A PRELIMINARY INVESTIGATION OF THE USE OF EXPANDERS TO
GENERATE HYPersonic FLOW IN A WIND TUNNEL

by

H. Y. T. Wong
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SUMMARY

A preliminary investigation of secondary nozzles was carried out using the UTIA 5" x 7" supersonic wind tunnel. These secondary nozzles, called expanders, are mounted on the main tunnel nozzle and serve to accelerate a supersonic flow to higher Mach numbers with attached boundary layers. In the present tests the speed of the wind tunnel, in which the flow with atmospheric inlet was normally separated for pitot Mach number $M_H = 4.0$, was increased to $M_H = 5.15$, with attached and relatively thin boundary layers. The presence of the expanders reduced the effective working section area to 3" x 5" but a relatively small modification to the tunnel could yield a working section of useful size (5" x 5").
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**NOTATION**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>A</td>
<td>Geometric cross-section area</td>
</tr>
<tr>
<td>M</td>
<td>Mach number</td>
</tr>
<tr>
<td>MA</td>
<td>Mach number based on area ratio without boundary layer correction</td>
</tr>
<tr>
<td>MH</td>
<td>Mach number given by pitot measurement assuming isentropic flow upstream of the pitot tube</td>
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<tr>
<td>Pt1</td>
<td>Inlet stagnation pressure</td>
</tr>
<tr>
<td>Pt2</td>
<td>Measured pitot pressure</td>
</tr>
<tr>
<td>PtB</td>
<td>Break-down pressure</td>
</tr>
<tr>
<td>PtS</td>
<td>Starting pressure, above which supersonic flow cannot be established</td>
</tr>
<tr>
<td>XYZ</td>
<td>Right-handed Cartesian co-ordinate system with origin at the centre of the nozzle exit (see Fig. 2)</td>
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I. INTRODUCTION

The UTIA small supersonic wind tunnel is equipped with nozzle blocks in both the 5" x 7" and 5" x 5" configurations for area Mach numbers \( M_A \) up to 8.0. It has a closed jet powered intermittently by a vacuum-drive system operating in a circuit open to the atmosphere, (Refs. 1, 3 and 4).

One of the main problems associated with this tunnel is that the flow separates for a pitot Mach number \( M_H \) greater than about 4.0 (Ref. 4). This is so because for this tunnel inlet condition the flow Reynolds number per unit length at high Mach number is very small, as can be seen from Fig. 1, (Ref. 2); at these low Reynolds numbers the boundary layer is very thick and may even be separated. Most hypersonic tunnels in operation use high stagnation pressures which eliminate this difficulty. Pressurization was not considered here as a solution was sought which would not lead to extensive modifications to the tunnel structure.

Prior to the present investigation several attempts were made at UTIA to delay separation phenomenon to \( M_H > 4.0 \) in the two-dimensional nozzle. In one approach, energization of the boundary layer by applying roughness to the surface of the nozzle was investigated. Separation was prevented by this technique for \( M_H \) up to 5.7, at which \( M_H \) the boundary layer is very thick, e.g., about 1.62" in the 5" x 5" tunnel, (Ref. 4). In another attempt, axi-symmetric nozzles of \( M_A = 7.0 \) were designed and tested, but the flows were separated in these cases also, (Refs. 3 and 4).

Conventional boundary control techniques used on airfoils, viz., blowing and suction (Ref. 6) were considered at the beginning of the present investigation. Preliminary calculations indicated that the former is not very practical for this tunnel whereas suction was considered to be more complicated than the use of a flow "expander" as described in Ref. 5. An expander takes the form of a secondary nozzle placed in the wind tunnel nozzle and it was found in Ref. 5 that the Mach number of a large tunnel (24" x 24") could be boosted from 3.88 to about 5.4 by using a small expander (exit area 113 in. \(^2\)). Thus it appeared that a somewhat similar device might be used in the present investigation.

The expander system is based on the notions that (1) it can accelerate a supersonic stream flowing through it due to its divergence and (2) it has a shorter length than the tunnel nozzle, and hence the boundary layer grows on a shorter surface. Providing the expander does not diverge too greatly, the boundary layer on it is expected to be thinner than that on tunnel nozzle alone, at the same Mach number.

