TRANSVERSE INJECTION OF A PARTICLE-LADEN LIQUID JET INTO A SUPERSONIC AIR STREAM

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LIST OF SYMBOLS

Symbol	Definition	Units
h	height above the plate	mm
H	liquid plume penetration height	mm
I	intensity of the light that passes through the suspension	watts
I_o	intensity of the light that passes through when suspension is absent	watts
N	number of particles that light beam passes through	
$\bar{q}$	$= \rho_j v_j^2 \left(\rho_\infty v_\infty^2\right)^{-1}$, momentum flux ratio	
$\bar{q}_\ell$	$= \rho_\ell v_j^2 \left(\rho_\infty v_\infty^2\right)^{-1}$	
v	velocity	m/sec
ρ	density	gm/mm^3
γ	extinction coefficient per particle	

Subscripts

j	initial injectant conditions
ℓ	liquid
∞	air (free) stream conditions

INTRODUCTION

The drive to achieve increased range, compactness, and high-speed continuous power in missiles and aircraft has led to renewed interest in high-energy fuels. A number of these high-energy fuels are formed by suspending metal powders in conventional liquid hydrocarbon fuels. The metal powders, such as aluminum, magnesium, and boron, surpass liquid fuels in energy content as shown in Table 1. In terms of heat of combustion per unit volume or per unit pound of air, the metal powders possess values which are double or triple those of JP-4, a common liquid fuel.[1] These values are important since they determine how small the intake of the jet engine can be and how much fuel storage volume is required for a given mission.

The increased energy content of fuels is necessary for high performance and compactness. This level of performance is critically needed in the next generation of tactical and strategic missiles. The missiles need to be able to out-maneuver evasive targets, to penetrate the target's defenses, and to be fired from a greater standoff range than is required today. To insure that the missiles can meet these requirements, the missiles must have high specific thrust, high speed, and high continuous thrust.[2] A ramjet with high-energy fuels appears to be the most promising choice for the new generation of missiles.

From studies conducted at the NACA Lewis Laboratory[1,3] during the 1950's, some of the combustion characteristics of these slurry fuels are known and appear very promising. In a series of combustion tests

the slurry fuels produced higher air-specific impulse thrusts than ordinary liquid fuels. Whereas JP-4 produced a specific impulse of 170 kg-sec/kg air, 59% (by mass) slurries of boron and magnesium in JP-4 produced 176 and 184 kg-sec/kg air respectively. Aluminum powder produced a specific impulse of 213 kg-sec/kg air. Increases in combustion efficiency and blow-out velocity for the slurry fuels were also noted. The metal powders proved difficult to inject and ignite without a liquid carrier. The liquid fuel in which the metal particles were suspended greatly enhanced the ignition and simplified the injection of the powder. Higher combustion temperatures were, however, required for the slurries. The 50% slurries of boron and magnesium required temperatures of 2585 °K and 2640 °K respectively for combustion. The combustion temperature of JP-4 is 2320 °K.

Problems with long-term storage and undesirable combustion products were encountered during the NACA study. Since the oxides formed from such metals as boron and aluminum have extremely high melting and boiling temperatures, these combustion products exist in a combination of liquid and solid states at the temperatures encountered in jet engines. Consequently, the oxide particles are usually glutinous. The oxide particles agglomerate through collisions and collect on engine surfaces. The large mass of the agglomerated particles prevents the particles from remaining in velocity and temperature equilibrium with the exhaust gas. Since the agglomerates are not in equilibrium with the gas flow, they cannot contribute all of their energy to the gas as it expands through the nozzle. The loss in available energy directly

leads to a reduction in the amount of thrust obtainable.

In the late fifties when the problems with the slurry fuels were being discovered, advances in liquid fuel technology were being made. These factors, along with the lack of today's sophisticated guidance systems which can utilize the high performance possible with these slurry fuels, led to the shelving of slurry fuel research. Only within the last decade has research in this area been rekindled.

The present study was directed at examining the penetration and the break-up behavior of slurries injected transversely into a supersonic flow of air. This study would thus be of primary pertinence to supersonic combustion chambers, such as found in scramjets, although the research could be applied to subsonic situations. Little research has been performed with these particle-laden jets although more work has been done with solid-gas jets and pure liquid jets.

The solid-gas jet studies have determined a relationship between the size of the particles and their penetration when injected transversely into an air stream. Edelman, Economos, and Boccio[4] discovered that 1 to 5 micron diameter particles remained "locked" within the gas jet. Rudinger, commenting on a paper by Salzman and Schwartz[5], noted that in his tests, 33 micron particles were found to separate from the gas jet. The 15 micron particles used by Salzman remained within the confines of the gas jet, but the maximum of the particle concentration had shifted toward separation. The densities of the particles used in the preceding studies were approximately the same as the silicon dioxide (sp. gr. = 2.35) particles used in this study.

Several investigators have studied the behavior of a liquid injected transversely into an air stream (Ref. 6-11). As the liquid jet bends under the influence of the high speed air stream, high speed, large amplitude waves develop on the jet surface. The waves quickly grow, fracturing the jet into large clumps. Farther downstream, the clumps decompose into smaller clumps and, eventually, into droplets. The penetration of the jet was found to increase as the momentum flux ratio was increased.

In this study, the slurry fuels were simulated by suspensions of silicon dioxide particles in water. The particles had an average diameter of 5 microns which corresponds to the size of particles used in the NACA Lewis study (1 to 5 microns). Concentrations of particles of up to 60% by mass were tested. Streak photographs were taken to measure the liquid jet penetration and Nanoflash pictures were taken to study the jet break-up and the interaction between the particles and the liquid. A laser light-extinction survey was conducted in order to further quantify the behavior of the jet. All of the tests were conducted with a Mach 3.0 flow of air.

THEORETICAL CONSIDERATIONS

Light Extinction Measurements

To measure the concentration of small particles suspended in a medium, light extinction measurements are often taken. The extinction is the amount of light which is absorbed or scattered by the particles as a beam of light passes through the suspension. Light extinction surveys compare the intensity of light that passes through the test area when the suspension is present with the intensity when the suspension is absent. The difference in the two intensities is labelled the extinction.

