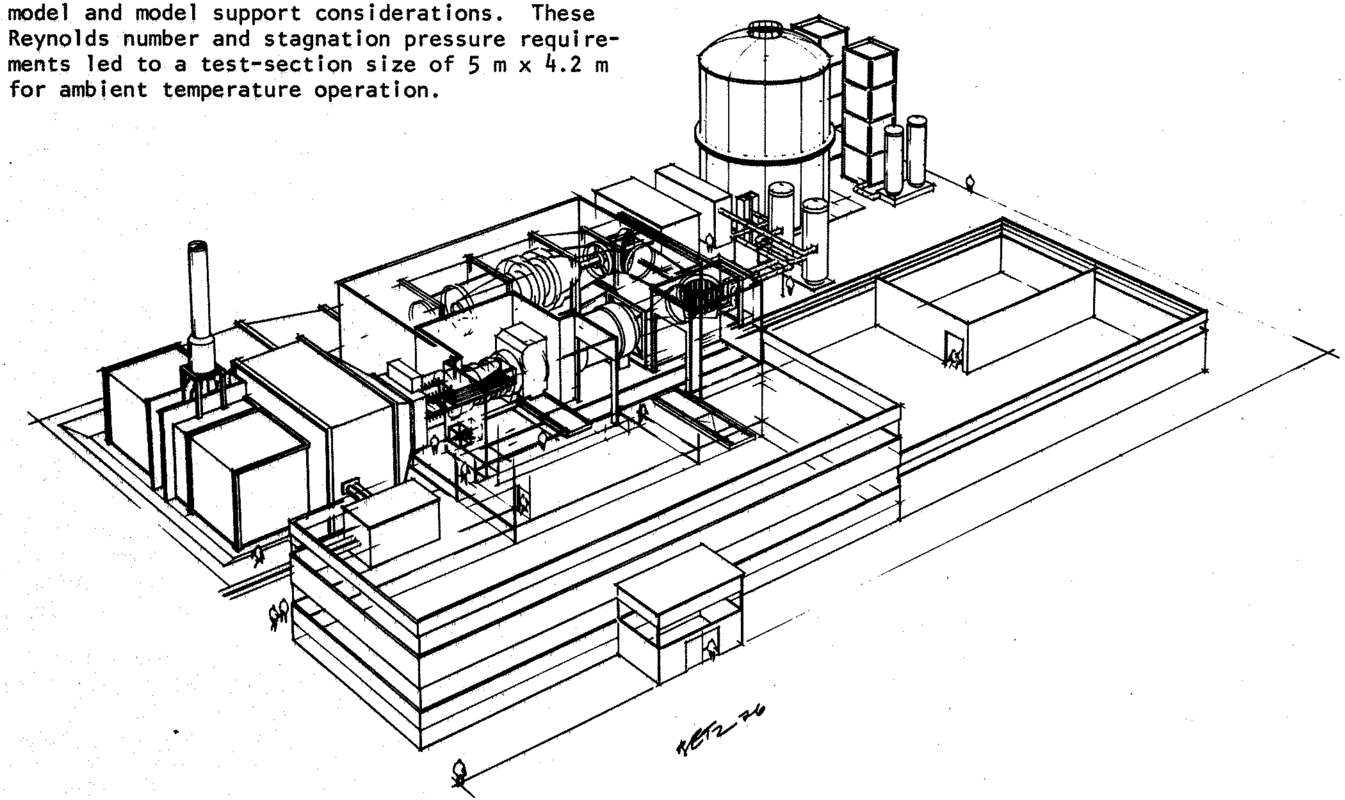

Fig. 3 Artists' conception of the European Transonic Windtunnel (ETW)

Gate valves are situated fore and aft of the test section to allow de-pressurization for access to the model. A flexible nozzle assures good Mach number distribution at supersonic speeds.

The tunnel shell is insulated from the environment by means of a cold box structure carrying a 0.30 m-thick layer of expanded polystyrene. The space between the tunnel shell and the insulation is purged and continuously filled with nitrogen gas, maintained at a pressure slightly above atmospheric to prevent any air or moisture leakage in the space and insulation.