This report deals with preliminary investigations of a set of different expander systems, designed with the objective of obtaining an effective working section of acceptable size, (\( \geq 3" \times 5" \)), with the minimum of modification to the present tunnel system.
II. EXPERIMENTAL APPARATUS AND TECHNIQUE

2.1 The Wind Tunnel

All tests were made with the UTIA 5" x 7" two-dimensional wind tunnel operated by a vacuum-drive system with an atmospheric inlet. The air was always dried to an inlet specific humidity of 0.0003 lb. water vapor per lb. dry air, or less. This humidity was measured by an electric hygrometer recently recalibrated, and was considered to be sufficiently low (Refs. 4 and 11) for total head measurements and boundary layers not to be significantly affected by vapor condensation. Heated flows were found to be unsteady due to the non-uniformity of the heater, so that all flows reported herein were unheated. (see section 2.3 for the question of air condensation).

For simplicity, the nozzle used had a straight contour except at the throat and the exit where it was rounded (see Fig. 3). The nozzle blocks were made of mahogany and were mounted on the upper and lower walls of the five-inch-wide tunnel, the distance between these walls being adjustable. By adjusting the upper and lower walls so that the throat area is set differently for different runs, while the test-section area remains 5" x 7", the nozzle blocks can be used for different Mach numbers, provided flow uniformity is not a major consideration. Three nozzle settings were tested, (see Table 1).

The diffuser of the wind tunnel was set to a simple divergent type and remained unchanged during this investigation.

2.2 The Expanders

In order to obtain a high expander exit Mach number, it is desirable to have a high expander inlet Mach number. In Ref. 5 the expander was located at the exit or the parallel part of the nozzle but the test section was large enough to avoid starting problems in spite of the fact that the passage around the expander was convergent. For the present nozzle, this location is not possible because the secondary passage area needed for flow starting would leave an undesirably small expander working section. The application of suction to the secondary passage (as in Ref. 12), would have entailed fairly large structural modifications and to avoid this the expander had to be mounted on the divergent part of the nozzle. Moreover the location of the expander inlet had to be arranged so that its $M_H$ is less than 3.8 for, otherwise, the flow on the nozzle might separate ahead of the inlet (Ref. 4). Therefore the expanders employed in this investigation were mounted on the divergent part of the nozzle using vertical struts inserted into the nozzle walls and held by bolts, (Figs. 2 and 3).

The expanders were straight and were originally designed to expand the flow in nozzle A (exit $M_A = 4.5$) from $M_A = 3.4$ to $M_A = 6.0$. 
Simple one-dimensional isentropic theory, as explained in Appendix I, was used to design the main passage. Radial flow theory (Ref. 7) which gives an approximation to the real flow, was used to calculate flow directions, and hence it was possible to establish the wave patterns at the expander inlets. The shock waves at the leading edge of the expanders strike the nozzle walls and shock reflection theory was used to calculate the flow in the secondary passage and its exit pressure. Boundary layer effects were ignored so that this calculation was treated as a rough approximation. The pressure discontinuity between the main and secondary flows at the expander outlet was designed to be less than that needed, as given in Ref. 10, for shock-induced turbulent boundary layer separation in the main passage.

The expanders were made of steel and were 16" long initially. After some tests were made with these expanders, one full expander was cut to a new length of 7.4" long, and this is referred to as the half expander. The width of the expanders was 5" and their side edges were grooved to accommodate rubber seals so as to prevent air flow from one surface of the expander to the other via the side edge.

Since the shock wave at the exit of the expander tends to separate the boundary layer, an extension, (parallel to the tunnel axis), was added to the exit of the expander in a number of tests to help to relieve this adverse effect. The extensions have a true length of 2.4".

A number of expander configurations were tested. These included the different nozzle throat areas, expander inlet and outlet areas, listed in Table II. The details of some of these configurations are shown in Figs. 2, 3, 4, and 5.

2.3 Pressure and Mach Number Measurements

The pressure in the vacuum sphere was measured by three Wallace and Tiernan dial-type absolute pressure gauges with different ranges. The inlet stagnation gauge pressure of the tunnel was measured by a pitot tube in the subsonic inlet connected to a butyl phthalate U-tube manometer.

Both the main flow and the boundary layer pressures were measured by cylindrical pitot tubes connected by plastic tubing to a Wallace and Tiernan precision mercurial pressure gauge with a stated accuracy of ±16 mm Hg. As a check on any out-gassing effect of the plastic tubing under the present flow conditions, steel tubings were also used. Pitot pressures were found to be the same.

Pitot readings were taken after they had remained steady for 40 secs. Assuming the local total pressure in front of the shock at the pitot is the same as the inlet value \( P_{t1} \), Mach number distributions in all cases except in nozzles B and C were calculated from pitot surveys.
The Mach number of equilibrium condensation \( M_c \) (Ref. 9) is about 5.1 (Fig. 6) for these conditions. The air condensation effects should therefore be negligible for Mach numbers below that value; for Mach numbers greater than 5.1, condensation effects increase. However, it is established that pitot readings are not sensitive to condensation shocks (Ref. 11) and Ref. 4 reported that \( M_H \) rises only 0.8% as \( T_o \) varies from 300\(^{\circ}\)K to 532\(^{\circ}\)K.