The Lambert-Beer Law, the governing law for extinction measurements, can be written as $I = I_o e^{-\gamma N}$. In this form of the equation, each particle is assumed to possess the same extinction coefficient, γ. This is not precisely true, since each particle will possess its own coefficient based on its cross section, absorptive properties, and index of refraction. Each of these properties are functions of the particle size; the latter two are also dependent on whether the particle is a liquid droplet or a solid particle (and on which liquid and which solid).[12,13] In general, a large particle scatters more light than a smaller one, but it will scatter the light through a smaller solid angle.[14]

The assumption that the extinction coefficient is constant in this investigation is a reasonable one and is born out by the results. The tests were conducted thirty millimeters downstream of the injection orifice. Previous investigations with liquid jets have shown

that the droplet size does not vary much in the transverse direction this far downstream, since the jet is fully atomized.[11] If the size does not vary much, neither should the extinction coefficient. From the results, the extinction due to a solid particle is similar to that of a liquid droplet.

A complication arises from the fact that despite how small or precise the measuring device is made, some light that is diffracted will be collected and measured. This complication occurs when the angle of diffraction is extremely small.[12] Only with large particles, however, is much light diffracted at very small angles. For the extinction equipment and particles used in this investigation, this effect was negligible.

An observation regarding the Lambert-Beer equation needs to be made. For the series of tests, I_o, the intensity measured when no suspension was present, was a constant. Assuming that γ is a constant, then the log of the intensity should be linearly proportional to the number of particles (including droplets) present. This fact was used in the reduction of the data.

Properties of Small Particles

Very small particles tend to flocculate when wetted forming extremely muddy suspensions. The flocculation is caused by the following interparticle attractive forces: gravitational, van der Waals, and dipole-dipole forces. These forces depend on the surface chemistry and the density and size of the particles. The smaller or less dense

the particles, the more important these forces become due to the increase in the surface-to-volume ratio and the reduction in particle mass. Increases in size and density lead to faster settling rates; the surface charge of the particles are no longer sufficient to keep the particles suspended.[15]

Surface-active agents may be added to the solution to disperse the particles. The additives surround the particles with charged ions which makes the particles mutually repulsive. Other types of additives surround the particles with a solvent aqueous envelope which prevents the particles from approaching each other, thus not allowing the interparticle forces to come into play.[15]

Suspensions of very small particles exhibit high viscosity. In the NACA studies, a 50% slurry of magnesium in liquid fuel had a viscosity equivalent to that of honey. Additions of surface active agents of only a few percent reduced the Brookfield viscosity by as much as two orders of magnitude. The trouble encountered with these agents was that as they decreased the viscosity, the settling rate increased dramatically. The fast settling rate made storage of the suspensions inconvenient and impractical.[16,17] NACA, for their tests, added a mixture of surface-active agents and gelling agents to their suspensions in order to achieve a practical compromise; a slurry that had a low enough viscosity so that it could flow through pipes easily but yet viscous enough to prevent rapid settling.[3]

The slurries are definitely non-Newtonian. The viscosity drops significantly with increases in the shear rate to which the slurry is

subjected. Consequently, agitation and the pumping of the slurry through pipes decreases the viscosity allowing the suspension to flow easily. The agitation and shear forces also serve to disperse the particles, thus forestalling settling.

In this investigation a mixing tank was used to agitate the suspension and to disperse the particles in the liquid. No agents were added to the slurry. For suspensions of 50% loading or less no significant problems were encountered with settling or pipes jamming. Suspensions of around 60% loading, however, presented settling and pipe jamming problems.

EXPERIMENTAL APPARATUS AND PROCEDURES

Test Facility

Tests were conducted in the Virginia Tech 23 cm by 23 cm supersonic tunnel. The tunnel is of the blow-down type and has interchangeable test sections. For this investigation a test section designed to produce a Mach number of 3.0 was used. The section was fitted with large windows of good Schlieren quality for photographic purposes. Figure 1 presents a sketch of the test facility.

Throughout the tests a stagnation pressure of 4.2 atm. $\pm$ 2% was maintained. The stagnation temperature was that of the ambient air, approximately 15 °C. The stagnation pressure and temperature, as measured by a transducer and thermocouple, were recorded on a HP 71008 strip chart, as was the output of the injection flow meter.

Flat Plate Model

The slurry was injected through a flat plate model having dimensions of 10.0 X 15.25 X 0.9 cm. The model had a sharp leading edge, as shown in Figure 2. The model was attached to the bottom of the test section by a 5.0 cm. support. The support had a diamond cross-section, and it was centered in the test section. The injection orifice was located 8.0 cm downstream of the leading edge. With a diameter of 1.0 mm, the injection orifice had a 1.6 mm straight run and a smooth conical entry passage.

Injectant

The high-energy fuels were simulated by a slurry formed by sus-

pending silicon dioxide particles in water. The decision to use a simulated fuel was dictated by safety considerations. The silicon dioxide particles had an average diameter of 5 microns and a density of 2.35 grams per milliliter. The particles were crude crystals in shape, with disorderly protrusions. In size and texture the particles resembled baking flour. The silicon dioxide particles were similar to the metal particles under consideration for use with liquid fuels in terms of size, shape, and density (see Table 1 for the densities of the metals). The particles were obtained from Atlantic Equipment Engineers.

Mixing Tank and Injection System

A Glascote anchor-type mixing tank was used to suspend the particles in the water. Equipped with a rotary mechanical seal, the tank could be pressurized to 34 atm for injection purposes. The mixing shaft was powered by an externally mounted motor. The 3500 RPM, 3 HP motor was geated down to 100 RPM in order to provide the needed power at the operating speed of the mixer. Two pressurized nitrogen bottles were required for the tank: one pressurized the tank, the other (at a slightly higher pressure) provided pressure to the seal. By controlling the pressure inside the tank, the rate of slurry flow could be regulated. Figure 3 shows the design of the mixing tank and the rest of the injection system.

Under pressure, the slurry would flow through an on-off ball valve and a Ramapo V-½ SS flow meter. The flow meter operated by measuring

the drag force of a body situated in the flow. The force was converted to an electrical signal by a set of strain gauges. The selection of the valve and flow meter was a crucial decision in the investigation. Several types of valves and flow meters were tested with the slurry; most jammed quite readily with the particles. The pressure activated valve and the flow meter used in this study handled the slurry well with only a minimum of trouble. The drag force-type flow meter also had the advantage of being independent of the loading of the slurry (with regard to the dynamic pressure).

The flow line was equipped with another valve to permit back-flushing of the line and flow meter. Without this flushing the pipe lines would jam and the flow meter would produce spurious readings. To further reduce the possibility of jamming and to reduce pipe wear and flow irregularities, sharp turns were avoided in the line.

With the described mixing system, uniformly-mixed slurries could be consistently obtained. Loadings of up to 68% were achieved and successively injected into the wind tunnel.