The high transport costs for liquid nitrogen necessitate an air separation plant and a liquefier on site. The plant could be run continuously and would require only modest power. The liquid nitrogen produced at a rate of about 3 tonnes/hour is stored in a tank. Based on the consumption during the most demanding two-week programme envisaged the tank capacity is chosen to be about 1500 tonnes, or 2400 m^3. Some auxiliary tanks, including gas accumulators, will be required to meet the maximum demand during a test run.

Access to the model is gained in the way illustrated in Figure 4. After a run the gate valves upstream and downstream of the test section are closed and the test section is reduced to atmospheric pressure. Inside a cold room (about - 40° C), at slightly higher pressure than the atmosphere, the test section and the model cart are moved sideways on rails. Subsequently the model cart is rolled backwards and the test section is put in place again. The model cart is then moved forwards until the model penetrates through the wall of the cold room into a chamber with controlled environment. Once the model is at a workable temperature level (and in air) part of the environmental chamber is removed, and model modification can start.

A second cold room is provided for model check-out and calibration under cryogenic conditions.

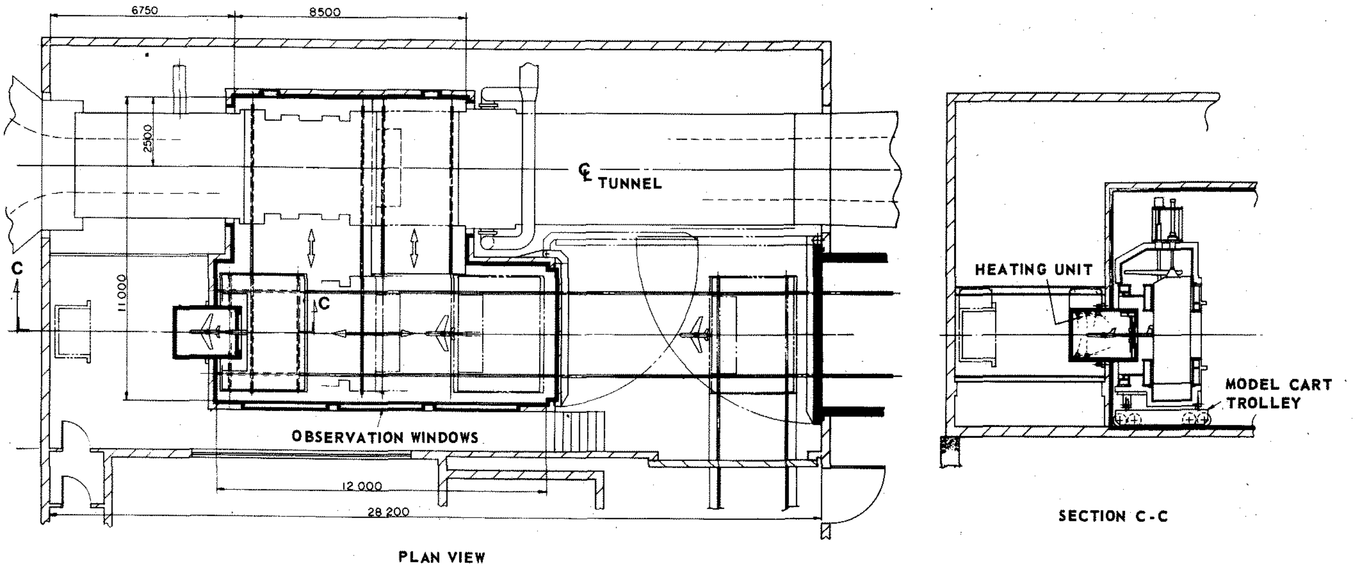

Fig. 4 Model access system as developed by DSMA (Ref. 5)

Performance

In Figure 5 an operating envelope (at M = 0.9) is presented with the assumption that the minimum operating temperature is determined by saturation at a local Mach number on the model of M = 1.7. As can be seen the LaWs functional specification can be met in a 1.95 m x 1.65 m facility at a stagnation pressure of 4.4 bars. The Reynolds number can be varied between 25 and 40 x 10^6 at constant dynamic pressure (and thus constant model deformation), enabling extrapolation of data without disturbing model deformation effects.

The maximum fan power is determined by Re = 25 x 10^6 and 4.4 bars (about 27 MW). Off-design performance for the ETW is presented in figure 6, where the Reynolds numbers attainable over the full Mach number range (up to M = 1.35) are compared to those of existing facilities in Europe. About Re = 18 x 10^6 can be reached at low subsonic speeds.

