Computer Program for Calculating Flow Parameters and Power Requirements for Cryogenic Wind Tunnels

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Acknowledgments

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Summary

A computer program has been written that performs the flow parameter calculations for cryogenic wind tunnels which use nitrogen as a test gas. The flow parameters calculated include static pressure, static temperature, compressibility factor, ratio of specific heats, dynamic viscosity, total and static density, velocity, dynamic pressure, mass-flow rate, and Reynolds number. Simplifying assumptions have been made so that the calculation of Reynolds number as well as the other flow parameters can be made on relatively small desktop digital computers. The program, which also includes various power calculations, has been developed to the point where it has become a very useful tool for the users and possible future designers of fan-driven continuous-flow cryogenic wind tunnels.

Introduction

Operating a wind tunnel at reduced temperatures, first proposed by Margoulis (refs. 1 and 2) in 1920, offers an attractive means of increasing Reynolds number while avoiding many of the practical problems associated with testing at high Reynolds numbers in conventional ambient temperature pressure tunnels. Personnel at the Langley Research Center have been studying the application of the cryogenic wind tunnel concept to various types of high Reynolds number transonic tunnels since the autumn of 1971. The usefulness of the concept (ref. 3) has been realized at Langley with the successful operation of the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT) (refs. 4 and 5) since August 1973 and with the recent completion of the National Transonic Facility (NTF) at the Langley Research Center (refs. 6 and 7).

In the early days of the application of the cryogenic concept at Langley, a computer program was written that aided in the development of cryogenic wind tunnels which use nitrogen as a test gas. This program performed the many flow parameter calculations necessary for cryogenic wind tunnels with operating temperature ranges from saturation to above ambient (≈78 to 350 K). Simplifying assumptions were made so that the calculation of Reynolds number as well as other flow parameters could be made on small desktop digital computers. The program, which also includes various power calculations, has grown to the point where it has become a very useful tool for the users and possible future designers of cryogenic wind tunnels, especially those that are fan driven. The purpose of this report is to document the current version of the program and demonstrate its use. A disk containing a copy of the program is available upon request. (See page 35.) Appendix A discusses the equations for calculating some of the properties of nitrogen. A listing of the program is included in appendix B.

Symbols

\( A \) \hspace{1cm} \text{area, m}^2

\( a \) \hspace{1cm} \text{speed of sound, m/sec}

\( C \) \hspace{1cm} \text{any aerodynamic coefficient (fig. 6)}

\( c_p \) \hspace{1cm} \text{specific heat at constant pressure, J/mol-K}

\( c_v \) \hspace{1cm} \text{specific heat at constant volume, J/mol-K}

\( E_m \) \hspace{1cm} \text{energy per unit mass, MW-sec/kg}

\( k \) \hspace{1cm} \text{thermal conductivity, W/m-K}

\( \ell \) \hspace{1cm} \text{measure of model or test-section linear dimension, m}

\( M \) \hspace{1cm} \text{Mach number}

\( M \) \hspace{1cm} \text{molecular weight of nitrogen, kg/mol}

\( m \) \hspace{1cm} \text{mass-flow rate, kg/sec}

\( P \) \hspace{1cm} \text{power, W}

\( p \) \hspace{1cm} \text{pressure, Pa (1 bar = 0.1 MPa; 1 atm = 0.10133 MPa)}

\( \text{per} \) \hspace{1cm} \text{test-section perimeter, m}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$</td>
<td>dynamic pressure, Pa (1 bar = 0.1 MPa)</td>
</tr>
<tr>
<td>$R$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$\mathcal{R}$</td>
<td>gas constant for nitrogen, J/kg-K</td>
</tr>
<tr>
<td>$r$</td>
<td>fan pressure ratio, $p_{t,2}/p_{t,1}$</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature, K</td>
</tr>
<tr>
<td>$t$</td>
<td>insulation thickness, m</td>
</tr>
<tr>
<td>$V$</td>
<td>velocity, m/sec</td>
</tr>
<tr>
<td>$Z$</td>
<td>compressibility factor</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>isentropic expansion coefficient</td>
</tr>
<tr>
<td>$\beta$</td>
<td>specific cooling capacity of liquid nitrogen, kJ/kg</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>ratio of specific heats</td>
</tr>
<tr>
<td>$\eta$</td>
<td>efficiency factor</td>
</tr>
<tr>
<td>$\mu$</td>
<td>dynamic viscosity, N-sec/m$^2$</td>
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<tr>
<td>$\rho$</td>
<td>density, kg/m$^3$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>plenum removal ($A/A^* - 1$)</td>
</tr>
</tbody>
</table>

**Subscripts:**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>plenum removal compressor</td>
</tr>
<tr>
<td>$\tilde{c}$</td>
<td>reference chord, $0.1\sqrt{A_{TS}}$</td>
</tr>
<tr>
<td>con</td>
<td>conduction</td>
</tr>
<tr>
<td>$f$</td>
<td>fan</td>
</tr>
<tr>
<td>$\text{hd}$</td>
<td>hydraulic diameter, $4A_{TS}/\text{per}$</td>
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<td>$i$</td>
<td>insulation surface</td>
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<tr>
<td>$L$</td>
<td>local condition</td>
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<tr>
<td>$\text{LN}_2$</td>
<td>liquid nitrogen</td>
</tr>
<tr>
<td>$m$</td>
<td>motor</td>
</tr>
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<td>max</td>
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<tr>
<td>min</td>
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<td>SF</td>
<td>tunnel surface</td>
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<tr>
<td>$s$</td>
<td>static condition</td>
</tr>
<tr>
<td>sat</td>
<td>saturation</td>
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<tr>
<td>TS</td>
<td>test section</td>
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<tr>
<td>$t$</td>
<td>total condition</td>
</tr>
<tr>
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<td>total</td>
</tr>
<tr>
<td>$v$</td>
<td>vapor</td>
</tr>
<tr>
<td>$1$</td>
<td>upstream of fan or compressor</td>
</tr>
<tr>
<td>$2$</td>
<td>downstream of fan or compressor</td>
</tr>
<tr>
<td>$\infty$</td>
<td>free-stream condition</td>
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</table>
Program Highlights

The tunnel flow parameters calculated in the program include static pressure, static temperature, compressibility factor, ratio of specific heats, dynamic viscosity, total and static density, velocity, dynamic pressure, mass-flow rate, and Reynolds number. These parameters are calculated based on user-supplied inputs of test-section area, test-section Mach number, total pressure, and total temperature option. The parameters are valid for any Mach number. The valid range of total pressure is from slightly above 0 to 7 atm, and the valid range of total temperature is from saturation to above ambient (~78 to 350 K). To use the program outside these ranges, the user should verify that the curve fits used in this program are valid for the ranges being considered.

In addition, the program calculates the drive-fan and plenum-removal compressor powers. For the drive-fan power calculations, the program uses either the fan pressure ratio correlation for the 0.3-m TCT or any fan pressure ratio entered by the user.

The drive-fan power calculation pertains to closed circuit cryogenic transonic tunnels with Mach numbers up to approximately 1.3. Above this Mach number, a fan-driven transonic tunnel, similar in design to the 0.3-m TCT (fig. 1), becomes very inefficient. The plenum-removal compressor power is calculated independently of drive-fan power for Mach numbers greater than 1. Other assumptions made with respect to these calculations are discussed in detail later.

The program also calculates liquid nitrogen information such as the specific cooling capacity, flow rates, and power required for continuous production of LN₂ at the rate of consumption required for continuous tunnel operation.

Tunnel Flow Parameter Equations

Static Pressure and Temperature

The program is based on inputs of total values of temperature and pressure. The static-to-total temperature and pressure expressions for isentropic flow of an ideal gas are used to calculate the appropriate static values. In reference 8, Adcock shows the validity of using these ideal-gas ratios with the real-gas nitrogen. The relevant ideal-gas ratios are defined as

\[
\frac{T_t}{T_s} = 1 + \frac{\gamma - 1}{2} M^2
\]

and

\[
\frac{P_t}{P_s} = \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\gamma/(\gamma-1)}
\]

Compressibility Factor, Ratio of Specific Heats, and Dynamic Viscosity

The values of compressibility factor \(Z\), ratio of specific heats \(\gamma\), and dynamic viscosity \(\mu\) are based on simplified curve fits to calculations of the properties of nitrogen from a National Bureau of Standards (NBS) computer program (ref. 9). The NBS program is based on Jacobsen’s equation of state (ref. 10). These simplified curve fits are discussed in more detail later.

