Starting Phenomena in a Supersonic Tube Wind Tunnel

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An experimental study has been performed of the unsteady processes in the starting period of a supersonic Ludwieg tube, a device which operates like an intermittent supersonic wind tunnel. A quick opening diaphragm located downstream of the nozzle initiates the flow. Pressure and density measurements are made in a variety of ways in Mach number 1.67 and 3.0 nozzles. For the starting conditions treated, supersonic flow is established in the nozzle without producing shock waves. Various time dependent functions are observed in the adjustment of gasdynamic parameters to their steady supersonic values. These changes of pressure etc., include undershoots, overshoots, and other variations of the final steady-state values. Calculations based on an assumed zero-length nozzle do not adequately predict starting times and pressures.

Nomenclature

M = Mach number
P = pressure (atm)
t = time (msec)
X = distance coordinate
ρ = density (g/cm^3)

Subscripts

1 = initial condition in high-pressure tube
4 = initial condition in low-pressure tube
st = steady state

I. Introduction

FOR vehicles that fly at $M > 3$, current testing facilities can simulate Reynolds numbers, Mach numbers, and flight environments with adequate success; so that flight performance can be predicted from model and full scale experiments.[1] However, in the Mach number range $0.8 < M < 3$, this is less true. The high Reynolds numbers experienced by aircraft and space vehicles cannot be satisfactorily reproduced in the laboratory. For example, at $M \sim 3.5$ the Saturn V flies at $Re \sim 2 \times 10^6$, whereas at $M \sim 1.5$ the Reynolds number is as high as 10^7 (based on vehicle length). Throughout this Mach number range, testing facilities currently available produce Reynolds numbers of only roughly 2×10^6. Since Reynolds number simulation under these circumstances is a crucial aspect of vehicle design, considerable interest has developed in attempts to produce testing facilities with high stagnation pressure, long test time at transonic and moderately supersonic speeds.

Several years ago, H. Ludwieg suggested, in a different context, a device that now appears to be remarkably well suited for this kind of application.[2] The device consisted of a long cylindrical tube as a container for the compressed air. One end of the tube is closed; the other end contained a supersonic nozzle, a test section, and a quick opening valve that is opened to the atmosphere. In the Yale University Ludwieg tube[3] a conventional shock tube configuration is modified by the insertion of a supersonic nozzle into the section upstream of the diaphragm (the high-pressure section). After the diaphragm breaks, a shock wave and a contact surface travel downstream and the head of the expansion wave moves upstream through the supersonic nozzle. After the remaining part of the expansion wave is swept back downstream, stable conditions of supersonic flow are maintained in the nozzle until the reflected expansion wave returns to the throat. The operating stages for this intermittent tube wind tunnel (also known as the Ludwieg tube) are indicated in Fig. 1. In the literature, one can find derivations of the formulas relating the nozzle parameters to the initial conditions in the tube. In these analyses, it is generally assumed that the nozzle has zero length, that the flow is one dimensional and inviscid and that one is dealing with a perfect gas as shown by Cable and Cox[4] and Becker.[5] With this device, high stagnation pressures can be maintained in the high-pressure side, and steady supersonic flow of relatively short but useful duration can be established in the test section. Furthermore, a practical advantage with respect to high-pressure blow-down tunnels arises from the fact that no valves are required to maintain steady nozzle supply conditions. For these reasons, interest now exists in the Ludwieg tube and in the nature of its possible application.

With regard to the starting stage, i.e., the elapsed time between the rupture of the diaphragm or the opening of a valve and the establishment of steady supersonic flow in the nozzle, some uncertainties have persisted. First, there is the question of whether or not starting shock waves are produced after sonic conditions are obtained at the throat of the nozzle. Such shocks may originate at the throat and travel downstream through the nozzle prior to the steady-flow stage and may have adverse effects on the model. In addition, there is the question of how, in fact, the steady-state parameters in the nozzle are acquired. Various pressure measurements for Ludwieg tubes are reported in Refs. 7 and 3. However, these experiments were designed to determine steady-state values and gave little information on the starting processes.

