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SIMULATION OF FLIGHT TEST CONDITIONS IN THE LANGLEY PILOT TRANSONIC CRYOGENIC TUNNEL

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SUMMARY

The theory and advantages of the cryogenic tunnel concept are briefly reviewed. The unique ability to vary temperature independently of pressure and Mach number allows, in addition to large reductions in model loads and tunnel power, the independent determination of Reynolds number, Mach number, and aeroelastic effects on the aerodynamic characteristics of the model. Various combinations of Reynolds number and dynamic pressure can be established to represent accurately flight variations of aeroelastic deformation with altitude changes. The consequences of the thermal and caloric imperfections of the test gas under cryogenic conditions have been examined and found to be insignificant for operating pressures up to 5 atm. The characteristics of the Langley pilot transonic cryogenic tunnel are described and the results of initial tunnel operation are presented. Tests of a two-dimensional airfoil at a Mach number of 0.85 show identical pressure distributions for a chord Reynolds number of 8.6×10^6 obtained first at a stagnation pressure of 4.91 atm at a stagnation temperature of 322.0 K and then at a stagnation pressure of 1.19 atm at a stagnation temperature of 116.5 K.

INTRODUCTION

It is widely recognized, both in the United States and in Europe, that there is an urgent need for wind tunnels capable of testing models at or near full-scale Reynolds number. The need is especially acute at transonic speeds where, because of the large power requirements of transonic tunnels, economic forces have dictated the use of relatively small tunnels; as a result, there is a large gap between test and flight Reynolds numbers. With ever increasing aircraft size, existing transonic tunnels are becoming even more inadequate in test Reynolds number capability. Operating at cryogenic temperatures, first proposed by Smelt in reference 1, offers an attractive means of increasing Reynolds number over a wide range of Mach number while avoiding many of the prac-

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tical problems associated with testing at high Reynolds numbers in conventional pressure tunnels.

In addition to the advantages of reduced dynamic pressures and reduced drive power requirements, the cryogenic tunnel concept offers some unique operating envelopes. In a cryogenic tunnel with independent control of temperature, pressure, and Mach number, it is possible to determine independently the effect of Reynolds number, aeroelastic distortion, and Mach number on the aerodynamic characteristics of the model.

Personnel of the NASA Langley Research Center have been studying the application of the cryogenic concept to high Reynolds number transonic tunnels since the fall of 1971. The results of a theoretical investigation aimed at extending the analysis of Smelt and the results of a low-speed experimental program have been reported in references 2 and 3. After the successful completion of the low-speed experimental program, the work on the cryogenic concept at Langley has been directed toward the development of a large high Reynolds number cryogenic transonic tunnel. Real-gas effects were studied to determine the operating limits set by saturation boundaries and to determine the consequences of the thermal and caloric imperfections both on isentropic flow and on the flow across a normal shock for nitrogen over a wide range of temperatures and pressures. To provide the experimental information required for the planning of a large high Reynolds number cryogenic tunnel, a pilot pressurized transonic cryogenic tunnel has been built and recently placed into operation. This paper contains a brief review of the cryogenic concept, a description of the unique testing capability available in a pressurized cryogenic tunnel, some of the results of the study of real-gas effects, and some of the results obtained during the initial operation of the Langley pilot transonic cryogenic tunnel.

SYMBOLS

a	local speed of sound, m/s
C	any aerodynamic coefficient
C_p	pressure coefficient, $\frac{p - p_\infty}{q_\infty}$
c	chord of two-dimensional airfoil, m
$\bar{c}$	mean geometric chord, m
ℓ	linear dimension, m
M	Mach number

M_l	local Mach number on model
p	pressure, atm (1 atm = 101.3 kN/m^2)
q	dynamic pressure, $\frac{1}{2}\rho V^2$, kN/m^2
R	Reynolds number
$R_{\bar{c}}$	Reynolds number based on $\bar{c}$
T	temperature, K
V	free-stream velocity, m/s
x	linear dimension along airfoil chord line, m
Z	compressibility factor
γ	ratio of specific heats
μ	free-stream viscosity, N-s/m^2
ρ	free-stream density, kg/m^3

Subscripts:

$\bar{c}$	mean geometric chord
max	maximum
min	minimum
t	stagnation conditions
∞	free stream
1	upstream of shock
2	downstream of shock

THE CRYOGENIC CONCEPT

In most wind-tunnel tests, it is necessary to match both Reynolds number and Mach number if the results obtained with the subscale model are to be applicable to full-scale flight conditions. The defining equations for these flow similarity parameters are

$$R = \frac{\rho V \ell}{\mu}$$

and

$$M = \frac{V}{a}$$

The Mach number is relatively easy to match in a wind tunnel. The Reynolds number corresponding to modern high-speed aircraft, however, cannot be matched in present tunnels where, in general, the Reynolds number available is an order of magnitude too low at best. From the equation for Reynolds number, it is seen that for a given test gas, Reynolds number can be increased in three ways. The tunnel size can be increased so that larger models with increased component lengths ℓ can be used. Design studies for tunnels capable of giving full-scale Reynolds number at normal temperatures and moderate pressure show that they would be very large, and therefore very costly, and would make heavy demands on power. The usual alternative of operating a smaller tunnel at elevated pressure, and thereby increasing Reynolds number by increasing density, is less prohibitive from a cost standpoint. However, the high pressures required for full-scale Reynolds number result in high dynamic pressures with attendant high model, balance, and sting stresses and an undesirable increase in various aeroelastic and support interference problems. The third method of increasing Reynolds number is to decrease the temperature of the test gas. As the temperature is decreased, the density ρ increases and the viscosity μ decreases. Both of these changes result in increased Reynolds number. With decreasing temperature, the speed of sound a decreases. For a given Mach number, this reduction in speed of sound results in a reduced velocity V which, while offsetting to some extent the Reynolds number increase due to the changes in ρ and μ, provides advantages with respect to dynamic pressure, drive power, and energy consumption.

The effects of a reduction in temperature on the gas properties, test conditions, and drive power are illustrated in figure 1. For comparison purposes, a stagnation temperature of 322 K for normal tunnels is assumed as a datum. It can be seen that an increase in Reynolds number by more than a factor of 6 is obtained with no increase in dynamic pressure and with a large reduction in the required drive power. To obtain such an

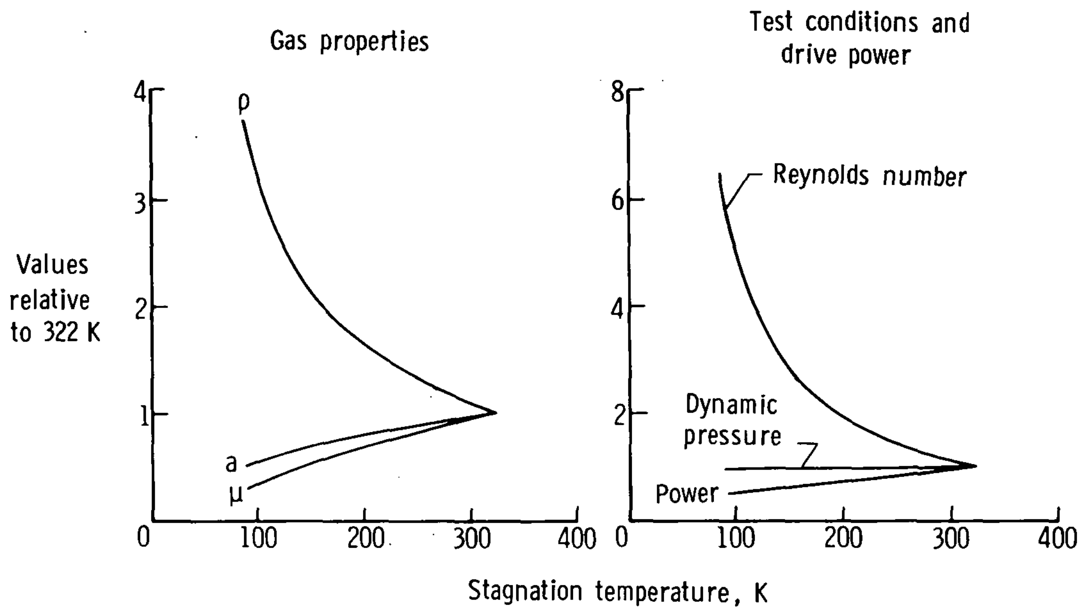

Figure 1.- Effect of temperature reduction on gas properties, test conditions, and drive power. $M_\infty = 1.0$; constant stagnation pressure and tunnel size.

increase in Reynolds number without increasing either the tunnel size or the operating pressure while actually reducing the drive power is extremely attractive and appears to make a high Reynolds number transonic tunnel much more feasible than previous approaches.