Density

A simple real-gas approximation is used in solving for the density \(\rho\) by using the ideal gas equation of state with the compressibility factor as

\[
\rho = \frac{P}{RTZ}
\]

Velocity

Velocity \(V\) is defined as

\[
V = Ma
\]
Another simple real-gas approximation is used for the speed of sound \( a \) by multiplying the ideal-gas value by \( \sqrt{\gamma} \) (ref. 11) where

\[
a = \sqrt{\gamma RTZ}
\]  
(4)

so that

\[
V = M \sqrt{\gamma RTZ}
\]  
(5)

**Dynamic Pressure**

Dynamic pressure \( q \) is defined as

\[
q = \frac{1}{2} \rho V^2
\]  
(6)

By using equations (3) and (5), the dynamic pressure can be expressed as

\[
q = \frac{1}{2} \gamma p_s M^2
\]  
(7)

**Mass Flow**

The mass-flow rate through the test section is given by

\[
\dot{m} = \rho VA_{TS}
\]

In terms of dynamic pressure, the mass-flow rate is expressed as

\[
\dot{m} = \frac{2A_{TS}q}{V}
\]  
(8)

For the case where \( M \geq 1 \), the mass-flow rate can be expressed as

\[
\dot{m} = \left( \frac{2}{\gamma + 1} \right)^{0.5[(\gamma+1)/(\gamma-1)]} \rho_{\text{th}} A^* \]

(9)

This equation (ref. 12) is derived by using the throat as the reference section. The term \( \gamma \) can be replaced with \( \alpha \), the isentropic expansion coefficient. By using \( \alpha = 1.4 \), the test-section area as the throat area, and equations (3) and (4), this mass-flow rate can be expressed as

\[
\dot{m} = \frac{(0.685) p_{\text{th}} A_{TS}}{\sqrt{\gamma RTZ}}
\]  
(10)

The term \( \alpha \) is discussed in detail later.

**Reynolds Number**

Reynolds number \( R \) is defined as

\[
R = \frac{\rho V \ell}{\mu}
\]  
(10)

Reynolds number per characteristic length \( R/\ell \) is then expressed as

\[
\frac{R}{\ell} = \frac{\rho V}{\mu}
\]

Expressing \( R/\ell \) in terms of \( q \) gives

\[
\frac{R}{\ell} = \frac{2q}{V\mu}
\]  
(11)
Tunnel Power Equations

Drive-Fan Power

A real-gas approximation for drive-fan power is

$$ P_f = \dot{m} \left[ \frac{\gamma}{\gamma - 1} R T_{t,1} (r^{(\gamma - 1)/\gamma} - 1) \right] Z $$

(12)

This equation (ref. 11) actually calculates that portion of the main-drive fan power that is added to the stream. This equation, which is based on an isentropic compression at the fan, is the ideal-gas power equation multiplied by the compressibility factor. It does not include any efficiency factors for the motor-drive system.

Plenum-Removal Compressor Power

The equation for plenum-removal compressor power is given as

$$ P_c = \frac{\omega \dot{m} c_p (T_{t,2} - T_{t,1})}{M \eta_c} $$

(13)

This equation is similar to equation (12) by noting that

$$ \frac{c_p}{M} = \left( \frac{\gamma}{\gamma - 1} \right) R $$

and

$$ T_{t,2} - T_{t,1} = T_{t,1} (r^{(\gamma - 1)/\gamma} - 1) $$

It has been modified to include a plenum-removal term $\omega$ which determines the amount of mass flow that needs to be removed to achieve a given test section Mach number. The term $\omega$ is defined as $(A/A^* - 1)$, where $A$ is the effective area at the model location in the test section and $A^*$ is the throat area. This assumes that you have a transonic tunnel with a ventilated, constant-area test section with the beginning of the test section acting as the throat.

For Mach numbers greater than 1, the Mach number at the throat would be 1 while the flow would expand to the desired Mach number at the model location by use of the ventilated walls and plenum-removal compressor. This simple equation assumes that all the flow through the walls is removed from the plenum, which is at static temperature and pressure, and re-injected at a location in the tunnel at total temperature and pressure conditions. Therefore, for this case,

$$ T_{t,1} = T_{s,1} $$

in equation (13). This equation can be useful for the rough sizing of a compressor for plenum suction. However, caution should be exercised when using this part of the program if the actual plenum removal being considered differs in detail from that described above.

Liquid Nitrogen Requirements

The liquid nitrogen flow rate required to offset the heat added to the flow by the drive fan and plenum-removal compressor is calculated by using the following equation (ref. 3):

$$ \dot{m}_{LN_2,f} = \frac{P_f + P_c}{\beta} $$

(14)

The liquid nitrogen flow rate required to offset the heat added to the flow by one-dimensional conduction through the thermal insulation from the air outside the tunnel is calculated by using the following equation:

$$ \dot{m}_{LN_2,con} = \frac{k A S F (T_i - T_t)}{t \beta} $$

(15)
The tunnel surface area term $A_{SF}$ is based on the empirical relation, $A_{SF} = 600A_{TS}$, which is a fairly accurate approximation for tunnels that are of a design similar to the 0.3-m TCT and to the NTF.

The power required for the continuous production of LN$_2$ at the rate of consumption required for tunnel operation is calculated by using the following equation (ref. 3):

$$P_{LN_2} = (\dot{m}_{LN_2,\text{tot}}) E_m$$

The term $\dot{m}_{LN_2,\text{tot}}$ is the total LN$_2$ mass flow obtained by adding equations (14) and (15). The term $E_m$ is the energy required to produce 1 kg of LN$_2$. Note that this power has the units of megawatts since $E_m$ is expressed in megawatt-seconds per kilogram.

Properties of Nitrogen at Cryogenic Temperatures

Some of the simplifying assumptions used in the program deal with the way the properties of nitrogen are calculated at cryogenic temperatures. For example, very precise values of the compressibility factor $Z$ can be obtained over the temperature range from 65 to 2000 K at pressures up to 10,000 atmospheres from the NBS computer program (ref. 9). However, the equation which covers these wide ranges of temperature and pressure has many more terms than are required to cover the limited range of temperature and pressure of interest in the study of a cryogenic wind tunnel. Therefore, a less complicated equation has been fitted to the NBS nitrogen data to allow its use with small desktop digital computers. The same situation is true for the ratio of specific heats, the dynamic viscosity, and the specific cooling capacity, where relatively simple equations are used to cover only the limited ranges of temperature and pressure of interest. No particular effort has been made to optimize the form of the simplified equations. In general, the forms are those which tend to linearize and therefore reduce the number of terms required to provide an adequate fit.

Compressibility Factor

For the ranges of temperature and pressure of interest, the compressibility factor $Z$ was calculated by using the NBS program and fitted with an equation of the form

$$Z = \frac{P}{\rho R T} = 1 + A p + B p^2$$

(17)

where a discussion of the parameters $A$ and $B$ is given in appendix A and in reference 3.

The values of $Z$ calculated by equation (17) agree with the values calculated by the NBS program generally within 0.05 percent for pressures from slightly above 0 to 7 atm and temperatures from saturation to 350 K.

Ratio of Specific Heats

The real-gas ratios of specific heats were calculated from the tabulated data of reference 10 and fitted with an equation of the form

$$\gamma = \frac{c_p}{c_v} = 1.4 + C p + D p^2$$

(18)

where a discussion of the parameters $C$ and $D$ is given in appendix A and in reference 3.

For most purposes, the values of $\gamma$ calculated from equation (18) are adequate for pressures from slightly above 0 to 7 atm and temperatures from saturation to 350 K. The values calculated from equation (18) agree with the values calculated from the data of reference 10 generally within 0.03 percent over the entire range of temperatures from saturation to 350 K for pressures of 4 atm or less. The greatest differences exist for conditions of high pressure and low temperature. For example, the value calculated from equation (18) is about 0.3 percent less than the value calculated from the data of reference 10 at 7 atm and 110 K.

As is shown in figure 2, the real-gas values of $\gamma$ vary significantly from the ideal diatomic gas value of 1.4 at the higher pressures and lower temperatures (ref. 8). As was shown by Adcock (ref. 8), the use of these values with the ideal-gas equations gives erroneous results when compared with the real-gas solutions. However, Adcock showed that by considering the isentropic expansion coefficient $\alpha$ in place of the ratio of specific heats $\gamma$, one can use the ideal-gas equations with $\alpha = 1.4$ because $\alpha$ remains very close
to this value over the temperature and pressure range of interest in a cryogenic wind tunnel. Therefore, $\alpha$ replaces $\gamma$ in the preceding equations in this report. The program uses a constant value of 1.4 for $\alpha$. For a detailed discussion of the isentropic expansion coefficient, see reference 8.

