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NOV.-DEC. 1969 J. AIRCRAFT VOL. 6, NO. 6

Peripheral Jets: Effect of Exit Geometry

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This investigation was designed to examine the effects of various geometric parameters of the exit on the lift of a peripheral jet device. The variables considered were: the operating height, the curtain thickness, the base extension beyond the curtain, and the shape of this base extension. Because of the large number of variables involved, a statistical method of data gathering was used. Recorded lampblack and kerosene streakline patterns and measured pressure distributions on the base of the model and on the ground plane revealed three distinct flow patterns in the vicinity of the exit depending on whether the curtain, as a result of its expansion due to mixing, left an open, a partially sealed, or a completely sealed gap between the base extension and the ground. The first occurrence of this sealing phenomenon was found to depend on the geometric parameters involved and to mark the point where the measured lift began to deviate appreciably from that predicted by the existing theories.

Nomenclature

A_g = augmentation ratio (integrated pressure on base and nose extension/jet momentum flux)
C = length of base
h = height of base above ground
$\dot{M}$ = mass flow flux from slot
N = base extension or overhang
p = static pressure (base or ground)
P_b = base static pressure
p_t = total pressure in reservoir
RN = Reynolds number based on nozzle exit conditions = $\rho_j V_j t/\mu$
t = thickness of nozzle slot
x = coordinate distance measured from inboard end of base
θ = inclination angle of nozzle measured from vertical

1. Introduction

THE peripheral-jet ground-support system is one of a variety of devices that have shown a good potential for lifting heavy loads at moderate ground clearances. The primary feature which distinguishes the peripheral-jet from other modes of fluid suspension is a jet curtain of fluid that exits from a nozzle-slot arrangement around the periphery of the base and is directed towards the ground. The deflection of this jet curtain by the ground sets up a pressure differential across the curtain. The pressure differential, in turn, acting on the base generates a lifting force.

A substantial number of theoretical and experimental studies have been conducted in an attempt to analyze the behavior of peripheral-jet support systems.[1–4] In all the studies of which the authors are aware, the nozzle and slot arrangement is always located on the outer periphery. However, it is not inconceivable to envision a ground-support system that employs a jet curtain that is located at a substantial distance inboard of the actual periphery of the device. As a matter of fact, due to stability and control problems, there are some current thoughts along this same line with regard to a support system for the tracked air-cushion vehicle (TACV).

The goal of this report is to present the results of a systematic experimental investigation that was directed to a determination of the operational performance of jet-curtain type ground-support systems that have a moderate amount of base extension or overhang outboard of the nozzle slot.

Previous researchers have established that there are a very large number of design parameters that influence the performance of peripheral-jet support systems. After considering both the magnitude of the problem and the limitations imposed on the authors by the test facilities available, the parameters and magnitudes chosen are shown in Table 1. Further, these parameters are in ratios comparable to those presently anticipated on the series of tracked air-cushion vehicles currently under development in this country.

2. Test Apparatus

Tests were conducted on a two-dimensional peripheral-jet device designed and constructed by Sandberg.[5] Slight modifications to the nozzle geometry of this device were made to provide for an adjustable slot width. In addition, extra

Received January 24, 1969; revision received May 1, 1969. This research was supported by the National Science Foundation under Grant GK-618.

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Table 1 Test Parameters

Parameter	Magnitude
Slot width	0.100 in., 0.075 in., 0.050 in.
Height of base above ground	0.75 in., 0.50 in., 0.25 in.
Nose extension or overhang	2.00 in., 1.00 in., 0.50 in.
Nose shape	Square, tapered

pressure taps were added on the ground and base plates in the region where the jet impinges on the ground plate.

Adjustments in the configuration of the test facility were rather simple. The height was varied by bolting the ground plate to the walls of the device through holes spaced at $\frac{1}{4}$-in. intervals. Heights ranging from $\frac{1}{4}$ in. to $1\frac{1}{2}$ in. could be obtained. The slot width was varied by means of adjusting screws which passed through $\frac{1}{2}$-in.-thick plexiglass nose pieces and screwed into internal support vanes. The width of the nose was adjusted by bolting to the nose plate one to three additional $\frac{1}{2}$-in.-thick sections of plexiglass. If a tapered shape was desired, a special section of plexiglass shaped in a wedge with a 5° taper was attached by screws to the last square section of plexiglass.