For nozzles alone, \( M_H \) and the Mach number based on the Rayleigh formula are practically the same for heated attached flows, (Ref. 4). This shows that the assumption of no stagnation pressure loss along a smooth nozzle is a good approximation. In the case of the expander system, however, there should be a stagnation pressure loss at the leading edge due to (1) the strong shock wave in the secondary passage arising from the deflection angle of the expander, (2) the weak wave in the main passage arising from a slight leading edge bluntness of about 0.001". The former shock wave does not affect the main flow while the latter shock wave occurs at \( M_H \leq 3.7 \) (depending on the different configurations listed in Table II) and has a shock angle of about 19\(^{\circ}\) (see Fig. 13). This means the stagnation pressure loss is less than 1%. For the range of Mach numbers concerned here 1% error in \( P_{t2}/P_{t1} \) causes only a fraction of a percent error in the Mach number. Thus, the Mach number measured should be accurate enough for a preliminary investigation.

2.4 Detection of Flow Separation

Since our aim was to have an attached boundary layer, it was important to detect flow separation. Two techniques were used, viz., observations of shock-wave reflection from the boundary layer, and pitot surveys in the boundary layer, with the latter being considered as the more reliable one. When an incident shock wave does not reflect from a boundary layer this is interpreted as indicating that it is separated.

III. RESULTS

3.1 Flow in Nozzles Without Expanders

The nozzles were calibrated without expanders by a pitot survey along the centre-line of the nozzles (see Table I). Pressure readings were steady and repeatable. For the case of setting A, the Mach number distribution was very uniform and agreed fairly well with values given by one-dimensional isentropic theory without boundary layer correction, as can be seen from Fig. 7. The Mach number estimated from a schlieren picture (not shown) of a flow about a 20\(^{\circ}\) wedge is also shown. When the boundary layer on the wedge was ignored, the estimated Mach number was much smaller than \( M_H \). When the boundary layer was taken into account by measuring the apparent boundary layer edge on the schlieren picture, the Mach number estimated was fairly close to the \( M_H \) measured. The pitot Mach number will be considered as more accurate
than the schlieren Mach number described, since it is difficult to measure the boundary layer on the wedge accurately. The boundary layer was indistinct at the nozzle exit (Fig. 8); the incident shock wave generated by a 20° wedge in the flow, however, reflected from the boundary layer, indicating a still attached flow.

Schlieren pictures for flows in nozzles B and C (Figs. 9 and 10) showed, on the other hand, that their boundary layers were very thick and perhaps separated. Of course it is difficult to tell definitely from the schlieren pictures alone whether these flows were separated. The associated pitot surveys along the tunnel (Figs. 11 and 12) however, showed that the flows deviated markedly from one-dimensional isentropic theory. There were sudden pitot jumps at $5.5'' < x < 7.0''$. Schlieren pictures of the flow at these locations could not be obtained since there was no window at this location. A 20° wedge placed at $x = 6.5''$, however, generated a steady shock wave (picture not shown) in both cases, indicating that the local flows were supersonic.

These jumps seemed to indicate flow separation. At $x$ about $9''$, the local $M_H$ was 4.4 for nozzle B, i.e., greater than the $M_H$ about 4.0 at which separation might take place (Ref. 4). If the boundary layer was assumed to separate near there, a system of oblique shocks starting from the boundary layer would reach the centre-line of the tunnel at about $5.5'' < x < 7.0''$, and this would cause a pitot pressure jump there. In fact, a system of oblique shocks would give pitot pressure jumps of the same order of magnitude as those observed. A similar situation could happen also for nozzle C.

When the expanders were in place, (Section 3.2.4), the pitot pressure jump was not present. This is further evidence that the pressure jump was associated with the separation of the boundary layer.

Hence, both the pitot pressure jumps and schlieren pictures seemed to confirm the interpretation that the flows in nozzles B and C were separated.