Testing Procedure

To minimize the collection of slurry and particles in the test section windows, the wind tunnel would be started before the injection began and would continue to run after the injection had terminated. The data was taken after both the air flow and injection had stabilized at steady conditions. For repeatability and convenience, these functions were performed by a timer. The strip chart, besides

recording the stagnation values and the slurry flow rate, also noted the time at which the data (or picture) was taken. Immediately following each run, the flow meter and line were back-flushed with water.

Photographic Procedures

Two types of photographs were taken: streak and nanoflash. To measure the penetration, a time-averaged view of the constantly fluctuating jet was required. A flash duration of at least a millisecond, producing a streak picture, was required to capture such a view. For stop-action shots that reveal the structure of the jet, a very short flash duration of the order of ten nanoseconds was needed.

A Vivitar 283 flash unit was used to produce the streak photographs. The flash unit was placed at the focus of a parabolic mirror. The flash was reflected off the mirror producing a parallel beam of light incident on the jet. The magnification factor of these photographs was one-to-one.

For the stop-action photographs, a Nanopulser was used. The flash duration of the Nanopulser was approximately 14 nanoseconds. The nanopulser was placed a few centimeters from the test section. A 20 cm focal length lens was positioned on the opposite side of the wind tunnel to achieve a 4X magnification. The two camera set ups are shown in Figure 4.

For both types of photographs a simple bellow-box camera was used. When used with the Nanopulser, the camera was placed at the focal plane of the lens. Both the lens and camera were mounted on an optical bench.

Polaroid Type 57 (3000 ASA) print film was used in a Polaroid film holder.

Extinction Measurements

The light source for the extinction measurements was a Spectra-Physics Model 120 Helium-Neon Laser (15 mW output, Class IIIb). The laser was powered by a Spectra-Physics Model 249 Laser Excitor. An optical bench possessing three degrees of movement was used to mount the laser and the rest of the optical equipment.

The light intensity was measured by a RCA C7164R photomultiplier tube. The photomultiplier was powered by an Ortec 456H High Voltage Power Supply set at 700 volts. A grounded, metallic cylinder encased the photomultiplier tube to prevent any stray radiation from interfering with the data. The cylinder had been painted flat black so that light would not reflect off it. On the tunnel-side of the cylinder, a black aperture plate was mounted. The plate had an aperture drilled into it which was slightly smaller than the laser beam. The diameter of the laser beam was 0.24 mm. In Figure 5 the optical set-up has been illustrated.

The output of the photomultiplier tube was fed into a logarithmic amplifier. The amplifier was based on the Burr-Brown Logarithmic Amplifier Chip 4127KG. Two Texas Instruments 718 chips buffered and inverted the signal. The output of the amplifier was fed into a Bascom-Turner 8110 Series data acquisition system. The system had been programmed to record 500 data points in a one second interval. Each set

of 500 data points constituted a single record. Five consecutive records were taken during each run. The data was recorded onto a disk and later plotted.

RESULTS

The penetration of the particle-laden liquid jet into a supersonic flow was complicated due to the separation of some of the solid particles from the liquid plume. The nanoflash photographs clearly showed agglomerates of solid particles penetrating further into the cross flow than the liquid (Figure 6). This separation was evident in the streak pictures as a smearing of the penetration profile (Figure 7). Whereas pure liquid injection produces a rather definite, easily discernible penetration profile, the slurry injection produced an indistinct profile whose outline could not be readily discerned.

The penetration height is usually defined as the vertical extent of the densest portion of the jet as viewed in the streak photographs. For the slurry jets this height corresponded to the extent of the liquid portion of the jet. Attempts to base the penetration height upon the penetration of the particles yielded inconsistent results. The streaks due to the particles (as in Figure 7) merged gradually into the airstream, thus defying attempts to clearly describe a penetration height for the separated particles.

The penetration height (for the liquid plume) was measured at a distance 30 mm (30 orifice diameters) downstream of the injection orifice. At this streamwise location, the jet had reached its maximum penetration into the airstream due to its transverse momentum. Turbulent mixing increased the apparent penetration farther downstream. In Table 2 the penetration height is given as a function of the momentum

flux ratio, $\bar{q} \equiv \rho_j v_j^2 \left(\rho_\infty v_\infty^2\right)^{-1}$, and the loading. The loading is defined as the percent of solid particles in the slurry by mass.

For a given loading, the penetration height follows the usual relationship with the momentum flux ratio: as $\bar{q}$ is increased, the penetration height increases as well. This relationship is shown visually in Figure 8. If, on the other hand, $\bar{q}$ is held constant as the loading is increased, the penetration decreases. This latter relationship can be attributed to the combined factors of particle-liquid interactions and the effects that the definition of $\bar{q}$ has on slurries.

The momentum flux ratio depends explicitly on the density of the slurry. This dependence upon the density is noteworthy since two jets with the same $\bar{q}$ but with different loadings (or densities) will possess two different jet velocities. The jet with the higher loading will have the smaller velocity and, as shown in Table 2, the lesser penetration.

Since some of the particles separated from the liquid portion of the jet, the jet should be treated as a two-phase phenomenon with a phase of solids and a phase of liquids. In a two-phase treatment one would expect the penetration of the liquid portion of the jet (for which the penetration was measured) to be largely independent of the loading. To verify this hypothesis a $\bar{q}_\ell$ was developed based on only the density of the liquid phase. By not being based on the density of the slurry, $\bar{q}_\ell$ would be independent of the loading. The penetration heights as a function of $\bar{q}_\ell$ and the loading are shown in Table 3. The usual relationship between the penetration and the momentum flux ratio

is evident in Table 3. The penetration height, for a given $\bar{q}_\ell$, however, appears to be independent of the loading. This independence supports the simple, two-phase jet hypothesis.

Although for loadings greater than 3%, the penetration of the liquid portion seems to be independent of the loading, there is a slight decrease in the penetration between loadings of 0% and 3%. The reduction in the penetration may be due to an interaction between the solid particles and the liquid. This interaction, which manifests itself only at very low loadings, may result from the particles breaking up the liquid jet as they separate from the liquid. The nanoflash photographs show no evidence of this, so any effect that the particles have on the break-up of the liquid must be too small to be identifiable in that way.

Further studies of the penetration were performed by light extinction methods. A liquid jet and a slurry jet of 40% loading were investigated. The momentum flux ratio (based on the density of the slurry) of both jets was seven. A transverse survey of each jet was performed at a location 30 mm downstream of the orifice. As was discussed previously, a high level of extinction (absorption) corresponds to a high concentration of particles.

