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A SIMPLIFIED METHOD FOR CALCULATING TEMPERATURE
TIME HISTORIES IN CRYOGENIC WIND TUNNELS

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A SIMPLIFIED METHOD FOR CALCULATING TEMPERATURE
TIME HISTORIES IN CRYOGENIC WIND TUNNELS

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SUMMARY

A simplified method for calculating average temperature time histories of the test gas and tunnel walls for cryogenic wind tunnels has been developed. Results from the method are in general agreement with limited preliminary experimental measurements obtained in the Langley 13.5-Inch Pilot Cryogenic Wind Tunnel.

INTRODUCTION

The advantages of operating a wind tunnel at cryogenic temperatures in order to obtain high test Reynolds number has been well documented in recent years. (See, for example, refs. 1 and 2.) The major advantages of operating at an extremely low temperature are reduced dynamic pressure for a given Reynolds number and, for fan-driven tunnels, greatly reduced drive-power requirements as compared to conventional wind tunnels. The need for improved Reynolds number capability, the advantages of a cryogenic tunnel with regard to capital cost, and the current national need to reduce energy consumption (ref. 3) were factors which contributed to the United States Government's decision to construct a large transonic tunnel at the Langley Research Center capable of operating at cryogenic temperatures. This facility, to be known as the National Transonic Facility, will have a 2.5 by 2.5 meter test section and will have a Reynolds number capability based on typical model chord of approximately 120×10^6 when operating in the cryogenic mode at its maximum operating pressure of 8.8 atmospheres.

Some early preliminary studies conducted at the Langley Research Center related to the feasibility of operating at cryogenic temperatures were concerned with the time required for tunnel "cool down" for cryogenic operation, the amount of coolant required to maintain the cryogenic temperatures during a cryogenic run, and the time required for tunnel "warm up" after completion of a cryogenic run. In order to estimate these parameters for various insulation thicknesses, structural weights, and test gas properties, a simplified method for calculating average conditions for the entire tunnel system was developed. This method is described in this report and some results are compared with preliminary measurements obtained in the Langley 13.5-Inch Pilot Cryogenic Wind Tunnel.

SYMBOLS

A	surface area of tunnel interior wall, m^2
A_{TS}	test section cross-sectional area, m^2
b	width of air gap, m
c_p	specific heat of test gas, $\frac{J}{kg - K}$
h	average heat transfer coefficient for tunnel interior wall, $\frac{J}{m^2 - sec - K}$
h_F	average heat transfer coefficient for natural convection over tunnel exterior wall, $\frac{J}{m^2 - sec - K}$
k_{air}	thermal conductivity of air, $\frac{J}{m - sec - K}$
\dot{m}	coolant mass flow rate, $\frac{kg}{sec}$
M_{TS}	test section Mach number
P_t	stagnation pressure, $\frac{N}{m^2}$

P_{TS}	test section static pressure, $\frac{N}{m^2}$
q	heat flux, $\frac{J}{sec}$
t	time, sec
T_{AMB}	atmospheric temperature, K
T_S	saturation temperature of coolant, K
T_T	test gas temperature, K
T_w	tunnel interior wall surface temperature, K
$T_{w,Bw}$	temperature of external wall surface, K
$T_{w,1}, T_{w,2}$	wall temperatures across air gap, K
\bar{w}	mass of test gas, kg
λ	latent heat of vaporization of coolant, $\frac{J}{kg}$
η	power coefficient (≈ 0.2 for $0.1 \leq M_{TS} \leq 1.0$)

ANALYSIS

The simple heat balance used in this analysis is based on average conditions throughout the tunnel system. For example, heat convected from the system is based on an average heat transfer coefficient, conduction through the tunnel walls is based on an average wall thickness, and the test gas temperature is calculated as an average temperature. With this in mind the heat balance equation becomes

$$q_{\text{test gas}} = q_{N_2} - q_{\text{conv.}} - q_{\text{comp.}} \quad (1)$$

where $q_{\text{test gas}}$ is the heat stored in the test gas, q_{N_2} is the cooling available from the liquid nitrogen, $q_{\text{conv.}}$ is the heat exchanged with the

