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# THE EFFECTS OF ACOUSTIC FEEDBACK ON THE SPREAD AND DECAY OF SUPERSONIC JETS*

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## Abstract

A supersonic air jet in air was investigated experimentally under conditions which resulted in wide variations in the rates of jet spread and decay. It was established that these variations are related to the acoustic feedback of certain sound waves generated in the downstream portions of the jet. The interactions of these sound waves with the initial portions of the jet, especially after reflection from a solid surface near the nozzle, are capable of altering the effective exchange coefficients and hence the progress of mixing. Pressure and total temperature measurements were made in the jet downstream of the supersonic core which show that the axial velocity without acoustic feedback can be from 50% to nearly 100% greater than the velocity with acoustic feedback, all other conditions being the same. The rate of jet spread was found to increase substantially when acoustic feedback occurs.

## I. Introduction

This work is the outgrowth of research related to supersonic oxygen nozzles used by the steel industry in the basic oxygen process of steelmaking. The nozzles used in that research were generally converging-diverging nozzles operating reasonably close to their design point. In several tests wide variations in the rate of jet spread and decay were unexpectedly encountered when only slight changes in the nozzle stagnation pressure were made.

Figure 1 demonstrates the problem under consideration here. In this graph the values of impact pressure, as measured on the jet axis 72 in. downstream of the nozzle exit, are plotted versus the nozzle inlet stagnation pressure. The downstream impact pressure generally increases with nozzle stagnation pressure, as expected, but at many points the impact pressure drops precipitously without any apparent reason. Separation within the nozzle could not be the cause at nozzle stagnation pressures above the design point of 100 psig.

The possibility of changes in the shock structure causing the erratic performance demonstrated by Fig. 1 was also investigated. Sixteen millimeter motion pictures were taken of the shadowgraphs occurring during a nozzle test in which the stagnation pressure was gradually reduced from 200 psig to 70 psig. Three frames of that movie have been reproduced and are shown in Fig. 2. The three shadowgraphs of Fig. 2 correspond to points "a", "b", and "c", respectively, of Fig. 1. It is clear that the shock structure in the "b" frame of Fig. 2 is not significantly different from that in either the "a" or the "c" frame. A slow but uniform progression in the shock structure is evident as the nozzle stagnation pressure increases from 137 to 154 psig, but there is nothing in the "b" frame which provides an explanation for the more rapid decay of jet velocity.

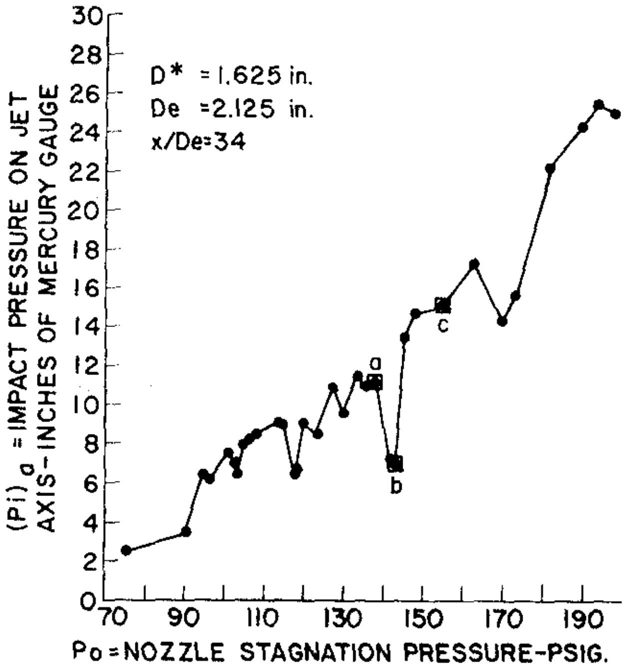

Fig. 1. Impact Pressure on Jet Axis vs. Nozzle Stagnation Pressure.

In an effort to further investigate this anomalous behavior, several small supersonic nozzles of 1/4 to 1/2 in. throat diameter were fabricated and tested. The initial tests, however, did not reproduce the anomalous behavior, so attempts were made to establish conditions which would

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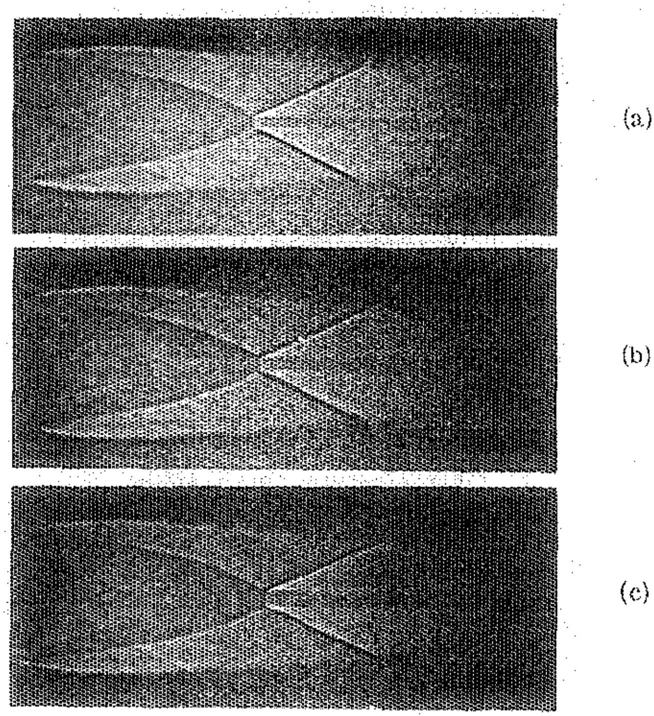
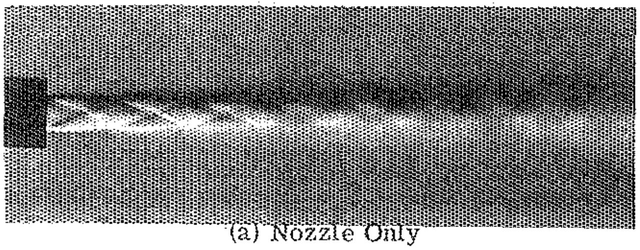


