High-Reynolds-Number Cryogenic Wind Tunnel

MICHAEL J. GOODYER*
University of Southampton, Southampton, England
AND
ROBERT A. KILGORE†
NASA Langley Research Center, Hampton, Va.

Theoretical considerations indicate that cooling the wind-tunnel test gas to cryogenic temperatures will provide a large increase in Reynolds number with no increase in dynamic pressure while reducing the tunnel drive-power requirements. Studies have been made to determine the expected variations of Reynolds number and other parameters over wide ranges of Mach number, pressure, and temperature with due regard to avoiding liquefaction and adverse real-gas effects. Practical operational procedures have been developed in a low-speed cryogenic tunnel. Aerodynamic experiments in the facility have demonstrated the theoretically predicted variations in Reynolds number and drive power. Force and moment measurements on a wing model mounted on a water-jacketed strain-gage sting balance have demonstrated the feasibility of operation of such balances in a cryogenic environment. Whereas most types of wind tunnels could operate with advantage at cryogenic temperatures, the continuous-flow fan-driven tunnel is particularly well suited to take full advantage of operating at cryogenic temperatures. Constructional and operational techniques are available, and costs appear acceptable.

Nomenclature

a = local speed of sound
$\bar{c}$ = mean aerodynamic chord
l = measure of scale in wind tunnel
M = Mach number
$M_{L_{max}}$ = maximum local Mach number on model
P = pressure
q = dynamic pressure, $q = \frac{1}{2}\rho v^2$
R = Reynolds number
$R_{\bar{c}}$ = Reynolds number based on $\bar{c}$
$\mathscr{R}$ = gas constant
T = temperature
v = freestream velocity
γ = ratio of specific heats
μ = freestream viscosity
ρ = freestream density
ξ = normal shock static pressure rise deviation factor

Subscripts
1 = upstream of shock
2 = downstream of shock
∞ = freestream
bl = in boundary layer
t = stagnation conditions

Introduction

IT is widely recognized that there is a requirement for wind tunnels which are capable of operating at near full-scale Reynolds numbers. Design studies for such tunnels capable of continuous running at normal temperatures and moderate pressure show them to be large and to make heavy demands on power. Their capital and operating costs would be high. The usual alternative of achieving near full-scale Reynolds number by operating a smaller tunnel at elevated pressures results in high dynamic pressures with attendant high model and sting loads and an undesirable increase in aeroelastic and support interference problems. This has led to the consideration of reducing the operating temperature as a means for reducing wind-tunnel size or operating pressure and cost. A theoretical investigation by Smelt indicated that the use of air at temperatures in the cryogenic range (below 172°K, −150°F) would permit large reductions of facility size and power requirements in comparison with a facility operated at normal temperature and at the same pressure, Mach, and Reynolds numbers.[1]

The advances that have been made in recent years in the field of cryogenic engineering have been such that a facility of this type appears feasible and should be given serious consideration. Following a theoretical investigation aimed at extending the analyses of Smelt, an experimental program was initiated in order to demonstrate the feasibility of the cryogenic wind tunnel and to verify some of the theoretical predictions. This paper contains portions of the theoretical and experimental results, together with suggestions for the exploitation of the benefits afforded by the cryogenic wind tunnel.

Methods for Increasing Test Reynolds Number

At a given Mach number, the Reynolds number of model tests in a wind tunnel may be increased, relative to some datum value, either by the use of a heavy gas, by increasing the size or the operating pressure of the facility, or by reducing the test temperature. The use of a heavy gas is a well-known method of achieving high Reynolds number without undue increase of facility size or dynamic pressure. Freon-12 is one gas that has been used with good results in subsonic tests. However, the ratio of specific heats γ for Freon-12 is considerably different from that for air. Apparently the consequences of this are small in subsonic flow, and where effects do exist there are techniques for correcting data. However, there are reservations about the validity of data that might be taken in this gas in transonic and supersonic flow. An important example of the differences between the behavior of this gas and air is the pressure change in a shock wave. The static pressure rise in a shock wave in air is 10% higher than in Freon-

Presented as Paper 72-995 at the AIAA 7th Aerodynamic Testing Conference, Palo Alto, Calif., September 13–15, 1972; submitted September 18, 1972; revision received January 2, 1972. Research was accomplished while M. J. Goodyer held a National Research Council Resident Research Associateship and was working in the High-Speed Aircraft Division of the NASA Langley Research Center.

Index categories: Research Facilities and Instrumentation; Aircraft and Component Wind Tunnel Testing.

*Lecturer, Department of Aeronautics and Astronautics. Member AIAA.

† Aerospace Engineer, High-Speed Aircraft Division. Member AIAA.