In this paper we shall present further initial results from our observations of starting processes in a supersonic Ludwieg tube.‡ Our approach has been phenomenological; we are concerned at this point only with experimentally determining what seems to us to be the gross qualitative features of this starting phase. We are interested in observing the sensitivity of the starting processes to changes in nozzle pressure, tube pressure ratio across the unruptured diaphragm, and nozzle Mach number.

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‡ Preliminary results have been given in Ref. 6.

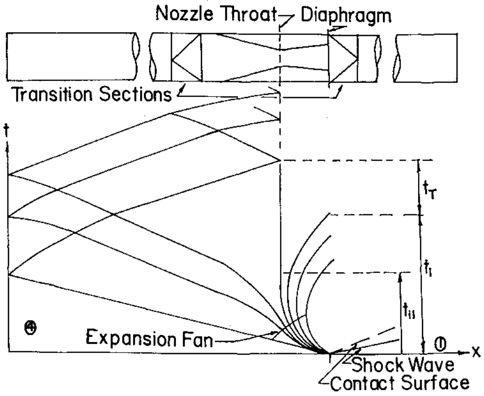

Fig. 1 Ludwieg tube: simplified $t - x$ plot; the times schematically indicated are t_i, the total starting time; t_{il}, the time required to establish sonic conditions at the nozzle's throat; t_T, the total time of stable supersonic flow.

II. Experimental Apparatus

The Yale University Ludwieg tube[3] is sketched in Fig. 2. The over-all length is 26 ft, and a diaphragm can be placed on either side of the test section.§ The two-dimensional wedge-nozzle used in most of these studies has an exit Mach number of 1.67 and a throat to exit distance of 6 in. with an expansion half-angle of 3°. It can be placed at various positions in the 1.5-ft test section so as to vary the field of view. Two sections immediately upstream and downstream of the test section, respectively, produce a smooth transition from the circular supply and dump tubes to the rectangular test section. In all experiments, the operating gas is dry nitrogen or dry air.

Three diagnostic techniques have been used in our investigations:

1) Timed shadowgraphs are made during the starting stage. High speed movie shadowgraphs with a 0.25-msec frame-to-frame sampling rate are taken, using a Fastax camera. Spark shadowgraphs are taken at 0.1-msec intervals using a 1-μsec 10,000 volt spark source.

2) Slit streak-interferometry is used to obtain density measurements as a function of time on the nozzle center-line. A horizontal slit is placed between the light source and the collimating lens so that its image appears at the test section with a width of 2 mm. This, together with the equivalent film speed of 300 m/sec, gives a time resolution of roughly 7 μsec. The Zeiss Mach Zehnder interferometer¶ (plate size; $4\frac{1}{8} \times 7$ in.) is adjusted so that the image of vertical interference fringes appears at the center of the test section. With the rotating prism in the Fastax movie camera removed and with the film moving in a vertical plane, continuous interferograms are obtained which allow one to follow the movement of each fringe; thus permitting a determination of the change in density with time at any position along the center-line of the nozzle. Shock waves would be noticeable as discontinuous jumps in the otherwise smooth increase and decreases in density that can be seen according to the direction of motion of the fringes. The system is found to be sensitive to density changes of less than 1.0%.

3) Static pressure measurements have been made in the supply tube and at various locations in the nozzle using a calibrated high-speed 3 μsec rise-time quartz pressure-transducer (Kistler, Model #606L).

III. Experimental Results

Spark shadowgraph pictures are taken during steady flow with a model inserted in the test section producing bow shock waves to confirm that supersonic flow is established. Movie shadowgraphs are taken with fiducial marks on the test section window and with adhesive strips along the diverging section of the nozzle and perpendicular to the flow. The relative position of the disturbances from the adhesive strips, with the marks on the window, indicates when supersonic flow begins and reaches steady state. Movie shadowgraphs, movie inteferograms, and spark shadowgraphs of the flow in the nozzle permit a search to be made for starting shocks in the starting stage. This is illustrated in Fig. 3 where $P_4 =$ 3.0 atm and $P_4/P_1 = 23$ for the $M = 1.67$ nozzle. Here one sees supersonic flow being established in the nozzle with no waves other than the disturbances from the adhesive strips on the nozzle block. In Fig. 4, one sees an example of the movie interferogram. The experiments during the time in which movie interferograms were made gave density histories at fixed nozzle positions and density profiles at specific times in the starting stage. The supersonic flow appears to develop smoothly at all points in the nozzle in the aforementioned examples. Similar results are obtained for all cases