tunnel wall, and $q_{\text{comp.}}$ is the energy flux transferred to the test gas by the drive-fan. Expressing the heat flux parameters in terms of the average spacial temperatures and thermal properties (the expression for $q_{\text{comp.}}$ is from ref. 2), equation (1) becomes:

$$-\bar{w}c_p \frac{dT_T}{dt} = \dot{m} \left[\lambda + c_p(T_T - T_S) \right] - hA(T_w - T_T) - 14.05 P_{TS} M_{TS}^3 \sqrt{T_T} A_{TS} \quad (2)$$

where T_T is the average test gas temperature at time t . The variation of T_T with time was obtained by solving equation (2) using a finite difference scheme resulting in the following equation:

$$(T_T)_{n+1} = (T_T)_n + \frac{hA}{\bar{w}_n c_p} \left[(T_w)_n - (T_T)_n \right] \Delta t + 14.05 P_{TS} M_{TS}^3 \sqrt{(T_T)_n} A_{TS} \left(\frac{\Delta t}{\bar{w}_n c_p} \right) - \frac{\dot{m} \Delta t}{\bar{w}_n c_p} \left\{ \lambda + c_p \left[(T_T)_n - T_S \right] \right\} \quad (3)$$

Therefore, if conditions at some initial time t are known the tunnel test gas temperature after a time increment Δt can be calculated. After the tunnel test gas temperature is calculated at time $t + \Delta t$ the change in tunnel wall temperature for this time increment can be calculated. For the present method, the wall temperatures were calculated from the program of reference 4 modified to include equation (3).

The finite difference solution of reference 4 applies to the case of a thermally thick wall with various modes of heat transfer, including convection, occurring at the exterior surface; however, the interior surface or back wall is assumed to be insulated. When applied to the tunnel wall case, the exterior surface as defined in reference 4 is actually the tunnel wall interior surface whereas the back wall as defined in reference 4 would be the exterior surface.

of the tunnel wall which is exposed to atmospheric or room condition. In this discussion terminology applicable to the tunnel wall case is used. Since an exchange of heat from the exterior wall and its surrounding environment will definitely occur, it is necessary that it be accounted for in the calculation. The desired noninsulated exterior wall boundary conditions were artificially obtained by making the proper choice of variables and modes of heat transfer available as options in the program that would be representative of the actual transfer of heat.

Two noninsulated conditions were considered for the present method. First and simplest of the two is the case where the exterior wall temperature is held constant at ambient room temperature. This condition was simulated in the program by locating a fictitious block having a large thermal mass adjacent to the exterior wall surface. The conduction of heat to this fictitious block maintains the exterior wall surface temperature at an essentially constant value and therefore correctly simulates the flow of heat through the tunnel wall for this hypothetical constant temperature boundary condition.

The second noninsulated condition considered for the exterior wall is the case of free convection to a standard atmospheric environment. The flow of the heat for this condition is governed by the equation

$$q = h_F A(T_{w,Bw} - T_{AMB}) \quad (4)$$

where h_F is the coefficient of heat transfer for free convection conditions, $T_{w,Bw}$ is the temperature of the exterior wall, and T_{AMB} is the ambient atmospheric temperature. Equation (4) is very similar in form to the following equation (eq. (7), ref. 4):

$$q_{air \text{ cond.}} = \frac{k_{air} A(T_{w,1} - T_{w,2})}{b} \quad (5)$$

for heat conduction across an air gap. The symbol k_{air} is the conductivity of air, $T_{w,1}$ and $T_{w,2}$ are the wall temperatures of the blocks on each side of the gap, and b is the width of the gap or the distance between the two blocks 1 and 2. If k_{air}/b is set equal to h_F , $T_{w,1}$ set equal to $T_{w,Bw}$, and $T_{w,2}$ set equal to T_{AMB} , then equations (4) and (5) are equal. If b is assumed to have unity value, then the value of k_{air} will equal the value of h_F . Therefore, free convection at the exterior wall can be artificially simulated in the program by assuming an air gap separates the exterior wall from a fictitious block having a very large density and specific heat. The initial temperature of the fictitious block is set equal to the ambient temperature and its mass and specific heat are fixed at sufficiently large values such that it remains at ambient temperature for the maximum time span of interest. The tunnel wall temperatures computed from the program would then represent the proper values for the case where the exterior wall is exchanging heat by free convection to an atmospheric environment.