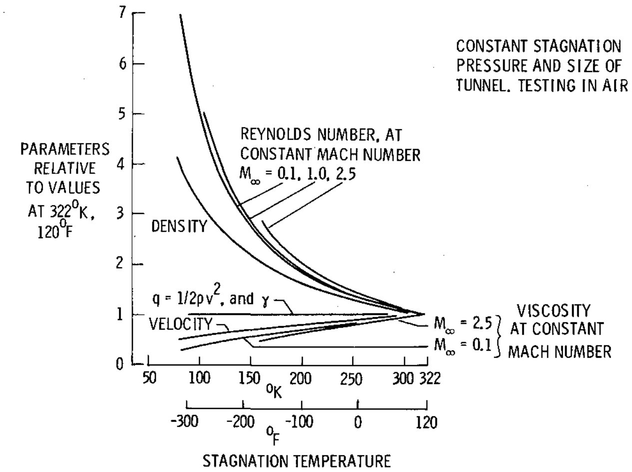


Fig. 1 Effect of temperature on test section flow parameters.

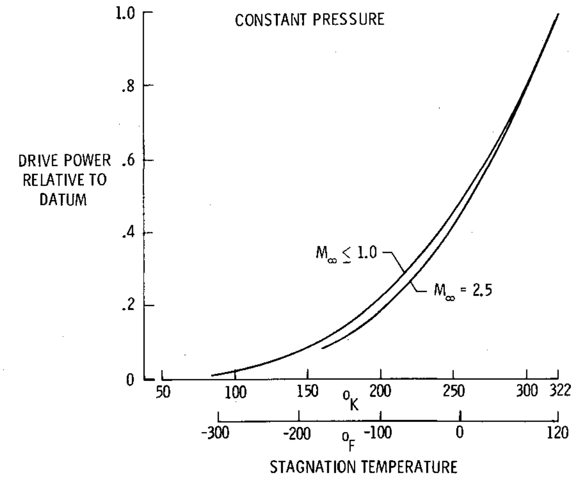


Fig. 2 Variation of drive power with temperature at constant Reynolds number, Mach number, and stagnation pressure in air.

12 at the same Mach number. In flowfields in which the stability of the position of the shock is sensitive to the interaction between the shock wave and boundary layer, significant differences could exist in shock position and hence in aerodynamic results.

Basic Gas Relations

The analysis which follows allows comparisons to be made between the three methods for increasing Reynolds number in air. Reynolds number is defined as

$$R = \rho v l/\mu \tag{1}$$

Considering a perfect gas, we can make substitutions for

$$\rho = P/\mathscr{R}T$$

and for

$$v = M_\infty a = M_\infty(\gamma \mathscr{R} T)^{1/2}$$

such that Eq. (1) becomes

$$R = (PM_\infty l/\mu)(\gamma/\mathscr{R}T)^{1/2}$$

where γ and $\mathscr{R}$ for a given gas are assumed constant. Following the assumption of constant test section Mach number for comparative purposes, the static temperature T, and static pressure P depend directly on the respective stagnation values. Hence, for a given gas

$$R \propto P_t l/\mu(T_t)^{1/2} \tag{2}$$

Dynamic pressure $q \equiv \frac{1}{2}\rho v^2$ may be written

$$q = (\gamma/2)P M_\infty{}^2$$

and following the assumption of constant γ and Mach number,

$$q \propto P_t \tag{3}$$

The Cryogenic Wind-Tunnel Concept

For a comparison of the cryogenic wind tunnel with others, a stagnation temperature for normal tunnels of 322°K (+120°F) is here assumed as a datum. The variation of several of the flow properties in the test section, as the stagnation temperature is reduced from the datum value, is shown in Fig. 1.

Increased Reynolds number

With reducing temperature, viscosity is reduced, density is increased, and because of a reduction of the speed of sound in a gas with reduced temperature and the assumption of constant Mach number, the velocity is reduced. The combined effect of these changes is an increase of Reynolds number as the test temperature is reduced, in accordance with Eq. (2). The variation of viscosity with stagnation temperature is a function of the assumed Mach number. The curves which show the relative change of Reynolds number with temperature are drawn for several freestream Mach numbers in which the appropriate variations of viscosity have been taken into account. The relative increase of Reynolds number at reduced test temperature is seen to be only a weak function of Mach number.

Loads

The aerodynamic loads which act on a particular model vary with incidence and q at a fixed Mach number. At fixed incidence, the stresses and deflections within the model vary in proportion to dynamic pressure, q. As the test temperature is reduced, there is no change of dynamic pressure. Therefore, by reducing temperature in a cryogenic facility, an increase of Reynolds number is achieved without increase of load, and any problems that might arise from aeroelastic distortion of the model or its supports are minimized. This constant dynamic pressure feature of the cryogenic tunnel is very important, particularly with regard to isolating Reynolds number effects from aeroelastic effects.

Reduced drive power

The variation of tunnel drive power with temperature is an important consideration. If it is assumed that at a constant test Mach number the loss of stagnation pressure around a tunnel circuit is proportional to the dynamic pressure q in the test section, then the drive power varies as qv, where v is the test section velocity.

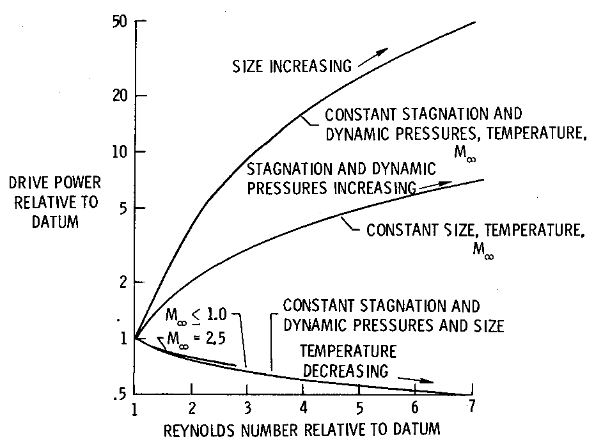


Fig. 3 Comparisons of drive power requirements for three methods of increasing Reynolds number.