It was possible to neglect the stagnation pressure loss for $x \geq 7.0''$; therefore the $P_t/2/P_t$ curves on Figs. 11 and 12 gave the $M_H$ for $x \geq 7.0''$. For $x \leq 7.0''$, this was not correct due to the pressure loss associated with the pressure jumps. The flow Mach numbers at $x = 4.5''$ were measured from the shock wave angles and wedge angles with corrections for their boundary layers (Figs. 9 and 10). Knowing the Mach number and the pitot pressure at $x = 4.5''$, it was possible to calculate the stagnation pressure there. This stagnation pressure was used to determine the flow Mach numbers for $x \leq 7.0''$ in both nozzles B and C and these are plotted on Figs. 11 and 12. (Nozzle C is included in this report only for comparison with the flows in the final expander configuration).
3.2 Flow in Expanders

Initially the full-length expanders were set in nozzle A in an attempt to raise the Mach number above 4.36, while maintaining thin attached boundary layers on the expander walls. Difficulties arose due to shock-boundary-layer interaction and a number of modifications were made to overcome this. The results of tests on successive configurations are given in the following paragraphs.

3.2.1 Flow in Full Expanders

With the nozzle in position of setting A, two full-length expanders were placed on the nozzle, (Configuration 1). The flow pattern at the expander inlet is shown on Fig. 13. On the inner side of the expander, there was a weak shock wave due to the leading edge thickness, followed by an expansion fan. This system of waves from one expander struck the other, hastening the growth of the latter's boundary layer.

The shock waves on the outer sides of the expander inlets caused the separation of the boundary layers on the nozzle walls, (Fig. 13). By allowing a larger secondary passage, (see Section 3.2.4), as in Fig. 14, the nozzle boundary layers became thinner and their separation was delayed. The flow within the expanders was separated in both the above configurations (e.g., Fig. 15) and even when the flow expansion ratio of the expanders was decreased, (Configuration 3), the boundary layer was still very thick (Fig. 16). The $M_H$ for Configuration 3 was 5.2, which is 19% higher than that for nozzle A alone.

3.2.2 Expanders in Radial Configuration

The expander configurations discussed in the previous section were all designed to expand the flow to a high Mach number. The resulting flows were all separated and this suggested an investigation of the use of the expanders purely as surfaces on which to grow a new boundary layer without attempting to expand the flow to a high Mach number.

Using radial flow theory, (Ref. 7), the apparent location of the source of the nozzle A and hence the radial flow directions in it were calculated and the expanders were set parallel to the streamlines.

The expander inlet for this configuration was larger than that for Configuration 3. Here the inlet shock wave struck the boundary layer in the main flow at a more downstream location than that in Fig. 13, as shown in Fig. 17 and the boundary layers on the expanders and the nozzle walls were thinner than that shown in Fig. 14. The flow in the expanders is shown in Fig. 18, where the boundary layer is relatively thin and there is no strong shock wave at the expander exit.
The measured pitot Mach number for this expander system was 4.29, the same (within experimental errors) as that for the nozzle alone, as would be expected.

### 3.2.3 Flow Over One Expander

The radial configuration gave thin boundary layers but no speed augmentation while all other previous set-ups had separated boundary layers. This suggested an investigation of the flow over only one expander (Configuration 4) to determine its ability to generate a higher speed with an attached boundary layer on the expander. For the same Mach number, the boundary layer on the expander in this case was expected to be thinner than that on the expanders in the previous expanding configurations because there would be no second inlet shock wave to hasten the boundary layer growth.

The flow pattern for this case (Fig. 19) showed that an incident shock wave reflected from the boundary layer, indicating that the boundary layer on the expander was attached. This boundary layer was thinner than that for the case of two expanders, e.g., Fig. 15, because (1) the flow Mach number was smaller for the present case and (2) there was no second inlet shock wave to thicken the expander boundary layer. Attempts to get a higher Mach number by increasing the expander inclination above the value for Configuration 4 were not successful because the boundary layer was then separated.

The pitot Mach number distribution for Configuration 4, as given in Fig. 20, agreed well with the simple one-dimensional isentropic theory. The $M_H$ obtained was 4.65 against the value of 4.36 for nozzle A alone.

In order to check the effect of the expander exit shock wave on the boundary layer, an extension was added to Configuration 4. It was thought that this extension might help in delaying the influence of the shock wave on the expander boundary layer to a position further downstream, and therefore might give attached flow for higher expander inclinations.

The flow in this condition (Configuration 5) is shown on Fig. 21. No striking difference between this and Fig. 19 could be observed, although the measured $M_H$ was 4.75. The discrepancy between this and the value measured for Configuration 4, however, is of the order of the experimental errors, and tests further showed that the extension did not increase the expander inclination at which separation occurred.

Boundary layer measurements showed a steep initial slope in the pitot profile of both Configurations 4 and 5 (see Fig. 22), indicating the boundary layers on the expanders were attached. The slope of the profile near the nozzle wall, (Fig. 22) is small however, indicating a thick boundary layer there.
An effect of the extension can be seen from Fig. 22, where there is an indication that the distribution in a vertical plane is more uniform in the case with extension. For this reason the extension was retained in later tests.

