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A Fan Pressure Ratio Correlation in Terms of Mach Number and Reynolds Number for the Langley 0.3-Meter Transonic Cryogenic Tunnel

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SUMMARY

Calibration data for the two-dimensional test section of the Langley 0.3-Meter Transonic Cryogenic Tunnel are used to develop a Mach number-Reynolds number correlation for the fan pressure ratio in terms of test-section conditions. The relationship developed provides an excellent correlation of these data with the tunnel test section empty over a Mach number range from 0.30 to 0.85 and a range of Reynolds number values which vary by a factor of 37. Well-known engineering approximations are used to derive an equation which is functionally analogous to the correlation deduced from these data. The success of the correlation is partially dependent on correctly calculating the fan pressure ratio from the static pressure measurements made on either side of the fan. The procedure for this calculation is described in the appendix.

Although initially developed to simplify automatic tunnel control schemes, the correlation also provides (for this particular configuration) a successful Reynolds-number scaling law valid over the factor of 37 in Reynolds number. Also, a loss coefficient is formed which is independent of Mach number and Reynolds number and is a function of tunnel geometry only. This geometric loss coefficient should be useful as a measure of tunnel efficiency for operationally similar tunnels.

INTRODUCTION

The development of the cryogenic wind-tunnel concept (refs. 1 and 2) has greatly expanded the subsonic and transonic test capabilities available to the researcher. In addition to providing a large increase in Reynolds number, the ability to independently vary pressure, Mach number, and temperature makes it possible to perform the highly desirable research task of separating the aeroelastic, compressible, and viscous effects for the aerodynamic parameters being measured. For fan-driven tunnels at equivalent Reynolds number, those operated cryogenically require less power at the drive motor than conventional ambient tunnels. However, the power used in the production of the liquid nitrogen required for cooling tends to offset the savings in drive power.

To utilize the cryogenic testing technique in an optimal manner, computerized tunnel controls are necessary to minimize the quantity, and thus the cost, of the liquid nitrogen used as coolant and also to reduce the time required per data point (ref. 3). The development of tunnel control computer software requires knowledge of the functional relationship of the tunnel drive-fan power to Mach number, pressure, Reynolds number, and temperature. Any anomalies in the nature of the tunnel flow processes, particularly as a function of the wide variation in Reynolds number, must also be understood. This paper provides some insight into the control problem and the tunnel flow processes through a correlation of the fan pressure ratio for the Langley 0.3-Meter Transonic Cryogenic Tunnel with Mach number and Reynolds number.

SYMBOLS

A	cross-sectional area open to flow
k	loss coefficient
k_o	loss coefficient independent of Reynolds number
M	Mach number
$\dot{m}$	mass flow
n	inverse of Reynolds number exponent
p	pressure, atm (1 atm = 101.3 kPa)
R	Reynolds number based on test-section hydraulic diameter
R_x	local Reynolds number based on length
$\mathcal{R}$	gas constant
r	fan pressure ratio, $p_{t,2}/p_{t,1}$
T	temperature
V	velocity
Z	compressibility factor, $p/\rho\mathcal{R}$
β	cooling capacity
γ	ratio of specific heats
η	efficiency factor
ρ	density

Subscripts:

1	upstream of fan
2	downstream of fan
f	at fan
s	static conditions
t	total conditions

WIND TUNNEL

The Langley 0.3-Meter Transonic Cryogenic Tunnel (TCT) is a single-return, fan-driven pressure tunnel with interchangeable test sections, including a 20- by 60-cm two-dimensional test section which was in place during the present tests. Sketches of the 0.3-m TCT and two-dimensional test section are shown in figure 1. The tunnel flow is maintained by a fixed-geometry single-stage fan driven by a 2.2-MW water-cooled synchronous electric motor. The motor, which is external to the tunnel, is powered from a variable-frequency source at fan speeds from 600 rpm to 5600 rpm. Further descriptions of the 0.3-m TCT may be found in references 3 and 4.

A theoretical operating envelope for the 0.3-m TCT at a test-section Mach number of 0.85 is shown in figure 2 in terms of power delivered to the stream by the fan as a function of Reynolds number for various values of total pressure and total temperature. The equation for fan power in cryogenic nitrogen may be found in reference 5. To obtain the wide range of temperatures shown in figure 2, liquid nitrogen (LN_2) is sprayed directly into the stream to offset the heat added to the stream as a result of the work done by the drive fan and the wall heat flux into the stream through the tunnel wall insulation. As a consequence of this direct method of cooling, gaseous nitrogen, rather than air, is the working fluid. An exhaust system which bleeds gaseous nitrogen from the low-speed end of the tunnel (fig. 1(b)) serves as the tunnel total pressure control.

EXPERIMENTAL DATA

The pressure ratio across the fan was computed from static pressure measurements taken from wall pressure taps upstream and downstream of the fan. The pressure measurements were taken during an initial calibration of the two-dimensional test section, which employs slotted top and bottom walls with 5 percent open area. The test section was empty except for the calibration rake. Data were taken for selected combinations of three values of total pressure, three values of total temperature, and nine values of test-section Mach number. Total pressure was varied from 1.23 to 4.80 atm, total temperature from 105 K to 301 K, and test-section Mach number from 0.30 to 0.87. The resulting test-section Reynolds number varied by a factor of 37 from 0.756×10^6 to 28.0×10^6 per meter (2.48×10^6 to 91.8×10^6 per foot).