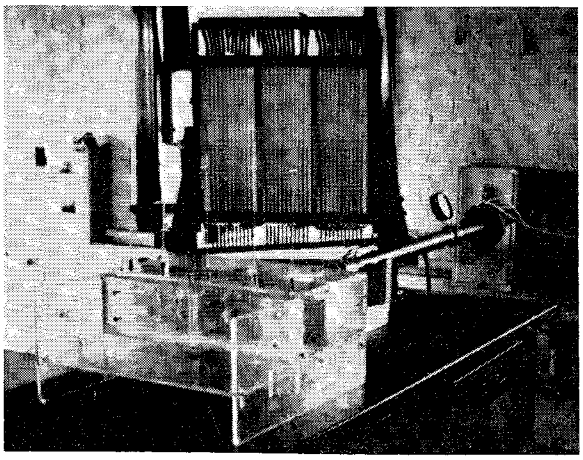
The air was supplied by tapping into a small compressed-air storage tank. The tank was of sufficient size to feed air at the steady rate of 0.0013 slug/sec for about $1\frac{1}{2}$ min and at the steady rate of 0.0040 slug/sec for about 45 sec. The airflow was metered through the use of a standard ASME 1-in. orifice, which was set into a 2-in.-diam feeder pipe. Over-all views of the test facility and the peripheral-jet test rig are pictured in Fig. 1a and 1b, respectively.

A scaled diagram of the peripheral-jet device is shown in Fig. 2. The flow of air enters the settling chamber through a diverging nozzle which tends to minimize any flow irregularities. A section of $\frac{1}{2}$-in.-thick urethane foam was set up across the settling chamber as an additional precaution against irregularities in the flow entering the reservoir. Five Pitot static probes were equally spaced across the reservoir chamber to measure the pressure and velocity of the air. (In all tests the velocity of the air in the chamber in regions away from the slot was negligible). Static pressure readings in the region between the ground and base were measured

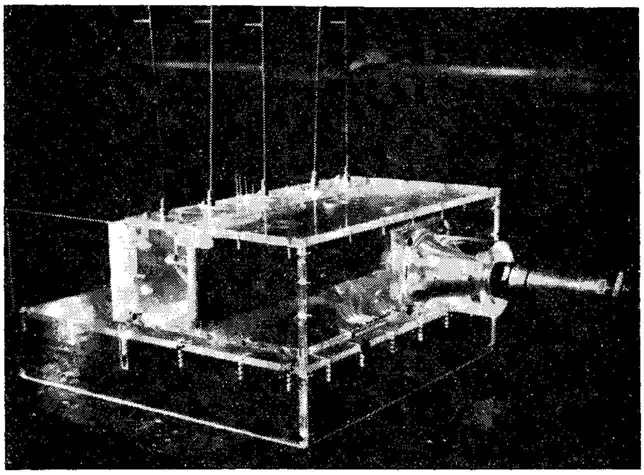
Table 2 Test conditions

Nose		0.0	0.5	1.0	2.0
		Square nose			
Height	Slot				
0.75	0.100	. . .	. . .	. . .	4
0.75	0.075	. . .	3	. . .	9[a]
0.75	0.050	. . .	. . .	11	. . .
0.50	0.100	. . .	. . .	14	. . .
0.50	0.075	. . .	. . .	7[a]	2
0.50	0.050	. . .	1	. . .	. . .
0.25	0.100	. . .	16	. . .	. . .
0.25	0.075	. . .	. . .	18	. . .
0.25	0.050	. . .	. . .	. . .	20
		Tapered nose			
Nose		0.0	0.5	1.0	2.0
Height	Slot				
0.75	0.100	. . .	. . .	15	. . .
0.75	0.075	5[b]	. . .	. . .	8
0.75	0.050	. . .	10	. . .	. . .
0.50	0.100	23[b]	13	. . .	. . .
0.50	0.075	. . .	. . .	6	. . .
0.50	0.050	. . .	. . .	. . .	12
0.25	0.100	22[b]	. . .	. . .	17
0.25	0.075	24[b]	19	. . .	. . .
0.25	0.050	. . .	. . .	21	. . .