3.2.4 Flow in One and a Half Expanders

Since it was not possible to generate an attached flow over one expander with \( M_H > 4.65 \), an investigation was made of the use of an additional short expander. In order to avoid the unfavourable boundary layer and expander inlet shock wave interaction (Section 3.2.1), the short expander was so positioned that its leading edge was downstream of the wave from the leading edge of the full-length expander, and the wave from the leading edge of the short expander would not strike the lower expander. This latter wave was surprisingly not seen in the schlieren pictures for configurations involving a full and a half expanders, (Figs. 23 and 24). When the full expander was removed, the leading edge wave from the short expander could be seen clearly and had a wave angle such that the wave should not strike the full expander if it were in place (Fig. 25).

The highest \( M_H \) with attached flow obtained with expander arrangement in nozzle A (Configuration 6) was 4.89, as compared with \( M_H = 4.36 \) for nozzle A alone. The boundary layers on the expander were seen to be attached and thin, (see Fig. 23).

The result of the test of Configuration 6 was indeed promising. This lead to the investigation of the possibility of obtaining still higher \( M_H \) with a similar expander system in a nozzle of higher \( M_A \). Testing a few different nozzle and expander configurations showed that, with expander exit limited to 3" x 5", Configuration 7 gave highest speed for a full and a half expander (\( M_H = 5.51 \)). A schlieren picture of the flow is shown in Fig. 24.

A pitot survey along a line \( Y = -0.6" \) in the tunnel central plane (Fig. 26) showed its agreement with simple one-dimensional theory was not as good as that for Configuration 4. This is probably in a large measure due to the thickening of the nozzle boundary layer by the presence of the half-expander, whereas the theory did not take into account its displacement thickness.

Pitot surveys of the boundary layers on the expanders showed that they were attached and relatively thin, having the thickness of 0.5" and 0.75" on the shorter and longer expanders respectively (see Figs. 27 and 28). Assuming a 1/7 power law profile so that the displacement thickness can be taken as 42% and 49% of the boundary layer thickness for \( M = 4.4 \) and 5.0 respectively, (Ref. 7), and roughly estimating the boundary layer thickness on the long expander at the short
expander inlet as 0.5", then the isentropic theory with these displacement area corrections would give \( M = 5.05 \). This is quite close to the \( M_H \) obtained, which was 5.15. The \( M_H \) distribution for nozzle B alone is replotted from Fig. 11 for comparison in Fig. 26 showing clearly that the expanders removed the pitot pressure jump at \( 7^\circ > x > 5.5^\circ \). The Mach number distribution in Configuration 7 was far more uniform than that in nozzle B, or that in nozzle C. Although the latter and Configuration 7 have about the same \( M_H \), the ratio of the boundary layer thickness to main flow area is seen to be bigger for nozzle C (compare Figs. 10 and 24).

Flows in the secondary passages were supersonic and separated from the nozzle walls. This could be seen respectively from the expansion wave at the corner of the expander extension and from the flow pattern without a clear boundary layer as shown in Figs. 23 and 24, for example. The leading edge shock waves from the expanders caused the nozzle boundary layer to separate (Figs. 13 and 14). At the expander exits where the primary and secondary flows meet, there is a system of shock and expansion waves, (Fig. 23).

For proper supersonic flow establishment in the secondary passage, it was found that it should have a minimum area not less than 135\% of the theoretical area needed to swallow a hypothetical normal shock wave at the expander inlet.

### 3.3 Effect of Expanders on Pressure Recovery and Running Time

Break-down pressure, \( P_{tB} \) and starting pressure \( P_{tS} \) were measured by connecting dial-type pressure gauges to the vacuum storage. Pressure readings were taken when the schlieren system showed flow just beginning to breakdown or to start respectively. These pressures are shown in Table III and are compared with those values obtained by assuming a normal shock at the test-section.

For the case of nozzle without expander (setting B), the measured \( P_{t1}/P_{tB} \) was 36\% greater than the theoretical value. The same ratio for other tunnels agrees closer with the normal shock theory (see Ref. 8) which means the present nozzle-diffuser system was not set efficiently.