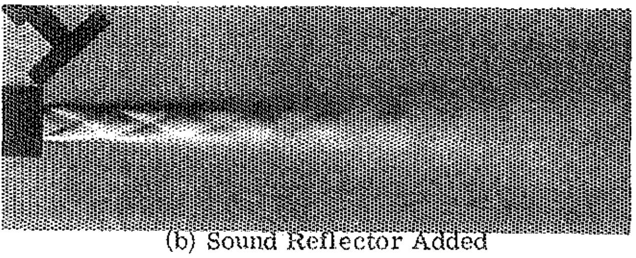
Fig. 2. Shadowgraphs of Initial Portions of Jets from a 1.625 Inch Nozzle.

produce the sharp changes in jet decay. Guided by the thought that changes in the flow pattern of the ambient air as it was "pulled" into the jet might have a profound effect, an ordinary clipboard was held at various positions outside of the jet from a 1/4 in. converging-diverging nozzle. For most of the board positions there was no discernible effect on the jet, but when the board was held near the nozzle exit at about 45° to the downstream jet axis, the downstream velocity on the jet axis was markedly reduced at certain operating conditions. Under these conditions, a high pitched screech could be heard over the jet noise. This coupling of changes in the jet sound with changes in the rate of jet mixing suggested that reflected sound was the culprit which brought about the increased rate of jet mixing. As a further demonstration, the clipboard was covered on one side with a 1 in. layer of Fiberglas insulation. The clipboard was then held near the nozzle as before. When the insulation was on the jet side of the clipboard, no discernible effect on the jet could be obtained and no jet screech was heard. However, when the non-insulated side faced the jet, a decrease in downstream jet velocity and the attendant screech could be readily obtained. It was thus evident that the changes in the jet mixing rate were not due to changes in the induced airflow pattern.

In order to investigate this effect further, an adjustable reflecting surface was attached to the nozzle and put into various positions as the nozzle stagnation pressure was varied. At certain pressures the jet appeared to be particularly susceptible to disturbances by reflected sound waves. One such pressure was 124 psig. The results of tests at this particular nozzle stagnation pressure are indicated in Fig. 3. The two schlieren pictures of Fig. 3 were obtained during tests which were made under essentially identical conditions except that the reflector disc was positioned for the test of the lower picture. During both tests the impact pressure on the jet axis, 12 in. downstream of the nozzle, was measured. Without the disc reflector the impact pressure was 8.4 in. of mercury gauge, while with the disc reflector (positioned to be most effective) the impact pressure was reduced to 3.4 in. of mercury. The more rapid mixing of the jet, with the reflector in place, is also indicated by the lower schlieren photograph of Fig. 3, the shock structure being destroyed in a shorter distance.



(a) Nozzle Only



(b) Sound Reflector Added

*Fig. 3. Schlieren Photographs of Jets—With and Without Special Sound Reflector.*

Related tests made with the reflector disc showed that the disc could be moved (in a direction perpendicular to the face of the disc) from a position of maximum effect on the jet, through a region of little effect, to another position where the effect on the jet was quite pronounced. This distance was on the order of 1 in. Since the screech frequency was on the order of 10,000 cycles per sec, and the sound was travelling through room air, this suggests a phase relation between the reflector position, the source of the sound, and the point at which the sound waves affect the jet. This particular approach was not pursued further, since it was very difficult to get precise correlation between reflector position and frequency.

An earlier study of the literature on the rate of mixing of supersonic jets, produced no references which dealt with the present problem of the sudden changes in the rate of jet decay. At this point a search of the available literature related to the effects of sound waves on jets was made. While none of these references were concerned directly with jet decay, some were quite pertinent to the problem and are now briefly discussed.

The fact that sound waves impinging on a laminar jet could induce transition to turbulence was demonstrated at least as early as 1935 by Brown[1]. Savic[2] developed a theoretical analysis which explained the results obtained by Brown. Savic applied Tollmein's general criterion of instability; he assumed an inflection in the velocity boundary of the jet near the nozzle exit.

The work of both Brown and Savic was limited to subsonic and initially laminar jets. Also, they considered only sound waves which were directed toward the jet from some external source. It would not seem that the results of the work by Brown and Savic would apply directly to the jet studies covered by the present report since in the present studies, (a) the Reynolds number based on nozzle diameter was typically on the order of one million, (b) there were no external sources of sound waves, and (c) the jet was initially supersonic.

A study by Powell[3] of the sound produced by the jet from a choked two-dimensional nozzle led to the conclusion that a "Screech" was created and that the frequency of the screech was related to the length of the shock cells within the jet. Powell found that the strongest radiation of the screech frequency was in an upstream direction from a source which was seemingly within the fourth shock cell in the jet. Also, the sound waves generated on the two sides of a two-dimensional jet were antisymmetric.

Powell extended his study[4] to choked converging axially symmetric nozzles with similar results. He developed general relations between screech frequency and operating conditions, but these relations did not account for the fact that while the screech frequency varied steadily with pressure over several ranges, discrete jumps in frequency occurred at certain pressures.

Davies and Oldfield[5] carried out extensive research into the frequencies and sources of tones produced by a choked axisymmetric jet. They confirmed and extended the results of Powell. Some of the results and conclusions presented by Davies and Oldfield are of interest here:

1. Several sources are responsible at one time for the tones emitted. These sources are located at the ends of the 4th to 7th shock cells, and the emission from the jet is fixed by the coupling of successive shock cells.
2. The sound waves generated by those sources are propagated upstream (outside the jet) and create disturbances in the jet near the nozzle exit.
3. These disturbances travel downstream and appear to develop into vorticies some distance downstream of the nozzle exit. Seemingly these vorticies are sometimes really one long vortex whose axis forms a spiral around the jet; either right or left handed spirals may be formed. At other times the vorticies may be in the form of a toroid. The emission from an axisymmetric jet is usually unstable to some extent.