[a] These runs were taken to test the statistical approach to data gathering. They were not included in the analysis.
[b] These runs were not analyzed statistically, but were used for comparison purposes with other experiments where $N = 0$, (Ref. 4).



a) Test facilities



b) Peripheral-jet test rig

Fig. 1 Test equipment.

from taps installed in the base plate, ground plate, and the nose. The base contained 12 static-pressure taps, the ground 22, and each $\frac{1}{2}$-in.-wide nose piece contained one tap. These taps not only were essential in calculating the lift on the base and nose, but they also aided in describing the flow pattern.

3. Statistical Analysis

As mentioned, this study is focussed on determining the effect of four physical design parameters on the performance of a peripheral-jet device. Three of these parameters vary between three levels whereas the fourth has two levels.§

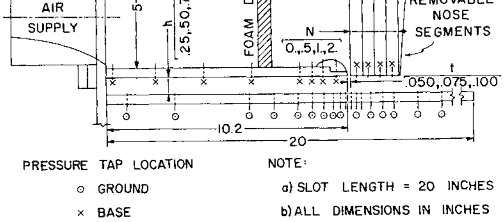


Fig. 2 Model cross-sectional geometry.

§ A level is the magnitude of each variable. A three-level change can produce a curve whereas a two-level test can only produce a straight line variation.

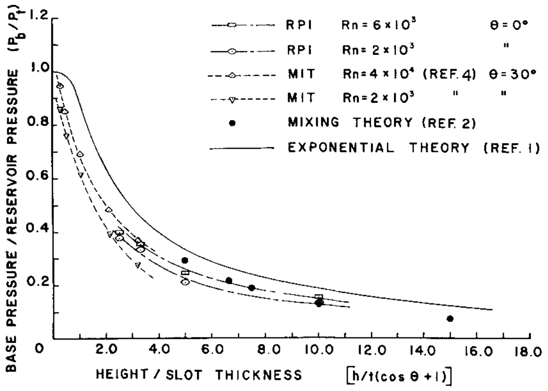


Fig. 3 p_b/p_t **vs** h/t **(cos** $\theta + 1$**) (**$N = 0$**).**

The total number of parametric combinations is therefore 54. The preparation, running and evaluation of 54 separate tests is not very desirable. For this reason a procedure of statistical analysis[6] was employed in gathering the data.

In statistically designing the experiment, a grid composing all 54 design possibilities was drawn (Table 2). The squares identified by the numbered boxes were then chosen as the runs of primary importance. The procedure for deciding upon these runs is as follows: for each nose shape one level of a particular parameter is arbitrarily chosen (for example, choose a $\frac{1}{2}$-in. nose width). There are then two three-leveled variables remaining. Though the total of combinations of these two variables number nine, three particular combinations can be chosen that include among them all levels of the two variables. Thus, runs 1, 3, and 16 have between them a run at each of the three slot widths, and a run at each of the three heights. With run 3 already chosen, runs 4 and 11 are then added. Runs 3, 4, and 11 now include each of the three slot widths and each of the three nose widths at a fixed height of $\frac{3}{4}$ in. The remaining runs were chosen in a similar manner expanding on the runs already established.