**Dynamic Viscosity**

Values of the dynamic viscosity of nitrogen $\mu$ were calculated by using the NBS program and fitted with an equation of the form

$$\mu = E + FT + GT^2$$  \hspace{1cm} (19)

where a discussion of the parameters $E$, $F$, and $G$ is given in appendix A and in reference 3.

The values of $\mu$ calculated from equation (19) agree with the values calculated by using the NBS program generally within 0.2 percent for pressures from slightly above 0 to 20 atm and temperatures from saturation to 350 K.

**Specific Cooling Capacity**

Values of the specific cooling capacity of nitrogen $f_3$ were calculated from the NBS program for pressures from 1 to 10 atm and for temperatures from saturation to 350 K. The calculated values of $f_3$ were fitted with an equation of the form

$$f_3 = H_0 T_1 + H_1 + H_2 \frac{1}{T_1}$$  \hspace{1cm} (20)

where a discussion of the parameters $H_0$, $H_1$, and $H_2$ is given in appendix A. Reference 13 has a more extensive discussion of the specific cooling capacity of liquid nitrogen as it pertains to cryogenic wind tunnels. Note that the units for $f_3$ are kilojoules per kilogram. The program converts the units to joules per kilogram before using $f_3$ in equations (14) and (15).

**Program Inputs**

The following parameters are user inputs to the program: test-section area, test-section Mach number, total pressure, total-temperature option, and fan pressure ratio. These inputs can be entered in either International System of Units (SI) or U.S. Customary Units.

For the total-temperature option, one can enter any desired temperature in the range from saturation to 350 K (option 1) or choose one of three other options. With option 2, the total temperature is calculated based on a curve fit for a typical local maximum Mach number on a model as shown in figure 3 (ref. 3). This curve was constructed from inspections of pressure distributions over typical wing sections. (Airfoils having peaky pressure distributions were not included.) With option 3, the total temperature is calculated based on free-stream saturation. (A detailed discussion of the condensation effects on airfoil testing at this lower limit of operating temperature is given in ref. 14.) Option 4 calculates a total temperature based on local saturation of the flow at any local Mach number that you subsequently enter. For options 2 through 4, the total temperatures are calculated by assuming that the nitrogen expands isentropically as an ideal gas from the tunnel settling chamber through to the Mach number region under consideration. In addition, the calculated static temperatures for options 2 through 4 lie along the saturation boundary as shown in figure 4.

The fan pressure ratio input allows the user to input a value or to use the value calculated for the 0.3-m TCT. The equation for fan pressure ratio for the 0.3-m TCT is

$$r = 0.8205 M^2 R_{nd}^{-0.096} + 1.001$$  \hspace{1cm} (21)

This equation is taken from reference 15 and was formulated based on data taken in the 0.3-m TCT with the tunnel empty. It is a valid expression for the 0.3-m TCT up to the point where the flow begins to choke. To calculate the hydraulic diameter, an additional input of test-section perimeter is required.

**Program Constants**

The following is a list of parameters which are given constant values in the program (these can be easily changed by the user by modifying the “Constants” section of the program):
1. Specific heat at constant pressure for nitrogen, $c_p = 29.15 \text{ J/mol-K}$ (this is the value of $c_p$ at 1 atm and 300 K)
2. Energy to produce 1 kg of LN2, $E_m = 2.6 \text{ MW-sec/kg}$ (ref. 16 uses a value of 2.6 MW-sec/kg; this value was verified by checking with the local LN2 plant that supplies the NTF; note that this value is an estimate which can change depending upon factors such as plant efficiency)
3. Thickness of insulation, $t = 0.1016 \text{ m}$
4. Thermal conductivity of insulation, $k = 0.033 \text{ W/m-K}$
5. Molecular weight of nitrogen, $M = 0.0280134 \text{ kg/mol}$
6. Efficiency of plenum-removal compressor, $\eta_e = 85 \text{ percent}$
7. Gas constant for nitrogen, $R = 296.7905 \text{ J/kg-K}$
8. Isentropic expansion coefficient, $\alpha = 1.4$

**Program Operation**

Following the input of tunnel-total-temperature option, the program branches to one of four locations depending upon which temperature option has been chosen.

If option 1 is chosen, the user enters any desired total temperature in the range from saturation to 350 K (170°F).

If option 2 is chosen, a typical local Mach number is calculated based on the test-section Mach number by using a curve fit to the data of figure 3. With this local Mach number, the tunnel total pressure, and equation (2), a local static pressure is calculated. By using the logarithm of this local static-pressure value and a curve fit to the data of figure 4, a local static temperature is calculated. This local static temperature and the local Mach number are used along with equation (1) to calculate the tunnel total temperature.

If option 3 is chosen, a test-section static pressure is calculated based on the total pressure and test-section Mach number by using equation (2). By using the logarithm of this static-pressure value and the curve fit to the data of figure 4, a test-section static temperature is calculated. This static temperature and the Mach number are used along with equation (1) to calculate a total temperature based on free-stream saturation.

If option 4 is chosen, the user subsequently inputs an arbitrary value of local Mach number, and the program proceeds as in option 2 following the point in that option where the local Mach number is calculated.

Note that for options 2 through 4, the static pressure is compared to the triple-point value of static pressure for nitrogen. (See fig. 4.) If it is below the triple-point value, the program aborts.

The following is a step-by-step description of the calculations that occur after a total temperature has been calculated:

**Step 1:** Test-section static temperature and pressure are calculated by equations (1) and (2), respectively. Note that option 3 performed the static-pressure calculation prior to calculating the total temperature. For option 1, this test-section static pressure is compared with the triple-point value of static pressure for nitrogen. If it is below the triple-point value, the program aborts. In addition, option 1 calculates a static temperature by using a curve fit to the saturation line in figure 4. If the test-section static temperature is less than the value on the saturation line, the program aborts.

**Step 2:** The compressibility factor $Z$ is calculated by using equation (17) based on the total temperature and pressure. It ($Z$) is also calculated based on the static conditions; however, the value obtained by using the total conditions is used in subsequent calculations (ref. 11).

**Step 3:** The real-gas value of the ratio of specific heats is calculated by using equation (18) with static values for temperature and pressure. This value is calculated to show its variation over the temperatures and pressures used in a cryogenic wind tunnel.

**Step 4:** The dynamic viscosity is calculated by using equation (19) with static values of temperature and pressure.

**Step 5:** The total and static densities are calculated by using equation (3).
Step 6: The velocity, dynamic pressure, and test-section mass-flow rate are calculated by using equations (5), (7), and (8), respectively. If $M \geq 1$, then the mass-flow rate is calculated by using equation (9).

Step 7: Reynolds number per unit length $R/\ell$ is calculated by using equation (11), and Reynolds number based on a characteristic length is calculated, where $\ell$ is defined as $0.1\sqrt{A_{TS}}$.

Step 8: The fan pressure ratio based on the correlation from the 0.3-m TCT is calculated by using equation (21) if this option is chosen. Otherwise, the input fan pressure ratio is utilized. The drive-fan power is then calculated by using equation (12). If $M > 1$, the plenum-removal compressor power is calculated by using equation (13).

Step 9: The specific cooling capacity is calculated by using equation (20).

Step 10: The LN2 flow rates due to the heat added to the circuit by the fan and conduction are calculated by using equations (14) and (15), respectively. These flow rates are added to get the total LN2 flow rate which is then expressed as a percent of the tunnel mass-flow rate.

Step 11: The power to produce LN2 is calculated by using equation (16).

Step 12: The results from equations (12), (13), and (16) are summed to get the total power. Note that the plenum-removal compressor power is 0 if $M < 1$.

Step 13: The results are printed in both SI and U.S. Customary Units.

Program Results

Figure 5 shows a sample output from the program. The results are listed in four categories: physical tunnel parameters, tunnel flow parameters, power parameters, and LN2 flow parameters. For options 2 and 4, there is a fifth category which lists the local conditions.

In addition to using the results in this format, the program can be used in conjunction with a graphics routine to generate plots of various parameters. For example, since a cryogenic wind tunnel has independent control of $M$, $R$, and $q$, operating envelopes in terms of two of these parameters can be generated while holding the third parameter constant. Samples of these plots are shown in figures 6, 7, and 8. In addition, plots involving power parameters can be generated as shown in figures 9 and 10. Also, performance charts, similar to the ones shown in figures 11 and 12, can be made by using this program. The program modifications necessary to generate these plots (figs. 6 through 12) are relatively straightforward and therefore are not described in this report.