The research reported on in Refs. 3, 4, and 5 was concerned with the source and nature of those tones (as opposed to overall noise) which are emitted by supersonic jets under certain conditions. In none of these cases was the exact mechanism of the source of the sound waves defined, although the nature of the feedback loop was discussed and expressions were developed which related frequency to cell size and operating conditions. Also, none of these references presented any information regarding the effects of these emitted sound waves (tones) on the rate of jet decay, the subject of the present research.

The work by Hammitt[6] comes closer to dealing with the problem of jet decay than any of the other references found. Hammitt worked with two-dimensional, overpressure sonic nozzles, using a spark schlieren system and microphones. He found that the interaction of the sound waves with the jet, near the base of the jet, affected the shock structure within the jet, but he did not measure the effect on jet spread and decay.

The preliminary tests discussed here have demonstrated that the rate of spread and decay of a supersonic jet could be appreciably increased by acoustic feedback. Many of the references cited discuss the existence and nature of acoustic feedback. A series of further tests was required to provide an indication of the magnitude of these acoustic feedback effects.

## II. Experiments

During most of the tests with smaller nozzles (1/4 to 1/2 in. throat) the stagnation temperature of the air was maintained within about $1^{\circ}F$ of the room air temperature, which was held near $70^{\circ}F$. The plenum chamber pressure and temperature were recorded during each test. Within the jet the local stagnation pressure and stagnation temperature were measured simultaneously by means of a calibrated combination total pressure-total temperature probe. This probe was slowly moved across the jet or along the axis of the jet by means of a small lathe with automatic feed. The probe travelled at a rate of 0.015 in./sec and its position was correlated with the pressure and temperature recorders. An 8 in. schlieren/shadowgraph system was used as needed and oscilloscope records were made of the sound waves picked up by a microphone.

Tests of converging nozzles at stagnation pressures above the critical pressure showed that wide variations in the rate of jet spread and decay were possible with converging nozzles as well as with converging-diverging nozzles. The following results were obtained using a converging nozzle having a throat diameter of 1/2 in. A constant area throat section about 1/2 in. long followed the converging part of the nozzle. Figure 4 shows the variation in the impact pressure, measured on the jet axis, with nozzle stagnation pressure at three different downstream positions. The curves of this figure were obtained without any artificial sound reflectors or absorbers. Clearly the effects of the sharp changes in the rate of jet decay are observable over a range of downstream positions at essentially the same nozzle stagnation pressures. The acoustic feedback between nozzle pressures of 45 and 55 psig was very erratic.

The nozzle and plenum system structure inadvertently presented various surfaces which acted as acoustic reflectors. In an attempt to reduce this reflection the entire plenum chamber and nozzle were wrapped with Fiberglas insulation. Only the nozzle exit and the immediately surrounding portion of the nozzle were not covered. Curve No. II of Fig. 5 was obtained with the jet thus insulated from the nozzle-plenum structure. Curve No. I of Fig. 5, which is the same as the middle curve of Fig. 4, was obtained at the same conditions except that the nozzle-plenum system was not insulated.

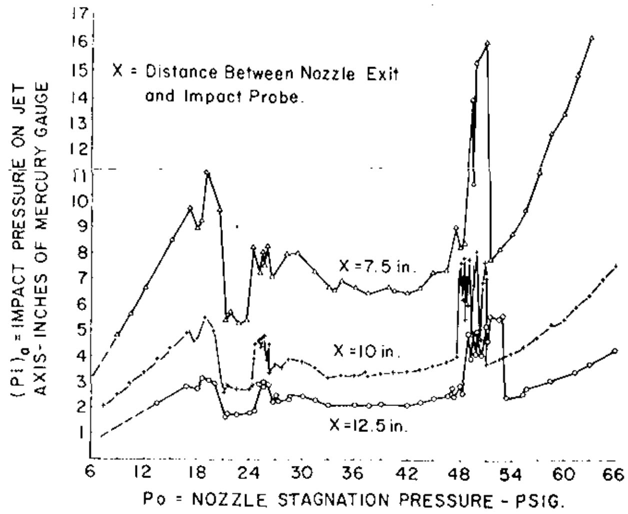


Fig. 4. Impact Pressure on Jet Axis at Various Downstream Distances.

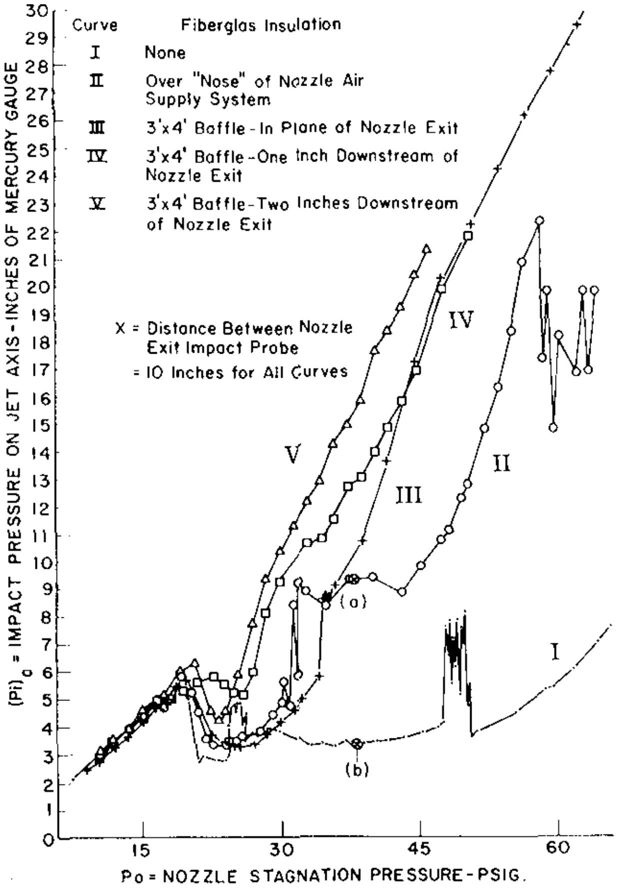
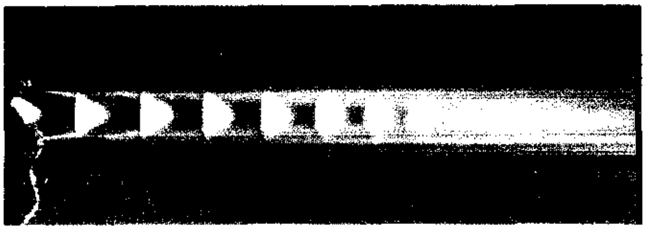