DISCUSSION

Data Analysis

The fan pressure ratio may be expressed either as the static or the total pressure rise across the fan. For this analysis, the total pressures on each side of the fan were derived from the static pressure measurements as discussed in the appendix. The value of the total pressure ratio across the fan at each calibration point is presented in figure 3 as a function of Reynolds number for the various nominal values of test-section Mach number. Inspection of these curves reveals, with one exception, a decreasing fan pressure ratio with increasing Reynolds number at a given Mach number as would be expected because of reduced viscous losses around the tunnel circuit. The exception noted occurs at $M = 0.87$. These data represent the tunnel operating in a choked condition, i.e., where an increase in fan speed and drive power produces no increase in test-section Mach number. In this condition, the pressure ratio is not related to Reynolds number, but rather to the fan-speed setting at which the tunnel operator judged the tunnel to be choked. Therefore, the fairing for the $M = 0.87$ data is dashed, since the individual data points cannot be considered to follow any logical trend. Also, solid symbols are used in figure 3 as well as several other figures to identify those points obtained under choked conditions. The data obtained under choked conditions are not considered in the ensuing calculations and discussion.

The pressure ratio across the fan represents the sum of the tunnel circuit pressure losses. The results in figure 3 illustrate the normally expected trend of increases in tunnel efficiency (decreasing fan pressure ratio) with increasing Reynolds number. Data fairings in this figure also indicate that the reduction in fan pressure ratio with increasing Reynolds number is gradual and well behaved; this result would be expected from decreasing viscous losses rather than more rapid changes such as might occur, for example, with improved diffuser performance due to a sudden reduction in the amount of diffuser separation. In order to more fully understand and predict the operating characteristics of the tunnel and to develop automatic tunnel control schemes, it is desirable to express the fan pressure ratio information in terms of the tunnel variables in as concise a form as possible.

Polynomial curve fits of the data shown in figure 3 are one means of relating the fan pressure ratio to the other tunnel variables. However, because of the broad range of operating conditions, an awkward number of coefficients are required to express the data in equation form to the desired degree of accuracy. Also, a simple polynomial curve-fit scheme which provides an acceptable match to the data over the entire range of variables was not found. As a result of these problems, an improved correlation scheme was sought.

The data in figure 3 indicate that the fan pressure ratio is a function of Mach number and Reynolds number. The relative effects of these two variables are shown in figure 4, where the data are plotted as a function of Mach number squared. As this figure indicates, the fan pressure ratio is approximately linear with Mach number squared, and the spread in the data is orderly with Reynolds number. A simple power-law function for Reynolds number was assumed, and the exponent was varied until an optimum collapse of the data spread was obtained. As illustrated by the data presented in figure 5 (except for the data obtained under choked conditions), this Mach number-Reynolds number function gives an excellent correlation of the experimental data. For convenience and for referencing of the results to test-section conditions, the Reynolds number was based on the test-section hydraulic diameter (test-section area multiplied by 4 and divided by test-section perimeter).

Theoretical Considerations

Although the relationship of fan pressure ratio to Mach number and Reynolds number described in the preceding paragraph was deduced from inspection of the data, a similar equation may be derived from conventional engineering relationships. As noted in reference 6, the pressure loss coefficient k may be written as $k = \frac{\Delta p\, A}{\frac{1}{2}\rho V^2 A}$, which is analogous to the drag coefficient in aerodynamic calculations. If A is the flow area in the region of the fan, and both Δp and $\frac{1}{2}\rho V^2$ are evaluated at this region, then k may be rewritten as

$$k = \frac{2(p_2 - p_1)}{\gamma p_1 M_1{}^2} = \frac{2}{\gamma M_1{}^2}\left(\frac{p_2}{p_1} - 1\right) = \frac{2}{\gamma M_1{}^2}(r_s - 1)$$

where r_s is the static pressure rise across the fan. This equation may now be written in terms of r_s; that is, $r_s = k \frac{\gamma}{2} M_1{}^2 + 1$.

Another engineering relationship, described in reference 7, expresses the friction loss coefficient as a product of an inverse function of a fractional power of the length Reynolds number and a constant of proportionality. An equivalent form of this expression for the present case might be $k = k_o R^{-1/n}$ where k_o is the constant of proportionality. Reference 7 also presents values of the exponent n as a function of length Reynolds number and shows that the value of n increases with increasing Reynolds number. This can be interpreted to mean that as the Reynolds number increases, the amount of reduction in the loss coefficient decreases. Figure 15 of reference 7 shows that for an increase in length Reynolds number for 10^4 to 10^9, the value of n increases from 3 to 9. In the present experiment, assignment of a length Reynolds number to the entire tunnel circuit is difficult. However, at a nominal test-section Mach number of 0.80, a total pressure of 3 atm, a total temperature of 200 K, and assuming a virtual origin of the flow at the tunnel screens, the length Reynolds number on the test-section wall is approximately 0.25×10^9. This value basically represents the length of the contraction section plus part of the test section and accounts for approximately 1/6 of the tunnel circuit length and a corresponding part of the circuit losses. It may be equally valid to assume the boundary-layer origin and termination at the fan, which increases the length by a factor of roughly 6. Thus, the length Reynolds numbers to be considered in choosing a value for n are on the order of 10^9. The experimentally derived value for $-1/n$ (−0.096; fig. 5) for the 0.3-m TCT circuit losses falls between −1/10 and −1/11, whereas reference 7 would predict a value of −1/8 to −1/9.

However, reference 7 presents results for the skin friction drag of flat-plate boundary layers and is probably not appropriate for estimating the effects of the more complicated tunnel circuit geometry. Reference 8 presents drag data for airships at length Reynolds number on the order of 10^9 which vary approximately as $R_x^{-1/10}$; these drag data are also quoted to vary with values of n as high as $R_x^{-1/12}$ (fig. 1 and page 2 of ch. 14 in ref. 8).

In light of the foregoing discussion, representation of the drag by a Reynolds number function of the type used here is not without precedent, and the value of the Reynolds number exponent is typical of other published data in this length Reynolds number regime. Thus the expression for fan pressure ratio might have been expected to have the form $r = k \frac{\gamma}{2} M^2 + 1$ where $k = k_o R^{-1/n}$, and the fan pressure ratio can be written $r = \frac{\gamma}{2} k_o R^{-1/n} M^2 + 1$ where $n \approx 10$. Note that k must be a function of geometry and Reynolds number, but k_o is a function of geometry only and thus represents a loss coefficient which is independent of Reynolds number.