The possible modes of operation have been considered in the light of productivity, liquid nitrogen consumption and cost. A number of 5.000 test periods per annum is foreseen, each of 10 seconds duration.

Because of the continuous fan drive 10 periods of 10 seconds are thought to be possible within one test run. After these 10 periods the tunnel has to stop for model changes or modifications. As discussed above, in such a test run several modes of operation are possible: constant M, constant q or constant Re. Consideration of the dynamics and control of the facility led to the conclusion that considerable time will be needed to proceed from one test condition to another. Including starting and stopping of the facility, it is estimated that the test-runs will take approximately 6 minutes for 10 periods of data taking.

When the fan has been stopped, an elaborate procedure will be necessary to gain access to the model. Based on a conceptual design a time schedule has been estimated, showing that approximately 30 minutes would be needed to gain access to the model and 25 minutes for model re-installation. Allowing 45 minutes for model modification results in a total time between runs of approximately 2 hours.

So a typical test program day is expected to consist of 4 runs each of 6 minutes at 2 hour intervals.

Flow quality

Criteria for pressure-fluctuation spectra have been developed for ETW(14). These are based on the philosophy of obtaining test results in 10 seconds running time with the same accuracy as in present-day continuous tunnels which generally have much longer running times Moreover the impact of flow fluctuation on model aerodynamics is of some concern (boundary layer development etc.)

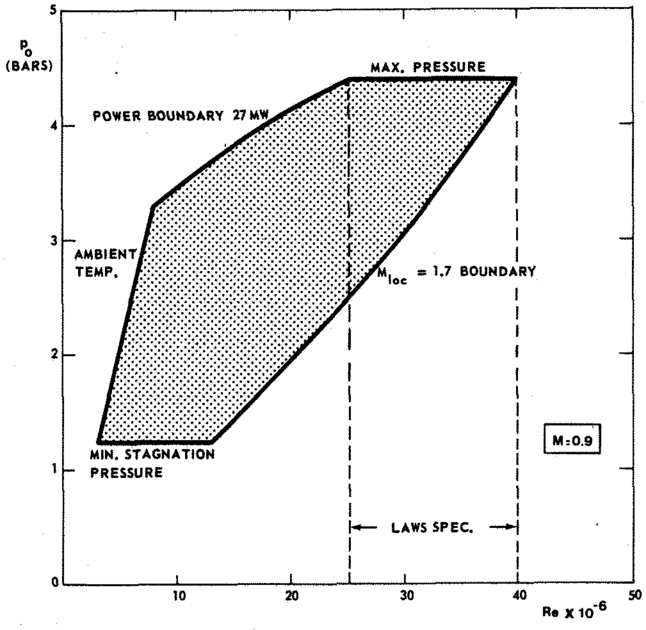

Fig. 5 Operating envelope for ETW at design conditions

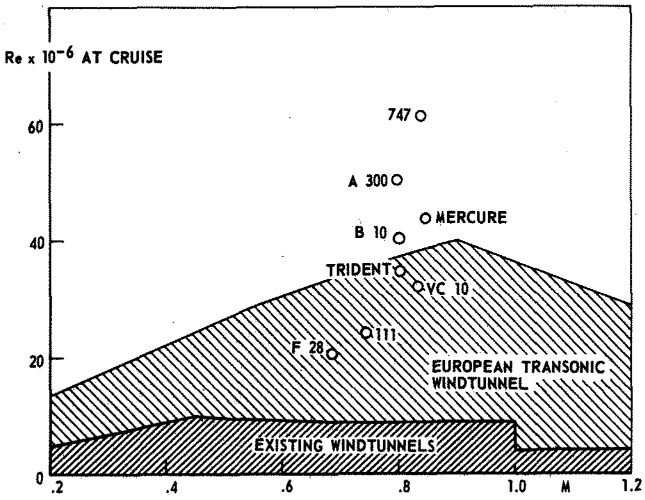

Fig. 6 Comparison of Reynolds number capability of ETW with existing windtunnels and with cruise Reynolds numbers.

Comparison of these requirements with results from existing continuous facilities indicates that in the region of reduced frequencies of interest for the various types of tests there exist several tunnels that have fluctuation spectra similar to or approaching the requirements(14). This indicates that by careful design of a new facility the requirements for allowable pressure fluctuations can be met in the reduced frequency domain of interest.