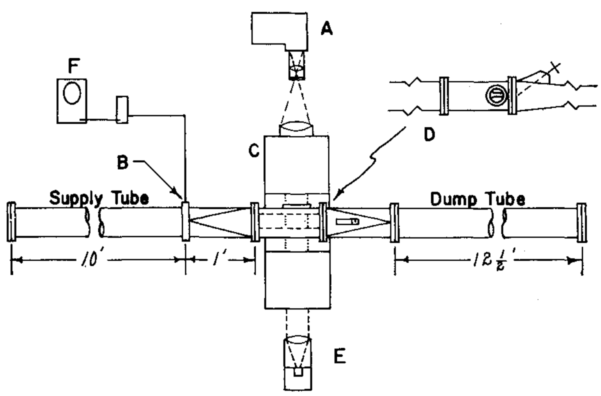

Fig. 2 Experimental apparatus: A) high-speed camera; B) pressure transducer (at upstream position); C) Mach-Zehnder interferometer; D) side view of test section [supply tube—5.30-in. i.d. dump tube, 3.76-in. i.d. nozzle; 2 in. $\times$ 2 in. at throat ($M = 1.67$ at exit)]; E) collimating lens and light source; and F) oscilloscope to record pressure traces.

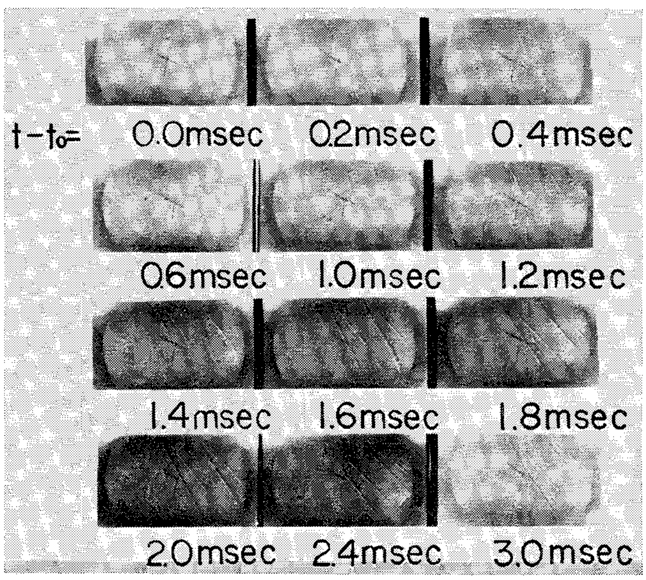

Fig. 3 Sequential shadowgraphs of the $M = 1.67$ nozzle in the starting stage; shock waves are produced by an adhesive strip taped to the top of the nozzle, downstream of the throat, and flow is from left to right.

§ The downstream diaphragm position has been used in all experiments.

¶ We are grateful to the U.S. Naval Ordnance Laboratory for loaning us this instrument.

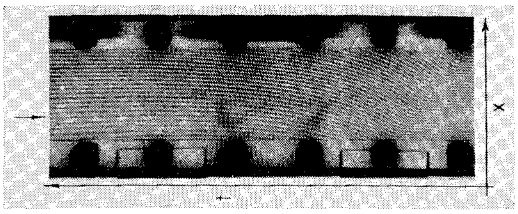

Fig. 4 Sample interferometer strip: the $M = 3.0$ nozzle's throat is indicated by the arrow, decreasing densities are indicated by the arrow, decreasing densities are indicated by the motion of fringes from left to right, and flow is from left to right.

studied by us. In addition, a set of spark shadowgraphs has been taken during the starting stage for $P_4 = 1.0$ and $P_4/P_1 = 7.7$ with a sampling rate of better than one every 0.1 msec.