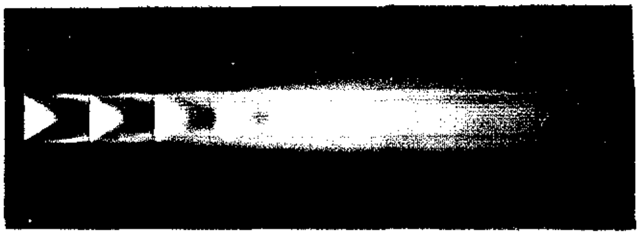
Fig. 5. Impact Pressure on Jet Axis With and Without "Insulation".

Curves III, IV, and V of Fig. 5 were obtained by placing an insulation (sound absorbing) baffle which was perpendicular to the jet axis at different axial positions with the jet passing through a hole in the baffle. The hole diameter was somewhat greater than the local jet diameter. The effects of the various configurations of insulating material are quite pronounced over most of the pressure ranges tested.

Shadowgraph pictures were taken of the jet at various conditions and in particular at conditions corresponding to points (a) and (b) of Curves II and I, respectively, of Fig. 5. These pictures are shown in Fig. 6. The effects of the acoustic feedback on the shock structure are indicated by the more rapid degeneration of the shock structure in Fig. 6(b).



(a) Insulation Separating Reflecting Surfaces from the Jet.



(b) No Insulation Separating Reflecting Surfaces from the Jet.

Fig. 6. Shadowgraphs of Jet With and Without Insulation.

Measurements were made to determine the frequency and relative intensity of the jet noise at various conditions. It was found that a dominant tone was present in those cases where the jet decayed very rapidly, such as the case indicated by the point (b) on Curve I of Fig. 5. In this particular case the frequency of the dominant tone was about 10,000 cycles/sec and was clearly audible as a "screech". At the conditions of point (a) of Curve II essentially the same frequency was indicated by the oscilloscope trace, but on an intermittent basis.

It is evident from Fig. 5 that the rate of jet decay is grossly affected by the insulation when suitably placed. It would be impossible to describe a jet which varies according to Curve II (for example) of Fig. 5 as "typical", since a different sound absorbing or reflecting system would produce a different curve for Fig. 5.

Since it was not considered practical to establish a "typical" intermediate reflector-absorber system, it was decided that only the two extremes would be investigated further. Two series of further tests were planned. In one series the acoustic effects were maximized by appropriate positioning of a metal reflecting surface upstream of the nozzle; this series is referred to simply as the "No Insulation" series. In the other series the acoustic effects were minimized by properly positioning a Fiberglas baffle; this series is referred to as the "Insulation" series.

Before choosing a particular reflector configuration for the "No Insulation" series of tests, several different ones were tried. As one extreme a nearly hemispherical reflector about 8 in. in diameter was employed. In these tests the reflector was centered on the nozzle so that the inner surface of the hemisphere faced downstream, thus tending to reflect sound waves from the downstream portions of the jet back into the jet near the nozzle exit. Tests made with this reflector resulted in an impact pressure curve which was somewhat lower at some nozzle pressures than Curve I of Fig. 5. In spite of this it was decided to make the "No Insulation" tests with a flat surface reflector, since the difference between the effects of the hemispherical and the flat reflector was not great and the flat reflector represented a somewhat more universal shape than did some arbitrary hemisphere. The flat reflector was fitted around the nozzle and positioned upstream of the nozzle exit.

Since particular frequencies are involved in this acoustic feedback problem, it would seem that by the suitable positioning of the reflector (e.g., the hemisphere or the flat disk) the acoustic effects could be minimized as well as maximized. In fact, however, no combination of reflector shape and position was ever found which was as effective as the Fiberglas insulation (absorber) in minimizing the acoustic feedback. This is presumably due, in part, to the fact that the acoustic feedback is not limited to only one frequency at a time, even though one frequency may appear to be dominant for a given set of operating conditions and configurations.

It should be noted that, while the "Insulation" tests were meant to demonstrate the minimum acoustical feedback effects and the "No Insulation" tests were meant to demonstrate the maximum acoustical effects, the results obtained do not necessarily represent the absolute minimum and maximum effects possible. There certainly must be other insulation and reflector configurations, respectively, which could extend the limits observed. It is believed, however, because of the many and varied configurations tested, that the results presented here represent nearly minimum and maximum acoustic effects for the particular nozzle and flow conditions tested.

