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# Qualitative Investigation of Cryogenic Injected Shock Dissipation

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# QUALITATIVE INVESTIGATION OF CRYOGENIC INJECTED SHOCK DISSIPATION

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## ABSTRACT

The injection of fluid nitrogen into the flow field discharged from a two-dimensional, ambient, static-temperature and static-pressure Mach = 2.7 nitrogen flow tunnel was observed. A bow shock stands approximately one diameter off the end of the 3.2 mm o.d. x 1.6 mm i.d. injection tube placed directly into the tunnel exhaust. Cryogenic injection creates a high density region in the injected region and within the bow shock wake but the standoff distance remains unchanged. However as the temperature reaches a critical value $T^*_{inj}$ the sharp shock interface begins to fade resembling the density gradient seen at the interface of a supercritical fluid and the shock interface begins to move into the supersonic stream. As the injection temperature decreases, the interface continues to move into the supersonic stream and becomes more diffuse; the shock interface can not be distinguished. The phenomena is completely reversible.

## INTRODUCTION

The fracturing of a supercritical-pressure water stream discharged to ambient conditions has been studied by Field and Lesser.[1] The shock structure is evidenced in his photographs and stream breakup is cataclysmic. Droplets are rapidly dispersed. The fracturing of sub- and supercritical-pressure, radial inward flows has been studied by Hendricks et al.[2] Motion pictures of the flow between parallel disks spaced 0.076 mm apart show rapid stream breakup immediately downstream of the exit plane. The flow appears finely dispersed with the potential of fluid fracture occurring within the passage. Fluid injection into high-velocity gas streams has been investigated by several authors interested in maintaining a film adjacent to the wall to provide film cooling (e.g., Papell[4] and Simon and Ciancone[5]). The injection of supercritical-pressure fluids into combustors is commonplace in rocket propulsion. In analyzing the streams, liquid is assumed to exist and to vaporize as the stream traverses the chamber.[6] Reichenback and Horn[7] related injection properties to penetrating distance for liquid injection into supersonic flow streams. Hendricks et al.[8] injected a M = 2.7 gaseous nitrogen flow field to determine the penetration distance with injection angles of 90 and 20 degrees to the flow. The injected fluid temperature of nitrogen was above $T^*_{inj}$ = 95 K.

From these experiments[1-3,7,8] it is clear that supercritical-pressure jets fracture almost immediately after discharge and that fluid streams can penetrate supersonic flow fields. It is not clear when the high-pressure stream is a cryogen and is injected directly into and opposing a supersonic gaseous flow, how the fracture will occur, or what are the effects of $T_{inj} < T^*_{inj}$ . This paper describes a qualitative investigation into this problem.

## EXPERIMENT

The experiment is classically simple. One designs and fabricates a Mach 2.7 two-dimensional gas nitrogen tunnel and couples it with a high pressure cryogenic source. The two-dimensional tunnel,[8] and cryogenic source,[9] both using nitrogen, are illustrated schematically in Fig. 1. The tunnel operates at 2.3 to 2.4 MPa in the chamber, achieving Mach 2.7 at ambient pressure. This flow field is maintained for nearly 760 mm and discharges to ambient.

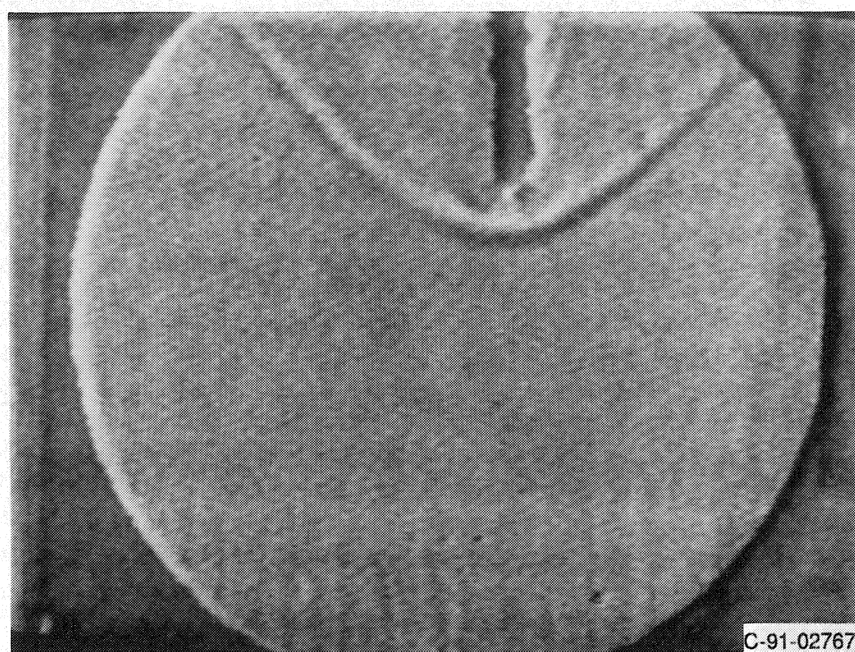


Figure 1.–Bow shock formation for gaseous nitrogen injection.