In none of these experiments have starting shock waves been observed. This is summarized in Table 1. Neither the shadowgraphs nor the interferograms show any indication of starting shock waves prior to the establishment of supersonic flow.

Examples of density measurements are given in Fig. 5. The throat of the nozzle is at $X = 0$ and the time scale is arbitrarily chosen so that $t = 0$ corresponds to the first appearance of the head of the expansion fan roughly 3.5 in. downstream of the throat. One can see the density drop to values that are at first below those of its final steady state. This "undershoot" is about 4% at $X = 0$; however, its magnitude decreases with increasing downstream distance. One also notices that the undershoot occurs in about 2 msec at the throat, and that it precedes the appearance of an undershoot at the downstream distances for $X > 0$. Density profiles are also shown in Fig. 5 for this case of $P_4 = 3.0$ atm and $P_1 = 0.40$ atm. At all times, the densities show a decrease with increasing downstream distance. Here, as before, there is no indication of starting shock waves. Comparisons of the density measurements in Fig. 5 with density measurements at other values of P_4 (with $P_4/P_1 = 7.7 =$ constant) have given the following results. The values of ρ/ρ_4 obtained at the throat are independent of P_4; hence the percentage undershoot is also independent of P_4. Further, the density profiles always show a monotonic decrease with increasing downstream distance. Generally, we have found that the data in Fig. 5 are representative of all density measurements performed.

Direct measurements of static pressure histories in the nozzle provide additional checks on the existence or absence of starting shock waves. In addition, comparisons can be made with the density histories previously mentioned.

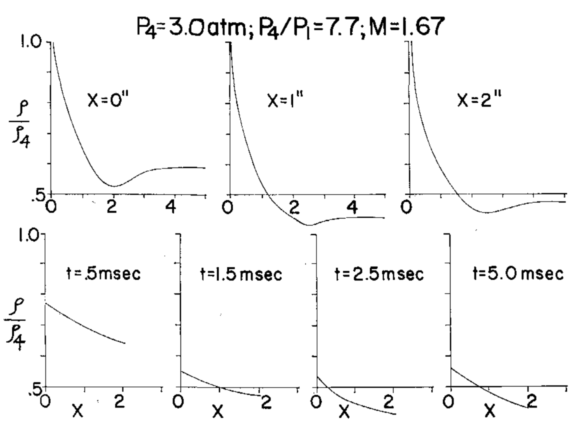

Fig. 5 Sample of density measurements: distances are measured in inches from the throat of the nozzle, and times are measured in msec, with $t = 0$ corresponding to first appearance of the expansion fan roughly 3.5 in. downstream of the throat.

Table 1 Summary of experiments $M = 1.67$

P_4 (atm)	P_4/P_1	No. of movie-shadowgraphs	No. of movie-interferograms	Starting shocks formed?
3.0	46	3	2	No
3.0	23	1	...	No
3.0	12	1	...	No
3.0	7.7	2	2	No
3.7	7.7	...	1	No
2.0	7.7	...	1	No
1.0	7.7	3	1	No

Pressure as a function of time at three different locations in the $M = 1.67$ nozzle is given in Fig. 6. The starting point of the time scale is arbitrary. At $X = 0$ in. the pressure drops initially below its final value, while at $X = 5.2$ in. this undershoot is considerably diminished; outside the nozzle at $X = 6.3$ in. this behavior has practically disappeared. These results are consistent with the density measurements shown in Fig. 5 where the relative undershoot also decreases with increasing downstream distance. Density measurements made at the nozzle's exit show the same qualitative trends as the pressure measurements in Fig. 6. Finally, Fig. 6 provides additional evidence for the smoothness and shock-free nature of the establishment of supersonic flow in the nozzle.