The best fit to the experimental data as shown in figure 5 is $r = 0.8205\ M^2 R^{-0.096} + 1.001$ which is functionally analogous to the expression derived in the preceding paragraph. The second term can also be written $1 + 0.001$, implying a small pressure-loss term independent of the Mach number-Reynolds number function, or a small systematic error in the data system. (Note that r may also be expressed as $\Delta p_{t,f}/p_t + 1$.) This small pressure-loss term is difficult to resolve because the bookkeeping on pressure losses around the circuit is complicated by the cooling method, which in the case of the 0.3-m TCT, consists of spraying liquid nitrogen directly into the tunnel circuit. An initial loss results from accelerating the injected liquid droplets, and a total pressure gain results from droplet evaporation. The aerothermodynamics of a similar process are discussed in reference 9. Preliminary estimates based on the information provided by reference 9 indicate a net gain in total pressure. However, there is also a pressure loss involved in exhausting gaseous nitrogen later in the tunnel circuit (the nitrogen exhausted is equal to the mass flow of the injected liquid nitrogen). The small size of the independent term (0.001) indicates, at least to the first order, that the gains and losses in total pressure due to the liquid-nitrogen cooling and exhaust system are largely self-canceling. Additional measurements in the 0.3-m TCT would be necessary to further resolve these second-order effects.

Application

A cryogenic tunnel of the type described in this paper is well suited to determining the value of tunnel-circuit loss coefficient, since the tunnel has a large Reynolds number range. The fan pressure ratio equation from figure 5 may be used to serve several purposes. It allows liquid-nitrogen requirements and power usage to be linked in a relatively simple manner to conditions in the test section. Figure 6 depicts an example of a tunnel performance map prepared using the fan pressure rise correlation; the power delivered by the fan to overcome the tunnel pressure losses is plotted as a function of the fan pressure ratio for a range of test conditions. This simplifies the scheduling of test points for minimum overall cost. Also, incorporation of the correlation in computerized tunnel control schemes improves efficiency and should lower testing costs. This is particularly true for anticipatory control algorithms which seek to arrive at a set point in the most efficient manner.

In a broader sense, the coefficient of the Mach number-Reynolds number term, which is also the slope of the straight-line curve fit in figure 5, serves as a measure of the tunnel circuit efficiency; the larger the coefficient, the less efficient the tunnel. Thus, the coefficient would be expected to vary with any change in tunnel losses such as drag due to models in the test section. These variations are expected to be second order in nature and, with increasing tunnel operation experience, should be predictable in terms of model type and attitude. Note that the coefficient is a function of geometry only and is independent of Reynolds number or Mach number. Thus, an expression of this type should serve to determine relative efficiency of comparable types of wind tunnels.

An additional observation is that, in the absence of shock losses, the fan pressure ratio correlation serves as a Reynolds number scaling law for this particular wind-tunnel configuration.

CONCLUDING REMARKS

Calibration data for the two-dimensional test section for the Langley 0.3-Meter Transonic Cryogenic Tunnel have been used to develop a Mach number-Reynolds number correlation for the fan pressure ratio in terms of test-section conditions. It has been shown that well-established engineering relationships can be combined to form an equation which is functionally analogous to the correlation. Additionally, a geometric loss coefficient which is independent of Reynolds number or Mach number can be determined. Present and anticipated uses of this concept include improvement of tunnel control schemes, comparison of efficiencies for operationally similar wind tunnels, prediction of tunnel test conditions and associated energy usage, and determination of Reynolds number scaling laws for similar fluid-flow systems.

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APPENDIX

CALCULATION OF FAN TOTAL PRESSURE RATIO

FROM MEASURED STATIC PRESSURES

During tunnel calibration tests of the Langley 0.30-Meter Transonic Cryrogenic Tunnel, static pressures were measured at stations upstream and downstream of the fan in addition to the measurements which were made to determine the test-section flow parameters. The cross-sectional areas at the static-pressure measurement stations were determined from design drawings. This information is sufficient, in the region of the fan, for calculating the total pressure ratio across the fan if it is assumed that there is negligible heat transfer at the tunnel walls and that the stagnation temperature at the station downstream of the fan is the same as that at the test section. The stagnation temperature may not be constant because of the exhausting of gaseous nitrogen that takes place in between these two stations, but the total pressure ratio calculation is not sensitive to this assumption.

To calculate the total pressure ratio, initial calculations are made with the assumption that liquid nitrogen is not being added in the circuit; thus, the mass flow at the fan is the same as the mass flow in the test section. The following equations are iteratively solved for the downstream total pressure, Mach number, and static temperature:

$$p_{t,2} = p_2\left(1 + \frac{\gamma-1}{2} M_2^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$T_{t,2} = T_2\left(1 + \frac{\gamma-1}{2} M_2^2\right)$$

$$\dot{m}_2 = \sqrt{\frac{\gamma}{\mathcal{R}T_2}}\, p_2 M_2 A_2 \sqrt{\frac{1}{Z_t}}$$

The term Z_t is a real gas correction described in reference 5. The ideal diatomic gas value of 1.4 is used throughout this report for the ratio of specific heats.