The injection tube was fabricated of 3.2 mm o.d. x 1.6 mm i.d. copper tubing. The pressure was measured prior to injection and the temperature was measured less than 1-diameter upstream from the injection plane on the outside of the copper tube. The thermocouple ball was soldered to the tube and the lead wires tightly wrapped around the tube out of the flow field.

The injection fluid was passed through a copper coiled heat exchanger in a liquid nitrogen bath open to ambient.

Calibrations indicated that the flow field Mach number was nearly 3.0 versus the 2.7 design value within the two-dimensional tunnel.

A shadowgraph scheme was devised to observe the flow field and the results were recorded on videotape. The flow field noise level was intense and strongly effected some video cameras.

## RESULTS

Figure 1 illustrates gaseous nitrogen injection into the supersonic flow field. The injection pressure is a nominal 6.9 MPa. The sharp interface of the bow shock is clear as are some aftershocks leaving the thermocouple lead wire wrapped about the injection tube.

With cryogenic injection, the injection tube is obscured and the details of the bow shock injection interface become unclear so the question of how the interface fractures can not be answered with fidelity. However the bow shock remains unchanged even though the aftershock region clearly shows a darkened region of higher density, Fig. 2. The injection temperature is above $T^*_{inj}$.

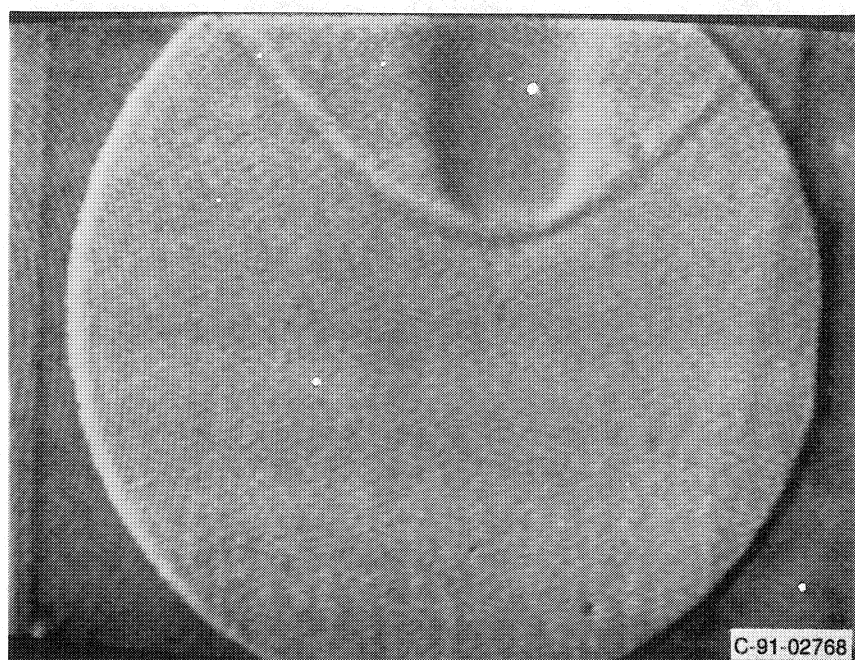


Figure 2.–Bow shock formation for cryogenic nitrogen injection with $T_{inj} > T^*_{inj}$.

As the injection temperature decreases to $T^*_{inj}$, the sharpness of the bow shock declines and the shock interface standoff distance increases as the shock begins to advance into the supersonic flow stream, Fig. 3.

For $T_{inj} < T^*_{inj}$ the appearance of Mach lines and the growth of the injected region continues. The standoff distance continues to increase, Fig. 4.