As shown in Figure 9, the pure liquid jet penetrated further and absorbed more light than the slurry jet. Furthermore, the extinction curve for the two jets have similar profiles except for the slopes on the upward part of the jets. The pure liquid jet has a steeper slope (i.e., the extinction decreased more rapidly) which corresponds to a

sharper penetration profile on the streak pictures. By having a less steep slope, the slurry jet produces a penetration profile that is smeared - a profile that is not well defined.

The definition of $\bar{q}$ can explain why the liquid jet absorbed more light than the slurry jet. Due to differences in density, the two jets had a different volume flow rate when injected at the same $\bar{q}$. The slurry jet had a 12% lower volume flow rate. In the extinction experiments, the slurry jet absorbed approximately 16% less light than the liquid jet. The remaining difference undoubtedly arises from a slight difference in the extinction coefficient due to different particle/droplet sizes.

An observation concerning the injection needs to be pointed out. The same orifice and injection system was used throughout this study, for both pure liquid and slurry jets. It was discovered that for a given $\bar{q}$, the same back pressure was needed for all injections. In other words, if a liquid and a slurry were injected from the same injection system under identical conditions, the same $\bar{q}$ would result. This independence of $\bar{q}$ from the loading was also observed in the calibration of the flow meter. From the preceding discussions, it is known that the liquid jet will have a higher volume flow rate than a slurry jet at the same $\bar{q}$. The lower volume flow rate of the slurry jets could have an impact on the performance of a jet engine if the same injection system that is used with liquid fuels is used with slurry fuels.

A previous study suggested that for a given $\bar{q}$, the center of mass of the plume does not shift with varying loading.[18] The extinction

study appears to confirm this idea. In Figure 9, taking into account the density and relative position of the particles in the plume, the center of mass of both jets lie about 12 mm above the plate.

The extinction experiments also raised some questions concerning the definition of penetration. The penetrations, as measured from the streak photographs, are marked on Figure 9 for both jets. Based on the extinction curves, the penetration heights have been rather arbitrarily chosen. The heights do not correspond directly to any physical phenomenon. Since the penetration heights that have been presented in this report are primarily for relative comparison purposes only, the ambiguity about the penetration does not adversely affect the stated results.

From the nanoflash photographs the particles are shown to penetrate 40-45% farther into the air stream than the liquid portion of the jet. This figure agrees well with the results of the extinction experiment. In the extinction data, material was discovered in both jets above the penetration height. This finding poses an interesting question: if the material above the penetration height is composed of solid particles in the slurry jet, then what composes the material above the penetration height for the liquid jet? A possible answer is that large water droplets penetrate beyond the "penetration height" and are quickly broken into very small droplets. The resulting droplets may be too small to be noticable in the photographs.

Another intriguing question arises from the opacity of the solid particles. Since the particles are opaque, it would be expected that

they would absorb more light than the transparent liquid droplets. The extinction should be greater for the slurry than for the pure liquid. Even taking into consideration the different volume flow rates, the pure liquid still absorbed (or diffracted) more light than the slurry. As was mentioned previously, the particle/droplet sizes may account for this unexpected result, but this may not be the whole explanation.

The break-up process of the slurry jet was noticably less violent than its pure liquid counterpart. The lessening of the violence can be seen in the raw data for the extinction tests which consisted of the time variation of the beam intensity. Both of the jets showed unsteadiness in the curves, as is evident in the sample curves presented in Figure 10. The amplitude of the fluctuations for the slurry jet were dramatically less than those for the pure liquid jet. There was up to a 50% difference in the amplitudes, the average difference being of the order 15-20%. Re-examination of the nanoflash pictures suggests that the slurry jets were indeed more steady than the liquid jets; there appears to be fewer "splotches" in the slurry plumes. Compare the jets in Figure 11 which are extreme examples of this phenomenon.

The maximum amplitudes in the fluctuations occurred 3 mm above the point of maximum extinction for each jet. The maximum amplitudes, in terms of the streak photographs, occurred at the penetration height of each jet. From previous studies (such as Ref. 8) it is known that the top of the penetration profile is very violent and unsteady with "arms" of material whipping out. The whipping action presumably is the source of the large extinction fluctuations.

The particles that separated from the liquid plume were actually agglomerates of particles. These clumps of particles ranged from 25 to 40 microns in diameter. The particles agglomerated or flocculated due to the interparticle attraction of the small wetted particles. Smaller agglomerates can be seen within the liquid plume (Figure 1 2). The sizes of these agglomerates and their relative position in the plume can be directly correlated with the results of the solid-gas jet studies.[4,5] Particles larger than 25 or 30 microns separate from the jet; particles that are smaller than 5 or 10 microns remain locked in the jet; intermediately sized particles remain within the jet but are displaced upward. This correlation applies to the solid particles in the solid-gas jets and to the agglomerates in this study. The change in the slopes of the extinction curves may be the result of the displacement of the intermediately sized agglomerates in the slurry jet.

From close examination of the nanoflash pictures, approximately one eighth of the particles separated from the liquid plume. This figure was calculated by counting the number of particles visible within a vertical strip on some selected photographs. This number was checked by first computing the flow rate of particles as known from $\bar{q}$, the loading, and the orifice diameter. By assuming an average, constant particle velocity, the number of particles that should have been present in the vertical strip was then calculated. The calculated number agreed favorably with the counted number, thus justifying this rather crude technique.

Water was contained within the separated agglomerates. In several

nanoflash pictures (Figure 13), water can be seen being sheared away from the particles. The shearing is visible in the comet-like structures: the "head" of the comet is the agglomerate and the "tail" is formed from the water as it was sheared away.

For loadings greater than 55% the surface chemistry of the particles played an important role in the behavior of the jet. When slurries of these high loadings were mixed it was observed that the slurry behaved more like a clay then a typical liquid. Indeed, when some ambient air injection trials were conducted, the injected slurry resembled toothpaste being squeezed out of a tube. In the wind tunnel tests these high loadings produced a jet which behaved noticably different than jets of lower loadings. Figure 14 shows injections of 50% and 60% for side-by-side comparisons (also compare Fig. 13 with Fig. 15).

The initial column of the highly loaded jets was much more rigid and extended significantly higher than the lower-loaded jets. Less material can be seen being sheared off the initial column. The wave activity of the windward part of the jet appears more pronounced on the highly loaded jets (Figure 15).

As the loading of the injectant was increased, the effects of high loading seemed to occur suddenly. The effects did not gradually develop with increasing loading. Since the effects were presumably caused by the surface chemistry of the particles, the sudden appearance of these effects can be explained. In order for the surface chemistry to have played a role in the behavior of the particles, the particles must have been within a critical distance from each other. As the

loading was increased, the spacing between the particles decreased. Around a loading of 55%, presumably, the critical spacing was achieved, thus the particles bound together, creating the observed high-loading effects.