The upstream flow condition can be solved with the assumption of fan efficiency factor,

$$\eta_f = \frac{\Delta T'}{\Delta T}$$

where $\Delta T'$ is the ideal temperature rise across the fan assuming isentropic compression, and ΔT is the actual temperature rise. The ideal temperature ratio across the fan is related to the pressure ratio by

$$\frac{T_{t,2}}{T_{t,1}} = \left(\frac{p_{t,2}}{p_{t,1}}\right)^{(\gamma-1)/\gamma}$$

or

$$\frac{\Delta T_t'}{T_{t,1}} = \left(\frac{p_{t,2}}{p_{t,1}}\right)^{(\gamma-1)/\gamma} - 1$$

where $\Delta T_t' = T_{t,2} - T_{t,1}$

Substituting for $\Delta T_t'$,

$$\frac{\Delta T}{T_{t,1}} = \frac{1}{\eta_f}\left[\left(\frac{p_{t,2}}{p_{t,1}}\right)^{(\gamma-1)/\gamma} - 1\right]$$

and

$$T_{t,1} = \frac{T_{t,2}}{\frac{1}{\eta_f}\left[\left(\frac{p_{t,2}}{p_{t,1}}\right)^{(\gamma-1)/\gamma} - 1\right] + 1}$$

This equation along with the equations

$$T_{t,1} = T_1\left(1 + \frac{\gamma-1}{2} M_1{}^2\right)$$

$$p_{t,1} = \frac{p_1}{\left(1 + \frac{\gamma-1}{2} M_1{}^2\right)^{-\gamma/(\gamma-1)}}$$

$$\dot{m}_1 = \sqrt{\frac{\gamma}{\mathcal{R}T_1}}\, p_1 M_1 A_1 \sqrt{\frac{1}{Z_t}}$$

are iteratively solved for $p_{t,1}$, $T_{t,1}$, M_1, and T_1.