Each test of the "No Insulation" and the "Insulation" series was made with nozzle stagnation pressures of either 1, 2, 3, or 4 atmospheres gauge. Figure 7 shows the results of the impact pressure measurements made along the jet axis while Fig. 8 presents the corresponding stagnation temperature results, plotted in terms of local stagnation temperature minus the ambient temperature. It is evident that there is a

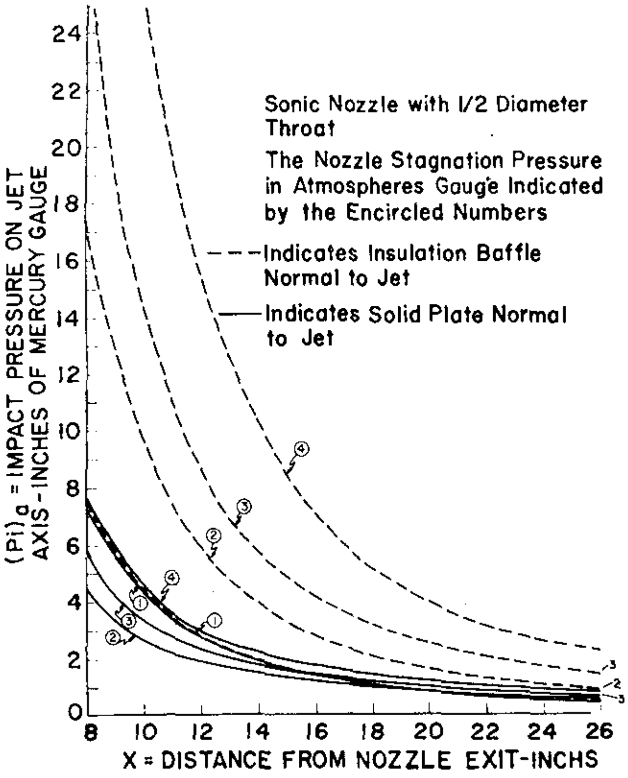


Fig. 7. Impact Pressure on Jet Axis vs. Distance from Nozzle Exit.

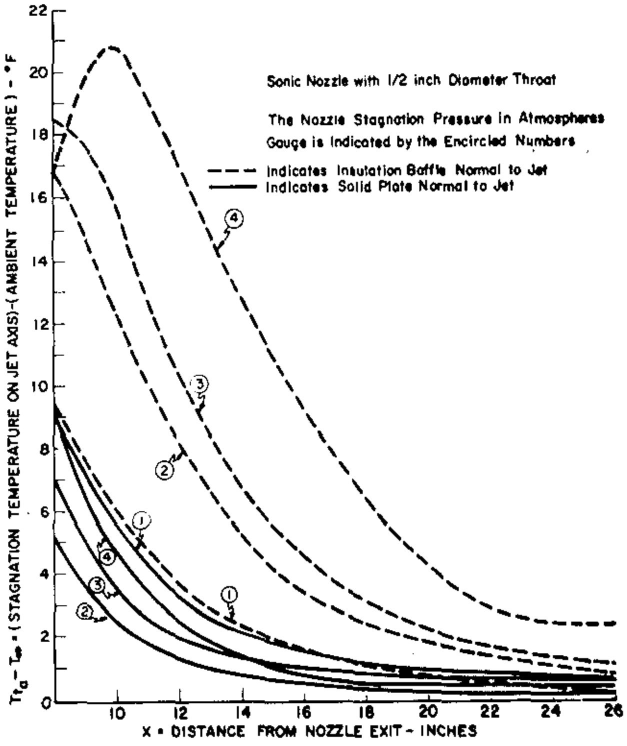


Fig. 8. Temperature Difference vs. Distance from Nozzle Exit.

significant difference between the "Insulation" and the "No Insulation" case except at the lower nozzle stagnation pressure of one atmosphere gauge. At this lower pressure the flow is barely supersonic and the shock waves are very weak. Since acoustic feedback is coupled with the shock structure it is reasonable to expect that acoustic feedback effects would disappear as the strength of the shocks in the jet approach zero.

Jet decay is frequently demonstrated by plotting the velocity on the jet axis ($V_a$) against the downstream distance (X). Such plots are made dimensionless, and hence more universal, by plotting the velocity on the jet axis divided by the nozzle exit velocity as a function of the downstream distance divided by the nozzle exit diameter (i.e. $V_a/V_e$ vs. $X/D_e$). In the present case most of the data was obtained with a convergent nozzle and with nozzle stagnation pressures well above the pressure required for choking. At some point downstream of an underexpanded nozzle the pressure in a submerged jet will be nearly equal to the ambient pressure. At this point the velocity of the jet and the diameter of the jet will approach the velocity and diameter, respectively, of a jet exiting from a properly designed nozzle, with the same stagnation and ambient pressures, respectively. The velocity and diameter at this point in the jet are referred to here as $V_e'$ and $D_e'$, and are computed in the same manner as one would compute the exit velocity and diameter of a correctly expanded nozzle. Any plots of experimental data presented here in the form of $V_a/V_e$ vs. $X/D_e$ are in fact $V_a/V_e'$ vs. $X/D_e'$.

The effects of acoustic feedback on decay are indicated by Curves I and II of Fig. 9 which are plots of $V_a/V_e'$ vs. $X/D_e'$. These two curves were computed from the data obtained during tests

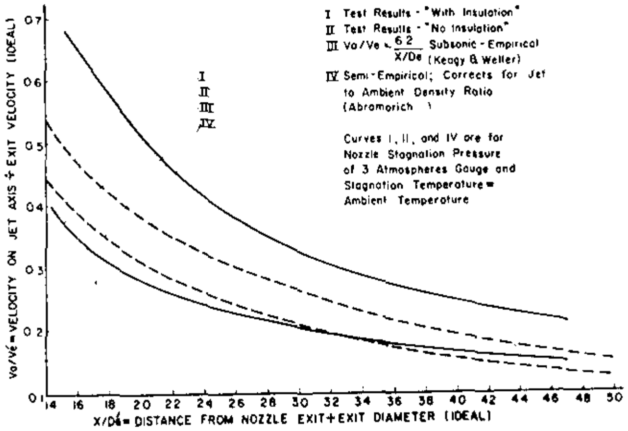


Fig. 9. Velocity Ratio vs. Dimensionless Downstream Distance.

of the 1/2 in. converging nozzle at a nozzle stagnation pressure of 3 atmospheres gauge ($V_e' = 1457$ ft/sec and $D_e' = 0.556$ in.). Curve I resulted from "Insulation" tests while Curve II resulted from "No Insulation" tests. At any given value of $X/D_e'$ between 15 and 47 the velocity is much lower when strong acoustic feedback occurs than it is when acoustic feedback is minimized. In these tests, made at a nozzle stagnation pressure of 3 atmospheres gauge, measurements within the jet were made only in the subsonic portions of the jet.

In order that these results may be compared with typical jet decay measurements, Fig. 9 includes two reference curves. Curve III is computed by an empirical equation presented by Keagy and Weller[7], which is:

$$V_a/V_e = 6.2/(X/D_e)$$

This equation is based on numerous tests of submerged subsonic jets in which the density of the gas in the jet was the same as that of the surrounding gas. Essentially identical results for these flow conditions are also presented by Abramovich[8] in his Fig. 7.37 in the form of a semi-empirical curve. Abramovich also presents test data which confirms, reasonably well, his semi-empirical curve.

In the present experiments the nozzle stagnation temperature was equal to the ambient air temperature. The static temperature at the nozzle exit was therefore less than ambient. In the tests with the nozzle stagnation pressure at 3 atmospheres gauge, the ideal exit temperature (Te', computed for complete expansion) was 353°R. The ratio of ideal exit temperature to the ambient air temperature was therefore:

$$Te'/T_\infty = 353/530 = 0.67$$

The ratio of ideal exit density to ambient air density was the inverse of 0.67.

The density of a jet relative to the density of its surroundings has a significant effect on the rate of jet decay. In particular, the greater the ratio of jet density to ambient density the less rapid will be the jet decay. Abramovich presents semi-empirical curves for a range of density ratios in his Fig. 7.37. These curves of Abramovich were used to compute Curve IV of Fig. 9 using a temperature ratio of 0.67. The effect of increased jet density is evident from a comparison of Curve IV (the greater density) with Curve III.

Abramovich also presents semi-empirical relations which are applicable to jets which are initially supersonic; the relations are not limited to the supersonic portions of the jet. These relations are developed for the limited case where the stagnation temperature of the jet at the nozzle exit is the same as the temperature of the gas surrounding the jet. Since this condition is met in the present tests, Abramovich's relations should be applicable. However, application of Abramovich's supersonic relations to the present case results in a curve which is essentially the same as Curve IV of Fig. 9, so an additional reference curve was not drawn on Fig. 9. Abramovich also presents test data for a jet having an initial Mach number of 1.5, which agrees reasonably well with Curve IV of Fig. 9.

It is clear from the above discussion that there is empirical justification for considering Curve IV of Fig. 9 representative of the velocity decay curve which might be expected under the test conditions of Curves I and II of Fig. 9. Obviously neither Curve I nor Curve II agree with Curve IV.

The rate at which a jet decays is indicated by the rate of jet spread as well as by the rate of velocity decrease along the jet axis. A series of tests were therefore made in which the stagnation temperature and pressure were measured along diameters through the jet. These traverses were made at axial positions 10, 15, 20, and 25 in. downstream of the nozzle exit. Half of these tests were made with Fiberglas insulation and half without, in order to compare the "Insulation" and the "No Insulation" cases. Figure 10 shows the variation of impact pressure with jet radius for these two cases. Plots of $V^2$ vs. jet radius would be very similar to the curves of Fig. 10 since the jet is subsonic and at constant pressure (ambient) in all cases.

Figure 11 is a plot of the difference between local stagnation temperature and ambient temperature vs. radial position within the jet. In the "No Insulation" case the maximum temperature differences were so slight (less than 1°F) at the 20 and 25 in. positions that the recorded temperature difference data were not meaningful. Variations in room air temperature were of almost the same order as the temperature differences being measured.

A comparison of the corresponding curves in Figs. 10 and 11 clearly demonstrates the extent of the effect of acoustic feedback on the spread and decay of the jet. At a downstream distance of 10 in., for example, the jet diameter is nearly doubled due to acoustic feedback and the centerline velocity reduced by over 50%.

The velocity profiles computed from the results of the "Insulation" and "No Insulation" tests for both the 10 in. and 15 in. locations are plotted in Fig. 12 in the form of $V/V_a$ vs. $r/r_o$. Here $V_a$ is defined as the velocity on the jet axis at the

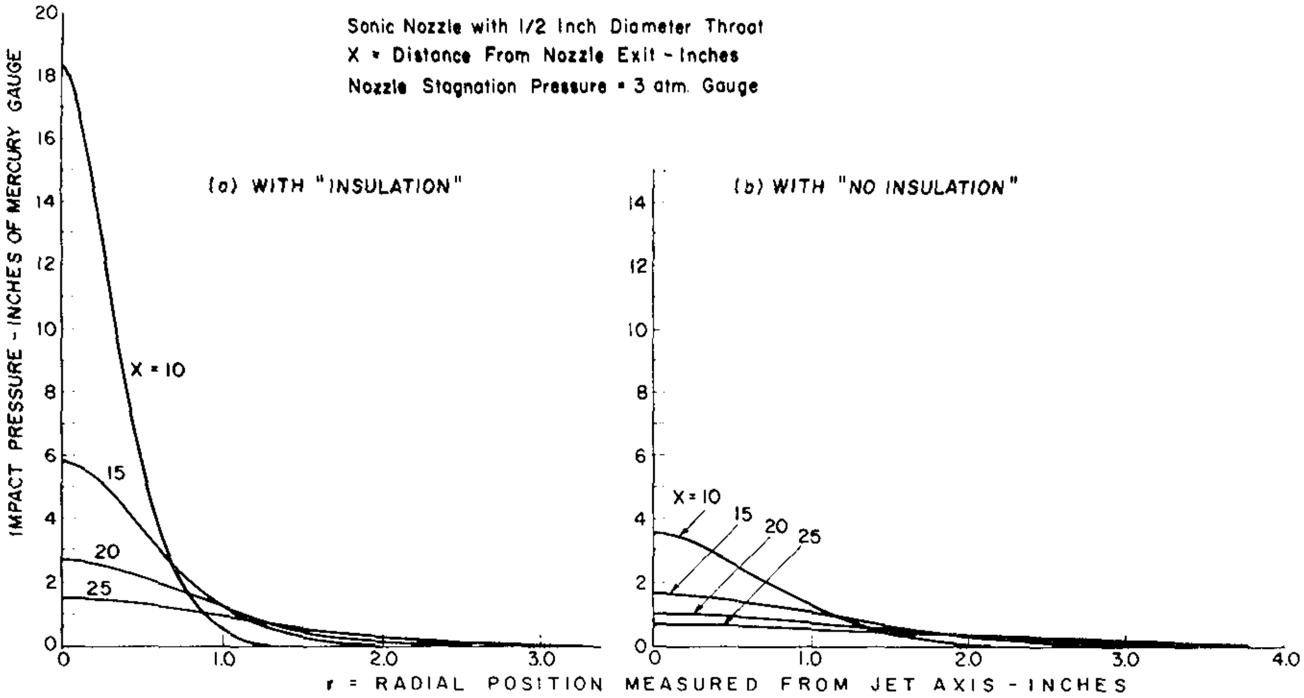


Fig. 10. Impact Pressure vs. Radial Position in Jet.

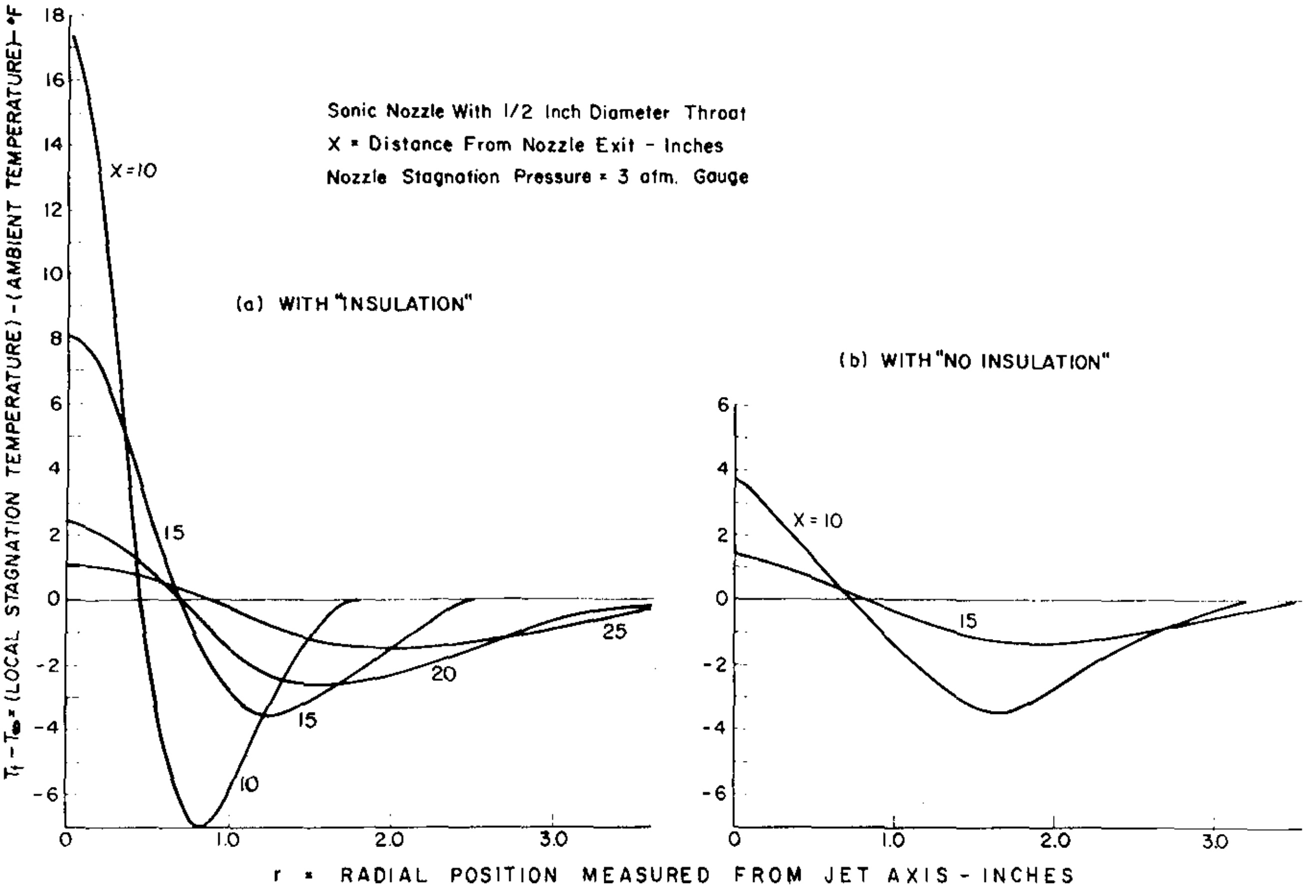


Fig. 11. Stagnation Temperature Difference vs. Radial Position in Jet.

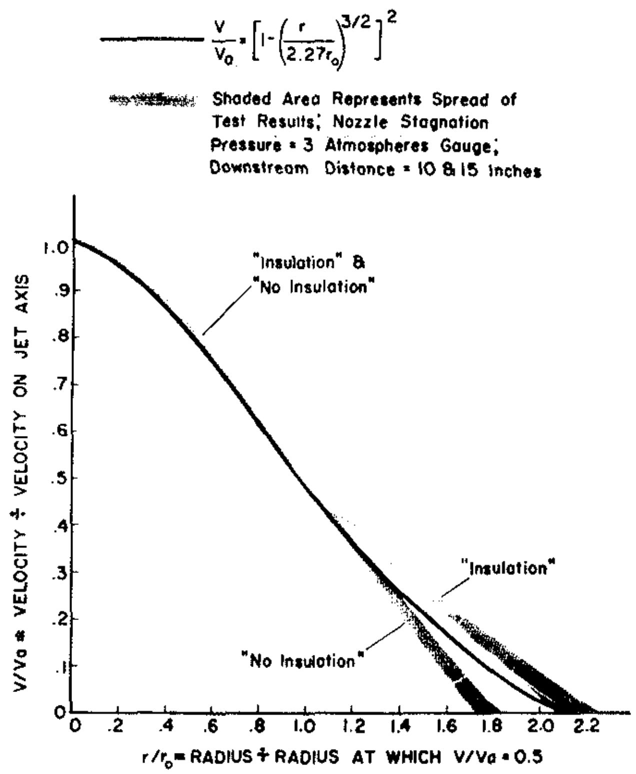


Fig. 12. Dimensionless Velocity Profiles.

particular downstream location in question, while $r_0$ is defined as the radial position within the jet at which $V = V_a/2$.

The dimensionless velocity profiles computed from the results of the "Insulation" and "No Insulation" tests, at downstream positions of 10 and 15 in., are represented by the shaded regions of Fig. 12. The single line curve of Fig. 12 was computed from the so-called "Schlichting formula" (Ref. 8, page 276). Dimensionless velocity profiles within the main region of turbulent jets typically fit this curve rather well, but usually with some scatter. It is evident from Fig. 12 that the results of the present tests fit this theoretical curve fairly well except near the outer portions of the jet. It is not surprising that some differences between the velocity profiles of the "Insulation" and the "No Insulation" tests occur, in view of the differences in these two cases as indicated by Figs. 10 and 11. It is surprising, however, that the dimensionless velocity profile for the "No Insulation" tests appears to depart appreciably from the typical profile, since the jet in this case has apparently mixed more rapidly, and in effect has had longer to become a well established subsonic turbulent jet. Many of the dimensionless velocity profile plots of test data by other investigators also demonstrate a rather wide scatter of data points near the jet boundary. In view of this it seems unwise to attempt to draw any conclusions from the discrepancy between these test results and the typical dimensionless velocity profile curve.

In Fig. 13 the jet radius and the half-velocity radius are plotted vs. downstream distance for the "Insulation" and the "No Insulation" cases at nozzle stagnation pressures of 3 atmospheres gauge. This figure clearly illustrates the fact that the jet with no insulation separating the jet from the reflecting surfaces spreads much more rapidly than does the jet in the "Insulation" case. At X = 10 in. for example, the jet diameter in the "No Insulation" case is almost twice the jet diameter of the "Insulation" case.

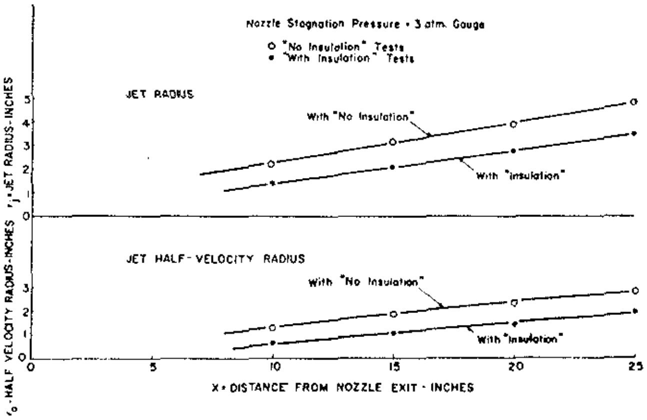


Fig. 13. Jet Radius and Half-Velocity Radius vs. Distance from Nozzle Exit.

The literature on turbulent jets (e.g., Abramovich[8]) frequently refers to the fact that the downstream or "main" part of the jet usually spreads at a constant angle (excluding such cases as extreme density differences). It is evident from Fig. 13 that this is also the case here, in that portion of the jet for which data are presented, even though the initial rates of spreading are quite different for the "Insulation" and "No Insulation" cases. Figure 13 also indicates that at the extreme downstream positions the percentage difference in jet diameters for these two cases will become smaller.

An attempt was made to determine the turbulent Prandtl number in the main part of the jet from the data available. The calculations indicated that it would have been necessary to make the traverses of the jet closer together to provide sufficient data for the calculation of the Prandtl number.

Further tests will be needed to establish in greater detail the nature and the extent of these acoustic feedback effects.

## III. Conclusions

Sound waves generated by a supersonic jet under certain conditions can significantly increase the rate of jet spread and decay. These sound waves are of particular frequencies, or ranges of frequency, for a given jet, and are apparently the same sound waves which cause "Jet Screech".

Velocities on the jet axis at downstream positions (e.g., 15 jet diameters) can be reduced by almost 50% and the rate of jet spread increased by nearly 50% by this acoustic feedback.

Although the general pattern of turbulent jet mixing under the effects of acoustic feedback is apparently in accordance with classical theories regarding turbulent jet mixing, the exchange coefficients appear to be higher than the literature usually indicates. In many applications it would be necessary to consider the acoustic feedback effects before selecting the values of the exchange coefficients to be used.

It appears that the destructive sound waves are produced in the supersonic part of the jet at some distance from the nozzle, travel upstream in the ambient air, and then act upon the initial portions of the jet. A sound absorbing material surrounding the jet (placed just downstream of the nozzle in such a way as to intercept the sound waves in the ambient air) can considerably reduce if not eliminate the effects of acoustic feedback. Disturbing the shock cell structure or making all shocks very weak may also reduce the effects of acoustic feedback.

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