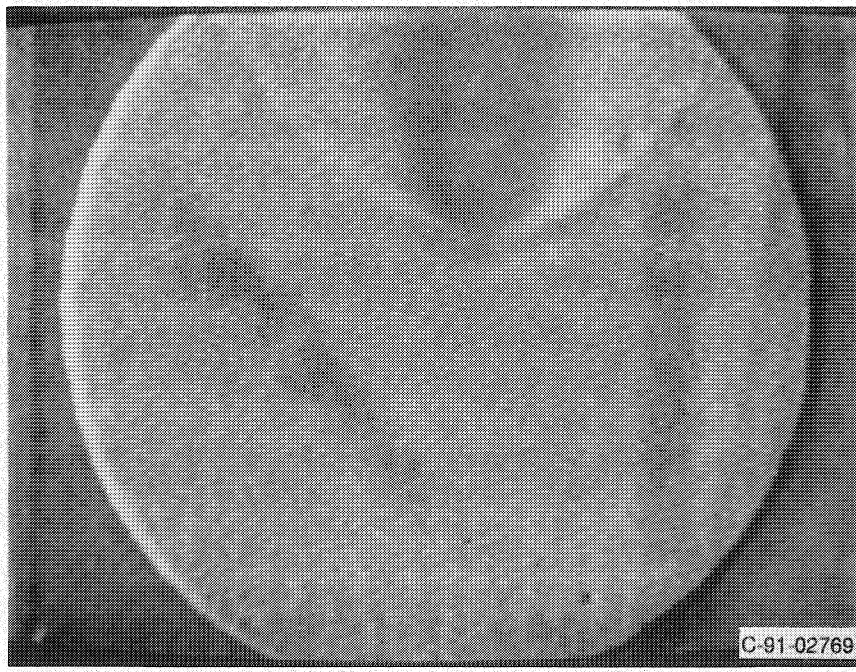


Figure 3.–Incipient shock dissipation for cryogenic nitrogen injection, $T_{inj} = T^*_{inj}$.

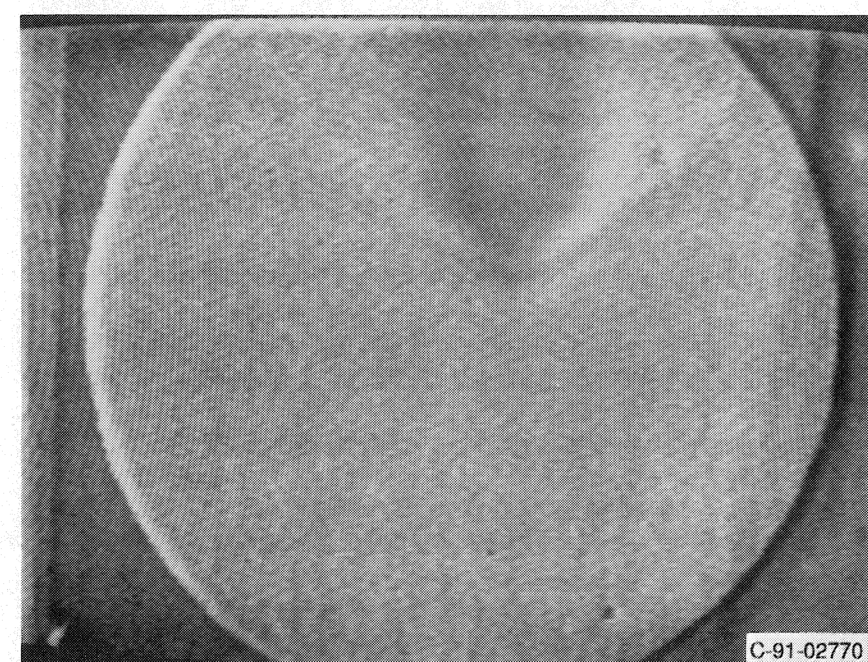


Figure 4.–Shock dissipation for cryogenic nitrogen injection $T_{inj} < T^*_{inj}$.