The stagnation conditions on both sides of the fan have been determined, but the addition of mass flow through the fan due to the injection of LN_2 for cooling has been neglected. The fan power can now be calculated from

$$\text{Power} = \left(\dot{m}\,\frac{\gamma}{\gamma - 1}\right)\mathcal{R}\,(T_{t,2} - T_{t,1})\,Z_t$$

The mass flow of LN_2 necessary to remove the energy being input by the fan is calculated from

$$\dot{m}_{LN_2} = \frac{\text{Power}}{\beta}$$

where β is the cooling capacity of LN_2 as given in reference 10. This mass flow is added to the test-section mass flow, and the whole series of iterative calculations are repeated with this additional mass flow through the fan. This procedure is repeated until there is no appreciable change in the mass flow going through the fan, and in general, takes only two or three iterations.

The calculations in this paper used a fan efficiency of 0.89. Calculations using other fan efficiencies indicate that the total-pressure ratio across the fan is insensitive to fan efficiency.

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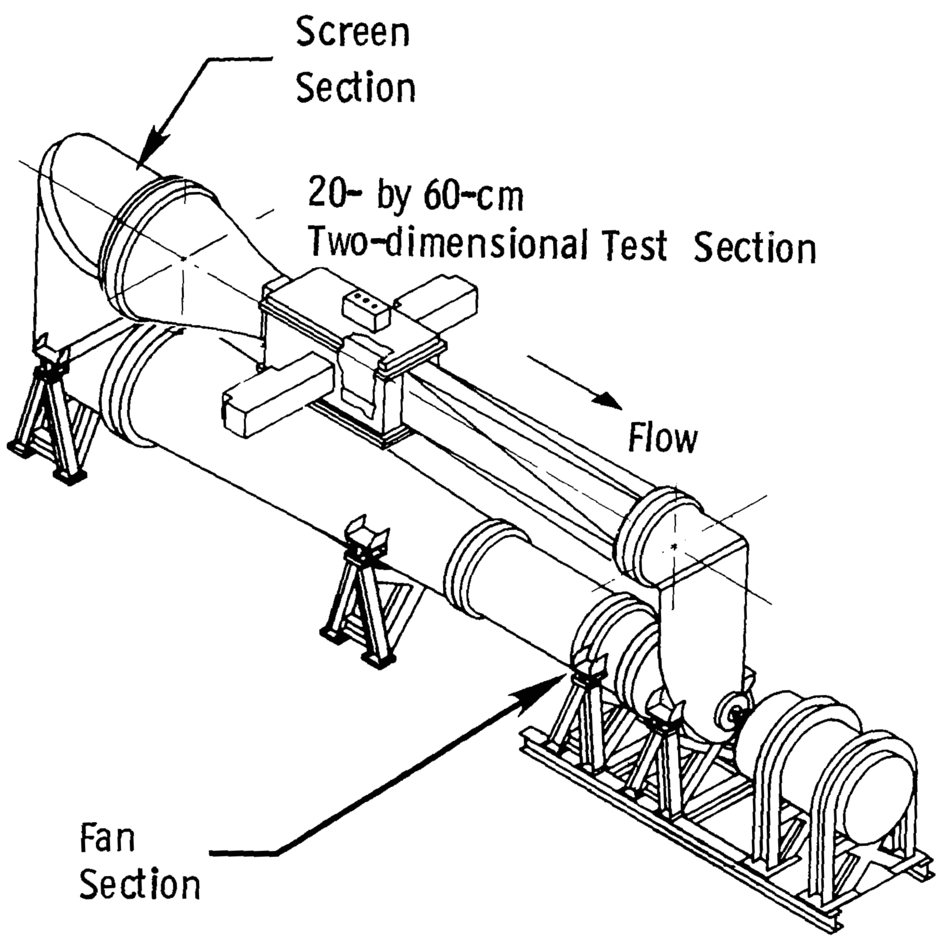
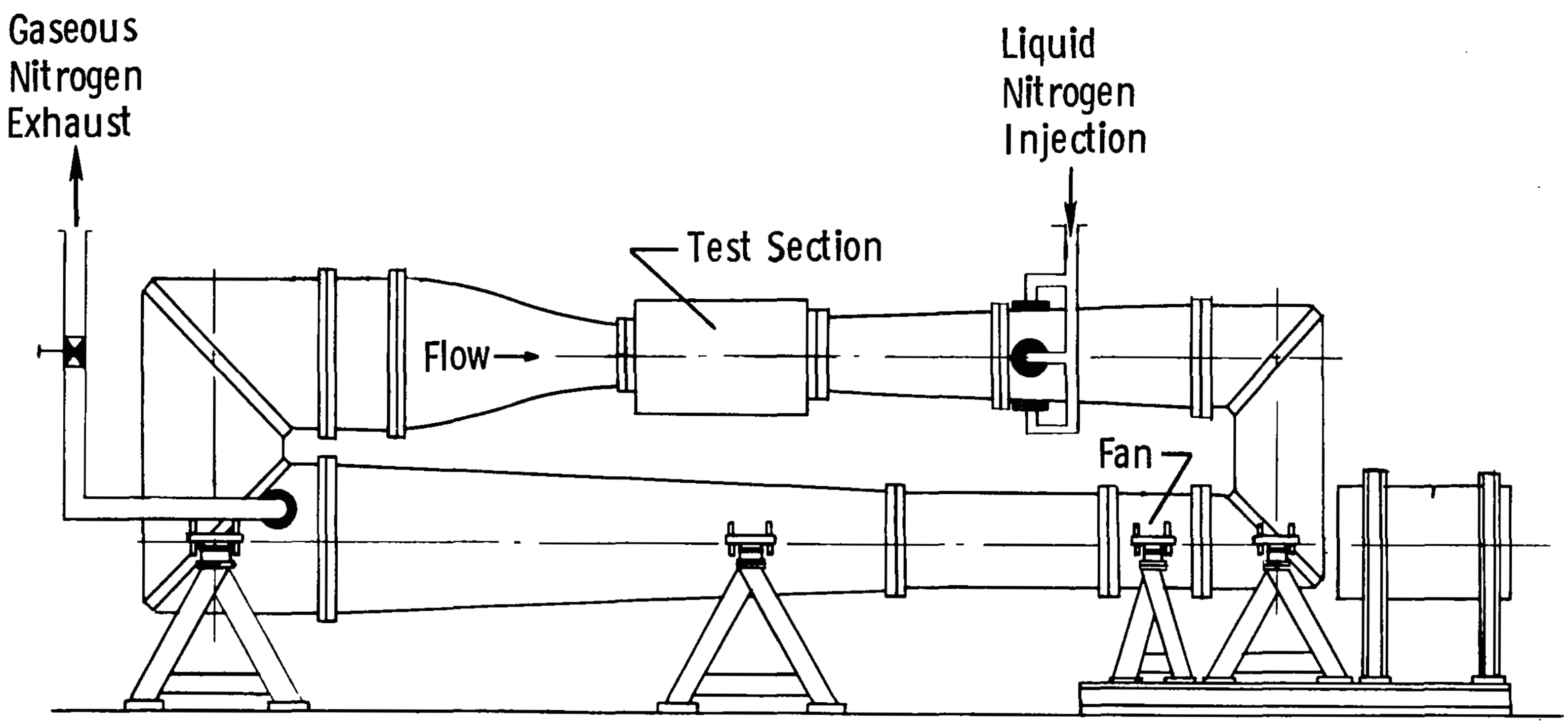