Data Comparisons

Figures 11 and 12 contain a few data points from the 0.3-m TCT and the NTF which are used for comparison with the values calculated from the program. These data are tabulated in table I. The drive-motor power data in table I is the amount of power supplied to the motor. To compare this with the drive-fan power calculated in the program, an overall drive-motor system and fan efficiency is assumed. For both tunnels, the overall efficiency is assumed to be 80 percent. The values plotted in figures 11 and 12 include the efficiency. Note that the fan power curves in these figures were generated by using equation (21) which is based on the 0.3-m TCT.

For the 0.3-m TCT data, the comparison is very good. All three values calculated by using the program are within 16 percent of their respective data values. Also, the percent difference decreases as the power level increases.

For the NTF data, the calculated values are within 33 and 9 percent of their respective data values. A more accurate comparison with the NTF data may be obtained if a fan power correlation for the NTF is used. Reference 17 contains such a correlation.

Note that the assumed overall efficiency of 80 percent for the drive-motor system and fan resulted in all five data values for $P_f$ being higher than their respective calculated program values. This trend may imply that an overall efficiency of 80 percent is too high for both tunnels.

Concluding Remarks

A computer program has been written that performs the flow parameter calculations for cryogenic wind tunnels which use nitrogen as a test gas. Simplifying assumptions have been made so that the
calculations of Reynolds number as well as other flow parameters can be made on relatively small desktop digital computers. The program, which also includes various power calculations, has been developed to the point where it has become a very useful tool for the users and possible future designers of fan-driven continuous-flow cryogenic wind tunnels.

The calculations by the program of drive-fan power agree well with the measured data from the 0.3-m TCT. Similar comparisons for the NTF were also good; however, a more accurate comparison with the measured NTF data may be obtained if a fan-power correlation for the NTF is used rather than the correlation for the 0.3-m TCT that is used by the program.
### TABLE I. SUMMARY OF TUNNEL DATA PLOTTED IN FIGURES 11 AND 12

Langley 0.3-Meter Transonic Cryogenic Tunnel ($\sqrt{A_{TS}} = 0.35$ m)

<table>
<thead>
<tr>
<th>Point</th>
<th>$M$</th>
<th>$p_t$, atm</th>
<th>$T_t$, K</th>
<th>$R_\xi$</th>
<th>$P_m$, kW</th>
<th>$P_f, a$ kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.700</td>
<td>1.36</td>
<td>105</td>
<td>$2.66 \times 10^6$</td>
<td>212</td>
<td>170</td>
</tr>
<tr>
<td>2</td>
<td>0.700</td>
<td>3.06</td>
<td>105</td>
<td>$5.98 \times 10^6$</td>
<td>400</td>
<td>320</td>
</tr>
<tr>
<td>3</td>
<td>0.700</td>
<td>5.85</td>
<td>105</td>
<td>$11.52 \times 10^6$</td>
<td>685</td>
<td>548</td>
</tr>
</tbody>
</table>

National Transonic Facility (NTF) at the Langley Research Center ($\sqrt{A_{TS}} = 2.5$ m)

<table>
<thead>
<tr>
<th>Point</th>
<th>$M$</th>
<th>$p_t$, atm</th>
<th>$T_t$, K</th>
<th>$R_\xi$</th>
<th>$P_m$, MW</th>
<th>$P_f, a$ MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.712</td>
<td>6.46</td>
<td>117</td>
<td>$77.00 \times 10^6$</td>
<td>49.3</td>
<td>39.4</td>
</tr>
<tr>
<td>2</td>
<td>0.972</td>
<td>2.03</td>
<td>113</td>
<td>$29.74 \times 10^6$</td>
<td>24.3</td>
<td>19.4</td>
</tr>
</tbody>
</table>

$^aP_f$ is calculated by using $P_m$ and assuming an efficiency of 80 percent.
Figure 1. Sketch of Langley 0.3-Meter Transonic Cryogenic Tunnel. (The size of two-dimensional test-section insert shown is 20 by 60 cm.)
Figure 2. Variation of ratio of specific heats $\gamma$ with temperature and pressure.
Maximum local Mach number, $M_{L,max}$

Typical local maximum Mach number

Free-stream Mach number, $M_{\infty}$

Figure 3. Assumed local Mach number as function of free-stream Mach number.
Figure 4. Vapor pressure for nitrogen as function of saturation temperature.
CRYOGENIC WIND TUNNEL FLOW PARAMETER PROGRAM 
UTILIZING NITROGEN AS THE TEST GAS

<table>
<thead>
<tr>
<th>PHYSICAL TUNNEL PARAMETERS</th>
<th>SI</th>
<th>U.S. CUSTOMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test section area</td>
<td>6.25 m$^2$</td>
<td>67.27 ft$^2$</td>
</tr>
<tr>
<td>Test section perimeter</td>
<td>10.00 m</td>
<td>32.81 ft</td>
</tr>
<tr>
<td>Reference chord</td>
<td>0.25 m</td>
<td>0.82 ft</td>
</tr>
<tr>
<td>Tunnel surface area</td>
<td>3750.00 m$^2$</td>
<td>40364.67 ft$^2$</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>0.10 m</td>
<td>0.33 ft</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TUNNEL FLOW PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pressure</td>
</tr>
<tr>
<td>Static pressure</td>
</tr>
<tr>
<td>Total temperature</td>
</tr>
<tr>
<td>Static temperature</td>
</tr>
<tr>
<td>Total density</td>
</tr>
<tr>
<td>Test section static density</td>
</tr>
<tr>
<td>Compressibility factor based on total temperature</td>
</tr>
<tr>
<td>Compressibility factor based on static temperature</td>
</tr>
<tr>
<td>Real gas ratio of specific heats</td>
</tr>
<tr>
<td>Viscosity</td>
</tr>
<tr>
<td>Mach number</td>
</tr>
<tr>
<td>Velocity</td>
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<tr>
<td>Test section mass flow</td>
</tr>
<tr>
<td>Dynamic pressure</td>
</tr>
<tr>
<td>Reynolds number per meter</td>
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<tr>
<td>Reynolds number per foot</td>
</tr>
<tr>
<td>Reynolds number based on reference chord</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POWER PARAMETERS</th>
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</thead>
<tbody>
<tr>
<td>Plenum removal</td>
</tr>
<tr>
<td>Plenum removal compressor efficiency</td>
</tr>
<tr>
<td>Fan pressure ratio</td>
</tr>
<tr>
<td>Fan power</td>
</tr>
<tr>
<td>Plenum removal compressor power</td>
</tr>
<tr>
<td>Total drive power</td>
</tr>
<tr>
<td>Power for continuous production of LN2</td>
</tr>
<tr>
<td>Total power for continuous running</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LN2 FLOW PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling capacity</td>
</tr>
<tr>
<td>LN2 flow rate for fan heat</td>
</tr>
<tr>
<td>LN2 flow rate for conduction</td>
</tr>
<tr>
<td>Total LN2 flow rate</td>
</tr>
<tr>
<td>Total LN2 flow/test section flow</td>
</tr>
</tbody>
</table>

Figure 5. Sample of program output. (Fan power was calculated by using eq. (21).)
\( M_\infty = 1.0, \text{ 2.5-by 2.5-m test section} \)

\( T_{t, \text{max}} = 340 \text{ K} \quad P_{t, \text{max}} = 8.9 \text{ bars} \)

\( P_{t, \text{min}} = 1.0 \text{ bars} \)

Figure 6. Constant Mach number operating envelope.

\( R_\infty = 50 \times 10^6, \text{ 2.5-by 2.5-m test section} \)

Mach number studies

Aeroelastic studies

\( M_{\infty, \text{max}} \)

\( P_{t, \text{max}} = 8.9 \text{ bars} \)

Figure 7. Constant Reynolds number operating envelope.
$q = 1 \text{ bar, 2.5-by 2.5-m test section}$

$P_t, \text{max} = 8.9 \text{ bars}$

$T_t, \text{max} = 340 \text{ K}$

Free-stream Mach number, $M_\infty$

Figure 8. Constant dynamic pressure operating envelope.

$M_\infty = 1.0, R_\infty = 50 \times 10^6$

2.5- by 2.5-m test section

Dynamic pressure

Fan power

Stagnation temperature, $T_t, \text{K}$

Figure 9. Variation of dynamic pressure and drive power with stagnation temperature. (Note that fan power was calculated by using eq. (21).)
Figure 10. Total power required for continuous running as a function of stagnation pressure for ambient and cryogenic fan-driven tunnels. $M_\infty = 1.0$, $Re = 50 \times 10^6$. (Note that fan power portions were calculated by using eq. (21).)
Figure 11. Performance chart for cryogenic nitrogen tunnel showing relationship between tunnel size, stagnation pressure, fan power, and Reynolds number. $M_\infty = 0.70; T_t = 105 \text{ K}$. (Note that fan power was calculated by using eq. (21) and test-section perimeter from 0.3-m TCT.)
Figure 12. Performance chart for cryogenic nitrogen tunnel showing relationship between tunnel size, stagnation pressure, fan power, and Reynolds number. (Note that fan power was calculated by using eq. (21) and test-section perimeter from NTF.)