THE ADVANTAGES OF A CRYOGENIC TUNNEL

Reduced Dynamic Pressure and Drive Power

Once a tunnel size has been selected and the required Reynolds number has been established, the previously described effects of cryogenic operation are manifested in large reductions in the required tunnel stagnation pressure and therefore, in large reductions in both the dynamic pressure and the drive power. These reductions are illustrated in figure 2, where both dynamic pressure and drive power are shown as functions of stagnation temperature for a tunnel having a 3- by 3-m test section at a constant-chord Reynolds number of 50×10^6 at $M_\infty = 1.0$, where the chord is taken to be one-tenth of the square root of the test-section area. As the tunnel operating temperature is reduced, the large reductions in both dynamic pressure and drive power are clearly evident and provide the desired relief from the extremely high values that would be required for a pressure tunnel operating at normal temperatures.

The large reduction in dynamic pressure is important in that it minimizes the problems illustrated in figure 3. Some of the specific advantages resulting from the reduction in dynamic pressure include reduced model and balance stresses, increased test lift coefficient capability, reduced sting size which results in reduced sting interference and aft fuselage distortion, and an increased stress margin for aeroelastic matching.

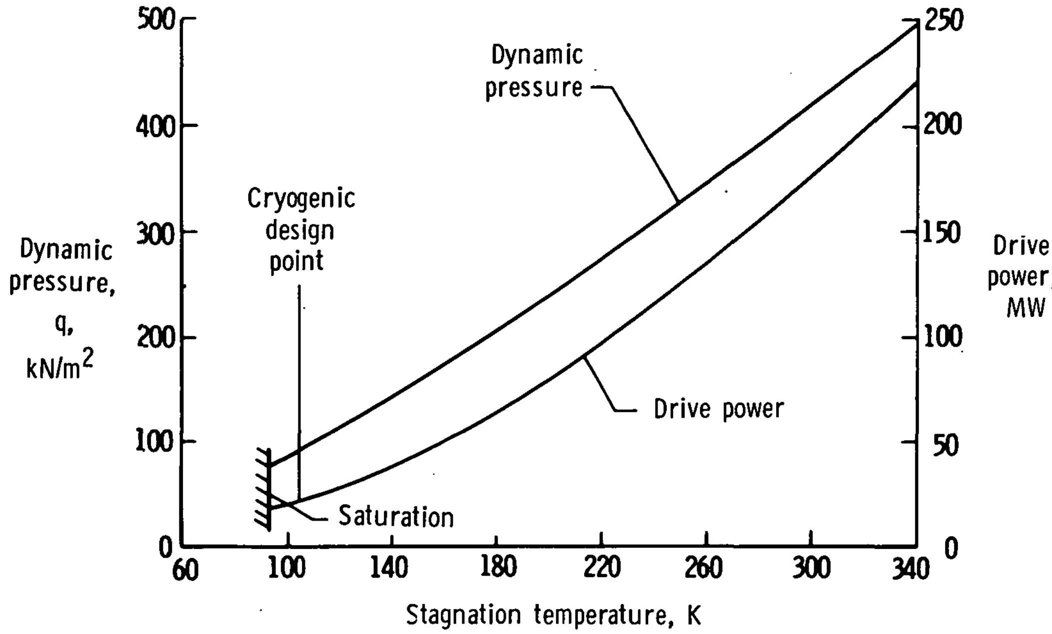

Figure 2.- Effect of temperature reduction on dynamic pressure and drive power. $M_\infty = 1.0$; $R_{\bar{c}} = 50 \times 10^6$; 3- by 3-m test section.

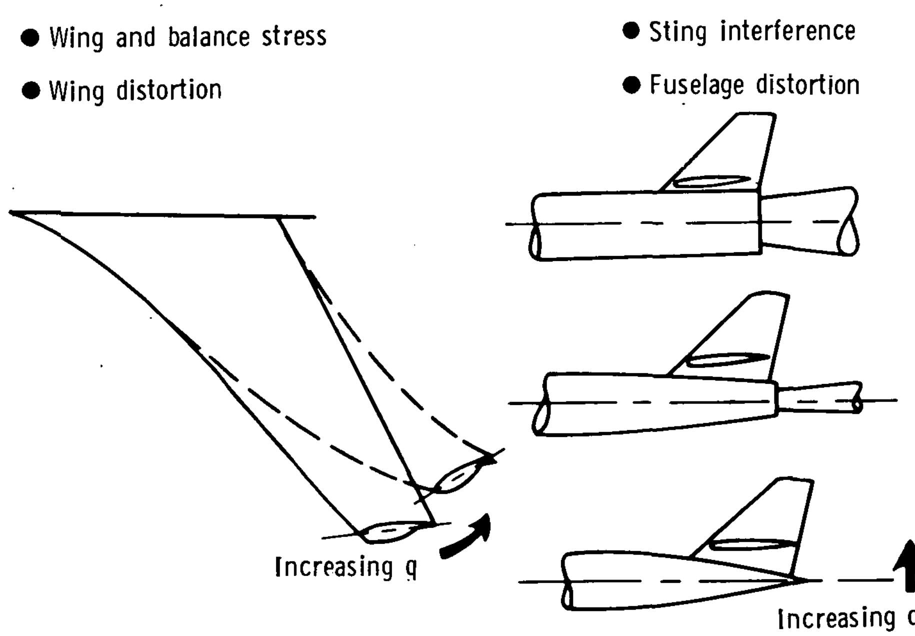

Figure 3.- Some problems with high dynamic pressure q.

The large reduction in drive power makes a fan-driven tunnel practical even at this high Reynolds number. The resulting efficiency and increased run time provide important advantages relative to intermittent tunnels, such as increased productivity, improved dynamic testing capability, and, for equal amounts of testing, reduced operating costs and reduced total energy consumption.

An additional advantage of a fan-driven tunnel is realized by having run times sufficient to insure the avoidance of problems caused by heat transfer between the model and the stream. As noted in reference 4, in tunnels where the flow is generated by expansion waves, spurious scale effects due to heat transfer can only be avoided by cooling the model to the expected recovery temperature. Such problems are avoided in a continuous-flow tunnel where the model is never far from thermal equilibrium with the stream. In general, no additional testing time is required to allow the model to achieve thermal equilibrium since the flow initiation process is gradual and test conditions are not changed abruptly in a fan-driven tunnel.

In figure 2, the advantages of the cryogenic concept with respect to reduced dynamic pressure and reduced drive power are shown for constant Reynolds number and constant test-section size. For a constant tunnel size, both the shell costs, which may account for as much as two-thirds of the total cost of a wind tunnel, and the costs of the drive system for the tunnel vary nearly linearly with the maximum stagnation pressure of the tunnel. Therefore, for conditions of constant Reynolds number and tunnel size, the reduction in the stagnation pressure which is needed to achieve the desired Reynolds number at cryogenic temperatures results in a reduction in capital costs even when the higher costs of structural materials used at cryogenic temperatures is taken into account.