(a) Two-dimensional test section in place.

Figure 1.- Langley 0.3-Meter Transonic Cryogenic Tunnel.



(b) Locations of tunnel injection and exhaust parts.

Figure 1.- Concluded.

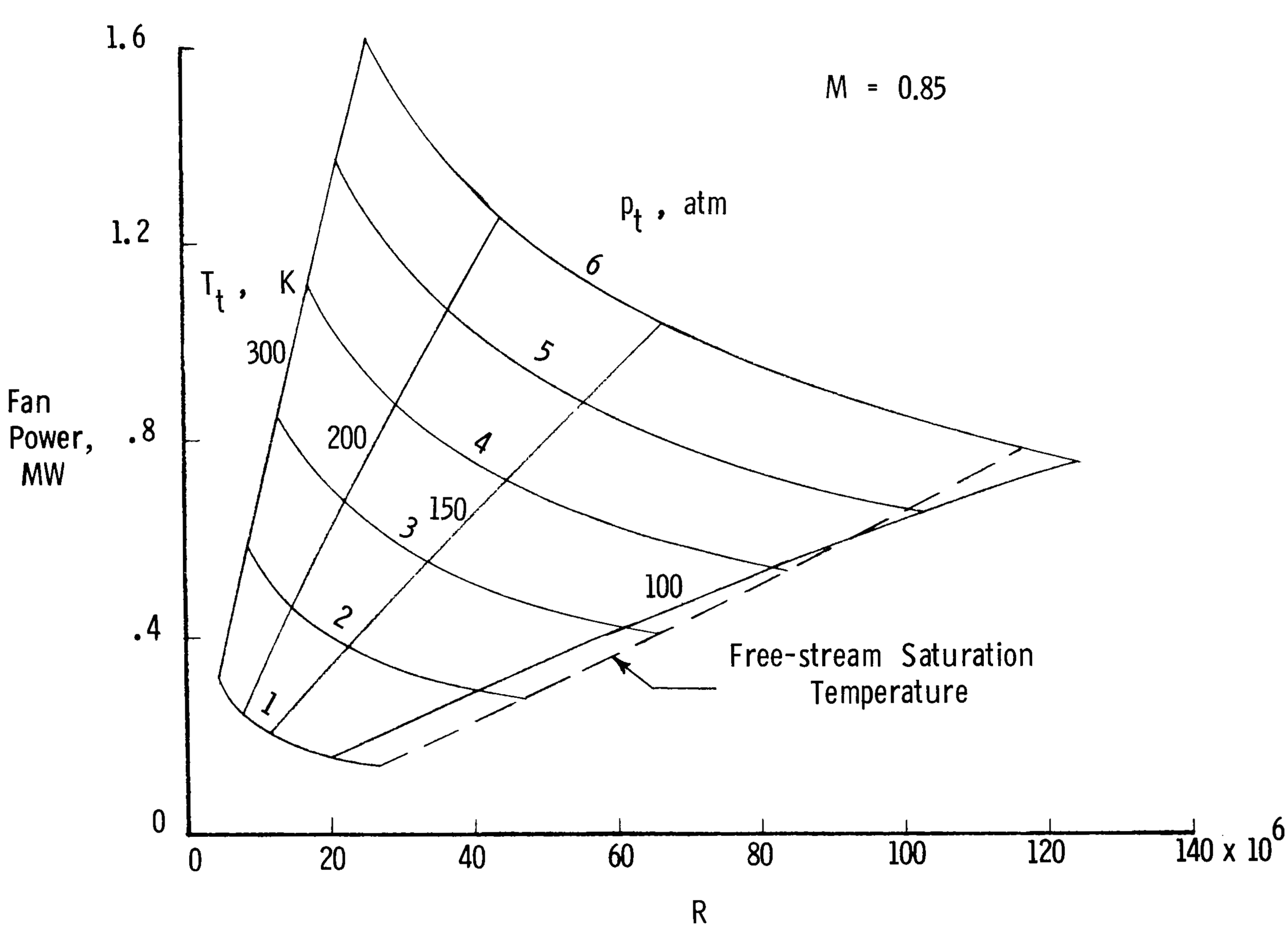


Figure 2.- Fan power requirements as a function of Reynolds number for a test-section Mach number of 0.85. (Reynolds number based on test-section hydraulic diameter.)

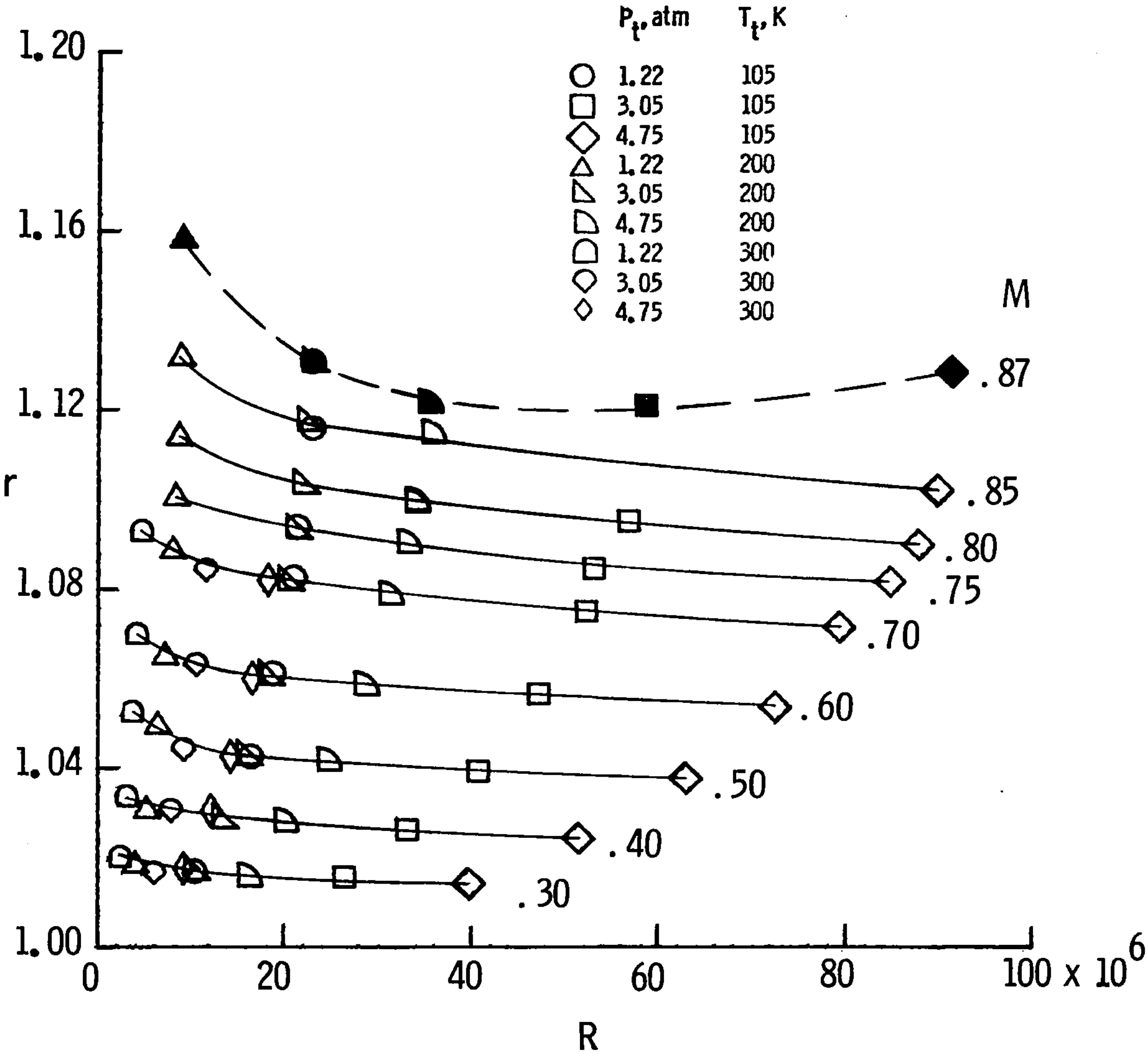


Figure 3.- Fan pressure ratio as a function of Reynolds number for a range of Mach numbers. (Solid symbols at $M = 0.87$ denote tunnel choked condition.)