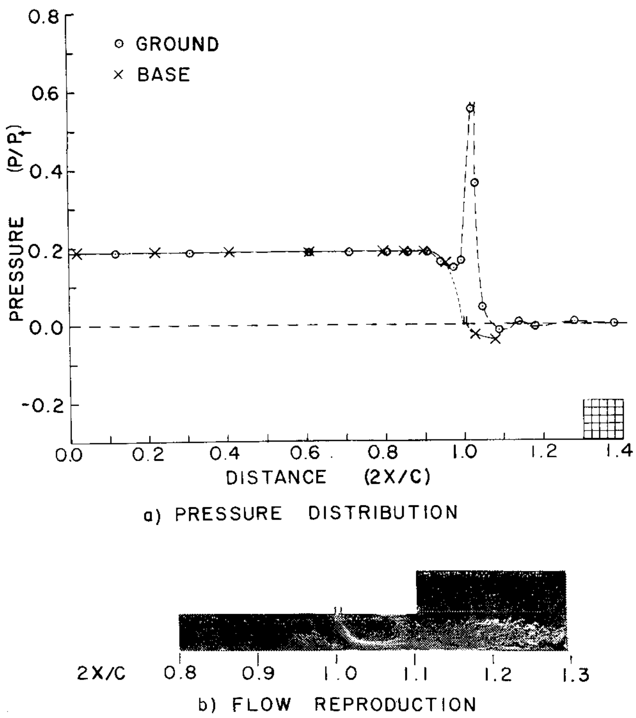


Fig. 4 Open exit $N = 1.0$, $h = 0.75$, $t = 0.050$, $p_t = 1.92$ **psig.**

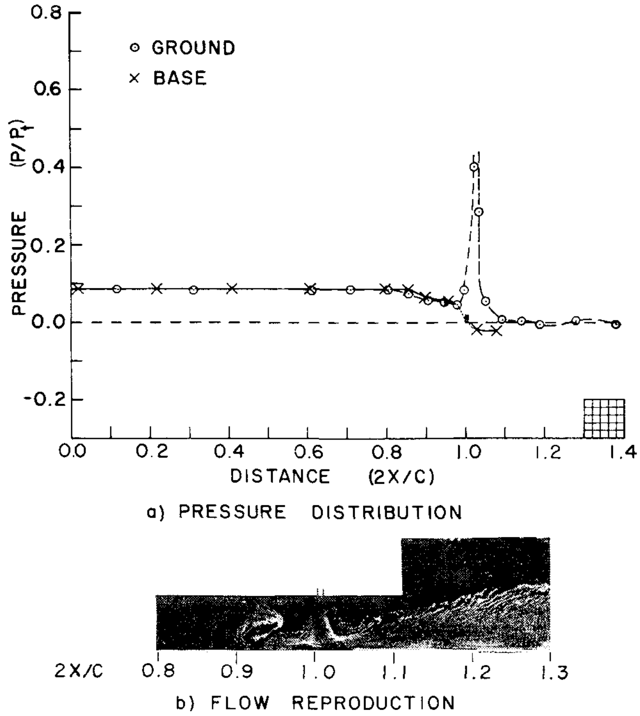


Fig. 5 Partially sealed exit $N = 1.0$, $h = 0.50$, $t = 0.075$, $p_t = 1.92$ **psig.**

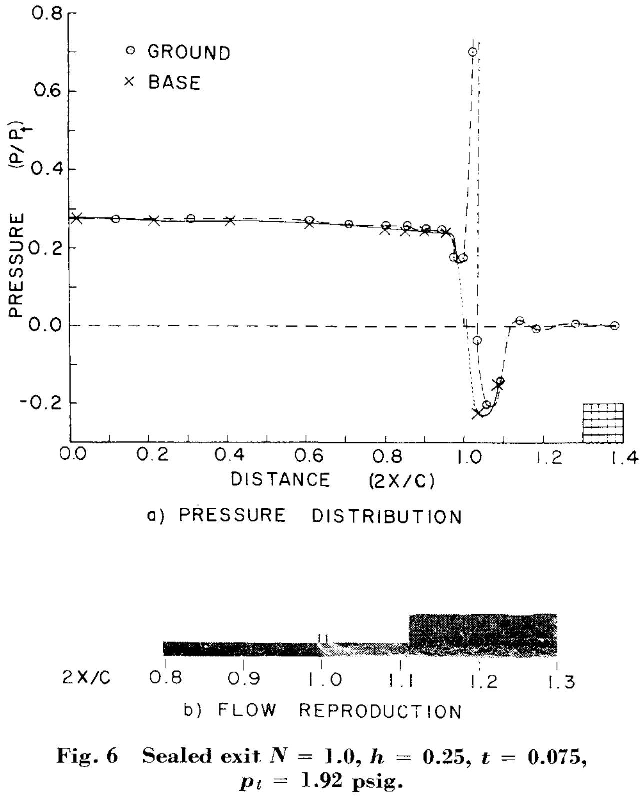


Fig. 6 Sealed exit $N = 1.0$, $h = 0.25$, $t = 0.075$, $p_t = 1.92$ **psig.**

4. Discussion

The purpose of this investigation was to study the effects of variations in the exit geometry on the performance of a peripheral-jet support system, operating under simulated hovering conditions. Statistical methods were employed in gathering data and reducing the results.