There is an even stronger impact of the cryogenic concept on capital costs if stagnation pressure is held constant and the cryogenic concept is used to reduce the tunnel size required for a given Reynolds number. At a constant pressure, the cost of the tunnel shell varies approximately with the cube of the tunnel size, whereas the cost of the drive system varies approximately with the square of the tunnel size. Thus, a reduction in tunnel size by a factor of 5 or 6, which, as can be seen from figure 1, may be realized by operating at cryogenic temperatures, represents a substantial savings in capital costs over the much larger ambient-temperature tunnel which would be required to achieve the desired Reynolds number at the same stagnation pressure.

Reduced Peak Power Demand and Reduced Total Energy Consumption

Because of the high peak power demands of large ambient-temperature transonic tunnels, the tunnel designer has, up until now, been forced to abandon the conventional continuous-flow tunnel and adopt some form of intermittent tunnel using energy storage techniques. However, since a fan is the most efficient method of driving a tunnel, the reduction in peak power demand obtained by going to energy storage techniques is realized only by accepting an increase in total energy consumption. By reducing the drive power requirements to a level where a fan drive again becomes practical even for large tunnels, the cryogenic concept not only makes available the many technical advantages of the conventional continuous-flow tunnel but, at the same time, reduces the total energy consumed during a test.

As noted in reference 2, for cryogenic operation, the tunnel circuit is cooled and the heat of compression added to the stream by the drive fan is balanced by spraying liquid nitrogen directly into the tunnel circuit. For cryogenic operation, therefore, the power and energy used for the production of the liquid nitrogen must be taken into account. To illustrate the contribution of nitrogen production to power demand and total-energy consumption, two tunnel stagnation pressures have been selected to allow comparisons to be made between ambient and cryogenic operation of fan-driven tunnels. At transonic speeds, stagnation pressures in excess of about 5 atm are highly undesirable even for developmental testing, particularly for large-aspect-ratio configurations, because of problems such as model and support stresses, balance loads, and aeroelasticity. (For example, see ref. 4.) Therefore, the first comparison will be made for a stagnation pressure of 5 atm. Secondly, since it would be highly desirable, particularly for a versatile research tunnel, to obtain the required Reynolds number without greatly exceeding the dynamic pressures encountered in existing transonic pressure tunnels, a comparison will be made for a stagnation pressure of 2.5 atm.

The following test conditions are assumed for both ambient and cryogenic operation for the first comparison:

$$M_\infty = 1.00$$

$$R_{\bar{c}} = 50 \times 10^6$$

$$\bar{c} = 0.1 \text{ (test-section area)}^{0.5}$$

$$p_t = 5 \text{ atm}$$

For operation at ambient temperatures with the tunnel cooled by a water-air heat exchanger, a stagnation temperature T_t of 322 K is assumed. To achieve the desired value of Reynolds number will require a test section 7.38 by 7.38 m, with a corresponding drive power of approximately 490 MW. Although a tunnel of this size and power requirement is technically feasible, the capital and operating costs would be very high.

For operation at cryogenic temperatures and cooling with liquid nitrogen, a stagnation temperature of 113 K is assumed. The resultant size of the test section is 1.69 by 1.69 m. Continuous operation of the tunnel under the assumed test conditions would require a drive power of 15 MW plus the additional power required to produce the liquid nitrogen. If it is assumed that the energy required to produce a unit mass of liquid nitrogen is 3.49 MJ/kg, the additional power required to produce liquid nitrogen for continuous running of the tunnel is about 200 MW. The total peak power for continuous running is therefore about 215 MW. However, the production and storage of liquid nitrogen for use in a cryogenic tunnel is analogous to the storage of high-pressure air for the operation of conventional blowdown or induced-flow tunnels, since a relatively low power device can be used to store energy over a long period for subsequent use during a short period. Liquid nitrogen plants generally operate continuously. Thus, for example, if a wind tunnel were to operate at cryogenic temperatures for 10 hr/week, the peak power demand for liquid nitrogen production would be only about 6 percent of the power equivalent of the liquid nitrogen used during the operation of the tunnel at cryogenic temperatures. For the assumed 10 hr of cryogenic operation per week, the peak power demand for both driving the fan and producing the liquid nitrogen is 27 MW, which is only 5.5 percent of the peak power required for an ambient-temperature fan-driven tunnel operating at the same test conditions.

The same test conditions are assumed for the second comparison, except for the stagnation pressure which is assumed to be 2.5 atm. To achieve the desired Reynolds number at ambient temperatures requires a test section 14.7 by 14.7 m, with a corresponding drive power of 980 MW.

For the lower stagnation pressure of 2.5 atm, a stagnation temperature of 105 K is assumed. The resultant size of the test section is 3.0 by 3.0 m. In this case, continuous operation of the tunnel would require a drive power of 23 MW plus an additional 318 MW for liquid nitrogen production for a total peak power of 341 MW. For an assumed 10 hr of cryogenic operation per week, the peak power demand for both driving the fan and producing the liquid nitrogen is 42 MW, which is 4.3 percent of the peak power required for an ambient-temperature fan-driven tunnel operating at 2.5 atm.

For a typical test program at transonic speeds, the liquid nitrogen used to cool the tunnel structure and to overcome the heat conducted through the insulated tunnel walls is insignificant when compared with the liquid nitrogen used to balance the heat of compression of the drive fan. Therefore, neglecting the liquid nitrogen used to cool down the tunnel and to overcome the heat conducted through the walls, the total energy required for a particular wind-tunnel test is the product of the total power required to operate the tunnel and the time required for the test.

If it is assumed that a given test will require the same amount of running time regardless of whether the testing is done at ambient or cryogenic temperatures, the ratio of peak total-power demand during tunnel operation is also the ratio of total-energy requirement. Thus, for the conditions assumed for operation at a stagnation pressure of 5 atm, testing at cryogenic temperatures requires only 44 percent of the energy required for the same test at ambient temperature. At a stagnation pressure of 2.5 atm, testing at cryogenic temperatures requires only 35 percent of the energy required at ambient temperature. In fact, operation at cryogenic temperatures at 2.5 atm requires only 70 percent of the energy required at 5 atm when operating at ambient temperatures. The reduction in total-energy requirement which results from cryogenic operation is especially significant in this age when the conservation of energy is assuming increasing importance.

Operating Envelopes

In addition to the advantages of reduced dynamic pressures and reduced drive-power requirements, the cryogenic tunnel concept offers some unique operating envelopes. For a given model orientation, any aerodynamic characteristic C is a function of, among other things, Reynolds number R, the aeroelastic distortion of the model, which is, in turn, a function of the dynamic pressure q, and Mach number M.

As previously mentioned, the ability to operate a cryogenic tunnel at a constant pressure over a range of temperatures allows tests to be made over a range of Reynolds numbers while dynamic pressure and Mach number are held constant. If the tunnel is also capable of operating over a range of pressures, tests can be made over a range of dynamic pressures while Mach number and also Reynolds number are held constant by a suitable adjustment of temperature. With the ability to vary Mach number, tests can be made over a range of Mach numbers while Reynolds number and dynamic pressure are held constant. Thus, in a cryogenic tunnel with the independent control of temperature, pressure, and Mach number, it is possible to determine independently the effect of Reynolds number, aeroelastic distortion, and Mach number on the aerodynamic characteristics of the model.

Expressed in terms of partial derivatives, this testing ability, which is unique to the pressurized cryogenic tunnel, allows the determination of the pure partial derivatives $\partial C/\partial R$, $\partial C/\partial q$, and $\partial C/\partial M$.