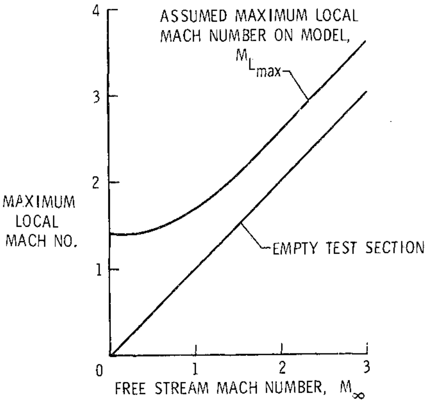


Fig. 4 Assumed maximum local Mach number on model as a function of freestream Mach number.

$$\text{Power} \propto l^2 qv$$
$$\propto l^2 q(T_t)^{1/2} \tag{4}$$

At constant Mach and Reynolds numbers, and constant stagnation pressure, the relationship between test section width, l, and temperature, is, from Eq. (2),

$$l \propto \mu(T_t)^{1/2}$$

Substitution in Eq. (4) yields

$$\text{Power} \propto \mu^2 T_t^{3/2} q$$

For the assumed conditions of constant stagnation pressure and Mach number, q is constant, hence

$$\text{Power} \propto \mu^2 T_t^{3/2} \tag{5}$$

The ratio of power at a temperature T_t to power at the datum temperature of 322°K, according to the assumptions relating to Eq. (5), is shown in Fig. 2. It is evident that considerable power savings can be realized at cryogenic temperatures. The variation of drive power, as Reynolds number is increased from some datum value, is shown in Fig. 3 for the three methods of increasing Reynolds number in air. It can be seen that as Reynolds number is increased by reducing test temperature, the drive power is reduced.

Operational limits

The minimum stagnation temperature which can be used in a cryogenic wind tunnel depends on several factors. It has been assumed that liquefaction must be avoided under the most adverse conditions to be met in the test section. The test gas is most likely to begin to condense in the localized low-pressure regions adjacent to the model. The local pressures in turn depend on the shape and attitude of the model, and on the test Mach number and stagnation pressure. In order to compute likely conditions in these regions, a variation of local maximum Mach number $M_{L_{max}}$ with freestream Mach number M_∞ has been assumed and is shown in Fig. 4. In order to compute the minimum temperatures that may be utilized, the two further assumptions have been made that the expansion of the test gas from the tunnel settling chamber through to the localized high-Mach-number regions is isentropic and that the saturation boundary for the test gas is not crossed.

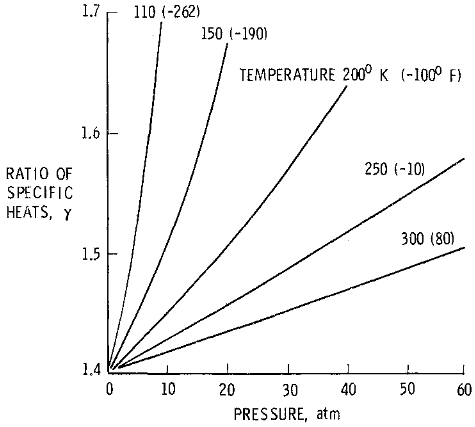


Fig. 5 Ratio of specific heats for air as a function of pressure and temperature. Data from Ref. 7.

The value of γ for air varies quite strongly with pressure and temperature as shown in Fig. 5 (data from Ref. 7). Thus, consideration of the variation of γ with pressure and temperature for air from the nominal value of 1.4 may dictate the use of temperatures somewhat higher than permitted by considerations of saturation. For the analysis in this paper, arbitrary limits have been set on the amount by which γ will be allowed to depart from the nominal value of 1.4. Because of possibly sensitive shock/boundary-layer interactions, the pressure changes which occur in a normal shock have been chosen as a criterion with which to constrain γ. A "shock pressure rise deviation factor" ξ has been defined for this purpose. This factor is the ratio of the pressure rise in a normal shock in the test gas to the pressure rise in a gas having $\gamma = 1.4$, the ratio being expressed as a percentage. The relevant analysis is in the Appendix where it is shown that for limits on ξ of $\pm 1\%$, γ must lie between 1.367 and 1.434. This criterion is adopted from hereon as a constraint to test gas conditions.

For tests at a freestream Mach number of unity in a cryogenic wind tunnel using air as the test gas, the variation of the permissible minimum stagnation temperature T_t with stagnation pressure P_t is shown in Table 1. The stagnation temperatures have been chosen such that the saturation boundary is not crossed at $M_{L_{max}} = 1.7$ and ξ is never greater than 1%.