RESULTS

In order to determine if the present method gave realistic estimates of temperature-time histories for the operation of a cryogenic tunnel, comparisons were made between calculations and experimental measurements of the test gas temperature obtained in the Langley 13.5-Inch Pilot Cryogenic Wind Tunnel (ref. 5). Tunnel specifications that were used as inputs to the program are shown in Table 1. Calculations were made for the pre-run cool-down period and the post-run warm-up period. During these periods, the exterior wall temperature was assumed to remain constant at 294 K and was incorporated into

the program using the first noninsulated method previously discussed.

Typical calculated cool-down temperature time histories are shown in figure 1 for $M_{TS} = 0.4$ and $P_t = 1$ atmosphere. Temperatures are shown for the test gas, the interior wall, and the exterior wall ($\equiv 294$ K). The calculations indicate that the test gas temperature and interior wall temperature decrease approximately linearly with time and reach the desired 78 K operating temperature in approximately 30 minutes. Also shown in figure 1 is a measured data point for the facility from reference 5 for similar test conditions. This measurement indicates the time required to cool the facility from approximately 294 K to 106 K is approximately 30 minutes as compared to approximately 24 minutes predicted by the present method.

Calculated temperature distributions through an average tunnel wall section are shown in figure 2 for several values of t during the cool-down period. Due to the large thermal-conductivity of aluminum, the temperature is essentially constant from the interior wall to the aluminum-urethane interface. Large temperature gradients occur through the urethane with the largest gradients occurring at the aluminum-urethane interface.

Shown in figure 3 is the effect of test section Mach number on calculated cool-down temperature-time histories for the test gas at a constant tunnel total pressure equal to 1 atmosphere. At the higher test-section Mach numbers, the results indicate a rapid increase in time required for cool-down with increasing Mach number. Although cool-down time measurements have not been obtained in the pilot tunnel over a wide range of Mach number, the trend of increasing cool-down time with increasing Mach number has been observed in the facility. This increase in time is a direct result of the increasing energy flux transferred by the fan to the stream with increasing Mach number.

As shown in equation (3), this energy varies as M_{TS}^3 .

Shown in figure 4 are calculated temperature-time histories for the test gas in the Pilot Cryogenic Tunnel during warm-up periods for stagnation pressures of 1 and 2 atmospheres and a test section Mach number of 0.6. During the warm-up period which occurs after completion of a cryogenic run, the flow of liquid nitrogen is terminated and the flow of heat through the tunnel walls and from the drive-fan increases the test gas temperature as indicated in figure 4. The calculated warm-up time for the case of 2 atmospheres tunnel pressure can be compared with measurements from reference 5 that are shown in figure 4 for similar conditions. The measured warm-up time from 106 K to 300 K is approximately 53 minutes as compared to approximately 60 minutes calculated from the present method. The calculations indicate that the warm-up time varies inversely proportional to the tunnel stagnation pressure.

The general agreement shown between calculations and measurements in figures 1 and 4 indicates that the present method does give realistic trends for the variation of average temperatures in a cryogenic wind tunnel. It should be recognized, however, that the results are for average conditions and can vary significantly from local conditions throughout the tunnel.

CONCLUDING REMARKS

A simplified method for calculating average temperature-time histories of the test gas and tunnel walls for cryogenic wind tunnels has been developed. Results from the method are in general agreement with limited preliminary experimental measurements obtained in the Langley 13.5-Inch Pilot Cryogenic Wind Tunnel.

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December 6, 1976

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Table 1. - PROGRAM INPUTS FOR 13.5-INCH PILOT CRYOGENIC WIND TUNNEL

1) Structural Material, Aluminum

(a) Mass = 3175kg

(b) Surface Area = 55.74 m²

(c) Average Thickness = $\frac{\text{Mass}}{\text{Surface Area} \times \text{Density}} = 2.11 \text{ cm}$

2) Insulation (External), Urethane

Average Thickness = 12.7 cm

3) Volume = 17 m³

4) Coolant, Liquid N₂

(a) T_T ≥ 78 Y: Flow rate = 1.02 $\frac{\text{kg}}{\text{sec}}$

(b) T_T = 78 K: Flow rate regulated to maintain this temperature.