A pressure transducer has been inserted at the flange which is located just upstream of the nozzle's throat. (See Fig. 2). Measurements of static pressure histories in this "stagnation region" have been obtained for all the experiments given in Table 1. Samples of these results are given in Fig. 7 for the $M = 1.67$ nozzle. An undershoot of the steady-state values is also seen as a persistent feature. In addition, one finds that the undershoot seems to be followed by an overshoot as the adjustment to steady flow values is taking place. By comparing the two results for $P_4 = 3.0$ atm and different P_1 values, one can see that P_1, the initial downstream tube pressure, is not the determining factor as far as the pressure history is concerned once P_1 is low enough to provide a sufficient pressure ratio for supersonic flow to be established. Changes in P_4 do cause changes in the magnitude of the pressure shifts during starting. However, the times required for the pressure to drop below its final values

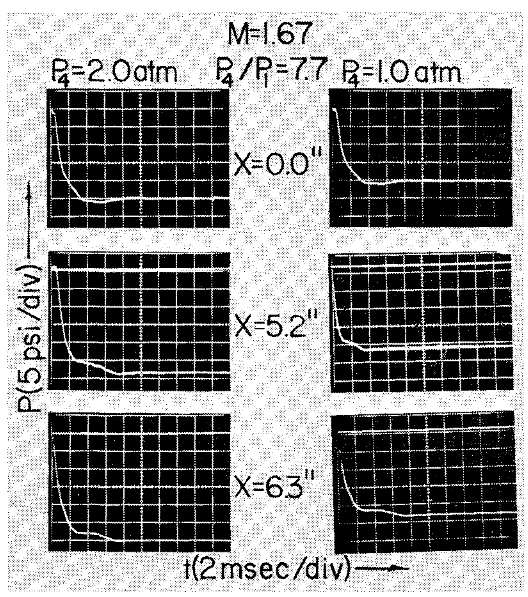

Fig. 6 Static pressure measurements in the $M = 1.67$ nozzle: the pressure gauge is being self-triggered in these measurements; the signal required for triggering corresponds to a pressure change of roughly 2 psi.

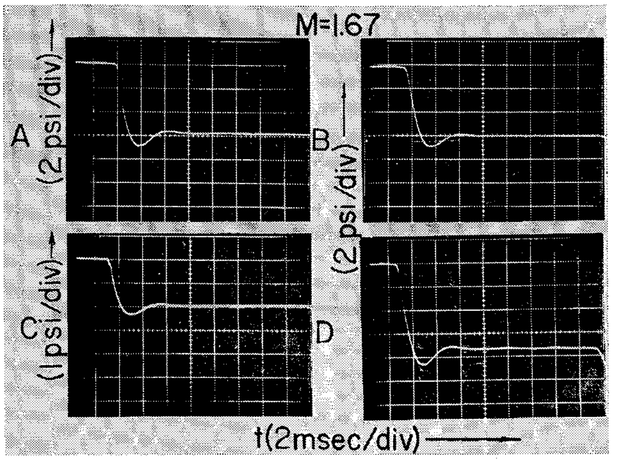

Fig. 7 Pressure measurements in the stagnation region: $M = 1.67$; A) $P_4 = 3.0$, $P_4/P_1 = 7.7$, B) $P_4 = 3.0$, $P_4/P_1 = 46$, C) $P_4 = 1.0$, $P_4/P_1 = 7.7$, D) $P_4 = 3.7$, $P_4/P_1 = 7.7$; the time scale is arbitrary; the pressure trace is triggered by a firing pin contact subsequent to the rupture of the diaphragm and P_4 is in atmospheres.

seem to be independent of both P_4 and P_4/P_1 within the limits stated.

For purposes of comparison, static pressure measurements have also been made in the stagnation region of a two-dimensional Mach number 3.0 nozzle. Samples of the data obtained are given in Fig. 8. Qualitatively, the results are similar to those observed at the lower Mach number.