Besides affecting the behavior of the injection, the high loadings exerted a toll upon the injection system. At these high loadings, jamming was a common occurrence. At loadings of 60% and greater, the force-type flow meter behaved erratically, since it could not be kept clear of settling particles. The highest loading that was injected through the system (but not accurately metered) was 69%. The highest loading that could be achieved in the laboratory (but not injected) was approximately 80%.

Previous to the tests conducted in this report, injections had been performed involving spherical glass beads of 1 to 44 microns in diameter.[18] The specific gravity of these beads were 2.8-3.0. Injection into still air attested to the increased stability the particle-laden jets had over the liquid jets. Liquid jets broke up sooner than highly-loaded jets (loading greater than 50%). When the slurry jet was injected into a supersonic crossflow, under wind tunnel conditions identical to those of this study, the glass beads were observed to agglomerate and separate from the liquid plume. The penetration (for a given $\bar{q}$)decreased as the loading was increased, in the same trend as was observed with the smaller silicon dioxide particles.

DISCUSSION

The separation of wet clumps of solid particles from the liquid plume and the subsequent shearing away of the liquid from these particles constitute a serious ignition problem. Metal particles are difficult to ignite when they are not immersed in liquid fuel. A possible solution to this difficulty would be the addition of surface active agents. When such agents are added to the slurry, they tend to prevent the particles from agglomerating. Due to their size and mass, unagglomerated particles do not separate but remain within the liquid plume.

The dynamics of the jet can be best described by treating the jet as a two-phase flow with a phase of solids and a phase of liquids. In such a treatment, the liquid plume penetration is independent of the loading, barring the minor effects of particle-liquid interactions. At very high loadings (above 55%), the interparticle forces serve to bind the slurry together. The binding can be observed in a variety of effects such as the rigidity of the initial jet column.

Since many of the observed results observed with the slurries of the 5 micron silicon dioxide particles matched the results obtained with the larger glass beads, the results of this report should presumably be applicable over a wide range of particle size, shape, and surface chemistry. These matching results include: the increased stability demonstrated by the slurry jets (especially with very high loadings), the agglomeration and separation of some of the particles, and the dependence of the liquid plume penetration upon $\bar{q}$ and the loading.

Further research is suggested in the following areas:

1) Closely examine the particle-liquid interactions most evident at very low loadings,
2) Study the effects of interparticle forces in relation to the observed behavior of highly loaded jets,
3) Re-examine the definition of jet penetration,
4) Experiment with surface additives to quantify their effects on particle agglomeration and the separation of particles from the liquid plume,
5) Study how particle separation, high loading effects, etc. affect jet engine performance.

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TABLE 1 - PROPERTIES OF FUELS AND METAL PARTICLES

FUEL	SPECIFIC GRAVITY	HEAT OF COMBUSTION		
		Joule/gm	kJoule/liter	Joule/gm air
JP-4	0.777	43,310	33,510	2,870
Aluminum	2.70	30,980	83,620	8,080
Boron	2.32	59,310	137,010	6,200
Carbon	2.26	32,800	74,130	2,860
Magnesium	1.74	25,140	43,710	8,870
Hydrogen	0.0708	120,160	8,490	3,510

TABLE 2 - PENERATION HEIGHT (in mm) AS A FUNCTION OF LOADING AND $\bar{q}$

$\bar{q}$	LOADING				
	0%	3%	17%	33%	50%
2	12.0	11.6	10.8	10.2	
4	13.5	13.3	12.2	12.0	11.6
6	17.0	16.0	14.0	14.5	14.2
8	19.2	18.6	16.5	16.5	16.2
10	22.2	20.5	19.5	17.8	18.0

TABLE 3 - PENETRATION HEIGHT (in mm) AS A FUNCTION OF LOADING AND $\bar{q}_\ell$

$\bar{q}_\ell$	LOADING 0%	3%	17%	33%	50%
2	12.0	11.6	11.0	11.5	
4	13.5	13.4	13.4	13.5	13.7
6	17.0	16.0	16.0	16.3	16.5
8	19.2	18.6	17.6	17.6	18.4
10	22.2	20.4	20.5	20.3	20.5