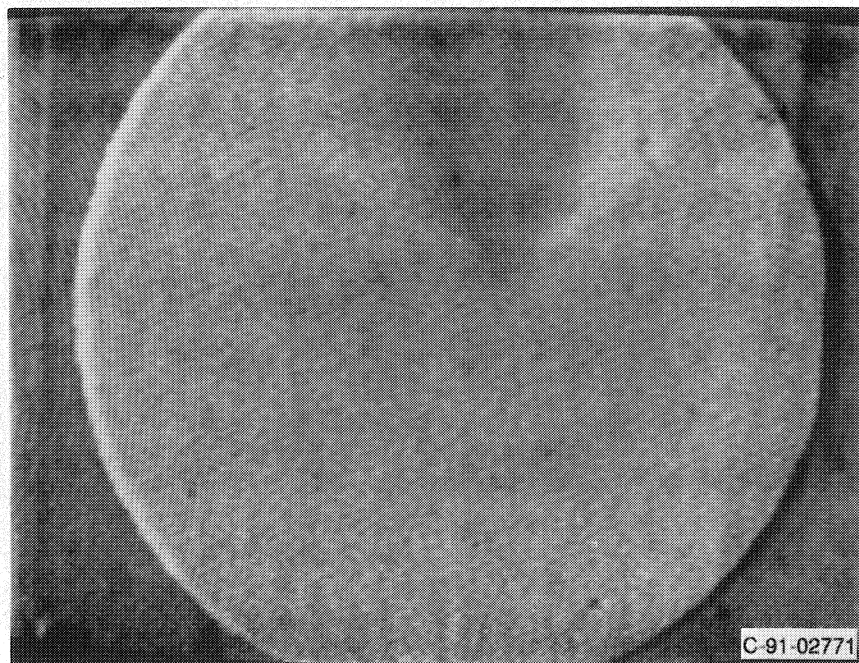


Figure 5.–Dissipation to a faint interface for cryogenic nitrogen injection $T_{inj} < T^*_{inj}$.

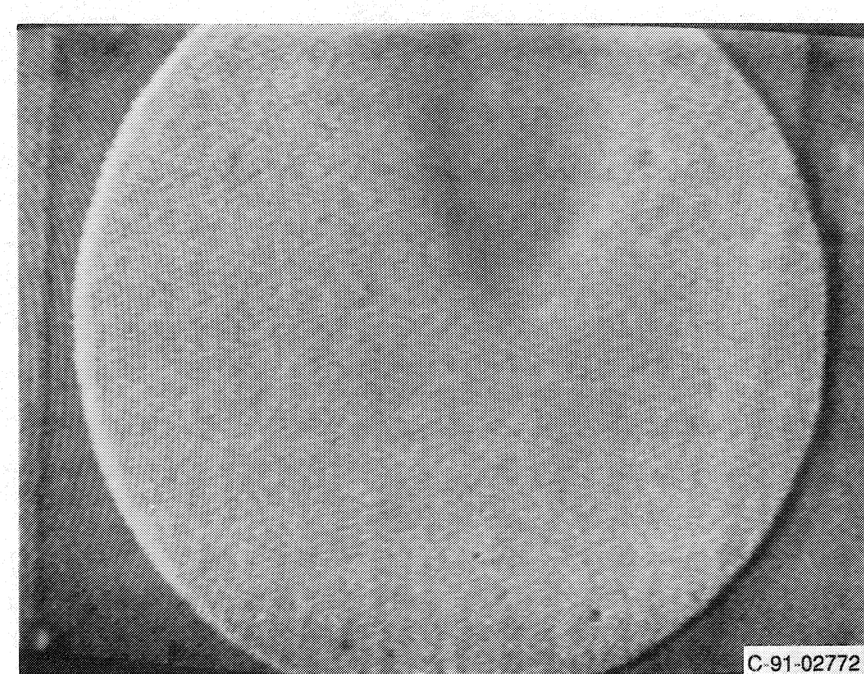


Figure 6.–Dissipation of the characteristic shock front for cryogenic nitrogen injection $T_{inj} < T^*_{inj}$.

Decreasing $T_{inj}$ still further, Fig. 5, only a faint resemblance of the shock region can be found.

At the lowest injection temperature provided from this system, the darkened region provides evidence of the cryogenic injection, but the shock appears dissipated, Fig. 6.

Each step of the shock dissipation can be readily retraced by increasing $T_{inj}$ until $T_{inj} = T^*_{inj}$ and the bow shock will reappear for all $T_{inj} > T^*_{inj}$. Small temperature changes about $T^*_{inj}$ provide a shock or no shock phenomena.

## SUMMARY

The effects of injecting supercritical pressure fluid nitrogen into a supersonic flow were observed. For injection temperatures above a critical value, there was no effect on the bow shock. At the critical injection temperature the shock strength weakens significantly and at lower injection temperatures the interface is diffusive. For a fixed injection pressure, there is no change in the standoff distance until the injection temperature is less than the critical injection temperature. The observed phenomena is completely reversible. Photographic details of the interface are lacking, so how the interface fractures is not resolved.

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