IV. Discussion of Results

For the flow conditions of the work, it has been shown that starting shock waves analogous to those which ordinarily appear in a conventional blow-down wind tunnel are not produced. The absence of starting shocks is important, because it reduces the transient forces on a model during tunnel starting and thereby decreases the chance of model breakage and lowers the design requirements of the model and its support. The $M = 1.67$ nozzle used in this work is a wedge-type nozzle with a 6-in. radius arc at the throat and a straight 3°-half-angle diverging section; and the $M = 3.0$ nozzle is a continuously expanding nozzle with a cubic profile, as compared to nozzles designed by using the method of characteristics that produce parallel supersonic flow at the exit. This nozzle design may effect the results. We recall that the diaphragms used in these experiments require less than 0.1 msec to burst. By contrast, roughly 1 msec is required for the head of the expansion wave to traverse the nozzle. This time is called the characteristic nozzle time. Thus, the diaphragm rupturing process is fast relative to the characteristic nozzle time. On the other hand, the valve opening process in a blowdown wind tunnel is typically slow relative to characteristic nozzle times. It is, therefore, possible that a Ludwieg tube using slow opening diaphragms or valves and a short nozzle would produce starting shock waves. For the $M = 1.67$ nozzle, boundary-layer effects are negligible in the experiments using supply pressures between 1.0 and 3.7 atm.[5] This conclusion follows from the density measurements obtained during the steady supersonic flow in the nozzle. It was found that the Mach number determined from the density ratio was practically equal to that predicted from the geometric area ratio.

However, the theory for the Ludwieg tube's operating parameters for zero nozzle length[4] is not entirely adequate. For example, it predicts for $M = 1.67$ that the steady-state static pressure should be 86% of the supply pressure ($P_{st}/P_4 = 0.86$), while the measured result is $P_{st}/P_4 = 0.83 \pm 0.01$. The predicted duration of the steady flow at the stagnation regions pressure station is 17 msec. The corresponding measured time between the appearance of the head of expansion wave and its reflection which terminates the steady flow agrees with the prediction. However, because of the starting process whose duration varies from 5-7 msec (depending on P_4), the actual time of steady flow is only about 12 msec.

It was found that we could make some correct predictions by using a simplified one-dimensional treatment. In these calculations, we use the method of characteristics applied to our tube configuration for unsteady one-dimensional flow in the $M = 1.67$ nozzle. It was assumed that the flow was initiated by an expansion fan at the diaphragm position. The gas was again assumed to be perfect and inviscid. It was then found theoretically that 1.6 msec after the arrival of the head of the expansion wave at the throat of the nozzle, the density at the throat ($X = 0$) is $\rho/\rho_4 = 0.51$. This can be compared with the measured undershoot time and density of $t = 1.9$ msec and $\rho/\rho_4 = 0.52$, respectively. Both theory and experiment give the steady-state values $\rho/\rho_4 = 0.57$, and, therefore, the initially lower density value is verified theoretically.

In Table 2, finally, two quantitative aspects of the undershoot in the static pressure measurements in the stagnation region are shown. First of all, it is suggested in our data that the ratio of minimum pressure to the steady-state pressure is independent of the upstream starting pressure. For a given nozzle, we show in Table 2 data at a single fixed pressure ratio. (For $M = 1.67$, $P_4/P_1 = 7.7$; for $M = 3.0$, $P_4/P_1 = 18.0$). However, the measurements at pressure ratios of 46, 23, and 12 for $M = 1.67$ and of 46 for $M = 3.0$ show these results to be indeed independent of pressure ratio. Secondly, the experiments suggest that the undershoot time and the overshoot time are independent of the starting pressure. This is also shown in Table 2. The time between

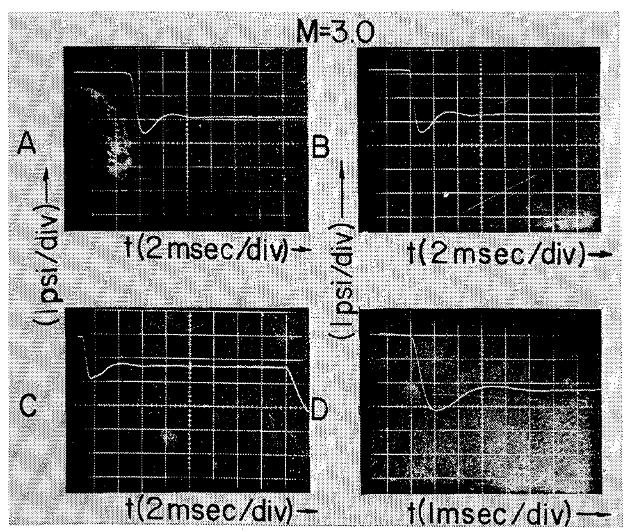

Fig. 8 Pressure measurements in the stagnation region: M = 3.0; A) $P_4 = 3.0$, $P_4/P_1 = 18$, B) $P_4 = 3.0$, $P_4/P_1 = 46$, C) $P_4 = 2.0$, $P_4/P_1 = 18$, D) $P_4 = 3.7$, $P_4/P_1 = 18$; the pressure gage triggering here is the same as in Fig. 7 and P_4 is in atmospheres.

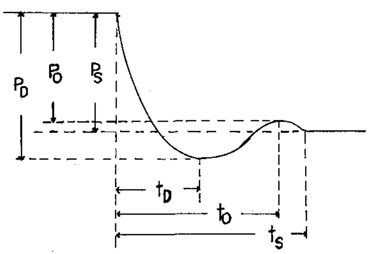

Fig. 9 Starting times and pressures in the stagnation region: nomenclature for Table 2.

Table 2 Starting times and pressures in the stagnation region[a]

P_4 (atm)	M	$\frac{\|P_D - P_S\|}{P_4} \Big/ \left(\frac{\|P_D - P_S\|}{P_4}\right)_{AV}$	$\frac{\|P_S\|}{P_4} \Big/ \left(\frac{\|P_S\|}{P_4}\right)_{AV}$	$\frac{t_D}{(t_D)_{AV}}$	$\frac{t_0}{(t_0)_{AV}}$
1.0	1.67	1.16	0.97	0.98	0.98
2.0	1.67	0.84	1.03	1.02	1.02
3.0	1.67	1.00	1.00	0.89	1.01
3.7	1.67	1.06	1.02	1.24	1.00
1.0	3.0	0.98	0.80	0.80	1.10
2.0	3.0	1.02	1.02	1.17	1.02
3.0	3.0	1.00	1.20	1.19	0.98
3.7	3.0	1.03	1.24	1.06	1.03

[a] See Fig. 9 for the nomenclature.

the onset and the termination of the expansion phase in the stagnation region is observed to be insensitive to changes in the upstream supply pressure. Nonetheless, the total starting time, not shown in these presentations, does seem to be sensitive to P_4.

V. Summary

From our experimental and theoretical studies of the starting processes for the Ludwieg tube wind tunnel with two nozzles of $M = 1.67$ and $M = 3.0$, respectively, for the range of conditions treated in our experiments, we find 1) Steady supersonic flow can be established smoothly throughout our type of continuously diverging nozzle past the throat, without the formation of starting shock waves. When sonic conditions have moved to the throat of the nozzle, supersonic flow has already begun in the downstream portion of the nozzle. These results appear to be independent of the supply pressure P_4 and of the starting pressure ratio P_4/P_1, once this ratio is sufficiently large to produce supersonic flow; 2) Static pressures and densities are found to first undershoot then adjust to their steady supersonic flow values. The values of the pressure and density drop below the final values decrease with increasing distance from the nozzle's throat. For a fixed Mach number the ratios of minimum pressure and density to supply tube pressure and density, respectively, and the ratios of time to minimum pressure to the total starting time are independent of P_4 and P_4/P_1; 3) For fixed nozzle Mach numbers, the ratios of steady-state pressure to supply tube pressure are independent of P_4 and P_4/P_1. However, the total starting time is found to be dependent on P_4 but not on P_4/P_1; and 4) A change in nozzle Mach number changes undershoot and steady-state pressures, densities, and time.

These results suggest that the deleterious effects arising from the interaction of starting shock waves with test models can be avoided in Ludwieg tube wind tunnels where use is made of fast opening diaphragms or valves. The observed variations in pressures and densities indicate important inadequacies in a simplified one-dimensional treatment of the gasdynamic processes and show that more sophisticated theoretical techniques are needed if correct predictions concerning the starting stage phenomena are to be obtained.

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