In the course of this work, corroborating and correlating studies of the details of flow patterns in the immediate

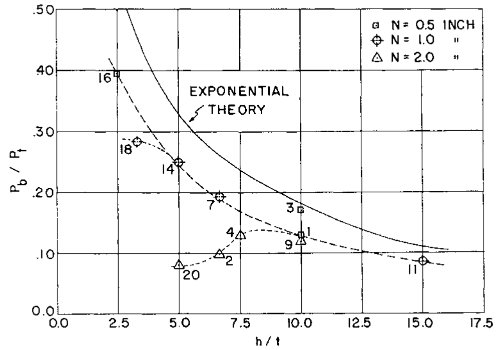


Fig. 7 p_b/p_t **vs** h/t, $\dot{M}$ = **1.58** × **10**$^{-3}$ **slug/ft-sec, square nose.**

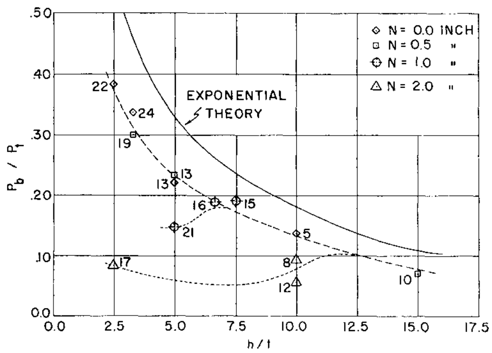


Fig. 8 p_b/p_t **vs** h/t, $\dot{M}$ = **1.58** × **10**$^{-3}$ **slug/ft-sec, tapered nose.**

proximity of the jet were also performed. Among these were: 1) a comparison with previous experimental data, 2) visualization studies of the flowfield under the base of the peripheral-jet device by the lampblack and kerosene technique, and 3) an investigation of the secondary flowfield outside the nose using the tuft technique.

Before testing could begin some assurance was needed that the settling chamber was successful in creating two-dimensional flow conditions at the slot. Measurements of the static and total pressure were taken at five fixed locations in the reservoir chamber. In addition, measurements were made of the jet-momentum-flux uniformity along its entire length. These preliminary tests indicated sufficient uniformity to consider the flow two-dimensional. The fact that the flow becomes three dimensional at the edges of the slot is not significant. The slot is of sufficient length to insure that conditions at the midpoint of the slot (where all measurements are made) are not influenced by any edge effects.

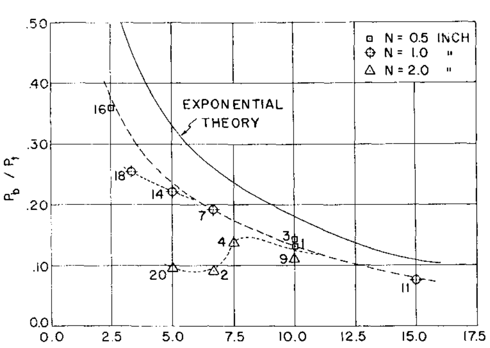


Fig. 9 p_b/p_t **vs** h/t, $\dot{M}$ = **2.39** × **10**$^{-3}$ **slug/ft-sec, square nose.**

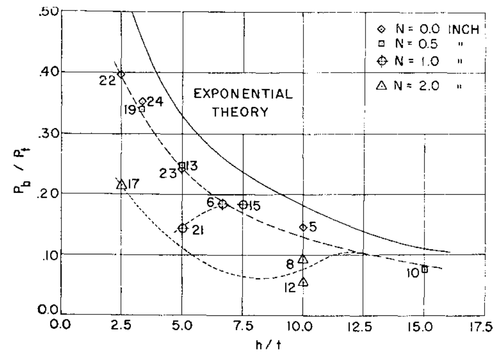


Fig. 10 p_b/p_t **vs** h/t, $\dot{M}$ = **2.39** × **10**$^{-3}$ **slug/ft-sec, tapered nose.**