Table 1 Permissible combinations of pressure and temperature for cryogenic tunnels using air

P_t, atm	1	2	3	4	5
T_t, °K	110.0	117.0	132.0	145.0	157.0
Reynolds number relative to datum (same P_t but $T_t = 322$°K)	4.57	4.16	3.46	3.01	2.68

The use of nitrogen as coolant and test gas

The properties of air and nitrogen are similar, and nitrogen might be used with advantage in the cryogenic wind tunnel. Lower test temperatures can be used with N_2 because its saturation temperature is lower than the dewpoint for air. Also, at low temperatures γ for nitrogen varies less from 1.4 than does γ for air.

Table 2 shows the permissible minimum operating temperatures for sonic testing in nitrogen, and is based on the same assumptions and is directly comparable with Table 1 for air.

The Reynolds number advantage of the nitrogen cryogenic wind tunnel over conventional tunnels operating at the same pressure for a range of freestream Mach numbers and pressures

Table 2 Permissible combinations of pressure and temperature for cryogenic tunnels using nitrogen

P_t, atm	1	2	3	4	5
T_t, °K	104.4	115.0	129.8	143.0	155.1
Reynolds number relative to datum (same P_t but $T_t = 322$°K)	4.96	4.27	3.55	3.07	2.73

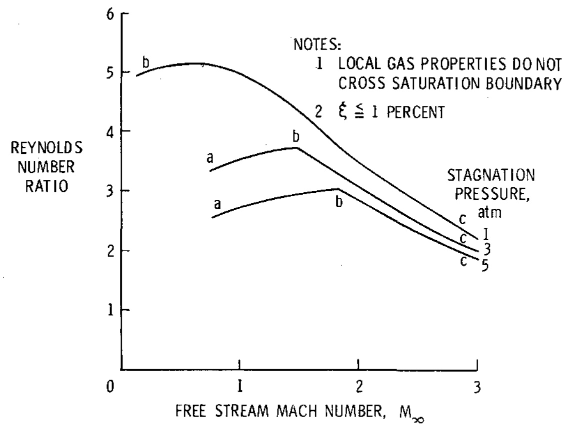


Fig. 6 Reynolds number in cryogenic nitrogen tunnel relative to that in a conventional tunnel of the same size, as a function of Mach number and stagnation pressure.

is shown on Fig. 6. Useful increases of Reynolds number are obtainable over a wide range of Mach number and pressure. Along the portions of curves a–b on Fig. 6 $\xi = +1\%$; along portions b–c $\xi < 1\%$ but the saturation boundary is reached at $M_{L_{max}}$. Corresponding operating temperatures are shown on Fig. 7. If future experience with cryogenic tunnels shows that the restriction on γ that has been here applied may be relaxed, the portions of curves a–b on Fig. 6 will be raised. If some supersaturation is permissible or when $M_{L_{max}}$ is not as high as shown on Fig. 4, the portions of curves b–c will be raised.

Because of its low cost and bulk availability, cooling the tunnel by means of evaporating liquid nitrogen (LN_2) offers an attractive alternative to mechanical refrigeration. Once nitrogen is admitted as a test gas, the particularly simple cooling technique is available of injecting and evaporating LN_2 inside the tunnel circuit.

Other Facility Applications

As far as can be seen at this time, cryogenic techniques might be applied with advantage in most types of wind tunnels with the obvious exception of the hypersonic tunnel. Brief comments will now be made on several facility types.

The cryogenic Ludwieg tube

Cryogenic techniques might be applied with advantage to a Ludwieg tube tunnel such as that described in Ref. 2. An anlysis presented in Ref. 2 considers the benefits of cooling a transonic Ludwieg tube tunnel to 239°K (−30°F) and indicates a potential savings of slightly over 30% on capital investment. However, cooling to 239°K (−30°F) results in relatively small benefits when contrasted with the benefits of cooling to cryogenic temperatures. Simply lowering the test temperature of the stored gas would result in increases of Reynolds number and run time. Run time would vary approximately inversely with the square root of T_t. The permissible temperature reductions from normal would be limited by the change of stagnation temperature which occurs during the passage of the expansion wave along the tube. Model precooling would be required. By injecting a cryogenic liquid directly into the tube and letting it evaporate, the recharging process might be simplified and shortened.

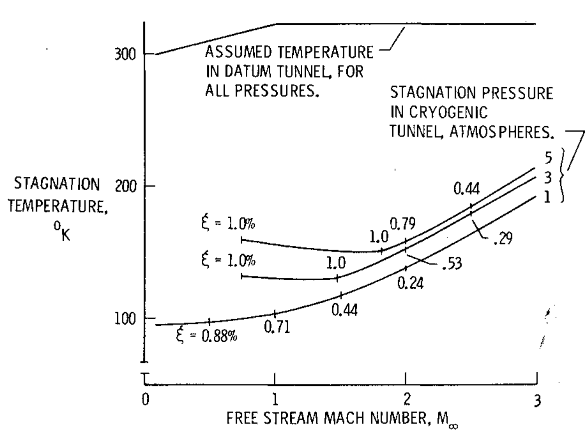


Fig. 7 Stagnation temperatures and shock pressure rise deviations ξ, corresponding to test conditions of Fig. 6.