To illustrate the manner in which this is accomplished, operating envelopes for three modes of operation are presented for a cryogenic transonic pressure tunnel having a 3- by 3-m test section. The main purpose of these operating envelopes is to illustrate the various modes of operation. However, the size of the tunnel and the ranges of temperature, pressure, and Mach number have been selected with some care to represent the anticipated characteristics of a future high Reynolds number transonic tunnel. For these operating envelopes, the values of $R_{\bar{c}}$ are based on

$$\bar{c} = 0.1 \text{ (test-section area)}^{0.5}$$

Constant Mach number mode.- A typical operating envelope showing the range of q and R available for sonic testing is presented in figure 4. The envelope is bounded by the maximum temperature boundary (taken in this example to be 350 K), the minimum temperature boundary (chosen to avoid saturation with $M_{l,max} = 1.40$), the maximum pressure boundary (4.0 atm), the minimum pressure boundary (0.2 atm), and a boundary determined by an assumed maximum available fan-drive power (45 MW). The arrows indicate typical paths which might be used in determining $\partial C/\partial R$ and $\partial C/\partial q$. With such an operating capability, it is possible, for example, to determine at a constant Mach number the true effect of Reynolds number on the aerodynamic characteristics of the model $\partial C/\partial R$, without having the results influenced by changing model shape due to changing dynamic pressure, as is the case in a conventional pressure tunnel. For most models, there will be a slight variation of the modulus of elasticity E with temperature. To correct for this slight variation in E, the dynamic pressure q is varied by varying total pressure so that the ratio q/E remains constant over the Reynolds number range.

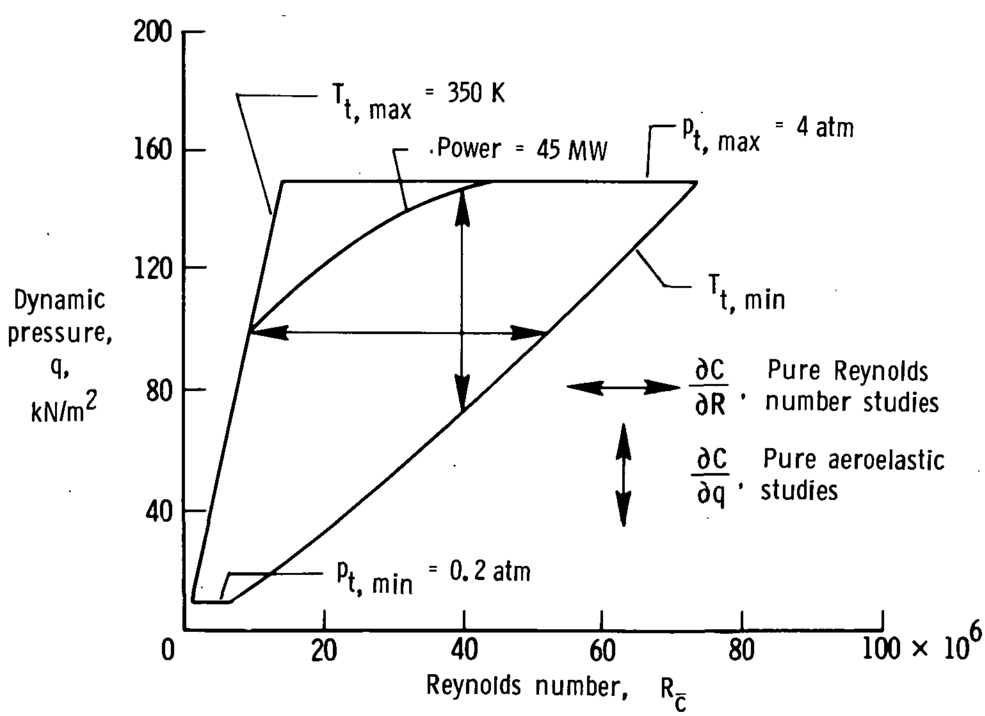

Figure 4.- Constant Mach number operating envelope for cryogenic nitrogen tunnel. $M_\infty = 1.00$; 3- by 3-m test section.

This ability to determine $\partial C/\partial R$ is of particular importance, for example, in research on the effects of the interaction between the shock and the boundary layer. As indicated by the envelope, pure aeroelastic studies can be made, and various combinations of R and q can be established to represent accurately the variations in flight of aeroelastic deformation and changes in Reynolds number with altitude. Similar envelopes are, of course, available for other Mach numbers.

Constant Reynolds number mode.- A typical operating envelope is presented in figure 5, which shows the range of q and M available for testing at a constant Reynolds number of 40×10^6. The maximum temperature limits, maximum and minimum pressure limits, and fan-drive power limits used in the previous section have been assumed. The minimum temperatures were never less than those consistent with avoiding saturation under local conditions where the maximum local Mach number varied with free-stream Mach number as assumed in the following table:

M_∞	0.33	0.40	0.60	0.80	1.00	1.20	1.30
$M_{l,max}$	0.87	0.92	1.05	1.22	1.40	1.60	1.69

The arrows indicate typical paths which might be used to determine $\partial C/\partial q$ and $\partial C/\partial M$. The derivative $\partial C/\partial q$ has been previously discussed. The unique capability associated with $\partial C/\partial M$ allows true Mach number effects to be obtained by eliminating the usual problem introduced by changes of Reynolds number or by changes in the aeroelastic effects.

Constant dynamic pressure mode.- Although the three derivatives were illustrated previously, an additional form of the envelopes is illustrated in figure 6, which shows the range of R and M available at a constant dynamic pressure of 100 kN/m^2. The arrows indicate typical paths which might be used in determining $\partial C/\partial M$ and $\partial C/\partial R$. The ability to determine $\partial C/\partial M$ can be used, for example, to determine the variation of drag coefficient with Mach number $\partial C_D/\partial M$ without the results being influenced in any way by Reynolds number or aeroelastic effects.

REAL-GAS CONSIDERATIONS

In the cryogenic tunnels considered to date, the test gas is nitrogen rather than air. Since air is about 78 percent nitrogen and 21 percent oxygen by volume and both nitrogen and oxygen are diatomic molecules having nearly the same molecular weights, there is no doubt that at ambient temperatures, test results obtained in nitrogen are equivalent to test results obtained in air. However, at cryogenic temperatures, whether testing in nitrogen or air, the magnitude of any real-gas effects and the possible operational limits which they might impose must be considered. The real-gas effects studied included liquefaction,

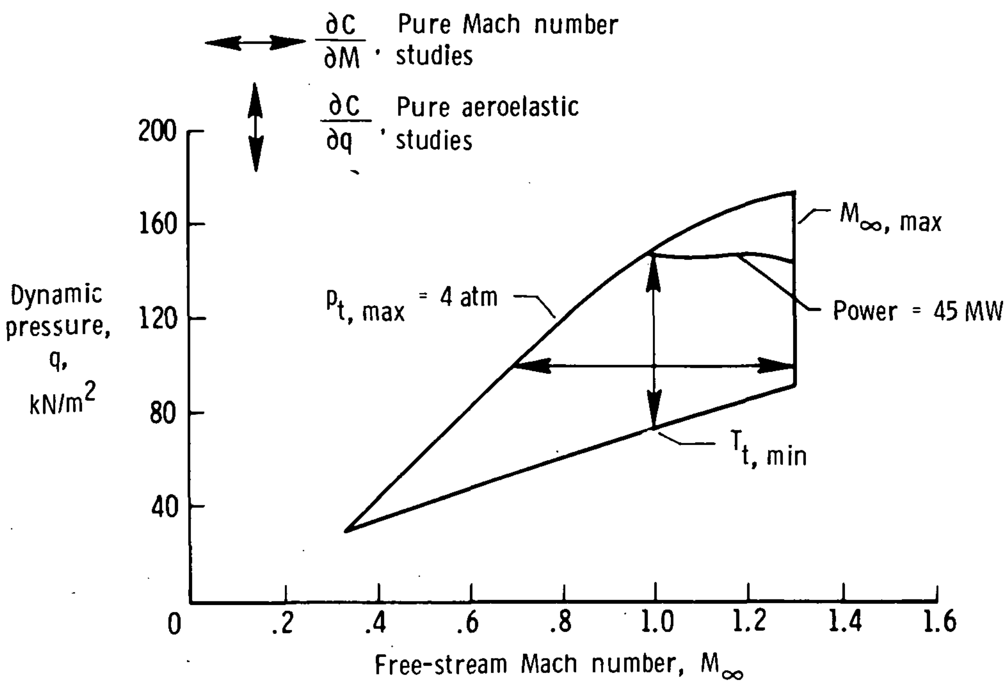

Figure 5.- Constant Reynolds number operating envelope for cryogenic nitrogen tunnel. $R_{\bar{c}} = 40 \times 10^6$; 3- by 3-m test section.