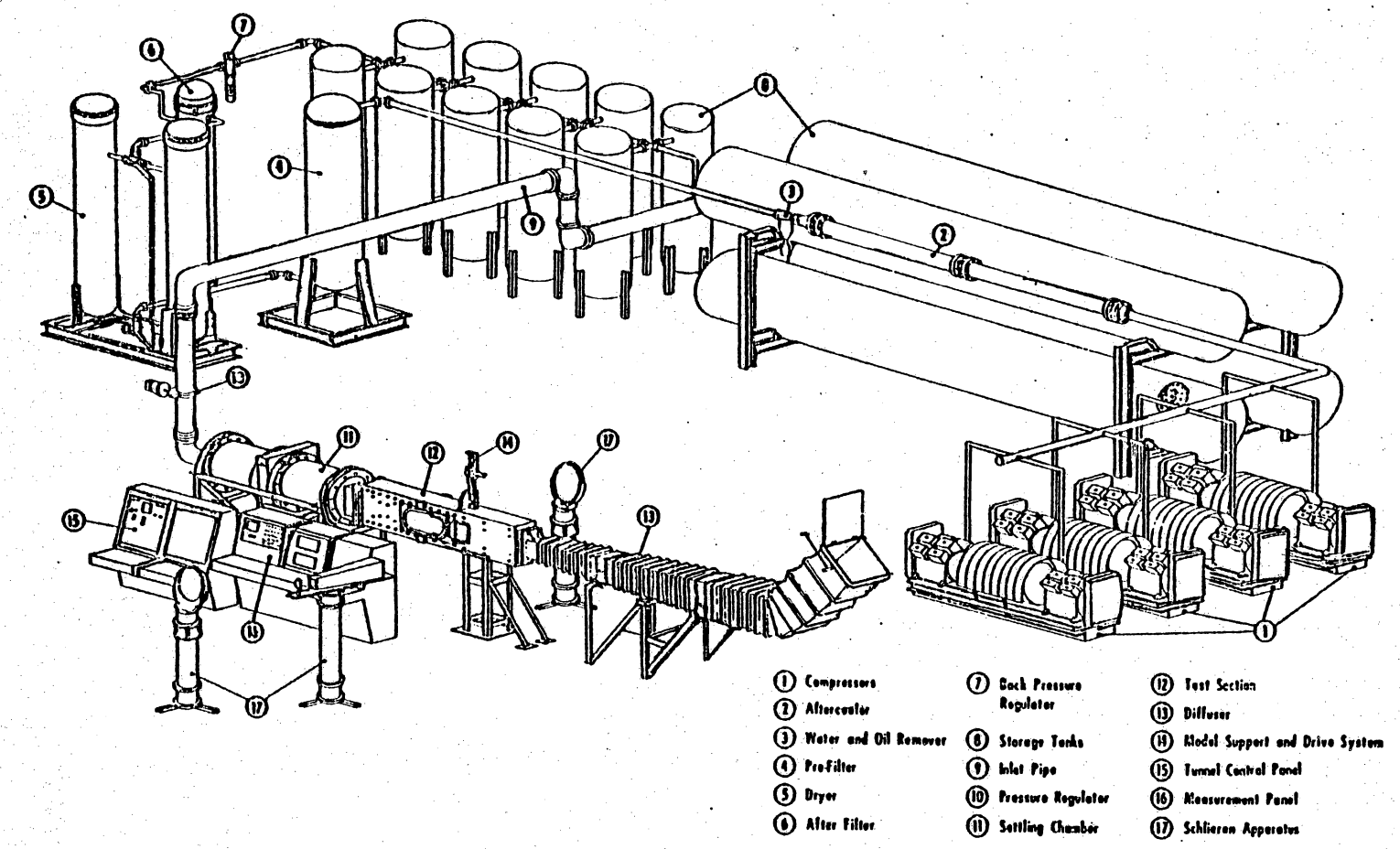


FIGURE 1 - SUPERSONIC WIND TUNNEL

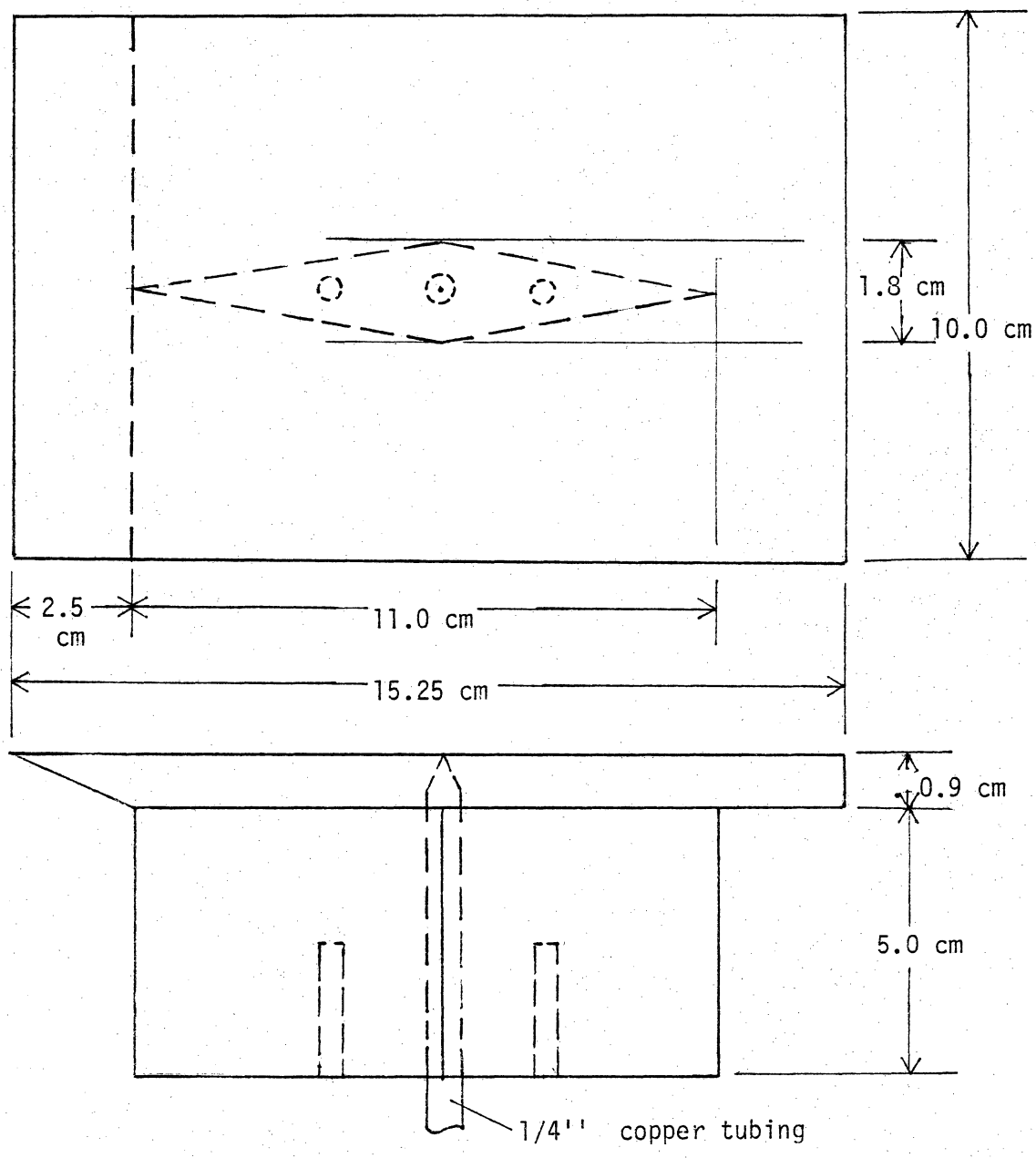


FIGURE 2 - FLAT PLATE MODEL

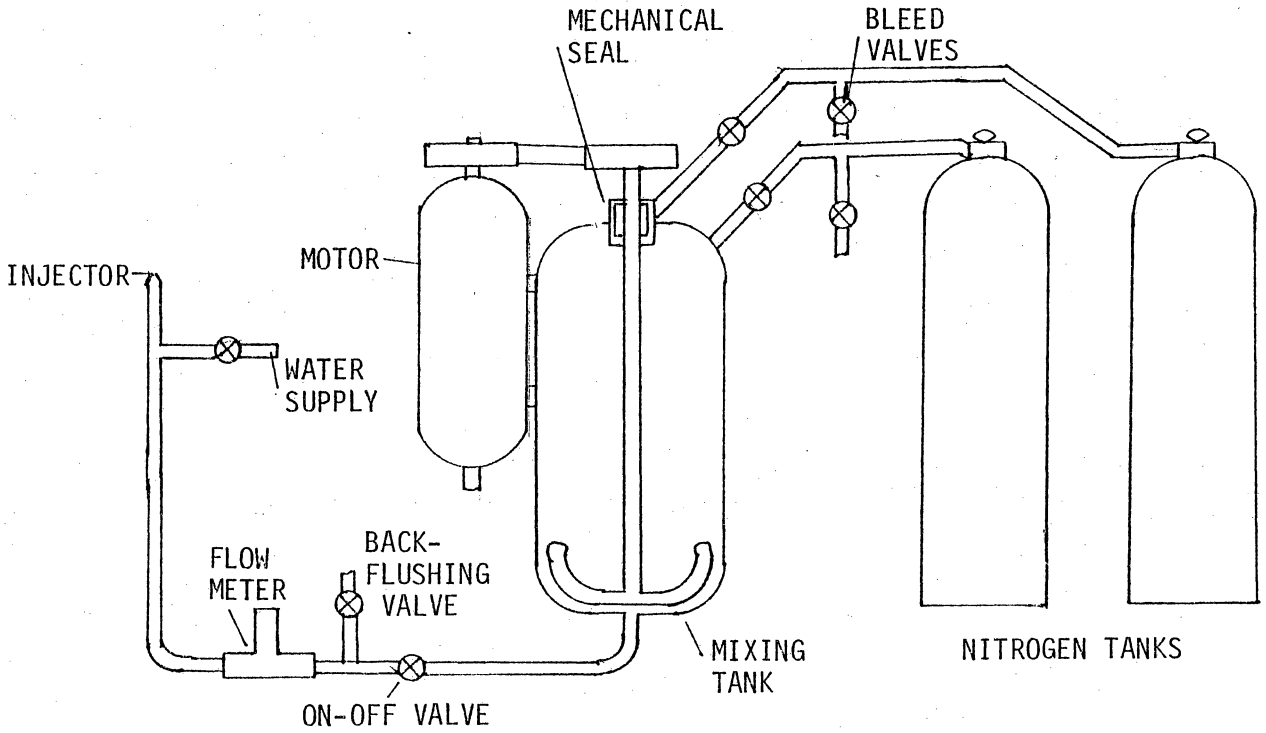


FIGURE 3 - MIXING TANK AND INJECTION SYSTEM