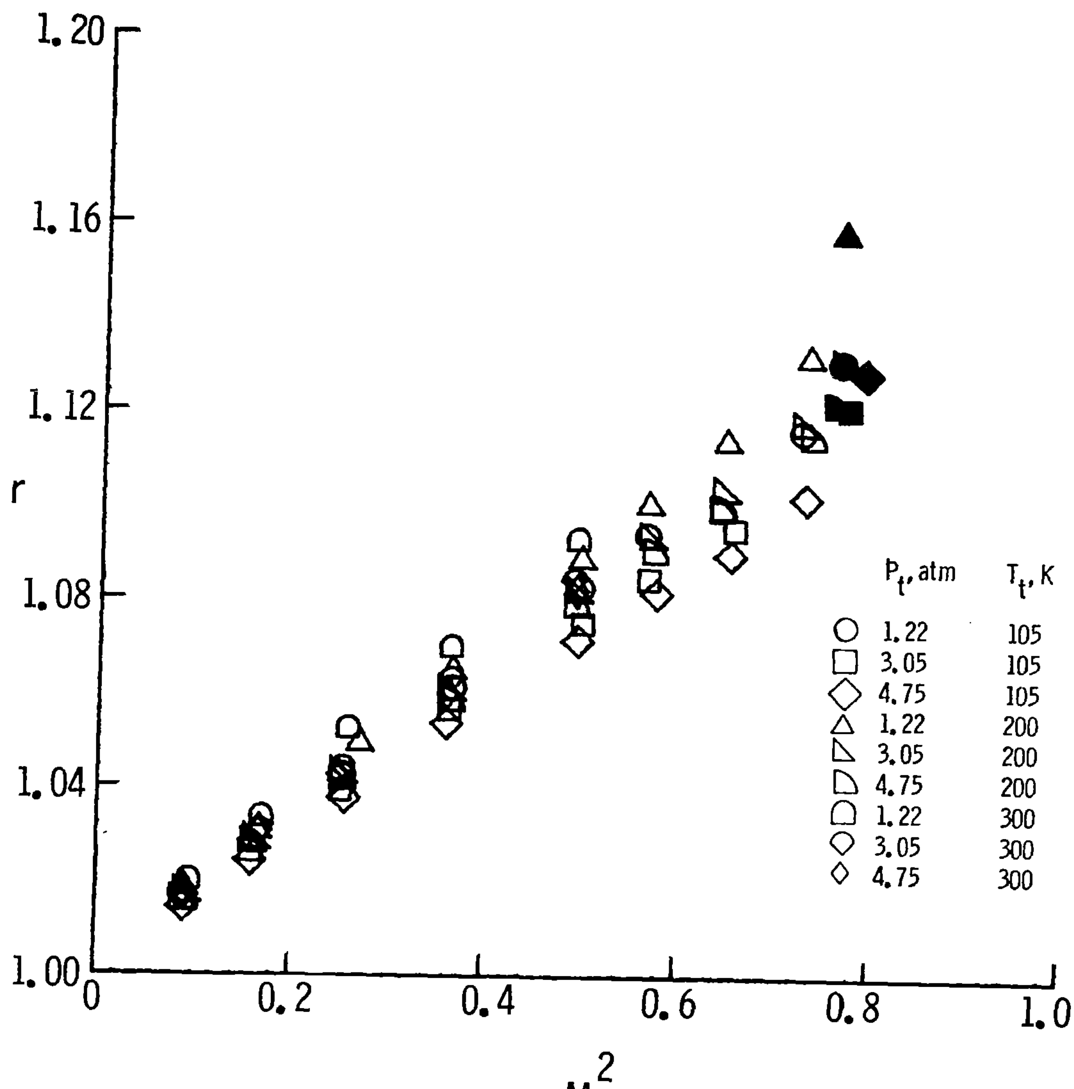


Figure 4.- Fan pressure ratio as a function of Mach number squared. (Solid symbols denote tunnel choked condition.)