When the expanders (Configuration 7) were in the tunnel, \( P_{t1}/P_{tB} \) increased slightly from 21.2 for setting B to 23.1. Thus the effect of the expanders was to increase \( P_{t1}/P_{tB} \) only by 8.7\%, but of course the Mach number also changed. Column 3 of Table III shows that the measured \( P_{tB} \) was only 26\% larger than that given by normal shock theory for the case of Configuration 7, compared with 36\% and 47\% for nozzles B and C. These indicate that the performance characteristics, in addition to Mach number distribution, could be approximated more closely by the one-dimensional theory for expanders than for nozzles with separated flows.
The maximum vacuum storage pressure necessary for establishing supersonic flow is about 95% of $P_{tB}$. The running time decreased from 180 secs to 165 secs., when the expanders were introduced, i.e., a decrease of 8.5%.

IV. DISCUSSION OF RESULTS

The tests described in the last section have shown that an improvement may be achieved in the performance of the UTIA 5" x 7" supersonic tunnel by the use of expanders but at the expense of a decreased test-section area. The best result was obtained in nozzle B which has a basic exit $M_H = 4.9$ and thick boundary layers. The use of expanders increased the Mach number to 5.15 and reduced the thickness of the boundary layers considerably, so that they occupied about 43% of the resulting 3" x 5" test-section. This should be compared with the result of Fig. 16 of Ref. 4, where surface roughness was used to control the boundary layer of the nozzle, and the boundary layer thickness was 1.4" for the same Mach number. Thus in that case the boundary layer occupied 56% of the test section area of 5" x 5". The maximum attached flow Mach number obtained with the use of roughness in Ref. 4 was 5.7, and boundary layer separation occurred at Mach numbers greater than about 4 for nozzles without surface roughness.

In the investigation of Ref. 5, the axi-symmetric expander was successful in expanding a nozzle Mach number of 3.88 to a flow with Mach numbers varying from 5.1 to 5.4. In that case, however, the expander exit area was only 20% of the large test-section area, so that the remaining secondary passage was large enough for starting. In the present investigation, no effort was directed towards increasing the Mach number range by using expander exit areas below 3" x 5", i.e., our minimum expander to tunnel area ratio was 43%. It was felt that any further reduction would result in an undesirably small test-section, while scaling up a configuration with exit area smaller than 3" x 5" would require extensive modifications to the existing tunnel structure. Without further complications in design, the present tunnel can be made to accommodate a nozzle of 11" x 5" fairly readily. This should increase the expander test-section area, according to the present result, to about 5" x 5", which is a useful size, although this would be at the expense of reducing the running time to 105 secs from the present 165 secs.

Application of suction to the secondary passage (as in Ref. 12) to reduce its boundary layer and its area requirement for starting, would allow an increase in the size of the expander working-section and expanders with larger expansion ratio (and in turn, shorter length) could be accommodated without flow-starting problems. The Configuration 7 had the first expander inlet at a position where $M_A = 3.8$, since it was felt that the inlet should not be located downstream of a section with separated flow and separation may occur at $M_H = 3.8$, on nozzles of the type used here according to Ref. 4. With suction applied to the secondary
passage, this nozzle flow separation might be delayed, so that the expanders could start at a higher inlet Mach number. Thus, with a larger nozzle area or with secondary flow suction, a better optimum configuration could be designed. This would have a higher expander inlet Mach number and shorter expander length than those tested here, and would generate a higher expander Mach number with attached flow. These ideas could be considered in the future development work. The asymmetry of the expander test section of Configuration 7 and the non-uniformity of the flow could be eliminated by shaping the expander and designing the exit portions so that they are parallel.

V. CONCLUSIONS

Tests have been made in the small UTIA supersonic tunnel on a number of flow expander systems similar to those first reported in Ref. 5. In the present work, however, the expanders played a dual role. Firstly, they were used to boost the basic Mach number of the nozzle and secondly, they acted as a starting point for a new boundary layer and hence, helped to overcome the adverse effects of separation. The most successful configuration was a slightly staggered set-up of a long and a short expander (Configuration 7), arranged so that the shock wave from one expander would not strike the other.

The performance characteristics, such as the running time, starting and break-down pressures of a pure nozzle with a given area were only slightly lowered by the presence of expanders.

It was found that the best configuration of the expanders increased the basic nozzle Mach number from 4.9 with thick boundary layers to 5.15 with attached, relatively thin boundary layers. The ratio of the cross-section area occupied by the boundary layer thickness to the total exit area for the expander system tested (43%) was found to be smaller than the same ratio of the nozzle in which separation was prevented by surface roughness (Ref. 4).

