CALIBRATION OF THE SHOCK TUNNEL COMPONENT OF COUNTERFLOW RANGE (I) AT MACH 7.5

J. H. Haun and Henry W. Ball
ARO, Inc.

May 1966

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This technical report has been reviewed and is approved.

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ABSTRACT

Calibration of the shock tunnel component of the Counterflow Range (I) operating with a new nozzle throat designed to yield Mach 7.5 is reported. Transverse pitot-pressure profiles and heat-transfer rates on a hemisphere-cylinder model in the test section were measured at four flow conditions. A single probe was traversed along the nozzle centerline to determine the streamwise pitot-pressure gradient. Shock detachment distances for a hemisphere-cylinder were measured to determine when helium from the shock tunnel driver entered the test section. Results from these tests indicate a repeatable test core of uniform flow having a 12.5-in. diameter. Test times of from 2.5 to 4 msec were recorded before large quantities of helium appeared to be entering the test section. The streamwise pressure measurements indicated a Mach number gradient of 0.2/ft.
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II. Summary of Test Section Measurements
III. Summary of Computed Free-Stream Conditions

NOMENCLATURE

\( d \) Diameter of driven tube, in.
\( d^* \) Throat diameter, in.
\( h \) Enthalpy, \( \text{ft}^2/\text{sec}^2 \)
\( L \) Length of driven tube, ft
\( M \) Mach number
\( p \) Pressure, atm
\( p_0 \) Test section pitot pressure, atm
\( q_0 \) Stagnation heat-transfer rate, Btu/ft\(^2\)-sec
\( q_{SH} \) Shoulder heat-transfer rate, Btu/ft\(^2\)-sec
\( R \) Model nose radius, in.
\( Re \) Reynolds number, in.\(^{-1}\)
\( T \) Temperature, °K
\( t \) Time, msec
\( u \) Velocity, ft/sec
\( z \) Distance along the centerline of the tunnel, in.
\( \rho \) Density, amagats
\( \delta \) Shock detachment distance, in.
SUBSCRIPTS

1  Initial driven tube charge conditions
4  Initial driver charge conditions
M  Measured
0  Tunnel reservoir conditions
s  Initial shock
T  Theoretical
∞  Free-stream conditions
SECTION I
INTRODUCTION

A calibration test was conducted in the Counterflow Range (I) of the von Kármán Gas Dynamics Facility (VKF) to study the flow conditions in the test section using a large nozzle throat and the highest allowable shock tube charge conditions. This test condition will provide flow at a sufficiently high density to maintain equilibrium conditions in the flow fields of models used during counterflow tests.

The quality of the test section flow was determined from measurements of (1) the transverse pitot-pressure profile, (2) the streamwise pitot-pressure gradient, (3) the stagnation and shoulder heat-transfer rates on a hemisphere-cylinder model, and (4) the time-resolved shock detachment distance on a hemisphere-cylinder model. The shock detachment distance measurements were intended to provide an indication of the arrival of the helium driver gas in the free stream.

The shock tube was operated at tailored interface conditions for room temperature He and air. The maximum driver pressure of 1000 atm produced tunnel reservoir conditions of 1800°K and 700 atm. The reservoir pressure was varied to a minimum of 100 atm during these tests.

SECTION II
APPARATUS

The shock tunnel component of Range I was the same as described in Ref. 1, with the exception that the throat diameter was increased to 1.16 in. in order to produce a high free-stream density test gas. The flow survey rake is shown in Fig. 1. It was mounted in a vertical orientation, and additional probes were positioned 1.75 in. from the top and bottom of the test section, as shown in Fig. 2. Two 1-in.-diam hemisphere-cylinder heat-transfer probes were mounted from the sides of the vertical rake and positioned with axes at 2 and 4 in. from the tunnel centerline.

The rake was instrumented with 50- and 100-psi fast-response, variable reluctance pressure transducers (Refs. 2 and 3). Thermocouple-type heat-transfer gages (Ref. 4) were used at the stagnation points of the heat-transfer probes, and thin-film-type gages were used at the shoulder positions. Reservoir pressures were measured with piezoelectric transducers at stations located 4 and 8 in. upstream of the nozzle throat. These pressures agreed within ±5 percent during each run.
A 2- or a 3-in. -diam hemisphere-cylinder model was used during the phase of the tests in which shock detachment distances were measured. A 16-mm high speed framing camera was used in the arrangement shown in Fig. 3 to take shadowgrams of the model and shock wave.

SECTION III
DISCUSSION OF RESULTS

A complete listing, by run number, of the test conditions covered in this calibration is presented in Tables I, II, and III. Typical reservoir pressure, $p_0$, and pitot pressure, $p'_0$, traces are shown in Figs. 4a and b. As illustrated in these figures, the period of constant $p_0$ and $p'_0$ decreased with increasing $p_0$. The constant-pressure period varied from 4 msec at $p_0 = 100$ atm to 2.5 msec at $p_0 = 700$ atm.

The pitot profiles which were obtained using the 1.16-in. -diam nozzle throat are presented in Fig. 5. The profiles are flat, within ±10 percent over a 12.5-in. -diam core of flow. The level of the pitot profile was repeatable from run to run within ±10 percent at all test conditions, corresponding to an average Mach number across the core of 7.5.

The pitot profiles which were obtained with the 0.5-in. -diam throat are compared in Fig. 6a to unpublished profiles obtained two years ago during the initial tunnel calibration program. These two sets of data are in good agreement.

The measured streamwise pitot-pressure gradient is shown in Fig. 6b. The gradient in $p_0/p'_0$ of 12 percent per foot, corresponds to a Mach number gradient of 0.2 or 2.5 percent per foot.

In Fig. 7, the measured stagnation heat-transfer rates and theoretical rates based on the Fay and Riddell theory are compared. Seventy-five percent of the data are within ±10 percent of the theoretical values. The agreement implies that the actual total flow enthalpy agrees with the total flow enthalpy calculated from shock tube theory.

The measured heat-transfer rates at the shoulder of the probe are plotted against measured stagnation heating rates in Fig. 8. One point is off considerably, but the bulk of the data lie within ±10 percent of a shoulder-to-stagnation heat ratio of 0.065. Based on the experimentally determined pressure distribution of Ref. 5 (for $M_0 = 8.1$) and the theory of Lees (Ref. 6), this ratio of heating rates should be 0.065 for the present case.
Figure 9 shows theoretical run times for the Range I shock tunnel, based on the criterion that the run is terminated by the arrival of the He/air interface at the nozzle throat. The curve marked inviscid flow was obtained considering alteration of the shock tube wave diagram (tailored interface conditions) with time as inviscid fluid passes the throat. The set of curves marked viscous flow was obtained considering additional interface acceleration as predicted by Mirels' theory (Ref. 7). For the large throat, \( d^* = 1.16 \) in., run times of 5.4, 5.7, 6.1, and 6.4 msec were obtained for reservoir pressures of 100, 225, 450, and 700 atm, respectively.

In order to examine experimentally the arrival of helium at the test section, tests were conducted during which the time-resolved shock detachment distance on a spherical-nosed model was photographically recorded. The calculations of Van Dyke and Gordon (Ref. 8) indicate that the detachment distance would increase measurably as the flow changed from pure air to pure helium. Although the Mach number and related quantities are not known when a significant amount of helium enters the test section, it is possible to estimate the limiting shock detachment distance on the basis that, for pure helium behaving as a perfect gas, nozzle expansion area ratio would dictate a maximum Mach number of 15.2, with a corresponding density ratio across a normal shock of 0.253. This Mach number would be reduced by boundary-layer growth on the nozzle walls, but density ratio, and therefore shock detachment distance, would be affected only negligibly. Hence, from Ref. 8, it is found that the detachment distance for pure helium would be 0.20 R.

The shadowgrams in Fig. 10 are typical of those obtained during these tests. During the run chosen for illustration, the detachment distance was nearly constant at 2, 3, and 4 msec but had increased 20 percent at 6 msec. At 10 msec, the model had begun to vibrate and had moved upward in the field of view. Zero time was defined as the instant when the first shock wave appeared at the nose of the model.

The detachment distance data are presented in Fig. 11 in terms of the detachment distance-to-model nose radius ratio as a function of run time. The data show that the detachment distance was erratic during the first 1.5 msec; this period also corresponds to the pitot-pressure rise time (see Fig. 4). For run times between 1.5 and 6 msec, a ±5-percent band is shown for the data to represent its estimated precision. An arbitrary ±5-percent band has also been associated with the theoretical shock detachment distance (Ref. 8) for air. Comparing the ±5-percent bands at the 450-atm condition, for example, it can be noted that during the period 1.5 to 3.5 msec the measured and theoretical shock detachment distances agree, whereas at 5 msec the measured distance is definitely greater than the theoretical value.
By noting similarly restricted run times for the data at all four reservoir pressures, the band marked arrival of helium limit (AEDC-I) in Fig. 12 was obtained. In this figure, the run times from Fig. 11 have been adjusted to a zero time which corresponds to the instant of reflection of the incident shock wave. The adjustment allows the experimental test section run times to be compared with the theoretical shock tube limits shown in Fig. 12. The run times of Fig. 11 were adjusted by adding the nozzle transient time of the starting shock wave (1.0 msec as illustrated by the displacement of the initial rise of the reservoir and pitot-pressure traces in Fig. 4) and subtracting the nozzle transient time of a gas particle during the run (1.4 msec from Ref. 9). The time of initial stabilization and the time of decay of the test section pitot pressure were adjusted in the same manner and are presented in Fig. 12.

The data of Fig. 12 show that at reservoir pressures below 300 atm the Range I run time is definitely limited by the influx of helium rather than by pitot-pressure decay; there is doubt that a helium-free test period exists at these conditions. At a reservoir pressure of 700 atm, however, there is a period of 2 msec during which the pitot pressure will be stable and the shock detachment distance will not differ from the theoretical distance by more than ±5 percent. The arrival of helium limit, obtained indirectly by measuring detachment distances, is shown in Fig. 12 to be in reasonable agreement with the results of experiments at DAL (Ref. 9) and CAL (Ref. 10), obtained directly from time-resolved gas samples. Notice that the present arrival of helium limit band lies 25 to 40 percent below the theoretical viscous flow limit.

SECTION IV
CONCLUSIONS

Tests were conducted in Range I to determine the quality of the shock tunnel flow using a 1.16-in. diam nozzle throat. The charge pressure of the helium driver gas was varied from 1000 atm, the maximum allowable, to 170 atm, resulting in a variation in nominal tunnel reservoir conditions from 1800°K and 700 atm to 1800°K and 100 atm. From these tests the following conclusions can be drawn:

1. The pitot-pressure distribution was uniform within ±10 percent over a 12.5-in. diam core of flow.
2. The level of the pitot-pressure profile was repeatable from run to run within ±10 percent. The average Mach number was 7.5, repeatable within ±3 percent.
3. Measurements of stagnation heat-transfer rate on a hemisphere-cylinder probe agreed with theoretical values computed from shock tube conditions within ±10 percent. The agreement implies that the actual total flow enthalpy agrees with the computed total flow enthalpy.

4. The Mach number gradient along the portion of the streamwise axis of the tunnel in the vicinity of the test section was approximately 0.2 per foot.

5. The period of steady pitot pressure varied with tunnel stagnation conditions from 4 msec at the 100-atm condition to 2.5 msec at the 700-atm condition.

6. Measurements of the shock detachment distance on a hemisphere-cylinder model at the high pressure condition, $p_0 = 700$ atm, agreed with theory within ±5 percent during the period 1.5 to 4 msec after arrival of flow in the test section. During the 4- to 6-msec period, large quantities of helium driver gas entered the test section flow. During tests at the lower pressure conditions, helium appeared to be entering the test section as early as 2.5 msec after the start of flow. The experimentally determined arrival of helium occurred 25 to 45 percent earlier than predicted for viscous flow.

REFERENCES


Fig. 1 Photograph of Pitot-Pressure Rake
Fig. 2 Photograph of Rake Installation
16-mm High Speed Camera
5500 Frames/sec
4-in. Extension

Camera Lens (6-in. Focal Length, f/4.5)

Hemisphere-Cylinder Model
0.020-in. Aperture

Tunnel Test Section

Mercury Vapor Lamp
2.5-in.-diam f/6 Uncorrected Lens

All Dimensions in Inches
≈16  ≈44  64.5  19.5

Note: Camera Focused on Centerline of Tunnel

Fig. 3 Schematic of Shock Detachment Distance Measurement Apparatus
Period of Constant $p_0$

- $p_0 = 8 \text{ in. from Throat}$
- $p_0 = 4 \text{ in. from Throat}$

Period of Constant $p_0^*$

- $p_0^* = 3.75 \text{ in. from Tunnel C}$
- $p_0^* = 2.5 \text{ in. from Tunnel C}$

Time from Diaphragm Break, msec

Fig. 4 Typical Reservoir and Pitot-Pressure Traces
Period of Constant $p_0$

Reservoir Pressure, $p_0 \approx 150$ atm/division

$\begin{align*}
\text{Time from Diaphragm Break, msec} \\
p_0 - 8 \text{ in. from Throat} \\
p_0 - 4 \text{ in. from Throat}
\end{align*}$

Period of Constant $p_0^-$

Pilot Pressure, $p_0^- \approx 1.5$ atm/division

$\begin{align*}
\text{Time from Diaphragm Break, msec} \\
p_0^- - 1.25 \text{ in. from Tunnel } C \\
p_0^- - 2.50 \text{ in. from Tunnel } C
\end{align*}$

b. $p_o = 700$ atm

Fig. 4 Concluded
<table>
<thead>
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<th>Sym</th>
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<td>499</td>
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\[ d^* = 1.16 \text{ in.} \]

\[ p_0' / p_0 \times 10^3 \]

\[ \begin{array}{c|c|c}
\hline
\text{Sym} & \text{Run No.} \\
\hline
\circ & 490 \\
\circ & 491 \\
\triangledown & 492 \\
\triangledown & 497 \\
\hline
\end{array} \]

\[ d^* = 1.16 \text{ in.} \]

\[ p_0' / p_0 \times 10^3 \]

\[ \begin{array}{c|c|c}
\hline
\text{Sym} & \text{Run No.} \\
\hline
\circ & 488 \\
\triangledown & 489 \\
\circ & 496 \\
\hline
\end{array} \]

\[ d^* = 1.16 \text{ in.} \]

\[ M_\infty = 7.3 \text{ Typ} \\
M_\infty = 7.7 \text{ Typ} \]

\[ \text{Bottom} \\ \text{Distance from } \zeta \text{ of Test Section, in.} \\
\text{Top} \]

\[ d. \ p_0 = 100 \text{ atm} \]

**Fig. 5** Summary of the Pitot-Pressure Profile Data
### Table: Sym and Run Numbers

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</table>

**Symbols**
- ●: Sym
- ■: Run No.

**Equations**
- $d^* = 0.50$ in.
- $p_0 \approx 550$ atm
- $\rho_0/\rho_0 \times 10^3$

**Graph**
- Data from Initial Calibration lie in Cross-Hatched Area
- $M_{\infty} = 10.8$
- $M_{\infty} = 11.3$

**Text**

a. Comparison of Mach 11 Pitot Profiles with Previous Calibration Results

b. Streamwise Pitot-Pressure Gradient

**Fig. 6** Additional Pitot-Pressure Measurements
Flagged Symbols Indicate Model
4 in. off C of Tunnel; Others Are
2 in. off C
Shaded Symbols Indicate Runs
with 0.5-in.-diam Throat

Fig. 7 Comparison of Measured and Theoretical Stagnation Heat-Transfer Rates
Flagged Symbols Indicate Model 4 in. off \( C_e \) of Tunnel; Others Are 2 in. off \( C_e \)

Shaded Symbols Indicate Runs with 0.5-in. -diam Throat

Fig. 8 Comparison of Measured Heat-Transfer Rates at the Shoulder and the Stagnation Point
Inviscid Flow in the Driven Tube

Viscous Flow

\[ p_0 = 700 \text{ atm} \]

Mirels (Ref. 7)

\[ M_s \approx 3.8 \]

---

**Fig. 9** Theoretical Run Time Limits Based upon Arrival of the Helium Driver Gas
Zero time is defined as the instant when the first shock wave appears at the nose of the model.

Fig. 10 Typical Shadowgrams of the Model and Bow Shock
Fig. 11 Summary of the Shock Detachment Distance Measurements
### Table

<table>
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<tr>
<th>SYM</th>
<th>FACILITY</th>
<th>DRIVEN TUBE LENGTH, L, FT</th>
<th>THROAT DIAM, d*, IN.</th>
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**NOTE:** $M_s \approx 3.8$, TAILORED He/AIR

---

**Fig. 12** Comparison of Experimental and Theoretical Shock Tunnel Run Times
# TABLE I

**SUMMARY OF SHOCK TUBE MEASUREMENTS AND COMPUTED STAGNATION CONDITIONS**

<table>
<thead>
<tr>
<th>Run No.</th>
<th>$P_4$, atm</th>
<th>$P_1$, atm</th>
<th>$P_4/P_1$</th>
<th>$M_S$</th>
<th>$P_0$, atm</th>
<th>$\rho_0$, amg</th>
<th>$T_0$, K</th>
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Calibration of the shock tunnel component of the Counterflow Range (I) operating with a new nozzle throat designed to yield Mach 7.5 is reported. Transverse pitot-pressure profiles and heat-transfer rates on a hemisphere-cylinder model in the test section were measured at four flow conditions. A single probe was traversed along the nozzle centerline to determine the streamwise pitot-pressure gradient. Shock detachment distances for a hemisphere-cylinder were measured to determine when helium from the shock tunnel driver entered the test section. Results from these tests indicate a repeatable test core of uniform flow having a 12.5-in. diameter. Test times of from 2.5 to 4 msec were recorded before large quantities of helium appeared to be entering the test section. The streamwise pressure measurements indicated a Mach number gradient of 0.2/ft.
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