The cryogenic induced-flow tunnel

The cryogenic mode of operation appears applicable to a closed-circuit induced-flow facility. In order to maintain a constant test temperature, the inducing gas must be cooled to match that of the tunnel circuit. Precooling of the model could be carried out simultaneously with the precooling of the tunnel. When testing in air, suitable proportions of LOX and LN_2 could be evaporated within the inducing airstream. For a given Mach number in the inducer throat and pressure of inducing gas the mass flow rate of this gas will increase as temperature is reduced. The changes of mass flow rate could adversely affect run times when operating from stored gas.

The cryogenic E.C.T.

The E.C.T. wind tunnel proposed by Evans is under investigation as a possible high Reynolds number facility at the Royal Aircraft Establishment, Farnborough, England.[3] The exploitation of low temperatures in this intermittent facility could offer significant advantages in Reynolds number and run time. Assuming a normal operating stagnation temperature of 300°K (80°F) at a test Mach number of unity, reducing the temperature to 130°K (−226°F) would increase Reynolds number by a factor of 3.23 and run time by a factor of 1.52. 130°K is a suitable temperature for testing at a stagnation pressure of 3 atm at $M_\infty = 1.0$. Piston velocity would be reduced by 34%.

The cryogenic blowdown tunnel

One mode of operation of this tunnel might be to store air at normal temperature, to precool the test section and model, and during a run to hold a constant test temperature by the injection and evaporation of coolant in the region of the settling chamber. As an example of some of the changes to facility design which would result from operation at cryogenic temperatures, a comparison can be made between a normal-temperature blowdown tunnel and an equivalent cryogenic tunnel which operates at the same Reynolds number, stagnation pressure (3 atm) and Mach number ($M_\infty = 1.0$). The test section of the cryogenic tunnel would be about 31% of the size of that for the normal tunnel, and when operating from the same-sized air storage bottles the cryogenic tunnel would run nine times as long. The flow rate of cryogenic liquid would be relatively high, comprising about 25% of the total flow rate through the test section.

The cryogenic continuous-flow tunnel

Because of large reductions of drive power and facility size or operating pressure afforded by the use of low temperatures, the continuous-flow high-Reynolds-number closed-circuit tunnel with its attractive operational characteristics again becomes an economic feasibility. With any facility concept a wide variety of permutation of design variables is possible. For the purpose of brief illustration, just two possible continuous-flow cryogenic wind tunnels are now compared at representative test conditions with their conventional counterparts giving the same Reynolds number and Mach number.

Low-speed testing ($M_\infty = 0.35$). At a stgnation pressure of 1 atm the cryogenic wind tunnel would be 20% of the size and require 2% of the drive power of a conventional tunnel.

Transonic testing ($M_\infty = 1.0$). At a stagnation pressure of 3 atm the cryogenic wind tunnel would be 28% of the size and require 5% of the drive power of a conventional 3-atm tunnel.

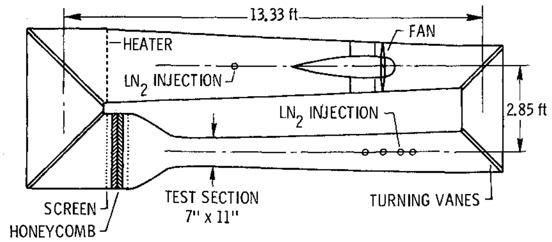


Fig. 8 7-in. by 11-in. cryogenic wind tunnel.

The reduction of capital outlay which is implied by the above figures, coupled with the convenience, high productivity, avoidance of problems associated with high model loads, and low operating costs per data point of such facilities has prompted further consideration of the continuous-flow cryogenic wind tunnel. Therefore, a low-speed continuous-flow cryogenic tunnel has been constructed at NASA Langley Research Center and will now be described.

The Low-Speed Cryogenic Wind-Tunnel Experiment

Description of Tunnel

The cryogenic tunnel was constructed with the objects of proving some of the preceding theoretical predictions, and to gain operational experience with a continuous-running cryogenic tunnel. The tunnel circuit is a $\frac{1}{24}$-scale model of an existing modern low-speed tunnel. The circuit outline is shown in Fig. 8. The tunnel can be driven at Mach numbers up to 0.20 by a water-cooled fan motor mounted in a nacelle in the return leg of the circuit. Materials of construction include wood, plexiglass, mild and stainless steels, aluminum, brass, copper, and fiberglas. The fan blades are wood.

The tunnel is cooled simply by spraying LN_2 directly into the circuit with the fan running. The test temperature is held by automatic control of the nitrogen flow rate to within $\pm 2°F$ of the mean.

Several simply constructed viewing ports allow inspection of key areas which include the settling chamber, working section, corner vanes, and spray zones. Thermal insulation for the remainder of the circuit is a 3–4-in. layer of styrofoam applied to the outside of the existing wall structure with a polyethylene vapor barrier on the outside.

A simple wire-grid electrical heater is installed to assist in the rapid warmup of the facility and to provide fine temperature control when desired. Surplus nitrogen gas is taken away in a duct leading from the circuit in the region of the heater.