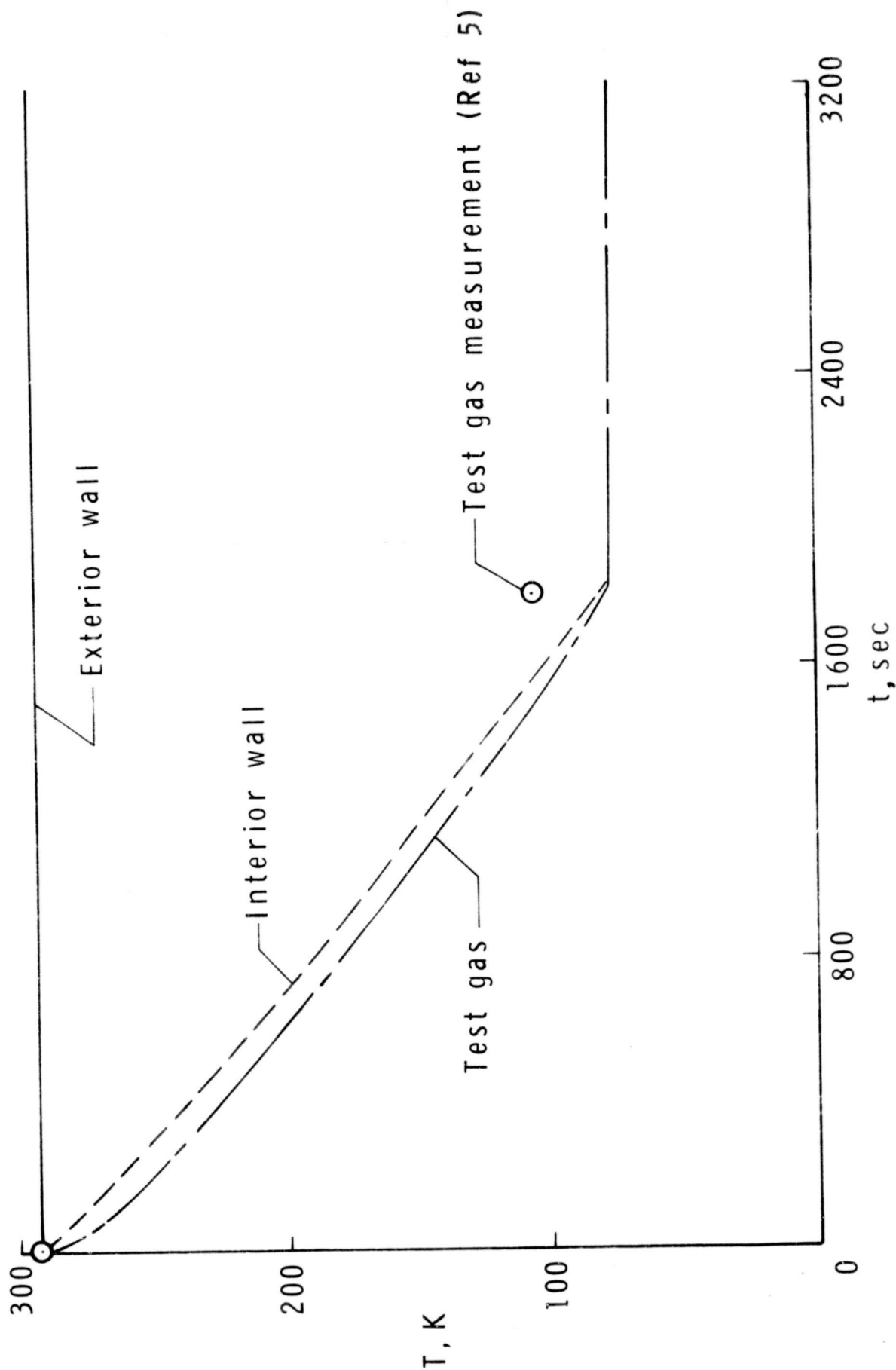


Figure 1.- Typical temperature-time histories during cool-down of Langley 13.5-Inch Pilot Cryogenic Wind Tunnel calculated from present method, $MTS=0.4$, $P_t=1.0$ atm.