It is suggested that the UTIA wind tunnel can be readily modified to operate on an expander system with an effective working section of 5" x 5". To operate at a much higher Mach number would require fairly extensive modification to the present wind tunnel structure.
# REFERENCES

1. **Stewart, J. D.**  

2. **Ames Research Staff**  

3. **Enkenhus, K. R. Tucker, N. B.**  

4. **Tucker, N. B.**  

5. **Salmi, R. J.**  
   A Three-Dimensional Flow Expander as a Device to Increase the Mach Number in a Supersonic Wind Tunnel, NASA Memo 10-6-58E.

6. **Schlichting, H.**  

7. **Ruptash, J.**  

8. **Liepmann, H. W. Roshko, A.**  
   Elements of Gasdynamics, New York, J. Wiley & Sons, Inc., (1957), Sections 5.7 and 5.8.

9. **Wegener, P. etc.**  
   "NOL Hyperballistics Tunnel No. 4 Results 1: Air Liquefaction", NOL NAVORD Report No. 1742, (1951).

10. **Tucker, M.**  

11. **Lukasiewicz, J.**  

12. **Hertzberg, A. et al**  
APPENDIX I

Simple One-Dimensional Area-Ratio Theory for the Nozzle-Expander System

It is well known that one-dimensional isentropic flow theory gives a good approximation to flow in nozzles, where the Mach number distribution is a function of the flow area. As an approximation, this theory is applied to the nozzle-expander system as follows.

Let $A$ and $M$ denote area and Mach number, with subscripts denoting the station as shown in the following figure:

When supersonic flow is established, $M_1$ is given by the isentropic equation for air

$$\frac{A_1}{A_T} = \frac{125}{216} \left(1 + \frac{M_1^2}{5}\right)^3$$

(Ref. 2)

The mass flow through area $A_2$ has to flow through $A_3$, so that $M_3$ is given by

$$\frac{A_3}{A_2} = \frac{M_2}{M_3} \left(1 + \frac{M_3^2}{5}\right)^3$$

where $M_2 = M_1$

or

$$\frac{A_3}{A_\infty} = \frac{A_3}{A_2} \frac{A_2}{A_T} = \frac{125}{216} \frac{A_1}{M_3} \left(1 + \frac{M_3^2}{5}\right)^3$$

where $A_\infty$ is the fictitious critical area.
Similarly, $M_5$ and $M_6$ are given by

\[
\frac{A_5}{A_1} = \frac{A_5}{A_4} \frac{A_5}{A_2} \frac{A_1}{A_T} = \frac{125}{216} M_5 \left(1 + \frac{M_5}{5}\right)^3
\]

\[
\frac{A_6}{A_1} = \frac{A_6}{A_4} \frac{A_5}{A_2} \frac{A_1}{A_T} = \frac{125}{216} M_6 \left(1 + \frac{M_6}{5}\right)^3
\]

The accuracy of these equations is not so good if the boundary layers are thick. For better accuracy, the areas used in the calculation should be the geometrical areas minus the boundary layer displacement thickness area.
TABLE I

NOZZLES TESTED

<table>
<thead>
<tr>
<th>Nozzle Setting</th>
<th>Area Mach Number</th>
<th>Test Section</th>
<th>Pitot Mach Number*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.50</td>
<td>5'' x 7''</td>
<td>4.36</td>
</tr>
<tr>
<td>B</td>
<td>5.05</td>
<td>5'' x 7''</td>
<td>4.9 **</td>
</tr>
<tr>
<td>C</td>
<td>5.50</td>
<td>5'' x 7''</td>
<td>5.1 **</td>
</tr>
</tbody>
</table>

* See Section 3.1
** Based on schlieren picture and pitot pressure
<table>
<thead>
<tr>
<th>Expander Configurations</th>
<th>Main Nozzle Setting</th>
<th>Number of Expanders</th>
<th>Expander Lengths Inches</th>
<th>Expander Inlet Areas Sq. Inches</th>
<th>Expander Outlet Areas, Sq. In.</th>
<th>Expander $M_A$</th>
<th>Expander $M_H$ (From Sec. 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>2</td>
<td>16</td>
<td>.400 x 5</td>
<td>3.660 x 5</td>
<td>6.0</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>2</td>
<td>16</td>
<td>.328 x 5</td>
<td>3.000 x 5</td>
<td>6.0</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>2</td>
<td>16</td>
<td>.554 x 5</td>
<td>3.500 x 5</td>
<td>5.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Radial</td>
<td>A</td>
<td>2</td>
<td>16</td>
<td>.900 x 5</td>
<td>2.400 x 5</td>
<td>4.5</td>
<td>4.29</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>1</td>
<td>16</td>
<td>1.606 x 5</td>
<td>5.500 x 5</td>
<td>4.73</td>
<td>4.65</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>1 + Extension Ext.</td>
<td>16 + Ext.</td>
<td>1.606 x 5</td>
<td>5.500 x 5</td>
<td>4.73</td>
<td>4.75</td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td>1+1/2 + Exts.</td>
<td>16 + Ext. 7.4 + Ext.</td>
<td>1.606 x 5</td>
<td>3.012 x 5</td>
<td>5.04</td>
<td>4.89</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
<td>1+1/2 + Exts.</td>
<td>16 + Ext. 7.4 + Ext.</td>
<td>1.561 x 5</td>
<td>3.065 x 5</td>
<td>5.53</td>
<td>5.15</td>
</tr>
</tbody>
</table>
### TABLE III