A. Comparison with Other Experiments

As indicated in Table 2, four tests were performed with a base extension of zero (N = 0). By installing only the tapered nose segment, the nose configuration approximates that used at MIT by Richardson and Ribich.[4] Thus, the results of these four tests can be directly compared with those of Ref. 4 and provide a basis for establishing the accuracy and validity of all other tests conducted in this series.

These test results, as well as the MIT data are shown in Fig. 3. Although comparison cannot be made over an extended h/t range, in the region where overlap of the experiments did occur, agreement was good. The minor discrepancies in the reported results are most likely attributable to differences in the operating Reynolds number (RN) and in the details of the nozzle geometry.

Also shown in Fig. 3 is a plot of the theoretical pressure ratio, p_b/p_t, vs h/t $(1 + \cos\theta)$ as predicted by the exponential theory.[1] Both the RPI (Rensselaer Polytechnic Institute) and MIT sets of data differ from this theoretical curve. Chaplin[2] attributes the reduced base pressure to mixing between the jet curtain and the surrounding fluid. Applying Chaplin's correction for mixing to the exponential theory a base pressure is predicted which agrees well with experiment provided $h/t > 5$. Since Chaplin's analysis

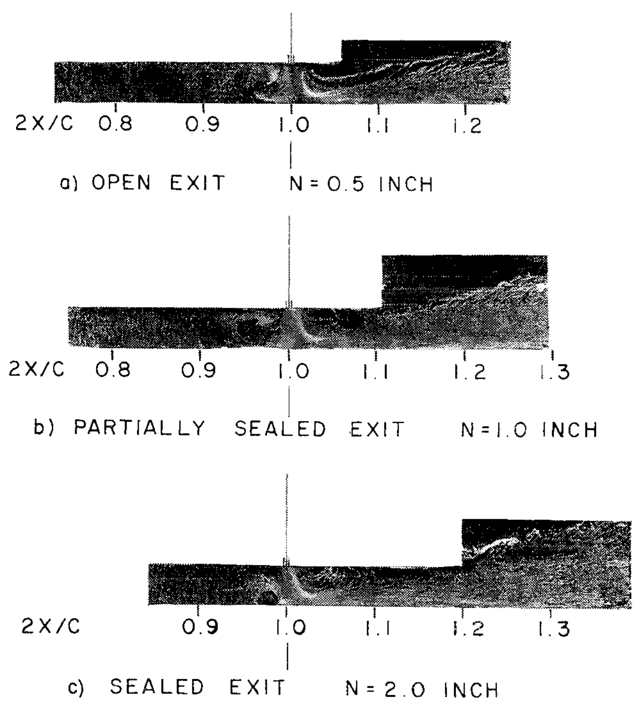
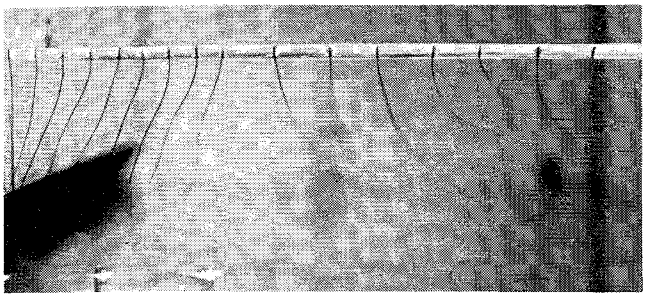
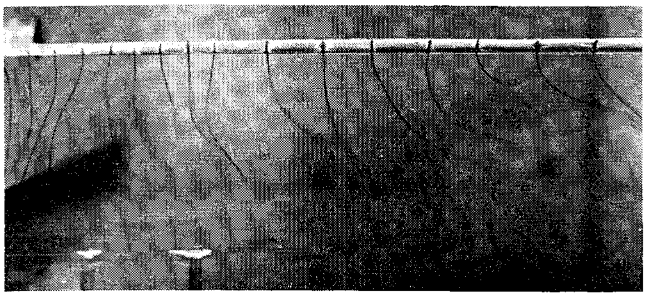