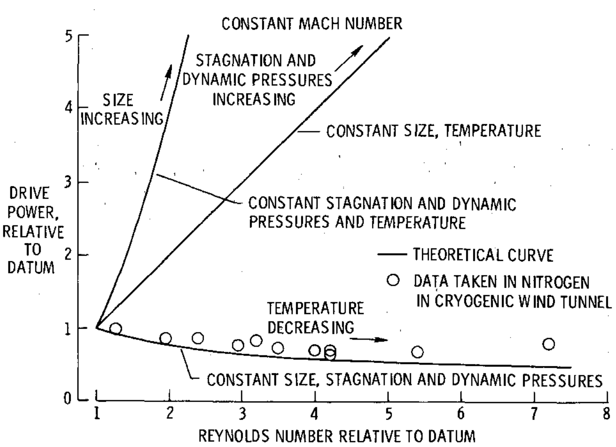


Fig. 9 Theoretical comparisons of tunnel drive power for three methods of increasing Reynolds number with test data from the prototype cryogenic wind tunnel.

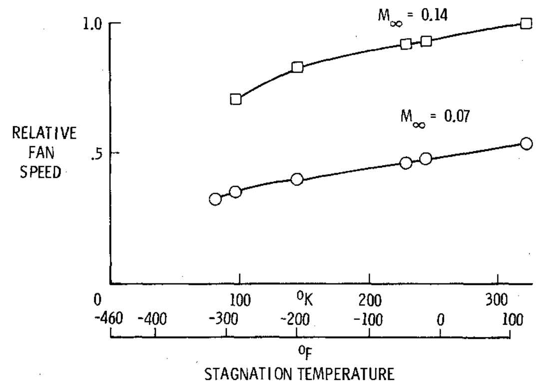


Fig. 10 Variation of fan speed with temperature and Mach number in the prototype cryogenic tunnel.

Experimental Results

General operating characteristics

Complete evaporation of the LN_2 is achieved, giving a dry gas in the test section down to the lowest temperature explored, 80°K (−316°F), where Reynolds number is 7 times that in a normal tunnel. This is close to the saturation temperature of nitrogen of 77.4°K (−320.4°F) at 1 atm. The rate of cooling is such that, for example, a temperature of 116°K (−250°F) can be stabilized within 10 min of initiation of cooling from room temperature. Because of the chosen method of cooling, the working fluid is nitrogen gas. Test pressure is 1 atm.

Drive motor and power

No fan blade or drive motor problems have been encountered. The theoretical variation of drive power with increase of Reynolds number above the value at room temperature, for constant Mach number, is shown in Fig. 9 for three methods of increasing the Reynolds number in air. Shown also are the measured power variations taken with nitrogen in the cryogenic tunnel at $M_\infty \approx 0.1$. (The different coefficients of expansion of the materials used to build the low-speed tunnel results in gaps opening up around the tunnel circuit as the operating temperature is reduced. The additional circuit losses caused by these gaps causes the measured values of drive power to be greater than the predicted values.)

The velocities of the gas around the circuit are a function of test section Mach number and temperature. Fan rotational speed is roughly proportional to gas velocity. The measured variation of fan speed with M_∞ and temperature is shown in Fig. 10. At constant M_∞, the fan speed varies approximately as the square root of the absolute temperature.

Reynolds number

An experiment was devised to demonstrate the changes of Reynolds number that accompany changes of conditions in the test section. A pitot tube was mounted at a fixed position on a flat plate in the test section. The location of the pitot tube was chosen such that it would lie always in the laminar portion of the boundary layer. The dynamic pressure recorded by this pitot tube depended on the boundary-layer thickness which is a function of Reynolds number, and on freestream dynamic pressure. In this tunnel, Reynolds number could be changed by changing either M_∞ or temperature. In Fig. 11, the ratio of boundary layer to freestream dynamic pressures, and the corresponding range of unit Reynolds number in the freestream, are shown plotted against M_∞. Theoretical curves for various temperatures are shown, together with measurements at the same temperatures. The experimental data follow the theoretical curves and show Reynolds number increasing with M_∞ at constant

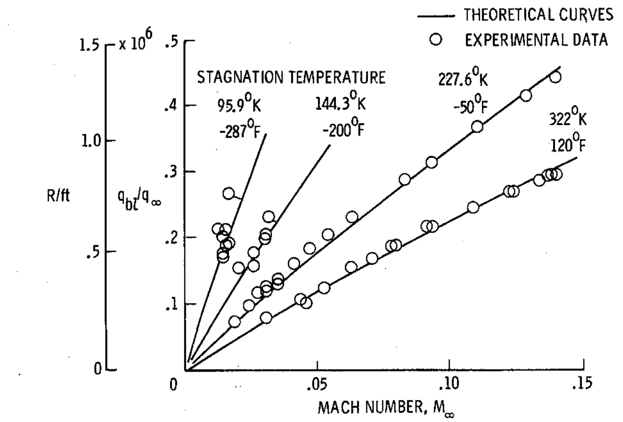


Fig. 11 Reynolds number per foot and ratio of q in boundary layer to q in freestream as a function of Mach number and stagnation temperature.

temperature, but also show Reynolds number increasing as temperature is reduced at constant M_∞.