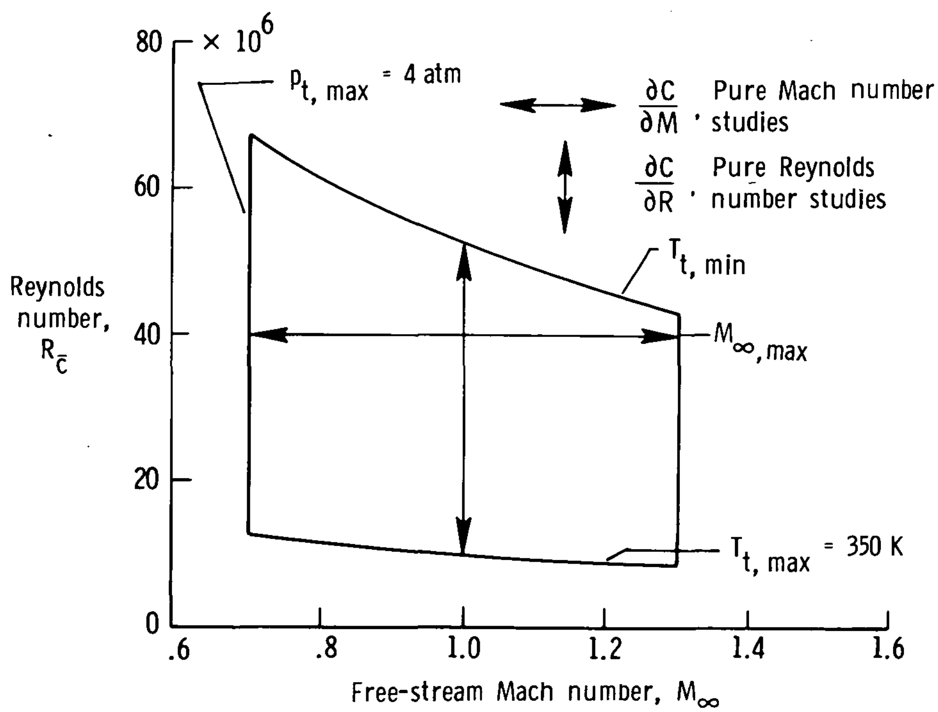

Figure 6.- Constant dynamic pressure operating envelope for cryogenic nitrogen tunnel. $q = 100$ kN/m^2; 3- by 3-m test section.

thermal imperfections, and caloric imperfections. These real-gas effects were studied to determine any operating limits set by saturation boundaries and to determine the consequences of the thermal and caloric imperfections both on isentropic flow and on the flow across a normal shock for nitrogen over a wide range of temperatures and pressures.

Saturation Boundaries

By using the equation for vapor pressure for nitrogen from reference 5, the minimum stagnation temperatures, which can be used to avoid saturation with nitrogen as the test gas, have been calculated for a range of Mach numbers and stagnation pressures. Figure 7 illustrates the restrictions imposed at sonic speeds on stagnation temperatures by three saturation boundaries corresponding to three assumed values of maximum local Mach number for various values of stagnation pressure. At a given stagnation pressure, the Reynolds number which can be obtained without liquefaction is reduced as the maximum local Mach number $M_{l,max}$ is increased, since the saturation boundary, and thus the possibility of liquefaction, is determined by the local values of temperature and pressure rather than by the free-stream values. Also shown in figure 7 is the operating condition corresponding to $R_{\bar{c}} = 50 \times 10^6$ at $M_\infty = 1.0$ in a tunnel having a 3- by 3-m test section where it is assumed that $M_{l,max} = 1.4$. With a knowledge of the maximum local Mach number expected during a test, the saturation boundary is well defined, and any possible problems due to liquefaction of the test gas can easily be avoided.

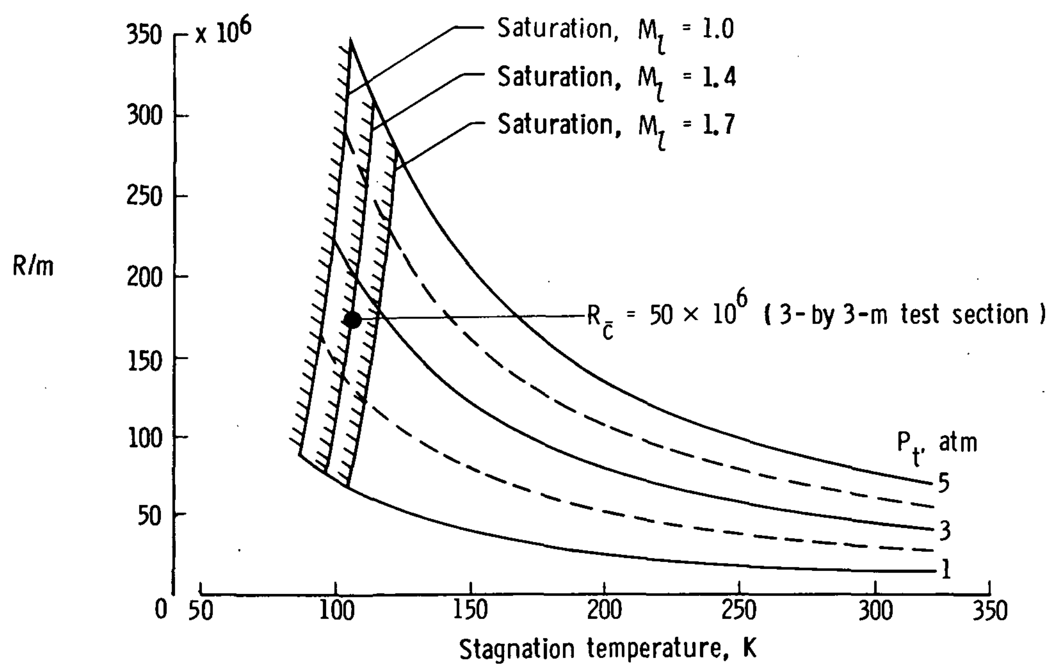

Figure 7.- Theoretical saturation boundaries. $M_\infty = 1.0$, testing in nitrogen.

Isentropic Expansions

The need to consider the thermal and caloric imperfections at cryogenic temperatures is illustrated in figure 8, where the compressibility factor Z and the ratio of specific heats γ for nitrogen are shown at a constant pressure of 5 atm over a range of temperatures. Both of these parameters depart from their ideal gas values by about 5 percent at the lower cryogenic temperatures.