(a) $M_\infty = 0.712; \ T_i = 117 \text{ K}.$
(b) $M_\infty = 0.972; T_i = 113$ K.

Figure 12. Concluded.
Appendix A

Equation Parameters for Calculating Properties of Nitrogen at Cryogenic Temperatures

Note that the values for pressure used in the equations in this appendix should be in atmospheres.

Compressibility Factor $Z$

The compressibility factor $Z$ is calculated by using equation (17), which is (ref. 3)

$$Z = \frac{p}{\rho RT} = 1 + Ap + Bp^2$$

The parameters $A$ and $B$ are given by

$$\ln(-A) = \sum_{i=0}^{4} a_i T^i$$

$$\ln(-B) = \sum_{i=0}^{4} b_i T^i$$

where the values of $a_i$ and $b_i$ are as follows:

$a_0 = 1.370$ 
$a_1 = -8.773 \times 10^{-2}$ 
$a_2 = 4.703 \times 10^{-4}$ 
$a_3 = -1.386 \times 10^{-6}$ 
$a_4 = 1.462 \times 10^{-9}$

$b_0 = 5.521$ 
$b_1 = -1.986 \times 10^{-1}$ 
$b_2 = 7.817 \times 10^{-4}$ 
$b_3 = -1.258 \times 10^{-6}$ 
$b_4 = 5.333 \times 10^{-10}$

Ratio of Specific Heats $\gamma$

The ratio of specific heats $\gamma$ is calculated by using equation (18), which is (ref. 3)

$$\gamma = \frac{c_p}{c_v} = 1.4 + Cp + Dp^2$$

The parameters $C$ and $D$ are given by

$$\ln C = \sum_{i=0}^{4} c_i T^i$$

$$\ln D = \sum_{i=0}^{1} d_i T^i$$

where the values of $c_i$ and $d_i$ are as follows:

$c_0 = 1.86799$ 
$c_1 = -9.52187 \times 10^{-2}$ 
$c_2 = 5.14638 \times 10^{-4}$ 
$c_3 = -1.35950 \times 10^{-6}$ 
$c_4 = 1.31676 \times 10^{-9}$

$d_0 = -1.25126$ 
$d_1 = -4.96900 \times 10^{-2}$
Dynamic Viscosity $\mu$

The dynamic viscosity is calculated by using equation (19), which is (ref. 3)

$$\mu = E + FT + GT^2$$

The parameters $E$, $F$, and $G$ are given by

$$E = \sum_{i=0}^{2} e_i p^i$$

$$F = \sum_{i=0}^{2} f_i p^i$$

$$G = \sum_{i=0}^{2} g_i p^i$$

where the values $e_i$, $f_i$, and $g_i$ are as follows:

$e_0 = -2.86896 \times 10^{-7}$
$e_1 = 1.23678 \times 10^{-7}$
$e_2 = 1.29862 \times 10^{-9}$

$f_0 = 7.55226 \times 10^{-8}$
$f_1 = -6.10064 \times 10^{-10}$
$f_2 = -1.22089 \times 10^{-11}$

$g_0 = -4.89417 \times 10^{-11}$
$g_1 = 9.51640 \times 10^{-13}$
$g_2 = 2.52130 \times 10^{-14}$

Specific Cooling Capacity $\beta$

The specific cooling capacity is calculated by using equation (20), which is (ref. 13)

$$\beta = H_0 T_t + H_1 + H_2 \frac{1}{T_t}$$

The parameters $H_0$, $H_1$, and $H_2$ are given by

$$H_0 = 1.0379 - (3.9157 \times 10^{-3}) p_t$$
$$H_1 = (1.2125 \times 10^2) + 2.1577 p_t$$
$$H_2 = 66.585 - (3.9122 \times 10^2) p_t$$
Appendix B

Program Listing

This listing is written in IBM “Advanced Basic” language for the IBM Personal Computers PC/XT/AT.

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ALPHA is the isentropic expansion coefficient.

\[ \text{ALPHA} = 1.4 \]

\[ \text{RATIO1} = \frac{\text{ALPHA}}{\text{ALPHA}-1} \]

\[ \text{RATIO2} = \frac{(\text{ALPHA}-1)/2}{179} \]

Program Inputs in SI units

Program Inputs in English Units

\[ \text{TEST.SECT.AREA1} = \text{TEST.SECT.AREA2} \times 0.3048^2 \]

\[ \text{MACH.NUMBER} \]

\[ \text{RATIO1} = \frac{\text{ALPHA}}{\text{ALPHA}-1} \]

\[ \text{RATIO2} = \frac{(\text{ALPHA}-1)/2}{179} \]

\[ \text{TEST.SECT.AREA1} = \text{TEST.SECT.AREA2} \times 0.3048^2 \]

\[ \text{MACH.NUMBER} \leq 1.3 \text{ THEN } 1110 \]

\[ \text{MACH.NUMBER} = 1.4 \]

\[ \text{RATIO1} = \frac{\text{ALPHA}}{\text{ALPHA}-1} \]

\[ \text{RATIO2} = \frac{(\text{ALPHA}-1)/2}{179} \]

\[ \text{TEST.SECT.AREA1} = \text{TEST.SECT.AREA2} \times 0.3048^2 \]

\[ \text{MACH.NUMBER} = 1.4 \]

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\[ \text{RATIO1} = \frac{\text{ALPHA}}{\text{ALPHA}-1} \]

\[ \text{RATIO2} = \frac{(\text{ALPHA}-1)/2}{179} \]

\[ \text{TEST.SECT.AREA1} = \text{TEST.SECT.AREA2} \times 0.3048^2 \]

\[ \text{MACH.NUMBER} = 1.4 \]
1100 COLOR 12:LOCATE 15,40:PRINT "Out of range for "":LOCATE 16,40:PRINT "power calculations"
1110 COLOR 10:LOCATE 15,7:PRINT "Mach number":MACH.NUMBER:COLOR 15,1
1120 LOCATE 18,7:INPUT "Total pressure (lb/in^2)";TOTAL.PRESSURE2
1130 IF TOTAL.PRESSURE2>0 AND TOTAL.PRESSURE2<=103 THEN 1150
1140 COLOR 12:LOCATE 18,40:PRINT "0 < Pt < = 103":COLOR 28:LOCATE 18,55:PRINT "Out of range! Try again":COLOR 12:LOCATE 18,28:PRINT"":GOTO 1120
1150 COLOR 14:LOCATE 18,40:PRINT "0 < Pt < = 103":LOCATE 18,55:PRINT 
1160 COLOR 10:LOCATE 18,7:PRINT "Total pressure (lb/in^2)";TOTAL.PRESSURE2:COLOR 15,1
1170 ' Converting lb/in^2 to N/m^2
1180 TOTAL.PRESSURE3=TOTAL.PRESSURE2*6894.75715#
1190 ' Converting N/m^2 to bars
1200 TOTAL.PRESSURE1=TOTAL.PRESSURE3/100000!
1210 GOTO 1530
1220 ' ************************** INPUTS FOR SI UNITS **************************
1230 COLOR 15,1:LOCATE 13,7:PRINT "Test section area (m^2)"
1240 LOCATE 15,7:PRINT "Mach number"
1250 LOCATE 18,7:PRINT "Total pressure (bars)"
1260 COLOR 14:LOCATE 13,40:PRINT "No restriction"
1270 LOCATE 15,40:PRINT "No restriction for"
1280 LOCATE 16,40:PRINT "calculating flow parameters *
1290 LOCATE 18,40:PRINT "0 < Pt < = 7.1"
1300 LOCATE 23,5:PRINT "* The power calculations are subject to restrictions. See documentation."
1310 LOCATE 13,7,1,0,7:INPUT "Test section area (m^2)";TEST.SECT.AREA1
1320 COLOR 10:LOCATE 13,7:PRINT "Test section area (m^2)";TEST.SECT.AREA1:COLOR 15
1330 ' Converting m^2 to ft^2
1340 TEST.SECT.AREA2=TEST.SECT.AREA1/.3048^2
1350 LOCATE 15,7:INPUT "Mach number":MACH.NUMBER
1360 IF MACH.NUMBER<=1.3 THEN 1380
1370 COLOR 12:LOCATE 15,40:PRINT "Out of range for "":LOCATE 16,40:PRINT "power calculations"
1380 COLOR 10:LOCATE 15,7:PRINT "Mach number":MACH.NUMBER:COLOR 15,1
1390 LOCATE 18,7:INPUT "Total pressure (bars)";TOTAL.PRESSURE1
1400 IF TOTAL.PRESSURE1>0 AND TOTAL.PRESSURE1<7.1 THEN 1420
1410 COLOR 12:LOCATE 18,40:PRINT "0 < Pt < = 7.1":COLOR 28:LOCATE 18,55:PRINT "Out of range! Try again":COLOR 12:LOCATE 18,28:PRINT":GOTO 1390
1420 COLOR 14:LOCATE 18,40:PRINT "0 < Pt < = 7.1":LOCATE 18,55:PRINT 
1430 COLOR 10:LOCATE 18,7:PRINT "Total pressure (bars)";TOTAL.PRESSURE1:COLOR 15,1
1440 ' Converting bars to N/m^2
1450 TOTAL.PRESSURE3=TOTAL.PRESSURE1*100000!
1460 ' Converting N/m^2 lb/in^2
1470 TOTAL.PRESSURE3=TOTAL.PRESSURE3/6894.75715#
1480 ' Tunnel surface area expressed in meters
1490 ' (Note that using 600 as a multiplication factor gives
1500 ' the approximate external surface area for the 0.3-m TCT.
1510 ' This number may work for other typically designed tunnels
1520 ' or may be changed as required.)
1530 TUN.SURF.AREA1=TEST.SECT.AREA1*600
1540 ' Converting meters to feet
1550 TUN.SURF.AREA2=TUN.SURF.AREA1/.3048^2
1560 ' Converting N/m^2 to atmospheres
1570 TOTAL.PRESSURE4=TOTAL.PRESSURE3/101325!
1580 ' Expressing static pressures in atmospheres
ENTER 4 to run the program based on local saturation of the flow at any local Mach number that you desire to enter.