Strain-gage balance

In order to determine if conventional techniques might be used to make force and moment measurements at cryogenic temperatures, a delta-wing model was tested on an existing water-jacketed strain-gage balance at angles of attack from $-4°$ to about $+22°$ in the cryogenic tunnel. Since the purpose of the test was to investigate any possible adverse effects of cryogenic temperatures on the measuring techniques rather than the effect of Reynolds number on the model, a sharp leading-edge 74° delta-wing model was tested since it is known that the aerodynamic characteristics of this shape are relatively insensitive to Reynolds number. No problems have arisen and excellent agreement exists between data obtained at stagnation temperatures from 322°K (+120°F) to 111°K (−260°F). Based on these tests, there appear to be no fundamental or practical problems in obtaining force and moment data in a cryogenic tunnel using conventional strain-gage balance techniques.

Performance Chart for a Continuous-Flow Cryogenic Wind Tunnel

The preceding guidelines for operating conditions have been used in the construction of a chart showing some characteristics of cryogenic continuous-flow wind tunnels. The chart shows the variation of Reynolds number and drive power with size of test section and stagnation pressure for operation at a Mach number of 1.00. Reynolds number is based on mean aerodynamic chord $\bar{c}$, and $\bar{c}$ is taken as one-tenth of the width of the square test section. The chart is shown in Fig. 12, which includes the values for T_t and ξ at each operating pressure, and is used in the following manner. Assuming a Reynolds number of 40×10^6 based on $\bar{c}$ is desired in a 10-ft test section, then from Fig. 12 it can be seen that a stagnation pressure of $2\frac{1}{2}$ atm would be required with a drive power of about 35,000 hp. In a conventional tunnel at $2\frac{1}{2}$ atm, the same Reynolds number would be achieved in a 39-ft test section, and the drive power would be 860,000 hp.

Anticipated Design Features and Operation Techniques for the Pressurized Continuous-Flow Cryogenic Tunnel

The material which is presented in this section is based partly on experience gained with the low-speed cryogenic tunnel and is partly speculative. The techniques are not necessarily the best that can be devised, but are included in order to show that such a facility is feasible at this time. There is much still to be learned, and during the further exploration and development of the cryogenic wind-tunnel concept, new and better ideas will undoubtedly materialize.

The tunnel circuit

In order to minimize the consumption of coolant, and in order to maintain a dry outside wall, effective thermal insulation techniques must be used. Insulation might be applied to the inside in some regions in order to reduce the mass of structure to be cooled. It is anticipated that the tunnel circuit would be fabricated from some material such as 9% nickel steel which has acceptable structural properties down to the temperature of liquid nitrogen.

Provision will be necessary for an increased range of thermal expansion. The worst case might be where the whole of the pressure vessel is cooled to the temperature of the gas stream, where about 3 times the usual change of dimension would be experienced.

Nitrogen requirements

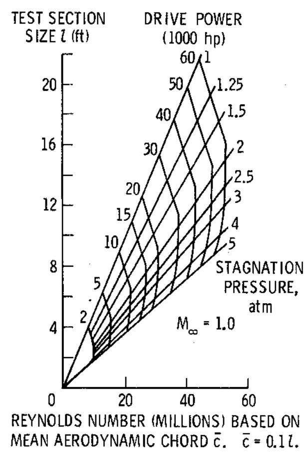
Locations for LN_2 atomizing injectors pose some interesting possibilities. Injection just downstream of the test section of a high-speed tunnel could realize an increase of stagnation pressure together with reduction of Mach number downstream of the zone of evaporation, by utilizing the Aerothermopressor principles which have been investigated by Shapiro.[4] Injection downstream of the fan could result in some attenuation of turbulence and noise in the circuit.

The discharge of nitrogen from the circuit should preferably be oxygenated to a safe level and warmed. Both might be achieved by discharging the nitrogen as the driver gas in an ejector which induces ambient air. In the case of transonic testing, the discharge might be taken from the test section plenum chamber.

The cooling thermal capacity of LN_2 is used to cool down the structure and to absorb drive motor power. An initial cool-down from room temperature to cryogenic test temperature would require about 0.2 lb of LN_2 per pound of steel. Cooling through this temperature range need not, however, be a regular occurrence. Between runs the tunnel circuit could remain cold. The heat to be removed from the structure before each run would amount to the heat soak, and by proper design this can be kept to an acceptably low level. The absorption of motor drive power would require an LN_2 flow rate of about 0.0065 lb/sec/hp. Estimates of the operating costs of high-Reynolds-number continuous-flow cryogenic wind tunnels on the basis of cost per unit time on line and including the cost of nitrogen, indicate that costs are acceptably low.

Model and instrumentation

It must be possible to rapidly carry out changes on a model, or to rectify faults in the balance. For this purpose the model and



STAGNATION PRESSURE, atm	STAGNATION TEMP., °K	ξ, %
1.0	104.4	0.7
1.25	106.4	.8
1.5	108.2	.9
2.0	115.0	1.0
2.5	123.0	1.0
3.0	129.8	1.0
4.0	143.0	1.0
5.0	155.1	1.0

Fig. 12 Test section design chart for transonic testing.