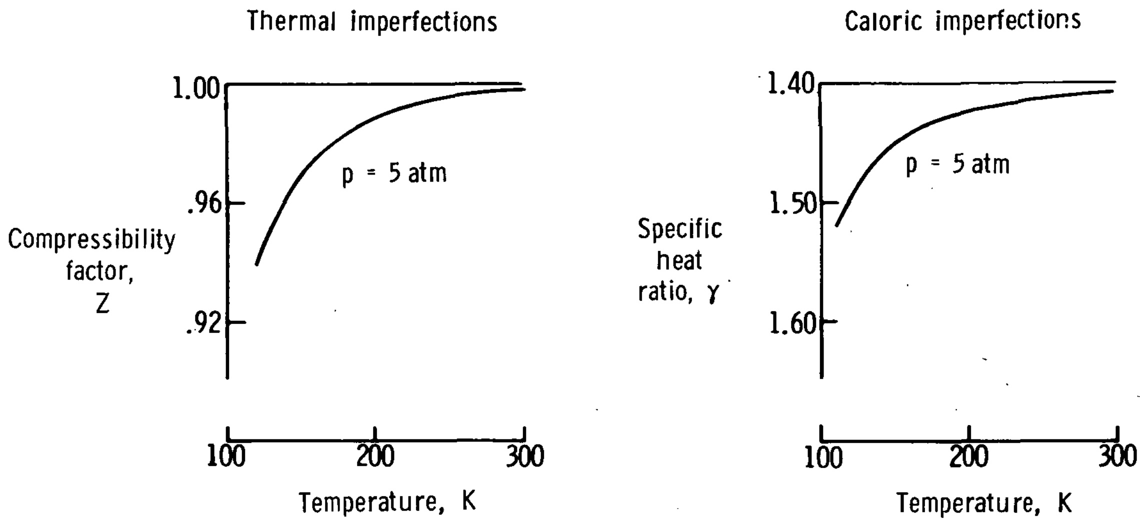

Figure 8.- Real-gas effects in nitrogen.

The thermodynamic properties for nitrogen were obtained from a National Bureau of Standards (NBS) program based on work by Jacobsen (ref. 5). The NBS program was modified so that isentropic expansions could be made. The various ratios which describe the expansion were calculated by using the real-gas properties and were compared with ratios derived from ideal-gas equations and ideal values of the compressibility factor ($Z = 1$) and the ratio of specific heats ($\gamma = 1.4$). An example of the results is presented in figure 9, where the ratio of the real and ideal pressure ratios necessary to expand isentropically to $M_\infty = 1.0$ is presented as a function of tunnel stagnation temperature and pressure. As can be seen, the effects are extremely small and, for $R_{\bar{c}} = 50 \times 10^6$ at cryogenic temperatures, the real-gas pressure ratio differs from the ideal-gas pressure ratio by only about 0.2 percent. It is interesting to note that the real-gas effect at cryogenic temperatures is actually less than the real-gas effect at ambient temperatures, where a considerably higher stagnation pressure is required to obtain $R_{\bar{c}} = 50 \times 10^6$.

The other real-gas ratios used to describe an isentropic expansion also differ from the ideal-gas ratios by this same, small percentage. In many cases, such as the determination of tunnel Mach number, for example, the real-gas equations can be used to avoid even this small error of 0.1 or 0.2 percent. However, errors of such magnitude are of

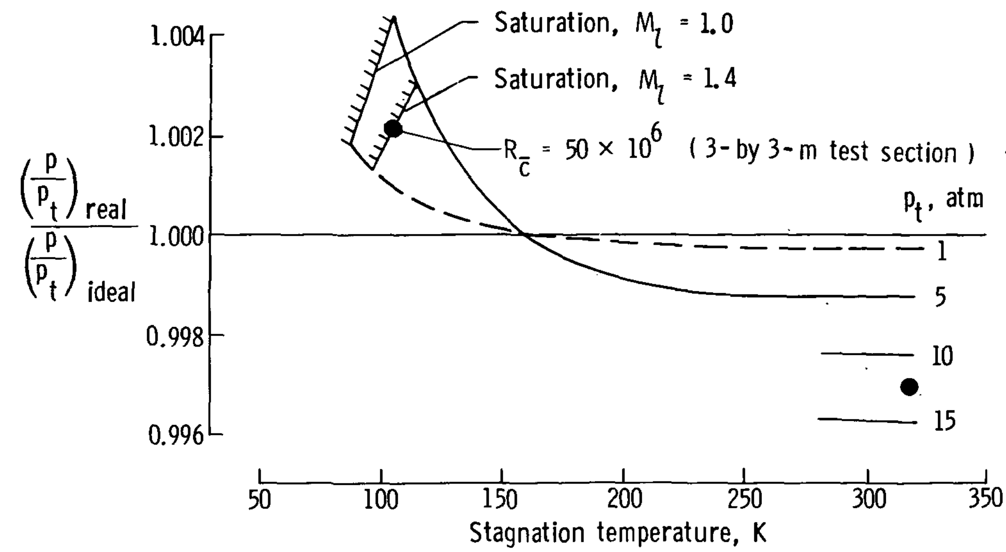

Figure 9.- Real-gas effects on isentropic expansions. $M_\infty = 1.0$ in nitrogen.

the same order as the uncertainty in measurements and would be considered insignificant in most wind-tunnel work.

Normal-Shock Flow

The NBS program previously mentioned was also modified so that the various ratios which describe normal-shock flow could be calculated by using the real-gas properties and compared with the corresponding ideal-gas ratios. An example of the results is presented in figure 10 where the ratio of the real to the ideal static-pressure ratio across a normal shock is presented as a function of tunnel stagnation temperature and pressure. As in the case of isentropic expansion, the effects are extremely small and for $R_{\bar{c}} = 50 \times 10^6$, the real-gas pressure ratio differs from the ideal-gas pressure ratio by only about 0.2 percent. The other real-gas ratios associated with normal-shock flow also differ from the ideal ratios by this same small percentage. As in the case of isentropic expansion, even in those situations where the real-gas equations cannot be used to take these effects into account, an error of this magnitude would usually be considered insignificant. Thus, even though the values of Z and γ depart significantly from their ideal-gas values at cryogenic temperatures, both the isentropic flow parameters and the normal-shock flow parameters are insignificantly affected by these real-gas effects.

THE PILOT TRANSONIC CRYOGENIC TUNNEL

After the completion of the low-speed tunnel work at the Langley Research Center, it was decided that a pilot continuous-flow fan-driven pressure tunnel would be required in order to extend the experimental study to transonic speeds. The purposes envisioned

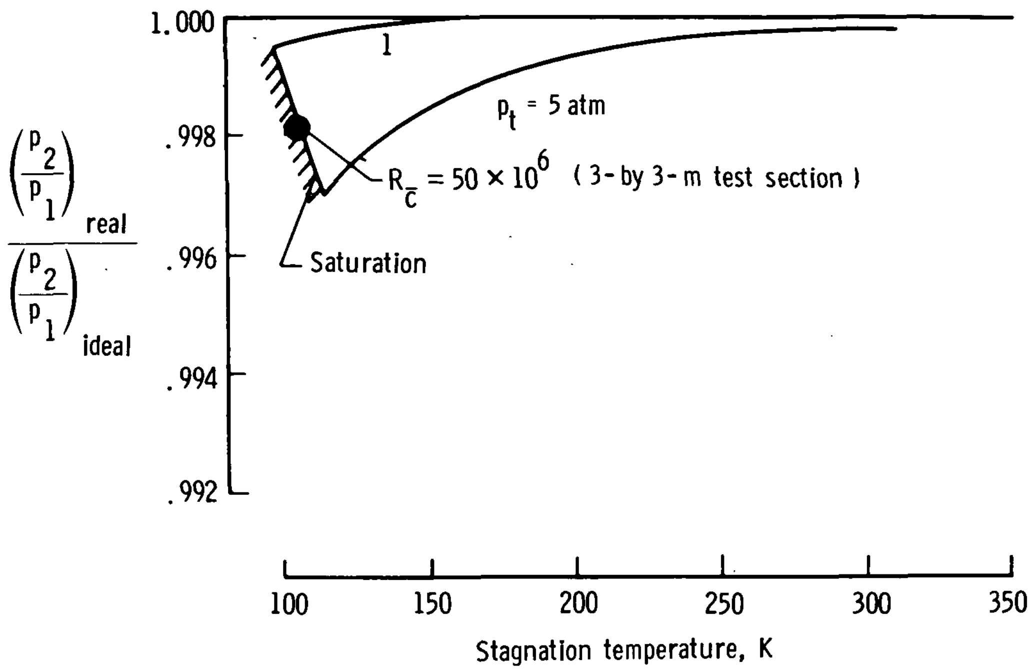

Figure 10.- Real-gas effects on normal shock static-pressure ratio.
$M_1 = 1.4$ in nitrogen.

for the pilot transonic cryogenic tunnel were to demonstrate in compressible flow that Reynolds numbers obtained by reducing temperature are equivalent to Reynolds numbers obtained by increasing pressure, to determine experimentally any limitations imposed by liquefaction, to verify engineering concepts with a realistic tunnel configuration, and to provide additional operational experience. Design of the transonic tunnel began in December 1972, and initial operation began in September 1973.

The Langley pilot transonic cryogenic tunnel is a single-return fan-driven tunnel with a slotted, octagonal test section 34 cm across flats. A sketch of the tunnel circuit is shown in figure 11. The tunnel pressure shell is constructed of 0.635-cm- and 1.270-cm-thick plates of 6061-T6 aluminum alloy. The flanges used to join the various sections of the tunnel were machined from plates of the same material. The bolts for the flanges were made from 2024-T4 aluminum alloy. These particular aluminum alloys were selected because they have good mechanical characteristics at cryogenic as well as ambient temperatures and could easily be fabricated by use of equipment and techniques available at Langley.

Viewing ports are provided to allow inspection of the plenum and test-section areas and the spray zones. Thermal insulation for most of the tunnel circuit consists of 12.7 cm of urethane foam applied to the outside of the tunnel structure with a vapor barrier of fiber-glass-reinforced epoxy on the outside. The fan is driven by a 2.2 MW variable-frequency motor which is capable of operating the tunnel at Mach numbers from

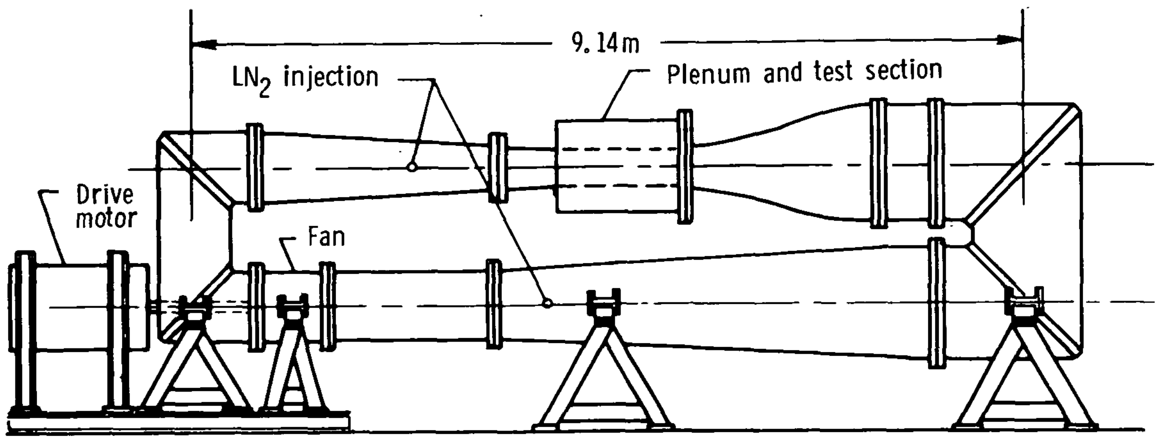

Figure 11.- Langley pilot transonic cryogenic tunnel.

about 0.1 to about 1.2 at stagnation pressures from slightly greater than 1 atm to 5 atm over a stagnation temperature range from 350 K to about 77 K. As was the case with the low-speed tunnel described in references 2 and 3, the wide range of operating temperatures is obtained by spraying liquid nitrogen (LN_2) directly into the tunnel circuit to cool the structure and the gas stream and to remove the heat of compression added to the stream by the drive fan.

In addition to special instrumentation required for test-section calibration and special aerodynamic tests, the tunnel is instrumented to measure temperatures and pressures around the circuit, dewpoint (or frost point) of the test gas, oxygen content of the test gas, pressure of the LN_2 supply, LN_2 flow rate, mass flow rate of the gas being exhausted from the stilling section and the plenum chamber, changes in the linear dimension of the tunnel with temperature, fan speed, and torque at the drive motor shaft.

Although the test section width is only 34 cm, the combination of a pressure of 5 atm and cryogenic capability provides a chord Reynolds number of 9×10^6 at $M_\infty = 1$, which is equivalent to an ambient tunnel having a test section 6.7 by 6.7 m. It also provides the opportunity of investigating independently the effects of temperature and pressure on Reynolds number over almost a five to one range of Reynolds number.

Acceptance tests and preliminary calibrations were completed by the end of November 1973 with no serious problems being encountered. Test-section flow looks excellent. An example of the temperature distribution in the stilling section is presented in figure 12, where it can be seen that the spread in temperature is only about 0.7 K at a nominal stagnation temperature of 112.4 K.

The combinations of operating conditions that have been covered at near-sonic speeds are presented in figure 13, where they are compared with the operating envelope for a tunnel having a 3- by 3-m test section and capable of providing $R_{\bar{c}}$ of 50×10^6.

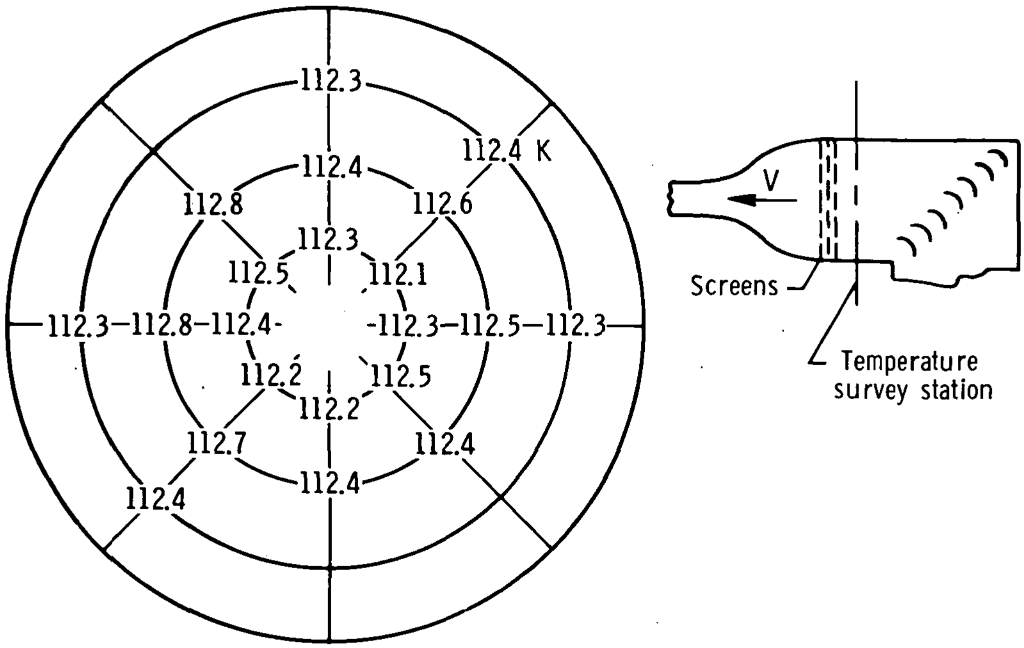

Figure 12.- Typical temperature distribution in pilot transonic cryogenic tunnel. $M_\infty = 0.8$; $p_t = 3.0$ atm; $T_t = 112.4$ K.

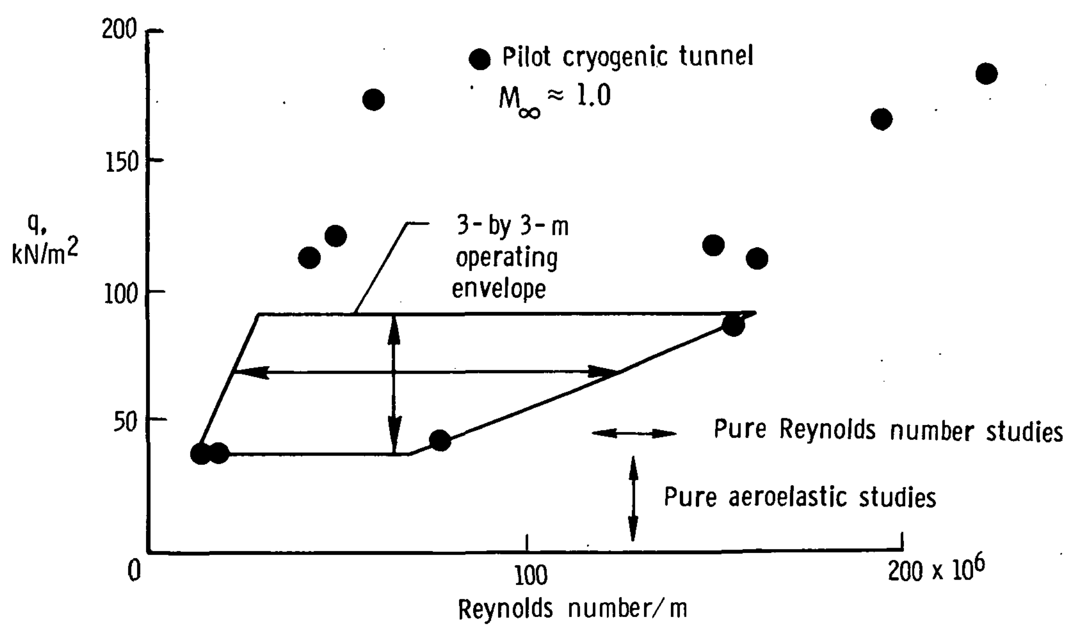

Figure 13.- Pilot transonic cryogenic tunnel calibration conditions completed at near-sonic speeds.

Reynolds number per meter has been used to provide consistency. It can be seen that the complete operating envelope for the large tunnel has been covered and that the combination of operating conditions needed for additional unit Reynolds number capability have been covered in the pilot tunnel. This fact, of course, provides additional design confidence if it were desired to increase the Reynolds number capability of the large tunnel by operating at increased stagnation pressure.

A series of aerodynamic experiments has been planned for the pilot cryogenic tunnel to provide experimental confirmation of the cryogenic concept at transonic speeds. In the first experiment a two-dimensional airfoil equipped with pressure orifices has been tested at a constant Mach number of 0.85, which is well into the supercritical flow region, with a chord Reynolds number of 8.6×10^6 obtained first with $p_t = 4.91$ atm and $T_t = 322.0$ K and then with $p_t = 1.19$ atm and $T_t = 116.5$ K. To allow any possible temperature effects on the boundary-layer development, the airfoil was tested with free transition. To eliminate any effect of changing dynamic pressure on model shape or incidence, the symmetrical airfoil was tested at zero incidence. A comparison of the pressure distributions for ambient and cryogenic temperature conditions is shown in figure 14 and it can be seen that the agreement is excellent. Additional tests were made over a range of Reynolds numbers at constant Mach number. These additional tests show

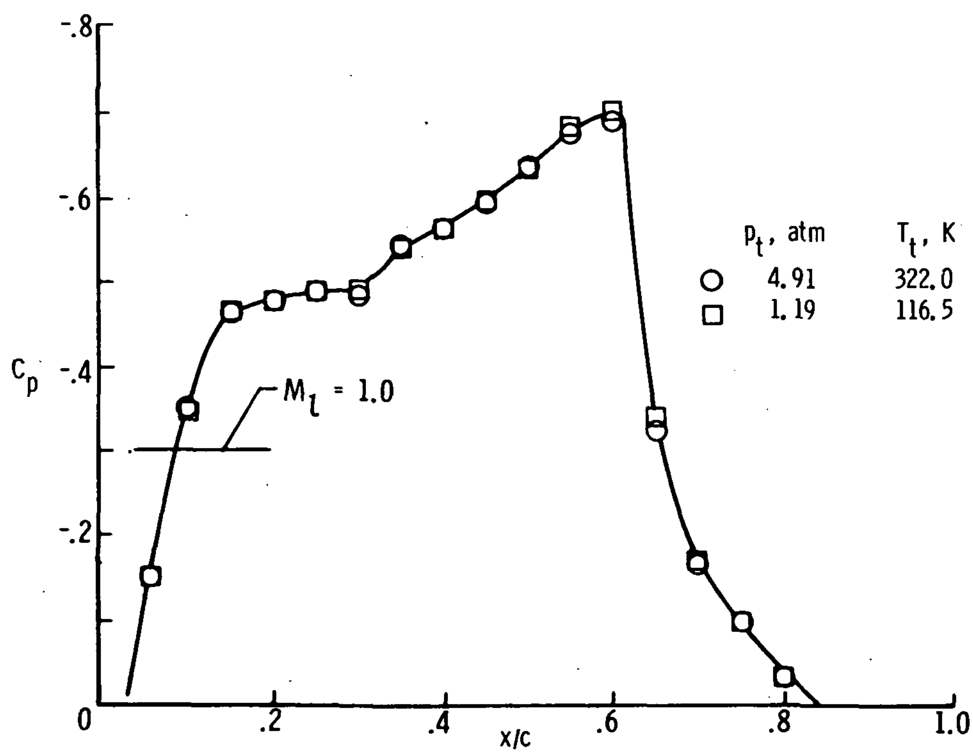

Figure 14.- Comparison of pressure distributions for ambient and cryogenic temperature conditions. NACA 0012-64 airfoil; $M_\infty = 0.85$; $R_{\bar{c}} = 8.6 \times 10^6$; angle of attack is 0°.

the pressure distribution for this airfoil to be sensitive to changes in Reynolds number as well as Mach number. Thus, the agreement between the pressure distributions shown in figure 14 indicates that the effect of Reynolds number obtained through the application of the cryogenic concept is, in this case, fully equivalent to the effect of the same Reynolds number obtained through increased pressure at ambient temperatures and that cryogenic gaseous nitrogen is a valid test medium.

CONCLUSIONS

The theory and advantages of the cryogenic tunnel concept were reviewed and the Langley pilot transonic cryogenic tunnel and the results of its initial operation were described. This discussion yielded the following conclusions:

1. Once a tunnel size and the required Reynolds number have been established, the use of cryogenic operating temperatures greatly reduces the required stagnation pressure of the tunnel and therefore greatly reduces both the dynamic pressure and drive power of the tunnel.

2. Even when the production of the liquid nitrogen required for cooling is taken into account, cryogenic operation of a fan-driven tunnel results in reduced peak-power demand and reduced total-energy consumption in comparison with ambient-temperature operation of a fan-driven tunnel at the same test conditions.

3. In a cryogenic tunnel with independent control of temperature, pressure, and Mach number, it is possible to determine independently the effect of Reynolds number, aeroelastic distortion, and Mach number on the aerodynamic characteristics of the model. Various combinations of Reynolds number and dynamic pressure can be established to represent accurately the variations in flight of aeroelastic deformation and changes in Reynolds number with altitude changes.

4. Saturation boundaries are well defined and liquefaction effects are easily avoided.

5. Isentropic flow and normal-shock parameters are insignificantly affected by the thermal and caloric imperfections of nitrogen under cryogenic conditions for operating pressures up to 5 atm.

6. Successful initial operation of the Langley pilot transonic cryogenic tunnel indicates no problems with respect to flow quality or temperature distribution. Operation of the pilot tunnel over a wide range of conditions indicates that the technology is currently available for the design and construction of a large high Reynolds number cryogenic transonic pressure tunnel.

7. Tests of a two-dimensional airfoil at a Mach number of 0.85 show identical pressure distributions for a chord Reynolds number of 8.6×10^6 obtained first at a stagnation

pressure of 4.91 atm at a stagnation temperature of 322.0 K and then at a stagnation pressure of 1.19 atm at a stagnation temperature of 116.5 K.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., October 23, 1974.

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