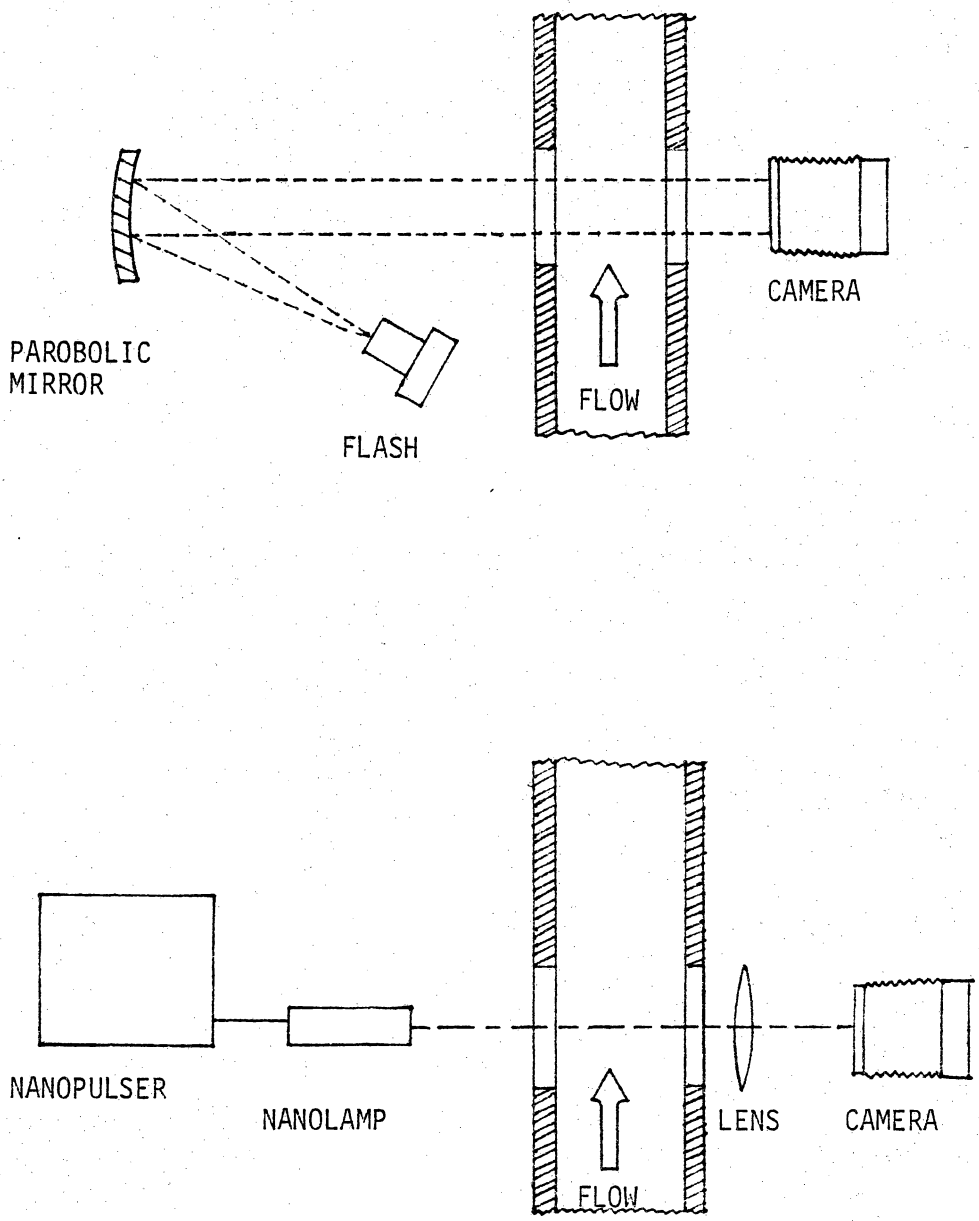


FIGURE 4 - SCHEMATIC OF THE PHOTOGRAPHIC SYSTEM

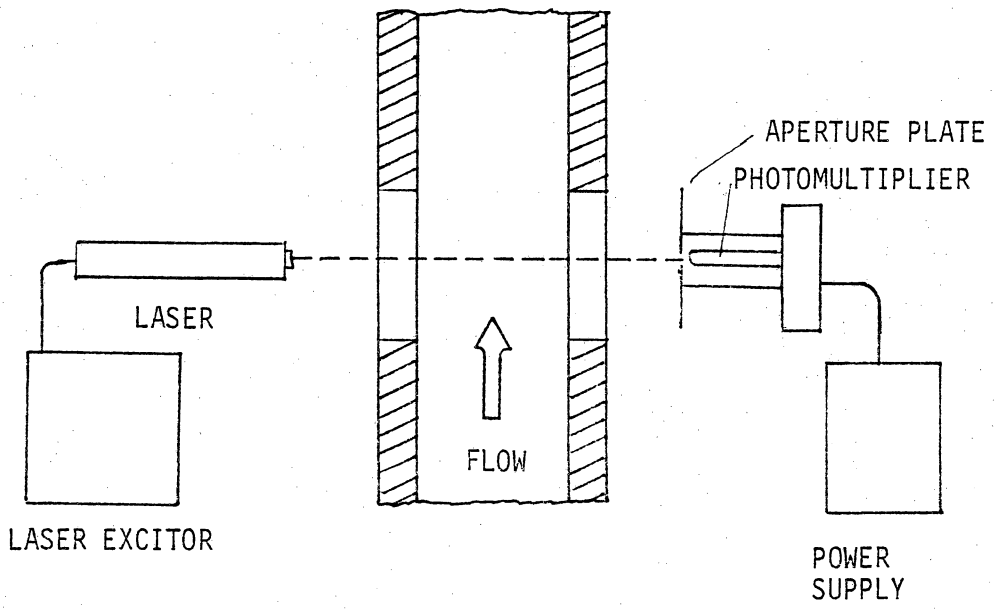
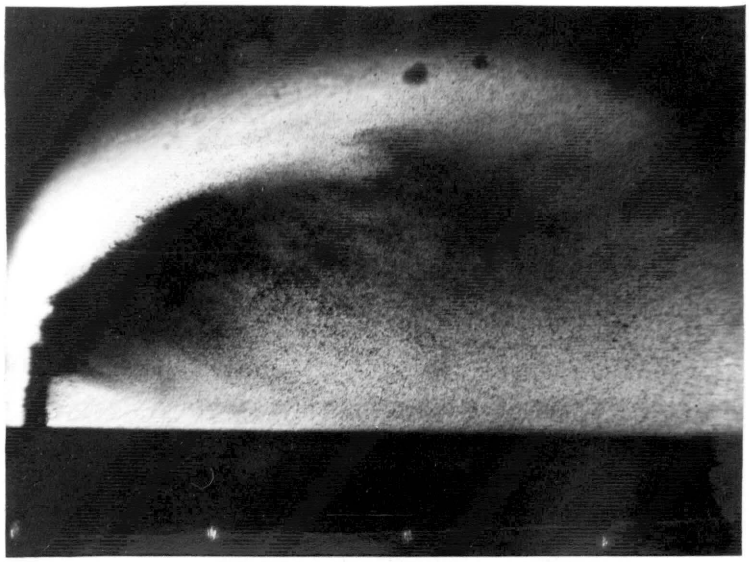


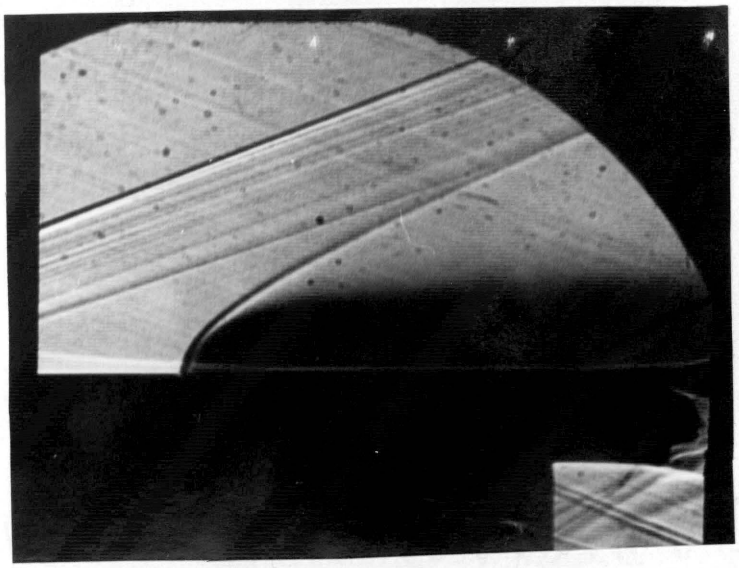
FIGURE 5 - SCHEMATIC OF THE EXTINCTION MEASURING SYSTEM