ENTER 3 to run the program based on free-stream saturation of the flow.

PRINT INPUT "Enter option number"; T.OPTION
IF T.OPTION=1 THEN GOSUB 4290

INPUT "Do you want to use the 0.3-m TCT's fan pressure ratio correlation? Yes=1, No=2"; FPR
IF FPR=2 THEN INPUT "Input fan pressure ratio"; FAN.PRESS.RATIO
IF FPR=2 THEN 1880
IF UNITS=1 THEN 1840

INPUT "Input test section perimeter in feet"; PERIMETER2
PERIMETER1=PERIMETER2*.3048
HYDR.DIAMETER2=4*TEST.SECT.AREA2/PERIMETER2
GOTO 1880

INPUT "Input test section perimeter in meters"; PERIMETER1
PERIMETER2=PERIMETER1/.3048
HYDR.DIAMETER1=4*TEST.SECT.AREA1/PERIMETER1
HYDR.DIAMETER2=HYDR.DIAMETER1/.3048

IF T.OPTION=4 THEN INPUT "Input local Mach Number"; LOCAL.MACH
GOSUB 4200
IF T.OPTION=1 THEN 1960
IF (T.OPTION=2) OR (T.OPTION=4) THEN GOSUB 4410
IF T.OPTION=3 THEN GOSUB 4680

' Converting from Kelvin to Fahrenheit
TOTAL.TEMP2=9/5*TOTAL.TEMP1-459.67

' Expressing static temperature in Kelvin
STATIC.TEMP1=TOTAL.TEMP1*(1+RATIO2*MACH.NUMBER^2)^(-1)

' Converting from Kelvin to Fahrenheit
STATIC.TEMP2=9/5*STATIC.TEMP1-459.67

' Expressing static pressures in N/m^2
STATIC.PRESS4=TOTAL.PRESSURE4*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)

' Expressing static pressures in lb/in^2
STATIC.PRESS2=TOTAL.PRESSURE2*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)

' Expressing static pressure in bars
STATIC.PRESS3=TOTAL.PRESSURE3*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)

' Expressing static pressure in atmospheres
STATIC.PRESS1=TOTAL.PRESSURE1*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)

' Checking static pressure to see if it's below the triple point value of 0.1237 atmospheres
CHECK1=LOG(STATIC.PRESS4)

IF STATIC.PRESS4>.1237 THEN 2150
ABORT1=1
GOTO 3500
\[ A = 1.37 - 0.08773 \times \text{STATIC.TEMP1} + 0.0004703 \times \text{STATIC.TEMP1}^2 - 1.386 \times 10^{-6} \times \text{STATIC.TEMP1}^3 + 1.462 \times 10^{-9} \times \text{STATIC.TEMP1}^4 \]

\[ B = 5.521 - 0.1986 \times \text{STATIC.TEMP1} + 0.0007817 \times \text{STATIC.TEMP1}^2 - 1.258 \times 10^{-6} \times \text{STATIC.TEMP1}^3 + 5.333 \times 10^{-10} \times \text{STATIC.TEMP1}^4 \]

\[ \text{COMPRES.FACTOR} = 1 - \exp(A) \times \text{TOTAL.PRESSURE4} - \exp(B) \times \text{TOTAL.PRESSURE4}^2 \]

\[ C = 1.86799 - 9.521871 \times 10^{-2} \times \text{STATIC.TEMP1} + 5.146381 \times 10^{-4} \times \text{STATIC.TEMP1}^2 - 1.3595 \times 10^{-6} \times \text{STATIC.TEMP1}^3 + 1.31676 \times 10^{-9} \times \text{STATIC.TEMP1}^4 \]

\[ D = -1.25126 - 0.04969 \times \text{STATIC.TEMP1} \]

\[ \text{GAMMA.REAL.GAS} = 1.4 + \exp(C) \times \text{STATIC.PRESS4} + \exp(D) \times \text{STATIC.PRESS4}^2 \]

\[ VISCOSITY1 = \exp(E) + F \times \text{STATIC.TEMP1} + G \times \text{STATIC.TEMP1}^2 \]

\[ VISCOSITY2 = VISCOSITY1 \times 0.209 \]

\[ \text{TOTAL.DENSITY1} = \text{TOTAL.PRESSURE3} / (\text{COMPRES.FACTOR} \times R \times \text{TOTAL.TEMP1}) \]

\[ \text{TOTAL.DENSITY2} = \text{TOTAL.DENSITY1} \times 0.00194 \]

\[ \text{STATIC.DENSITY1} = \text{STATIC.PRESS3} / (\text{COMPRES.FACTOR} \times R \times \text{STATIC.TEMP1}) \]

\[ \text{STATIC.DENSITY2} = \text{STATIC.DENSITY1} \times 0.00194 \]

\[ \text{VELOCITY1} = \text{MACH.NUMBER} \times (\text{ALPHA} \times \text{COMPRES.FACTOR} \times R \times \text{STATIC.TEMP1})^{0.5} \]

\[ \text{VELOCITY2} = \text{VELOCITY1} \times 0.3048 \]

\[ \text{DYNAMIC.PRESSURE} = \text{TOTAL.DENSITY2} \times \text{STATIC.DENSITY2} \]
The fan pressure ratio is calculated based on a correlation of data taken in the 0.3-m TCT. Delta T is the temperature difference across the insulation with 300 K being the ambient temperature.

\[ \Delta T = 300 - T_{\text{TOTAL TEMP}} \]

Liquid nitrogen flow rate due to tunnel drive fan in kg/s

\[ \text{LN FLWRATE CON} = K \times \text{TUN SURF AREA} \times \Delta T \left( \frac{1}{\text{INSUL THICKNESS} \times \text{COOL CAPACITY}} \right) \]

Converting kg/s to slugs/s

\[ \text{LN FLWRATE CON} = \frac{\text{LN FLWRATE CON}}{14.5939029} \]

Specific cooling capacity of liquid nitrogen in

\[ \text{COOL CAPACITY} = H_0 \times T_{\text{TOTAL TEMP}} + H_1 + H_2 \]

Converting kJ/kg to J/kg

\[ \text{COOL CAPACITY} = \frac{\text{COOL CAPACITY}}{1000} \]

Converting watts to megawatts

\[ \text{FAN POWER} = \frac{\text{FAN POWER}}{1000000} \]

Converting watts to hp

\[ \text{FAN POWER} = \frac{\text{FAN POWER}}{746} \]

PLENUM POWER = 0

PLENUM POWER = PLENUM POWER = PLENUM POWER = PLENUM POWER = 0

Total D POWER = FAN POWER + PLENUM POWER

Writing force

\[ \text{DYNM PRESSURE} = \frac{\text{ALPHA}}{2} \times \text{MACH NUMBER}^2 \times \text{STAT Press} \]