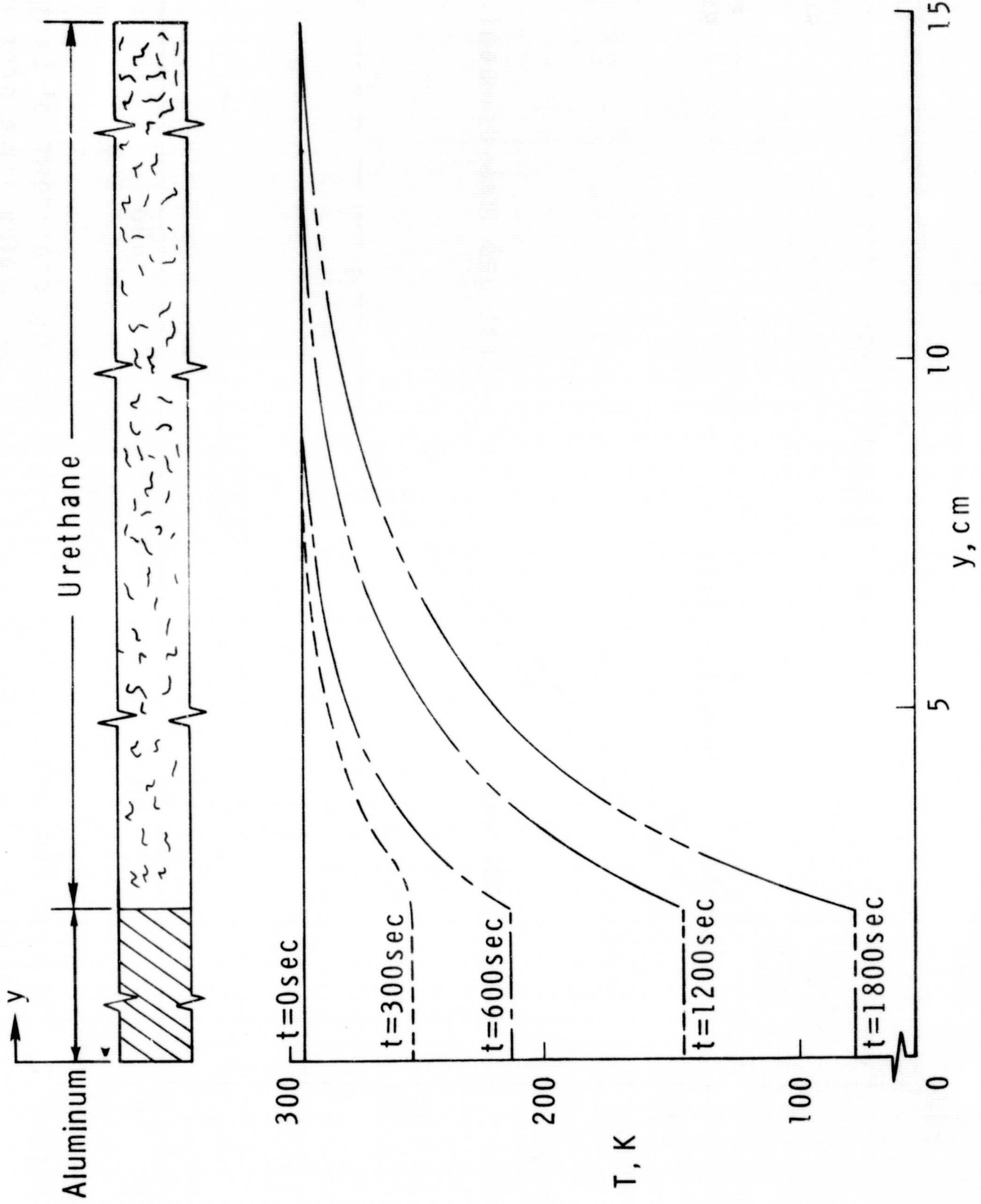


Figure 2.- Calculated temperature distributions through average wall section of 13.5-Inch Pilot Tunnel. $M_{TS} = 0.4$, $P_t = 1.0 \text{ atm}$.