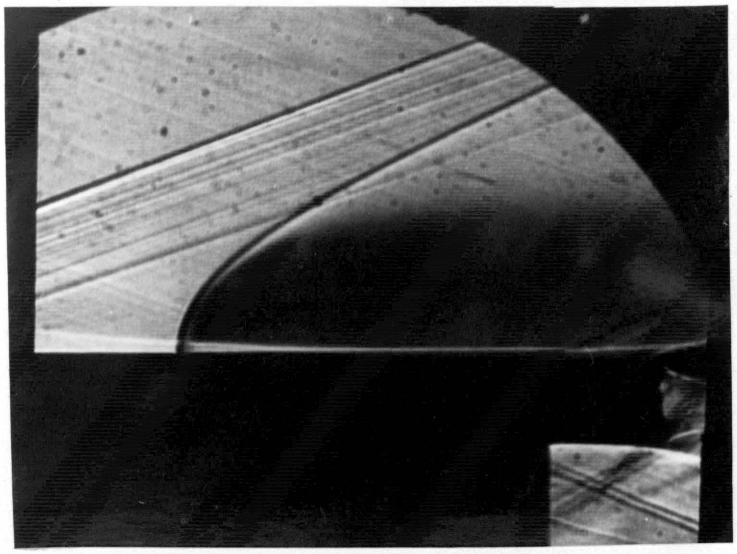
a) Loading = 33%, $\overline{q}$ = 5.9

b) Loading = 59%, $\overline{q}$ = 14

FIGURE 6 - SEPARATION OF PARTICLES FROM THE LIQUID PLUME - NANOFLASH PHOTOGRAPH

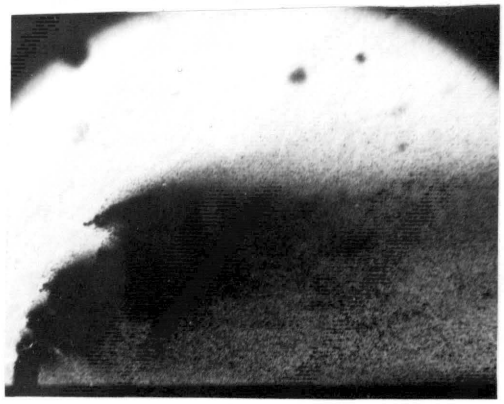


a) