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MEMORANDUM

CRYOGENIC WIND TUNNELS - UNIQUE

CAPABILITIES FOR THE AERODYNAMICIST

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16. Abstract

During 1971 the Langley Research Center began to develop the cryogenic wind-tunnel concept as a practical means for improving ground simulation of transonic flight conditions. Since that time, the Langley 1/3-meter transonic cryogenic tunnel has become operational and the design of a cryogenic National Transonic Facility has been undertaken. A review of some of the unique capabilities of cryogenic wind tunnels is presented herein. In particular, the advantages of having independent control of tunnel Mach number, total pressure, and total temperature are highlighted. This separate control over the three tunnel parameters will open new frontiers in Mach number, Reynolds number, aeroelastic, and model-tunnel interaction studies.

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CRYOGENIC WIND TUNNELS — UNIQUE CAPABILITIES FOR THE AERODYNAMICIST

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SUMMARY

During 1971 the Langley Research Center began to develop the cryogenic wind-tunnel concept as a practical means for improving ground simulation of transonic flight conditions. Since that time, the Langley 1/3-meter transonic cryogenic tunnel has become operational and the design of a cryogenic National Transonic Facility has been undertaken. A review of some of the unique capabilities of cryogenic wind tunnels is presented herein. In particular, the advantages of having independent control of tunnel Mach number, total pressure, and total temperature are highlighted. This separate control over the three tunnel parameters will open new frontiers in Mach number, Reynolds number, aeroelastic, and model-tunnel interaction studies.

INTRODUCTION

The idea of increasing unit Reynolds number by cooling the tunnel test gas to cryogenic temperatures was first proposed during the mid-1940's. The concept remained essentially dormant until 1971 when it resurfaced at the NASA Langley Research Center. As reported in references 1 to 6, the concept has been developed at Langley from an idea into a practical scheme for both obtaining high Reynolds number transonic flow at reasonable costs and for avoiding the large model loads associated with high pressure tunnels. To verify the soundness and practicality of the cryogenic approach, a 1/3-meter pilot transonic cryogenic tunnel was built at Langley. The verification tests in this tunnel proved to be so successful that the pilot tunnel was designated the Langley 1/3-meter transonic cryogenic tunnel and is now being used for aerodynamic studies. Also as a result of this successful program in the 1/3-meter tunnel, a larger National Transonic Facility (NTF) is being designed and will also be located at Langley. As explained in reference 7, the NTF will take advantage of both the cryogenic concept and increased pressures to obtain full-scale Reynolds numbers for most flight envelopes.

In addition to the benefits of reduced costs and lower aerodynamic loads, the Langley studies also surfaced some unique operating envelopes which result from the total temperature and pressure control available in a pressurized cryogenic wind tunnel. These unique envelopes provide the aerodynamicist with research capabilities never before available. While many of these capabilities are described in reference 1 and in the other general papers mentioned above, the purpose of this paper is to summarize and expand somewhat the previous studies with regard to these unique research capabilities.

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SYMBOLS

a	sound speed
C	nondimensionalized aerodynamic coefficient
ℓ	characteristic length
m	molecular weight
M	Mach number
p	pressure
q	dynamic pressure
R	Reynolds number
R	universal gas constant
T	temperature
u	velocity
W	wind-tunnel parameter
γ	ratio of specific heats
μ	viscosity
ρ	density

Subscripts

t	total conditions

CRYOGENIC CONCEPT

A brief review of the cryogenic concept and its advantages is given in figure 1, which shows the effects of temperature reduction for a given free-stream Mach number, total pressure, and tunnel size. The values of certain gas properties relative to their ambient temperature values are plotted as a function of total temperature in figure 1(a). As the total temperature decreases, density increases while sound speed and viscosity decrease. This

behavior of the gas properties results in a large increase in Reynolds number
as the temperature drops, as shown in figure 1(b). While Reynolds number is
increasing, dynamic pressure remains constant and tunnel drive power actually
decreases. Consequently, the increase in Reynolds number due to temperature
reduction does not increase model loads and actually reduces drive-motor
energy consumption. Temperature reduction, therefore, minimizes many of the
problems associated with other approaches to high Reynolds number operation.

In the cryogenic concept as developed by Langley, the test gas is cooled
to temperatures as low as 80 K by the direct injection of liquid nitrogen into
the tunnel circuit. Because of the injection of liquid nitrogen, the test gas
is gaseous nitrogen rather than air.

FLEXIBLE OPERATING ENVELOPE

Because the amount of liquid nitrogen being injected for cooling can be
regulated, the pressurized cryogenic wind tunnel can operate over a very wide
range of total temperatures. As an example, the anticipated operating
envelope for the National Transonic Facility is shown in figure 2. The
minimum temperature boundary in this figure, as in later figures, will be
arbitrarily chosen to avoid saturation for local Mach numbers of 1.4. Since
existing experimental evidence suggests that this boundary may be conservative,
the placement of the actual minimum temperature boundary is currently under
study at Langley.

Also shown in figure 2 are the operating envelopes for both an atmospheric
and a pressurized conventional, ambient-temperature wind tunnel. In the
conventional atmospheric tunnel, using the air exchange method of cooling, the
experimentalist has essentially no control over either the total temperature

or the total pressure of the test. In a conventional pressurized tunnel, using an air-water heat exchanger for cooling, the experimentalist can vary the total pressure within the pressurization capability of the tunnel being used, but has little control of temperature. Only the pressurized cryogenic tunnel has the capability of significant total temperature control.

UNIQUE CAPABILITIES

Because of the flexible operating envelope, pressurized cryogenic wind tunnels offer unique experimental capabilities in addition to high Reynolds number testing. These unique capabilities will allow systematic analyses of the individual effects of Mach number, Reynolds number, dynamic pressure, and wind-tunnel interaction on the aerodynamic coefficients of a flight vehicle.

Aerodynamic coefficients are a convenient non-dimensional representation of the various forces, moments and pressures acting on a vehicle. Of course, these coefficients will be a function of Mach number, M, and Reynolds number, R, for an aircraft or model in free flight. If, as in the usual case, the aircraft or model is not rigid, but elastic, its shape and therefore its aerodynamic characteristics will also be a function of the loads acting on the aircraft or model which in turn are a function of the dynamic pressure, q. Thus, for the free-flight case, the aerodynamic coefficients can be written as a function of M,R, and q. Letting C represent any of the aerodynamic coefficients, we have

$$C = f(M, R, q) \tag{1}$$

When testing models in wind tunnels, the aerodynamic coefficients are influenced by the amount of blockage during the test, the sting interference, and other related aspects of the particular wind tunnel and model combination being used. Even though corrections for these interference effects can be introduced, the coefficients should also be considered weak functions of the wind tunnel and model combination, which may be represented by some parameter, W. Thus, for testing models in wind tunnels we have

$$C = F(M, R, q, W) \tag{2}$$

With conventional wind tunnels it has always been difficult to directly measure the functional dependence of C on M, R, q, or W individually. That is, it has been difficult to determine the partial derivatives

$$\frac{\partial C}{\partial M}, \frac{\partial C}{\partial R}, \frac{\partial C}{\partial q}, \text{ or } \frac{\partial C}{\partial W}$$

In a pressurized cryogenic tunnel, the first three of these derivatives can be directly measured while much information about the fourth derivative can also be obtained.

Determining Effects of Mach Number, $\partial C/\partial M$

Since any aircraft designed to fly at transonic speeds must, of course, operate from low Mach numbers to sonic Mach numbers, it will experience varying degrees of compressibility effects. Thus, it may be beneficial for the aerodynamicist to determine the change in various aerodynamic coefficients, C,

due to Mach number changes while holding R and q constant. To determine
under what conditions in the wind tunnel this is possible, expressions for R
and q may be examined. By definition

$$R = \frac{\rho u \ell}{\mu} \tag{3}$$

Substituting for ρ from the equation of state of a perfect gas and replacing
velocity with Mach number multiplied by sound speed, one finds that

$$R = \frac{p\ell M}{\mu} \sqrt{\frac{m\gamma}{RT}} \tag{4}$$

One may increase R either by increasing p, M, or ℓ or by decreasing T
and therefore μ. Next, q is defined as

$$q = \frac{\rho u^2}{2} \tag{5}$$

Substituting Mach number multiplied by sound speed for velocity results in

$$q = \frac{\gamma p M^2}{2} \tag{6}$$

Thus, q is independent of tunnel temperature.

Equations (4) and (6) may be used to construct a constant dynamic pres-
sure envelope as shown in figure 3. Although the values of γ and m used
are those for gaseous nitrogen, the envelope applies to air as well because,
as noted by Adcock in reference 4, the properties of air are essentially the

same. The scales on the graph were calculated using the anticipated size, pressure range, and temperature range of the NTF.

As seen in figure 3, pure Mach number effects can be analyzed by adjusting the tunnel total pressure and total temperature in such a manner as to hold the value of Reynolds number constant. As is also evident, a conventional pressure tunnel will be able to change pressure and Mach number to keep dynamic pressure constant, but it will not be able to keep Reynolds number constant because it is restricted to a particular total temperature line. Furthermore, in a conventional tunnel without pressure control, only one value of q is possible at a particular Mach number. Consequently, only the pressurized cryogenic wind tunnel will give the aerodynamicist the means of directly measuring the change in aerodynamics coefficients due to Mach number effects while holding both dynamic pressure and Reynolds number constant.

Determining Effects of Reynolds Number, $\partial C/\partial R$

Because of the increasing size of transport aircraft being designed, an understanding of the effects of Reynolds number on complex flows, such as shock-boundary-layer interactions, becomes crucial for the proper prediction of aerodynamic characteristics. Thus, once again valuable information could be gained if Reynolds number effects could be isolated from Mach number and dynamic pressure effects.

Referring to figure 4, it is seen how such an experiment could be carried out in a tunnel with total temperature and total pressure control. By holding Mach number and total pressure constant, Reynolds number effects can be measured by varying total temperature. A conventional tunnel, with or without pressurization, is not able to directly measure this quantity.

Many times Reynolds number studies have been undertaken in conventional wind tunnels by varying model size. In addition to the high cost of multiple models, the shortcoming of this approach is that the tunnel parameter, W, is also changing. For example, if the different-sized models are tested in the same tunnel, then W is changing due to the difference in blockage ratio. If the different models are tested in various facilities to preserve the same blockage ratio, then other differences may change W — sting shapes, test-section geometries, tunnel calibrations, and so forth. Unfortunately, any change in W may effectively mask any Reynolds number effect in the aerodynamic coefficients.

Determining Effects of Dynamic Pressure, $\partial C/\partial q$

All aircraft distort to varying degrees during flight because of the necessity for both lift and low structural weight. Furthermore, with many transonic wind tunnels using total pressures of 5 or more atmospheres, wind-tunnel model designers also have to concern themselves with dynamic pressure affecting model shape and aerodynamics. Valuable information on dynamic pressure effects could therefore be obtained if dynamic pressure could be varied while holding the other test conditions constant.

A graph showing an operating envelope of a pressurized cryogenic tunnel in a constant Mach number mode is shown in figure 5. The boundaries of this graph were again drawn to approximate the specifications and capabilities of NTF. The Mach number for this graph was taken to be 1. By varying total temperature and total pressure to keep Reynolds number constant, one may isolate aeroelastic effects with a pressurized cryogenic wind tunnel. This would not be possible in a conventional tunnel, with or without pressurization.

Effects of Tunnel Parameter, $\partial C/\partial W$

As was mentioned earlier in this report, aerodynamic coefficients measured with a model mounted in a tunnel are a weak function of the model-tunnel interaction, which was symbolized by the parameter W in equation (2). The model-tunnel interaction manifests itself in many ways — blockage ratio, sting interference, streamline perturbations due to wall interferences, and so forth. Many of these interactions, such as blockage ratio or streamline perturbations, are dependent on the ratio of model size to test-section size.

The effects on the aerodynamic coefficients due to changes in the ratio of model size to test-section size can be readily investigated in a pressurized cryogenic tunnel. A series of geometrically similar models could be built to different sizes for testing in a particular cryogenic tunnel. For model lengths within a factor of 5, Reynolds number could be held constant by compensating for the change in model characteristic length ℓ with an appropriate change in temperature. Of course, Mach number could be held constant by properly adjusting fan speed, and dynamic pressure could be held constant by holding total pressure fixed. Thus, any change in aerodynamic characteristics would be directly attributable to a difference in the ratio of model to tunnel size. Such a test program could furnish new information on the old question of how large a model can be successfully tested in a given-sized wind tunnel.

CONCLUDING REMARKS

This paper has reviewed and expanded studies made at the Langley Reserach Center concerning the unique operating envelopes and the aerodynamic research capabilities afforded by the pressurized cryogenic wind tunnel concept. This new type of wind tunnel offers the aerodynamicist more than just high Reynolds number capability. It offers the unique capabilities of directly measuring the individual effects of Mach number, Reynolds number, and dynamic pressure on the aerodynamic coefficients of a flight vehicle. In addition, the pressurized cryogenic tunnel is ideally suited for further investigations into the effects of wind-tunnel and model interaction.

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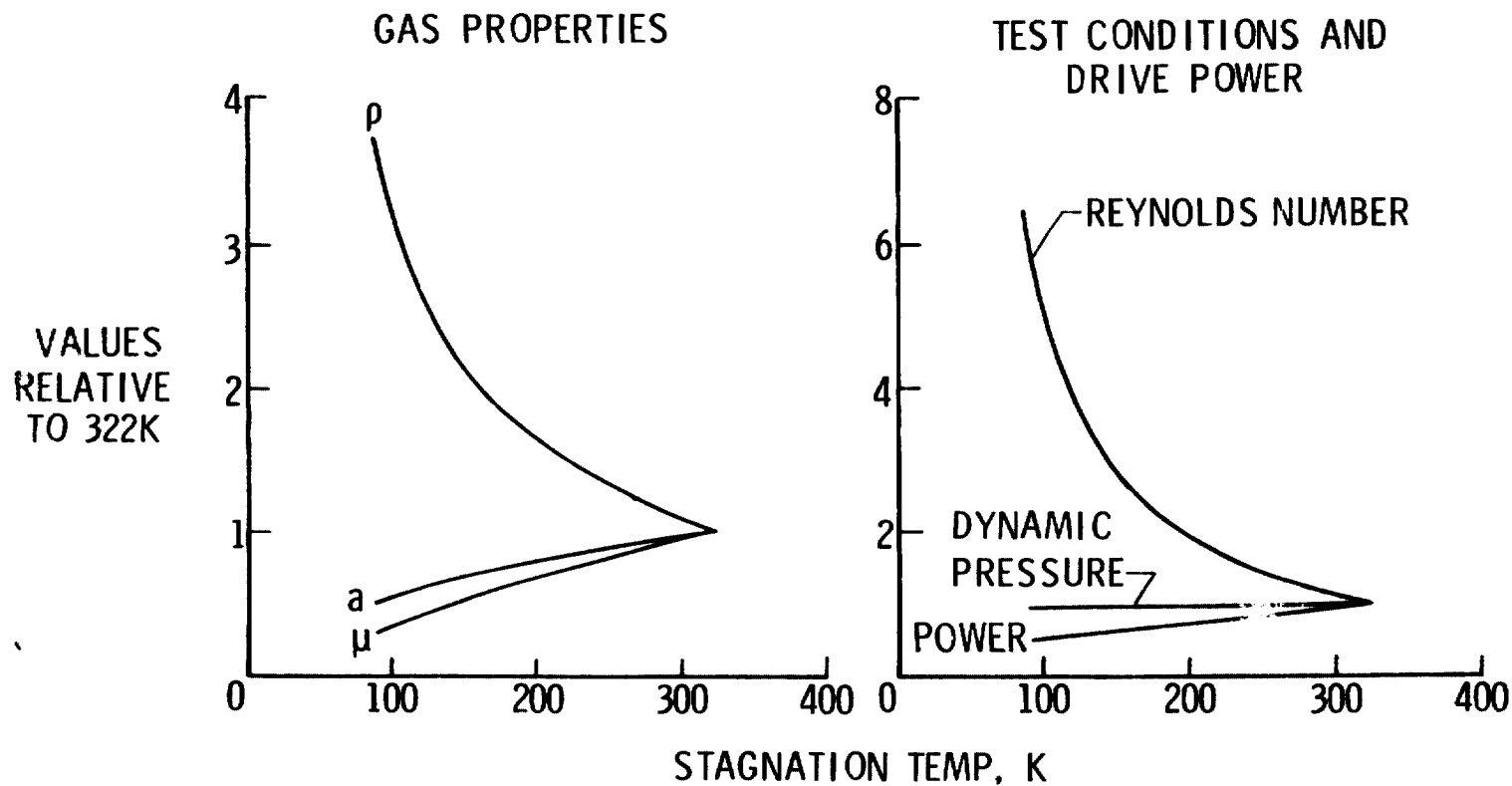
GAS PROPERTIES

TEST CONDITIONS AND
DRIVE POWER

VALUES
RELATIVE
TO 322K

ρ

a
μ

REYNOLDS NUMBER

DYNAMIC
PRESSURE

POWER

STAGNATION TEMP, K

Figure 1. Effect of temperature reduction. $M_\infty = 1.0$, constant P_t and size.
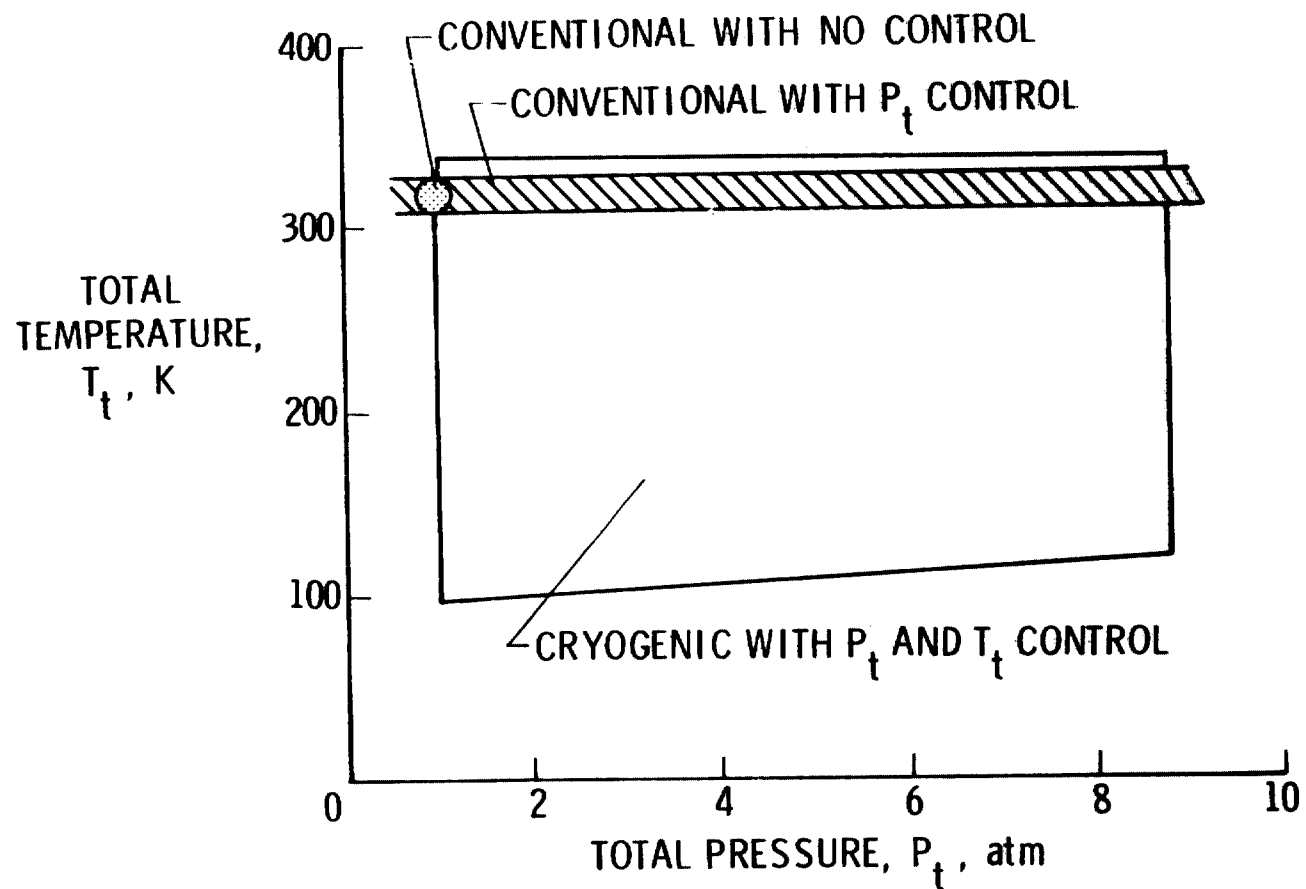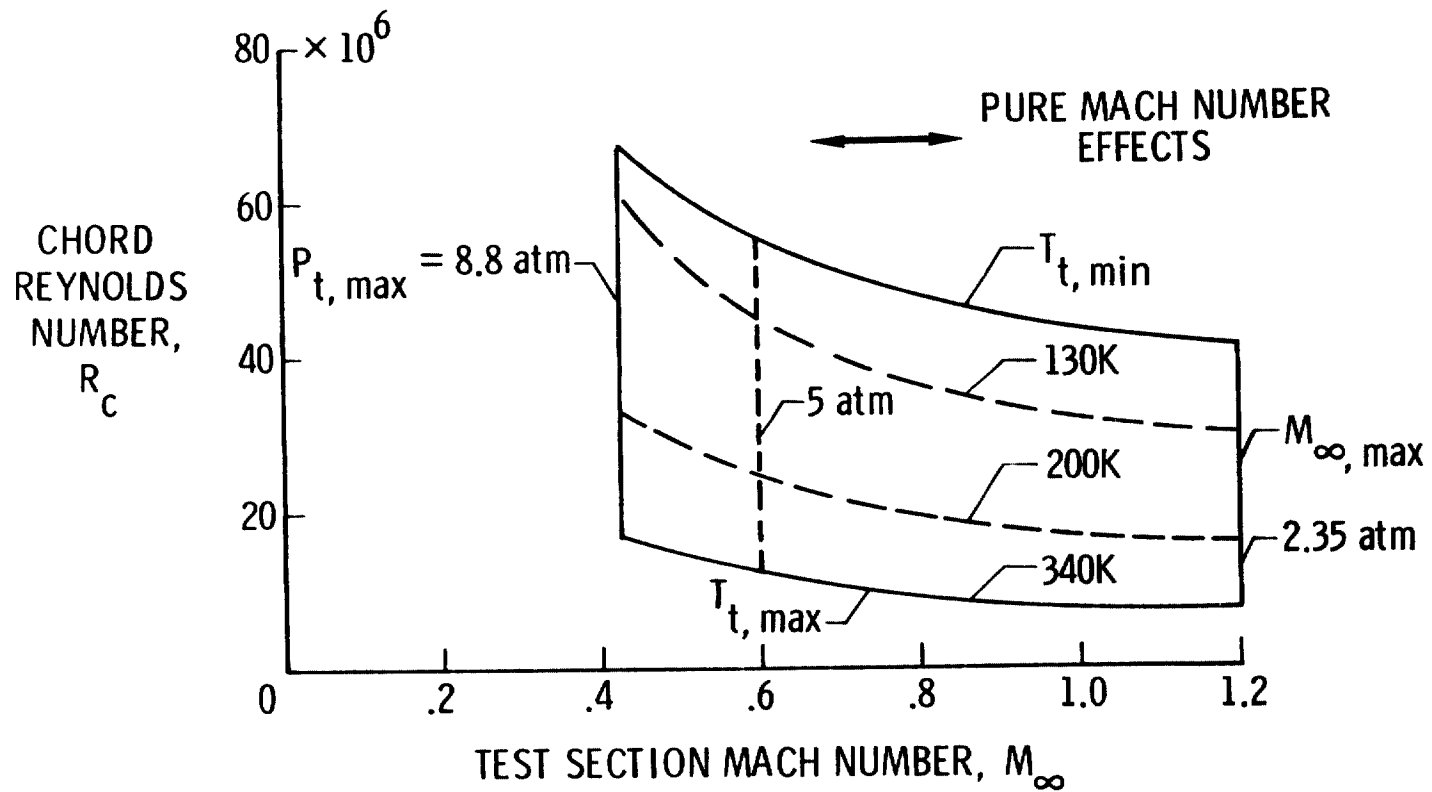
Figure 2. Wind-tunnel operating envelopes.

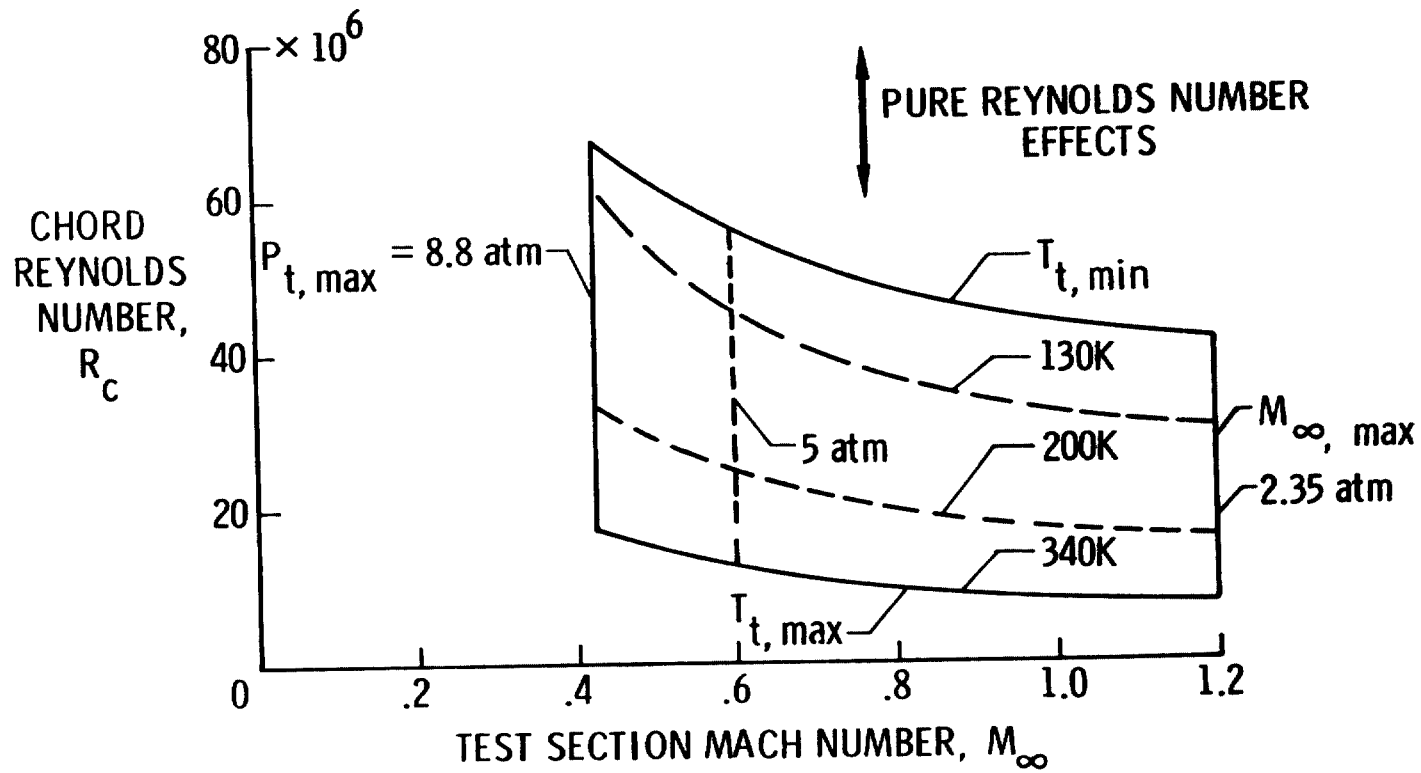Figure 3. Determining Mach number effects. $q = 100$ kN/m^2; 2.5- by 2.5-m test section.