As explained in reference 14, the contribution to the broadband noise level at the higher reduced frequencies primarily originates from the test sections, fans, model supports and diffusers. The contribution from the test section is inherent in the wall configuration that will finally be chosen. Contributions from model supports and diffusers can be minimized again by careful design (eg operation with a sonic throat downstream of the test section). As far as fan noise is concerned, attention will have to be paid during the design stage to the requirement of low noise level.

In conclusion, it can be expected that the noise from the circuit and the fan in a cryogenic continuous facility can be reduced to the desired levels through careful design and, possibly through careful study and optimization in a pilot facility.

As noted in reference 14, very little is known about turbulence levels in transonic test sections, due to measurement and interpretation difficulties (concomittant pressure fluctuations). It can be expected however that the turbulence level in a cryogenic facility can be made low (of the desired order of 0.1%) by means of anti-turbulence devices (screens) and a sufficiently large contraction ratio from settling chamber to test section.

Tests in the NASA 0.3 m cryogenic facility(4) have shown that the temperature distribution in the settling chamber, obtained with an unsophisticated liquid nitrogen injection system, is comparable with those in present-day good continuous transonic facilities. Hence, no problems are expected here.

Controls

Earlier engineering studies(5) have shown that about 60% of the liquid nitrogen needed is for compensation of the heat energy introduced by the fan. About 35% of the total yearly consumption is needed during transients, going from set-point to set-point (Figure 7).

The high cost of energy necessitates an optimum control system and much attention is presently paid to a study of the dynamics of the flow in the circuit, aiming at such an optimized control system. The highly interactive nature of the variables (speed, pressure, temperature, liquid nitrogen injection and blow-off) makes this a difficult problem .

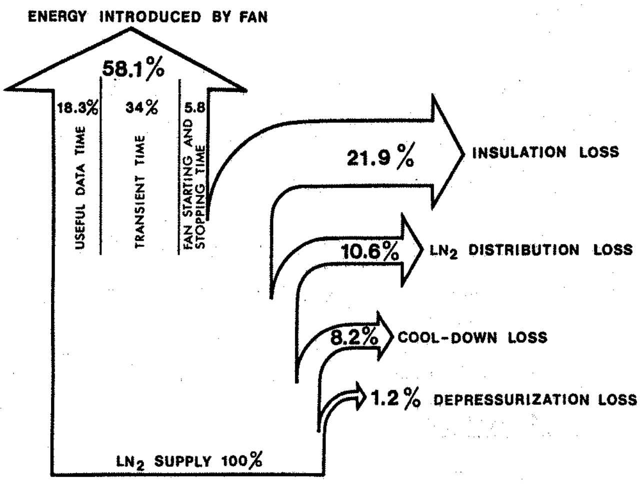

Fig. 7 Annual LN_2 consumption

Pilottunnel

For measuring the flow quality, and for experimental studies on the dynamic behaviour of the flow in the circuit, a pilot windtunnel (named PETW) will be built at NLR.

The tunnel will be operational towards the end of 1979. It will be a scaled-down version (about 1 : 7) of ETW, with a test-section width of about 0.25 m. The pilot facility will be located at the National Aerospace Laboratory, NLR, Amsterdam.

Concluding Remarks

A new transonic high-Reynolds-number windtunnel ETW is being planned by four European nations acting in concert. The project presents problems and challenges on a variety of levels, namely windtunnel technology; cryogenic engineering; communication and cooperation between Governments, industrial firms and research establishments; organisation and administration of an international team.

So far good progress has been made on all of these levels, and it is hoped that after the successful completion of the present Preliminary Design of the ETW (and the construction of the PETW) the participating Governments will decide possibly to proceed into the Final Design and Construction of ETW. If they do so, this new high-Reynolds-number transonic facility can be available by 1984 for the indispensable support of the European aircraft industry.

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List of symbols

a = Speed of sound

L = Typical length

M = Mach number

p = Pressure

p_o = Stagnation pressure

P = Fan drive power

q = Dynamic pressure

Re = Reynolds number

T_o = Stagnation temperature

V = Velocity

α = Expansion coefficient

γ = Ratio of specific heats

ρ = Density

μ = Viscosity