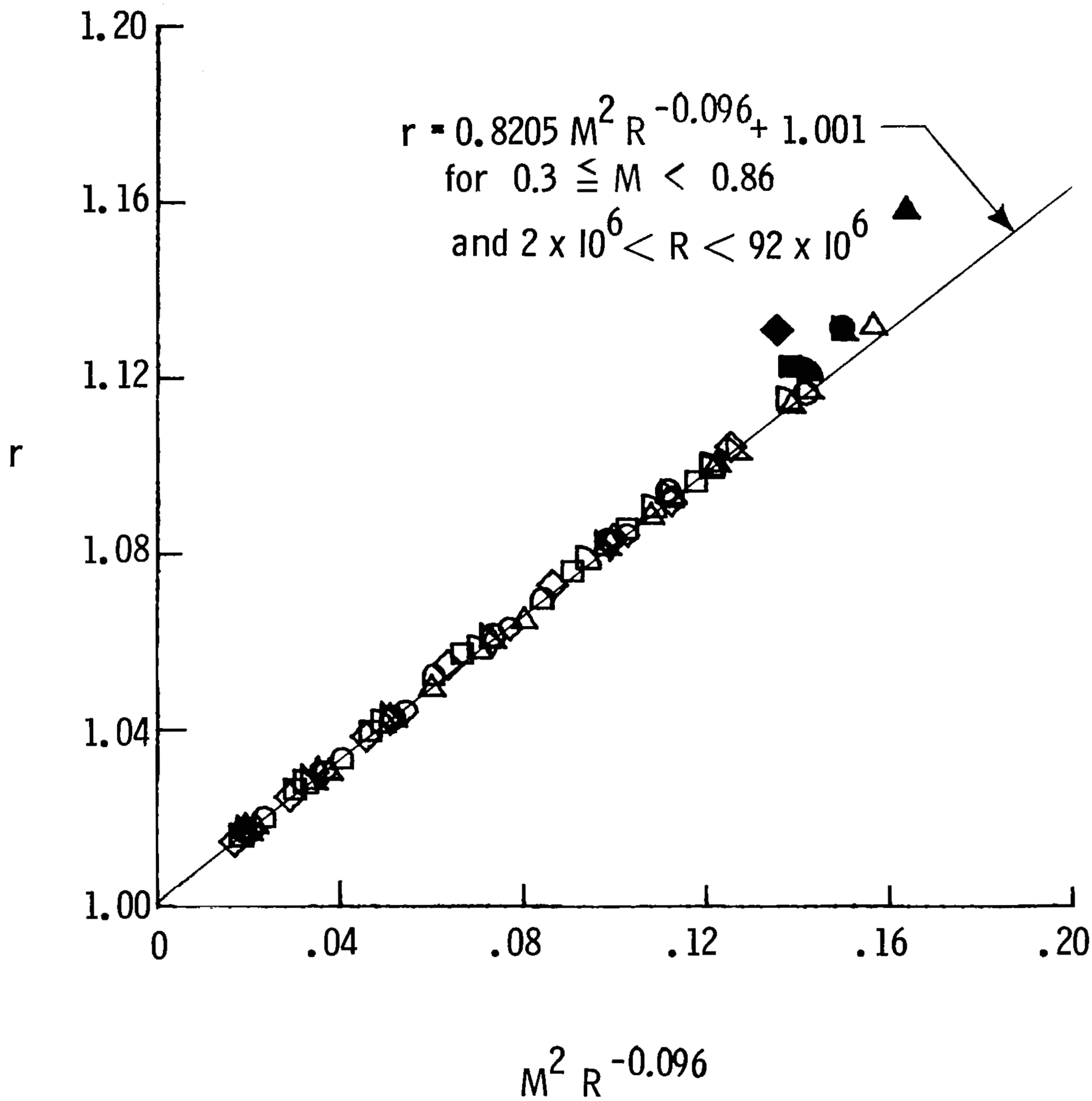


Figure 5.- Fan pressure ratio correlated in terms of Mach number and Reynolds number. (Solid symbols, which denote tunnel choked condition, were not used in curve fit.)

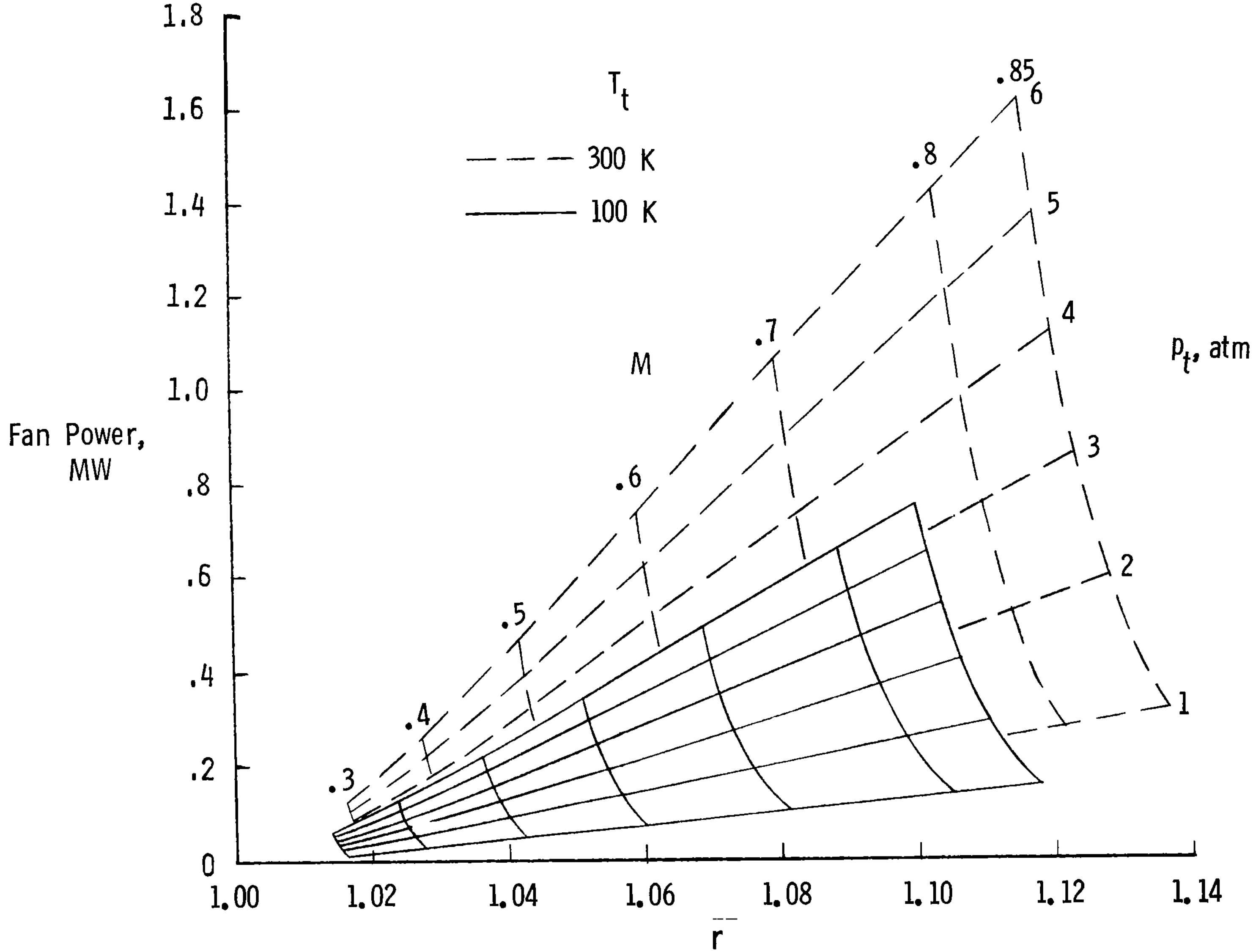


Figure 6.- Fan power as a function of fan pressure ratio for typical ambient and cryogenic operating points, assuming a fan efficiency of 0.89.

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