Figure 4. Determining Reynolds number effects. $q = 100$ kN/m^2; 2.5- by 2.5-m test section.
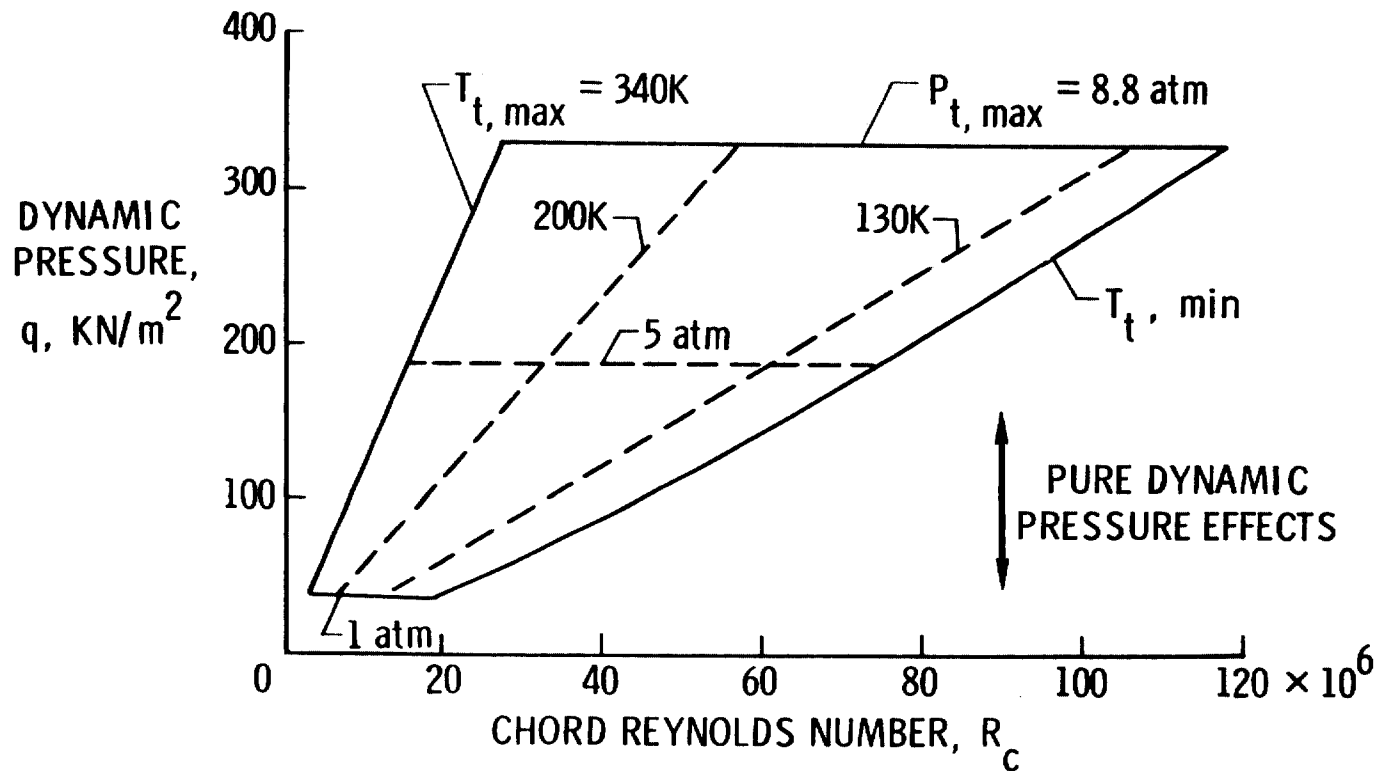
Figure 5. Determining dynamic pressure effects. $M_\infty = 1.0$; 2.5- by 2.5-m test section.