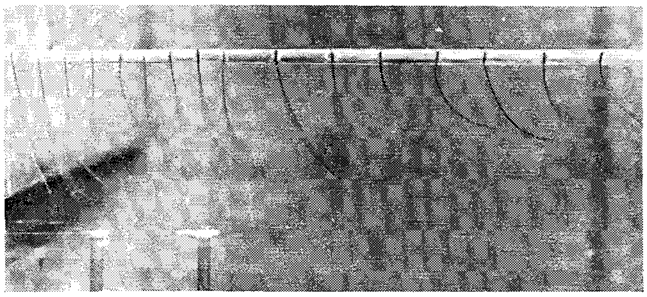
Fig. 11 Flowfield reproductions h = **0.50,** t = **0.75,** p_t = **1.92 psig.**



a) Open exit



b) Partially sealed exit



c) Sealed exit

Fig. 12 Tuft photographs.

postulates that the mixing of the jet occurs predominantly along the jet path between the exit and the ground impingement point, such a limit is reasonable. Obviously at very small h/t ratios substantial mixing occurs in a horizontal direction after the jet has impinged on the ground.

B. Studies of Base Extension Beyond Jet (Square Nose)

A main goal of this research has been to examine the effects of a base extension on the operation of a peripheral jet. Two nose shapes were examined in this study, a square-edged nose and a 5° tapered nose. Since both nose shapes exhibit the same qualitative trends in the data, this discussion will be restricted to an analysis of the results for the square-edged nose.

Typical pressure distributions are shown in Figs. 4a–6a. Except for the region in the immediate vicinity of the jet and nose, the pressure distribution on the base and ground plate is quite uniform. The ratio of the base pressure to the reservoir total pressure vs the height to thickness ratio is shown in Figs. 7–10. Also shown is the plot of the exponential-theory-predicted performance of a peripheral jet.

A large number of data points form a single curve approximately parallel to the theoretical one but lower than it by almost 15 to 35%. In addition, there appears to be a series of branches off the main experimental curve, each branch deviating further from exponential theory. A separate branch occurs for each nose size. These branches break from the main experimental curve at higher h/t ratios as the nose length is increased.

Qualitatively, these deviations can be explained by considering the interaction between the jet and the nose. As N increases and h/t decreases, the deflected jet expands sufficiently, while still under the nose, to completely fill the exit, and thus seal the gap. Sealing results in a low-pressure area under the nose, as shown in Fig. 6a. Since the jet requires a fixed pressure differential for turning, the lower pressure on the outer edge of the jet results in a correspondingly lower base pressure.

In order to more fully understand the mechanism of sealing, the flowfield in the vicinity of the jet was studied through observations of kerosene and lampblack streakline patterns. Typical flow patterns are shown in Fig. 11. This figure illustrates a progression from an open exit condition to a sealed exit with increasing nose length at a fixed h/t. Similar results for a fixed nose length but varying h/t are shown

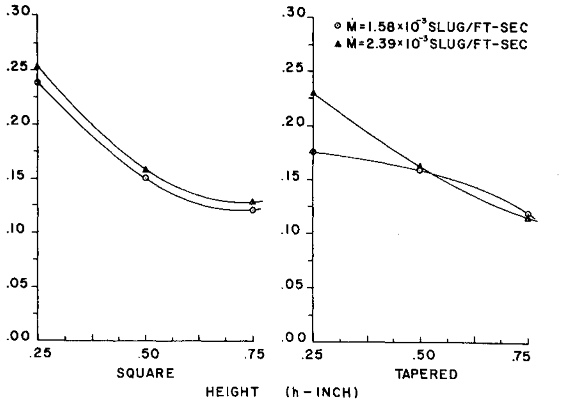


Fig. 14 p_b/p_t vs height (N and t statistically averaged).

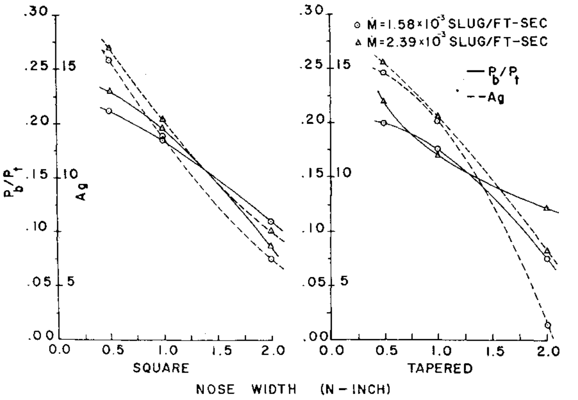


Fig. 13 A_g and P_b/P_t vs nose width (t and h statistically averaged).

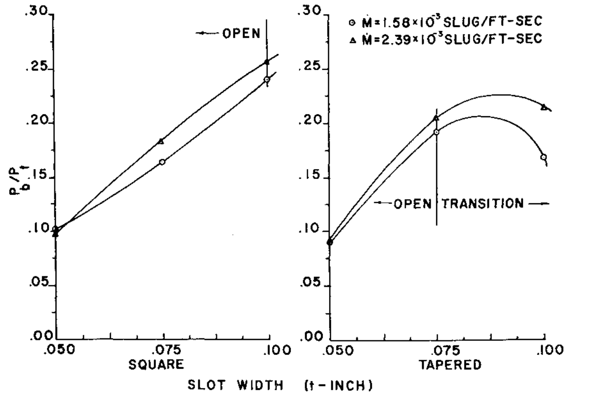


Fig. 15 p_b/p_t vs slot width (N and h statistically averaged).

in Figs. 4b, 5b, and 6b. A comparison between the corresponding pressure distribution and flow patterns may be made in these three figures. Figure 6 clearly shows the very low pressure region under the nose (6a) and the small trapped vortex between the jet and the nose (6b).

The flow pattern in front of the nose was examined from tuft photographs. In Fig. 12a (unsealed gap), the tufts close to the nose indicate that external, or secondary flow is drawn under the nose. Figure 12b shows the same effect, but to a lesser extent. Finally, Fig. 12c shows that the underside of the nose is separated from the external flowfield when the exit is sealed.

C. Statistical Analysis

The procedure employed in the statistical analysis of the data was to maintain one variable at a specific value and then average over the remaining variables. The results of this procedure are shown in Figs. 13, 14, and 15.

Figure 13 illustrates the variation in the pressure ratio (p_b/p_t) with nose extension (N), at an averaged height (h) and slot thickness (t). The results for the square and tapered nose shape have the same trend—namely increasing p_b/p_t with decreasing N. Also shown is the augmentation (A_g) vs N. Since the pressure under the nose decreases as the exit gap seals, the augmentation, which includes the integrated effect of this lowered pressure, has a greater variation with N than the variation of p_b/p_t with N.

Figure 14 shows the effect on p_b/p_t due to variations in height (h) at averaged values of N and t. This figure shows that p_b/p_t decreases with increasing height—the trend of which is in general agreement with existing theories.

The effect of variations in slot width on the pressure ratio at average N and h is presented in Fig. 15. Unlike the results presented in Figs. 13 and 14, a pronounced difference is evident between the tapered and the square nose shapes. This difference follows from an analysis of Figs. 7–10, where it can be seen that the sealing of the exit occurs at a larger h/t ratio for a tapered configuration than for a square one. Apparently the tapered segment, when attached to the nose, increases the effective nose width, therefore enhancing the sealing of the exit gap. The estimated slot thickness which results in the onset of exit sealing is also shown in Fig. 15.

5. Conclusions

This research investigated the effect of exit geometry on the performance of a two-dimensional peripheral-jet support system. Measured pressure distributions on the base of the model and on the ground plane, in addition to recorded lampblack and kerosene streakline patterns disclosed three distinct flow patterns in the vicinity of the exit depending on whether the jet curtain left an open, a partially sealed, or a completely sealed gap between the base extension and the ground. The first occurrence of this sealing phenomenon marks the point where the measured base pressure begins to deviate appreciably from that predicted by existing theories.

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