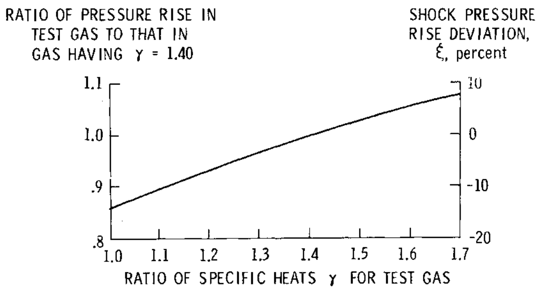


Fig. 13 Variation of shock pressure rise deviation ξ with ratio of specific heats γ for test gas.

sting would be mechanically removed from the test section into an airlock for warming. The strain-gage balance and pressure transducers would be calibrated at room temperature, and, while in use in the cryogenic tunnel, kept at this temperature by heating.

By completely eliminating support interference and the compromise of model shape which is inherent in conventional model support schemes, the magnetic balance and suspension system[5] is particularly well suited for the proper exploitation and preservation over the model of the high-quality flows which will be a necessary feature of high-Reynolds-number facilities.[6] In addition, the ease and rapidity with which the model may be orientated on the tunnel center line with the magnetic balance will facilitate the rapid acquisition of aerodynamic data. Removal of the model for changes would be a simple operation.

Conclusions

1) Cryogenic subsonic, transonic, and supersonic wind tunnels offer significant increases of test Reynolds number without increase of aerodynamic loads. For example, Reynolds number may be increased by a factor of about 7 in tests at low subsonic speeds, or by a factor of 5 at transonic speeds with no increase in dynamic pressure. 2) The drive power for a cryogenic tunnel is considerably lower than for a conventional continuous-flow tunnel. 3) Recent advances in the field of cryogenic engineering are such that there should be no insuperable engineering problems involved in the design and construction of a cryogenic wind tunnel. 4) A high-Reynolds-number continuous-flow tunnel is now affordable because of the reduced dimensions and reduced drive-power requirement of the cryogenic tunnel. Operating costs appear acceptable. 5) Practical operational procedures for a high-Reynolds-number test facility can be devised. 6) Low-speed cryogenic wind-tunnel experiments have demonstrated the predicted changes of drive power, Reynolds number, and fan speed with temperature, while operating with nitrogen as test gas. The experiments have also demonstrated that cooling by sprayed liquid nitrogen is practical and that working temperature can be controlled within acceptable limits. A water-jacketed strain-gage balance has demonstrated satisfactory operation in the low-speed cryogenic wind tunnel. 7) The use of a magnetic suspension and balance system in conjunction with the cryogenic tunnel appears to be an extremely attractive combination. 8) There is a need for a pilot transonic continuous-flow pressure facility to provide further design data and operational experience.

Appendix: Derivation of the Normal Shock Pressure Rise Deviation Factor ξ

The ratio of static pressures either side of a normal shock is

$$P_2/P_1 = (2\gamma M_1{}^2 - \gamma + 1)/(\gamma + 1) \tag{A1}$$

The ratio of pressure rise $\Delta P = P_2 - P_1$ to upstream static pressure P_1 is

$$\Delta P/P_1 = [2\gamma/(\gamma+1)](M_1{}^2 - 1) \tag{A2}$$

The ratio of the rise of static pressure in a gas having ratio of specific heats γ_a to the pressure rise in another gas having ratio of specific heats γ_b, each initially at the same static pressure P_1 and moving at Mach number M_1 has been defined as the shock pressure rise deviation ξ, and is given by

$$\xi = (\Delta P_a/\Delta P_b)(\gamma_a/\gamma_b)[(\gamma_b + 1)/(\gamma_a + 1)] \tag{A3}$$

For a reference gas b ("air") having $\gamma_b = 1.4$, the above expression is plotted in Fig. 13 as a function of γ_a. The deviation factor as a percentage is shown on the right.

References

[1] Smelt, R., "Power Economy in High-Speed Wind Tunnels by Choice of Working Fluid and Temperature," Rept. Aero. 2081, Aug. 1945, Royal Aircraft Establishment, Farnborough, England.

[2] Whitfield, J. D., Schueler, C. J., and Starr, R. F., "High Reynolds Number Transonic Wind Tunnels—Blowdown or Ludwieg Tube," Paper 29, AGARD CP 83-71, April 1971.

[3] Evans, J. and Pugh, P., "A Proposed High Reynolds Number, ECT Driven Transonic Wind Tunnel at RAE Bedford," RAE TR 72054, Feb. 1972, Royal Aircraft Establishment, Farnborough, England.

[4] Shapiro, A. H. et al., "The Aerothermopressor—A Device for Improving the Performance of a Gas Turbine Power Plant," *Transactions of the ASME*, April 1956, p. 617.

[5] *Proceedings of the Second International Symposium on Magnetic Balance and Suspension Systems*, Dept. of Aeronautics and Astronautics, Univ. of Southampton, Southampton, England, 1971.

[6] "Facilities and Techniques for Aerodynamic Testing at Transonic Speeds and High Reynolds Number," AGARD Conference Preprint 83, April 1971.

[7] Hilsenrath, J. et al., "Tables of Thermal Properties of Gases," Circular 564, Nov. 1955, National Bureau of Standards.