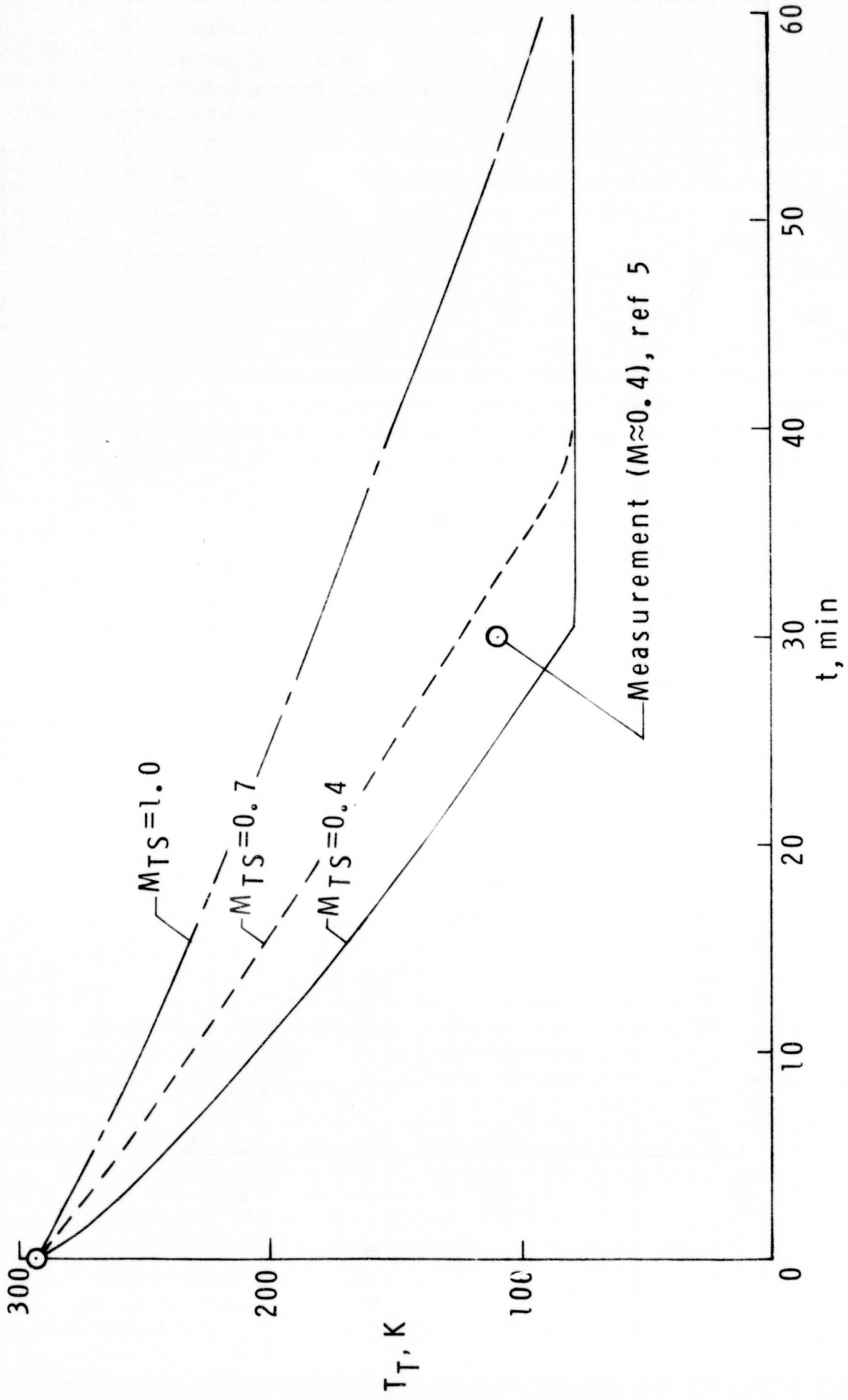


Figure 3.- Effect of test section Mach number on calculated temperature-time histories for test gas in 13.5-Inch Pilot Tunnel, $P_t=1.0$ atm.