**PERFORMANCE CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Nozzle or Configuration</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\frac{P_t}{P_{tB}}) Measured</td>
<td>(\frac{P_t}{P_{tB}}) Normal Shock Theory Based on (M)</td>
<td>(\frac{P_t}{P_{tB}})_measured</td>
<td>Measured running time, sec.</td>
<td></td>
</tr>
<tr>
<td>Nozzle B</td>
<td>21.2</td>
<td>15.6</td>
<td>1.36</td>
<td>0.95 + 3%</td>
<td>180</td>
</tr>
<tr>
<td>Configuration 7</td>
<td>21.3</td>
<td>18.2</td>
<td>1.26</td>
<td>0.95 + 3%</td>
<td>165</td>
</tr>
<tr>
<td>Nozzle C</td>
<td>28.9</td>
<td>19.6</td>
<td>1.47</td>
<td>0.95 + 3%</td>
<td>125</td>
</tr>
</tbody>
</table>
FIG. 1. REYNOLDS NUMBER VERSUS MACH NUMBER

- $P_{t1} = 14.5$ PSIA
- $T_t = 70^\circ F$
- $200^\circ F$
- $300^\circ F$
- $400^\circ F$
FIG. 2. EXPANDER CONFIGURATION 1
FIG. 6. $M_c$, MACH NUMBER OF EQUILIBRIUM CONDENSATION AS FUNCTION OF $T_t$
Fig. 7. Mach Number Distribution in Nozzle A

Y = Z = 0

- $M_A$
- $M_H$
- M measured from picture with boundary layer correction
- M measured from picture without correction

X, inches from nozzle exit
FIG. 8. FLOW IN TEST-SECTION OF NOZZLE A
Fig. 11. Distribution of \( M \) and \( P_{t2}/P_{t1} \) along centre-line of nozzle B.
FIG. 12. DISTRIBUTION OF M AND $P_{t2}/P_{t1}$ ALONG CENTER-LINE OF NOZZLE C
FIG. 14. FLOW AT INLET OF EXPANDER CONFIGURATION 2
FIG. 15. FLOW IN EXPANDER CONFIGURATION 2
FIG. 16. FLOW IN EXPANDER CONFIGURATION 3
FIG. 17. FLOW PATTERN AT INLET OF RADIAL EXPANDER
FIG. 20. MACH NO. DISTRIBUTION FOR CONFIGURATION 4
FIG. 21. EXPANDER CONFIGURATION 5 WITH SHOCK WAVE GENERATED BY A 20° WEDGE
FIG. 22 BOUNDARY LAYER SURVEY ON EXPANDER
FIG. 23. FLOW IN EXPANDER CONFIGURATION 7
(THE UPPER EXPANDER IS THE SHORT ONE)
\[
\left\{ \begin{array}{l}
Y = -0.6 \quad Z = 0 \\
\text{SIMPLE ONE-DIMENSIONAL ISENTROPIC APPROXIMATION} \\
\text{EXPERIMENTAL VALUES, CONFIGURATION 7} \\
\end{array} \right.
\]

FIG. 26. MACH NUMBER DISTRIBUTION IN CONFIGURATION 7

X, INCHES

MACH NUMBER

6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6

NOZZLE B
<table>
<thead>
<tr>
<th>$P_{t1}$</th>
<th>$P_{t2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>.06</td>
<td></td>
</tr>
<tr>
<td>.05</td>
<td></td>
</tr>
<tr>
<td>.04</td>
<td></td>
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<td></td>
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<tr>
<td>.01</td>
<td></td>
</tr>
<tr>
<td>.00</td>
<td></td>
</tr>
</tbody>
</table>

DISTANCE FROM EXPANDER, INCHES

FIG. 27. BOUNDARY LAYER ON THE SHORT EXPANDER, CONFIGURATION 7
FIG. 28. BOUNDARY LAYER SURVEY ON THE LONG EXPANDER, CONFIGURATION 7

DISTANCE ABOVE EXPANDER, INCHES