Converting N/m² to lb/ft²

\[ \text{DYNM PRESSURE} = \frac{\text{DYNM PRESSURE}}{47.880258} \]

Converting N/m² to bars

\[ \text{DYNM PRESSURE} = \frac{\text{DYNM PRESSURE}}{100000} \]

IF MACH NUMBER > 1 THEN GOSUB 4870

IF MACH NUMBER > 1 THEN 2790

Test section flow in kg/s

\[ \text{TEST SECT FLOW} = 2 \times \text{TEST SECT AREA} \times \text{DYNM PRESSURE} \times \text{VELOCITY} \]

Converting kg/s to slugs/s

\[ \text{TEST SECT FLOW} = \frac{\text{TEST SECT FLOW}}{14.5939029} \]

Reynolds number per meter

\[ \text{REY NUMBER PER METER} = \frac{2 \times \text{DYNM PRESSURE}}{\text{VISCOSITY} \times \text{VELOCITY}} \]

Reynolds number per foot

\[ \text{REY NUMBER PER FOOT} = \text{REY NUMBER PER METER} \times 0.3048 \]

Reynolds number hydraulic diameter

\[ \text{REY NUMBER HYD DIAM} = \text{REY NUMBER PER FOOT} \times \text{HYDR DIAMETER} \]

Reynolds number chord

\[ \text{REYNOLDS NUMBER} = \frac{\text{REY NUMBER PER METER} \times \text{HYDR DIAMETER}}{2} \]

Reynolds number

\[ \text{REYNOLDS NUMBER} = \frac{2 \times \text{DYNM PRESSURE}}{\text{VISCOSITY} \times \text{VELOCITY}} \]

If FPR = 2 THEN 2900

\[ \text{HO, HI, and H2 are coefficients used to calculate the liquid nitrogen cooling capacity.} \]

\[ \text{HO} = 1.0379 - 0.039157 \times \text{TOTAL PRESSURE} \]

\[ \text{HI} = 121.25 + 2.1577 \times \text{TOTAL PRESSURE} \]

\[ \text{H2} = 66.585 - 391.22 \times \text{TOTAL PRESSURE} \]

\[ \text{COOL CAPACITY} = \text{HO} \times \text{TOTAL TEMP} + \text{HI} + \text{H2} \]

Converting kJ/kg to J/kg

\[ \text{COOL CAPACITY} = \frac{\text{COOL CAPACITY}}{1000} \]

Converting kJ/kg to Btu/1bm

\[ \text{COOL CAPACITY} = \text{COOL CAPACITY} \times 0.43021 \]

Dynamic pressure

\[ \text{DYNM PRESSURE} = \frac{\text{ALPHA}}{2} \times \text{MACH NUMBER}^2 \times \text{STAT Press} \]

Converting N/m² to lb/ft²

\[ \text{DYNM PRESSURE} = \frac{\text{DYNM PRESSURE}}{47.880258} \]

Converting N/m² to bars

\[ \text{DYNM PRESSURE} = \frac{\text{DYNM PRESSURE}}{100000} \]

IF MACH NUMBER > 1 THEN GOSUB 5080

IF MACH NUMBER > 1 THEN 3010

Fan power in watts

\[ \text{FAN POWER} = \text{TEST SECT FLOW} \times \text{RATIO} \times \text{TOTAL TEMP} \left( \frac{(\text{FAN PRESS RATIO}^{1/RATIO}) - 1}{} \right) \times \text{COMPRES FACTOR} \]

Converting watts to megawatts

\[ \text{FAN POWER} = \frac{\text{FAN POWER}}{1000000} \]

Converting watts to hp

\[ \text{FAN POWER} = \frac{\text{FAN POWER}}{746} \]

PLENUM POWER = 0

PLENUM POWER = PLENUM POWER = PLENUM POWER = PLENUM POWER = 0

Total D POWER = FAN POWER + PLENUM POWER

Writing force
3270 LN_FLWRATE_FAN1=(FAN_POWER1+BL.COMP.Power1*BL.COMP.EFF/100)/COOL.CAPACITY1
3280 ' Converting kg/s to slugs/s
3290 LN_FLWRATE_FAN2=LN_FLWRATE_FAN1/14.5939029#
3300 ' Total liquid nitrogen flow rate in kg/s
3310 TOTAL_LN_FLOW1=LN_FLWRATE_FAN1+LN_FLWRATE_CON1
3320 ' Total liquid nitrogen flow rate in slugs/s
3330 TOTAL_LN_FLOW2=LN_FLWRATE_FAN2+LN_FLWRATE_CON2
3340 ' Liquid nitrogen flow expressed as a percent of the tunnel mass flow
3350 IF MACH.NUMBER>1 THEN 3380
3360 PERCENT_LN_FLOW=TOTAL_LN_FLOW1/TEST.SECT.FLOW1*100
3370 GOTO 3390
3380 PERCENT_LN_FLOW=TOTAL_LN_FLOW1/T.MASS.FLOW1*100
3390 'power to produce liquid nitrogen in MW
3400 POWER_PROD_LNIA=TOTAL_LN_FLOW1*EM
3410 ' Converting MW to horsepower
3420 POWER_PROD_LN2=POWER_PROD_LNIA*1340.4826#
3430 ' Total power required in MW
3440 TOTAL_POWERIA=TOTAL.D.POWERIA+POWER_PROD_LNIA
3450 ' Total power required in horsepower
3460 TOTAL_POWER2=TOTAL.D.POWER2+POWER_PROD_LN2
3470 ' **********************************************************************
3480 ' ****************** PRINTING SECTION **********************
3490 ' **********************************************************************
3500 IF T.OPTION=2 OR T.OPTION=4 THEN 3530
3510 PRINT #1,"PHYSICAL TUNNEL PARAMETERS SI U.S. C USTOMARY"
3520 GOTO 3540
3530 PRINT #1,"PHYSICAL TUNNEL PARAMETERS"
3540 PRINT #1,USING " Test section area ................. ###.### m^2 ###
3541 IF FPR = 2 THEN 3560
3542 PRINT #1,USING " Test section perimeter ................. ###.### m ###
3543 PRINT #1,USING " Reference chord ......................... ###.### m ###
3544 PRINT #1,USING " Tunnel surface area ................. #######.### m^2 ###
3545 PRINT #1,USING " Insulation thickness ......................... ###.### m ###
3546 PRINT #1,"";
3547 IF OUTPUT=2 THEN 3630
3548 PRINT "Press any key to continue"
3549 A$=INKEY$: IF A$="" THEN 3548
3550 PRINT #1,"PHYSICAL TUNNEL PARAMETERS";
3551 IF ABORT1=1 THEN PRINT #1,"The static pressure is below or equal to the triple point value of .1253 bars. The program has aborted."
3552 IF ABORT1=1 THEN 4160
3553 PRINT #1,"Total pressure ................. ###.### bars ###
3554 PRINT #1," Static pressure ................. ###.### bars ###
3555 PRINT #1," The static pressure is below or equal to the triple point value of .1253 bars. The program has aborted."
3556 PRINT #1,"Total temperature ................. ###.### K ###
3557 PRINT #1," Static temperature ................. ###.### K ###
3558 PRINT #1," The nitrogen is in a liquid state at these conditions (See figure 4). The program has aborted."
3559 PRINT #1,"Total density ................. ###.### kg/m^3 =###
3560 PRINT #1,"Total density1,TOTAL.DENSITY2"
PRINT #1, USING "Test section static density ........ #.### kg/m^3 = #.### slugs/ft^3"; STATIC.DENSITY1, STATIC.DENSITY2
PRINT #1, "Compressibility factor based on" DECOMPRESSION1, DECOMPRESSION2
PRINT #1, "Real gas ratio of specific heats ..... #.###"; GAMMA.REAL.GAS
PRINT #1, "Viscosity ................................ #.### N-s/m^2 = #.### lb-s/ft^2"; VISCOITY1, VISCOITY2
PRINT #1, "Mach number ................................ #.###"; MACH.NUMBER
PRINT #1, "Dynamic pressure ................................ #.### bars = #.### lb/ft^2"; DYNAM.PRESSURE1, DYNAM.PRESSURE2
PRINT #1, "Reynolds number per meter ................ #.###"; REYNOLDS.NUMBER.PERMETER
PRINT #1, "Reynolds number per foot ................... #.###"; REYNOLDS.NUMBER.PERFOOT
PRINT #1, "Reynolds number based on" REFERENCE.load
IF OUTPUT=2 THEN 3960
PRINT "Press any key to continue"
A$=INKEY$: IF A$="" THEN 3940
PRINT #1, "POWER PARAMETERS"
PRINT #1, "Plenum removal % ..................... #.###"; PLENUM.REMOVAL
PRINT #1, "Plenum removal compressor efficiency .......... #.###"; PLENUM.REMOVAL.EFFICIENCY
PRINT #1, "Fan pressure ratio ....................... #.###"; FAN.PRESS.RATIO
PRINT #1, "Fan power ................................ #.### MW = #.### hp"; FAN.POWER1, FAN.POWER2
PRINT #1, "Plenum removal compressor power .......... #.### MW = #.### hp"; PLENUM.POWER1, PLENUM.POWER2
PRINT #1, "Total drive power ............................ #.### MW = #.### hp"; TOTAL.D.POWER1, TOTAL.D.POWER2
PRINT #1, "Power for continuous" production of LN2 ...... #.### MW = #.### hp"; POWER.PROD.LN1, POWER.PROD.LN2
PRINT #1, "Total power for" continuous running ...... #.### MW = #.### hp"; TOTAL.POWER1, TOTAL.POWER2
PRINT #1, "LN2 FLOW PARAMETERS"
PRINT #1, "Cooling capacity ....................... #.### kJ/kg = #.### Btu/lb"; COOL.CAPACITY1, COOL.CAPACITY2
PRINT #1, "LN2 flow rate for fan heat ................... #.### kg/s = #.###
CRYOGENIC WIND TUNNEL FLOW PARAMETER PROGRAM