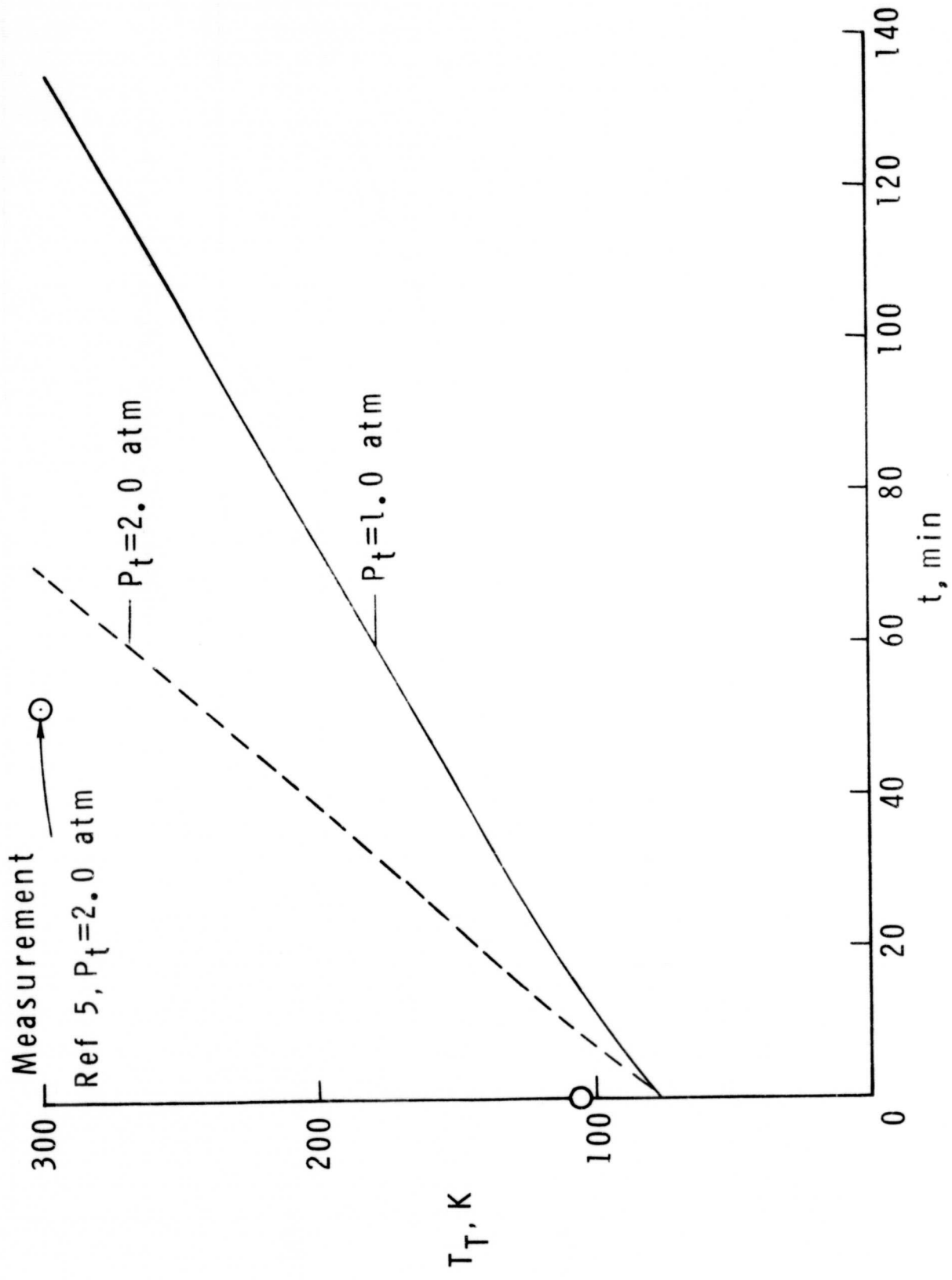


Figure 4.- Effect of tunnel pressure on calculated temperature-time histories during warm-up of 13.5-Inch Pilot Tunnel $M_{TS}=0.6$, $\dot{m}=0$.