UTILIZING NITROGEN AS THE TEST GAS

4130 PRINT #1, USING " LN2 flow rate for conduction .......... #.#.# kg/s  = #
4140 PRINT #1, USING " Total LN2 flow rate ................. #.#.#.# kg/s  = #
4150 PRINT #1, USING " Total LN2 flow/test section flow ..... #.#.# %; PERCENT.LN.FLOW

4160 END

4170 '   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
4180 '   TITLE SUBROUTINE ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
4190 '   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
4200 CLS
4210 PRINT #1, " CRYOGENIC WIND TUNNEL FLOW PARAMETER PROGRAM"
4220 PRINT #1, " UTILIZING NITROGEN AS THE TEST GAS"
4230 PRINT #1,"
4240 PRINT #1,"'
4250 RETURN
4260 '   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
4270 '   OPTION 1 SUBROUTINE ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
4280 '   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
4290 IF UNITS=2 THEN 4340
4300 INPUT "Input tunnel total temperature in Kelvin"; TOTAL.TEMP1
4310 ' Converting from Kelvin to Fahrenheit
4320 TOTAL.TEMP2=9/5*TOTAL.TEMP1-459.67
4330 GOTO 4370
4340 INPUT "Input tunnel total temperature in Fahrenheit"; TOTAL.TEMP2
4350 ' Converting from Fahrenheit to Kelvin
4360 TOTAL.TEMP1=5/9*(TOTAL.TEMP2+459.67)
4370 RETURN
4380 '   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
4390 '   OPTIONS 2 AND 4 SUBROUTINE ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
4400 '   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
4410 IF T.OPTION=4 THEN 4460
4420'
4430 '   The next equation is a curve fit to figure 3.
4440'
4450 LOCAL.MACH=.014236731*MACH.NUMBER^4-.13340558*MACH.NUMBER^3+.44529085*MACH.NUMBER^2+.3790048*MACH.NUMBER+.6949
4460 PRINT #1, "LOCAL CONDITIONS SI U.S. CU STOMARY"
4470 PRINT #1, USING " Mach number ......................... #.#.#"; LOCAL.MACH
4480 ' Local static pressure in bars
4490 L.STATIC.PRESS1=TOTAL.PRESSURE1*(1+RATIO2*LOCAL.MACH^2)^(-RATIO1)
4500 ' Local static pressure in lb/ft^2
4510 L.STATIC.PRESS2=TOTAL.PRESSURE2*(1+RATIO2*LOCAL.MACH^2)^(-RATIO1)
4520 ' Local static pressure in atmospheres
4530 L.STATIC.PRESS4=TOTAL.PRESSURE4*(1+RATIO2*LOCAL.MACH^2)^(-RATIO1)
4540 PRINT #1, USING " Static pressure ................. #.#.# bars  =###
4550 CHECK1=LOG(L.STATIC.PRESS1,L.STATIC.PRESS2)
4560 IF L.STATIC.PRESS4>.1237 THEN 4590
4570 ABORT1=1
4580 GOTO 3660
4590 L.STATIC.TEMP1=8.950359E-03*CHECK1^4+.12189951*CHECK1^3+1.014738*CHECK1^2+8.465183*CHECK1+7.33925
4600 L.STATIC.TEMP2=9/5*L.STATIC.TEMP1-459.67
4610 TOTAL.TEMP1=L.STATIC.TEMP1*(1+RATIO2*LOCAL.MACH^2)
4620 PRINT #1, USING " Static temperature ................. #.#.# K  =###
4630 PRINT #1,""
OPTION 3 SUBROUTINE

FOR RUNNING AT FREE-STREAM SATURATION

Expressing static pressure in bars
STATIC.PRESS1=TOTAL.PRESSURE1*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)

Expressing static pressures in lb/in^2
STATIC.PRESS2=TOTAL.PRESSURE2*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)

CHECK1=LOG(STATIC.PRESS4)

IF STATIC.PRESS4>.1237 THEN 4780
ABORT1=1
GOTO 3500

STATIC.TEMP=8.950359E-03*CHECK1^4+.12189951*CHECK1^3+1.014738*CHECK1^2+8.465183*CHECK1+77.33925

RETURN

SUBROUTINE TO CALCULATE MASS FLOW FOR MACH NUMBERS > 1

T.STATIC.PRESS4=.5283*TOTAL.PRESSURE4
T.STATIC.PRESS1=.5283*TOTAL.PRESSURE1
T.STATIC.PRESS2=.5283*TOTAL.PRESSURE2
T.STATIC.TEMP1=.8333*TOTAL.TEMP1
T.STATIC.TEMP2=.8333*TOTAL.TEMP2

D2=1.37-.08773*T.STATIC.TEMP1+.0004703*T.STATIC.TEMP1^2-1.386E-06*T.STATIC.TEMP1^3+1.462E-09*T.STATIC.TEMP1^4
E2=5.521-.1986*T.STATIC.TEMP1+.0007817*T.STATIC.TEMP1^2-1.258E-06*T.STATIC.TEMP1^3+5.333E-10*T.STATIC.TEMP1^4
T.COMPRES.FACT=1-EXP(D2)*T.STATIC.PRESS4-EXP(E2)*T.STATIC.PRESS4^2

FAN.POWER1=T.MASS.FLOW1*RATI01*R*TOTAL.TEMP3*(FAN.PRESS.RATIO^(-1/RATI01)-1)*COMPRES.FACT

Fan power in watts
FAN.POWER1=T.MASS.FLOW1*RATI01*R*TOTAL.TEMP3*(FAN.PRESS.RATIO^(-1/RATI01)-1)*COMPRES.FACT

Converting watts to megawatts
FAN.POWER1A=FAN.POWER1/1000000

Converting watts to hp
FAN.POWER2=FAN.POWER1/746

TEMP.DIFF=TOTAL.TEMP1-STATIC.TEMP1
AREA.RATIO=1.728*MACH.NUMBER*(1+.2*MACH.NUMBER^2)^(-3)
PLENUM.REMOVAL=1/AREA.RATIO-1
PLENUM.POWER1=PLENUM.REMOVAL*(T.MASS.FLOW1*CP/M*TEMP.DIFF/PL.COMP.EFF)
A 5¼-inch floppy disk containing a copy of the program in this report is available upon request from

Experimental Techniques Branch
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(804) 865-4363

The program is written in IBM "Advanced Basic" language for the IBM Personal Computers PC/XT/AT.
References

15. Lawing, Pierce L.; Adcock, Jerry B.; and Ladson, Charles L.: A Fan Pressure Ratio Correlation in Terms of Mach Number and Reynolds Number for the Langley 0.3-Meter Transonic Cryogenic Tunnel. NASA TP-1752, 1980.
A computer program has been written that performs the flow parameter calculations for cryogenic wind tunnels which use nitrogen as a test gas. The flow parameters calculated include static pressure, static temperature, compressibility factor, ratio of specific heats, dynamic viscosity, total and static density, velocity, dynamic pressure, mass-flow rate, and Reynolds number. Simplifying assumptions have been made so that the calculations of Reynolds number as well as the other flow parameters can be made on relatively small desktop digital computers. The program, which also includes various power calculations, has been developed to the point where it has become a very useful tool for the users and possible future designers of fan-driven continuous-flow cryogenic wind tunnels.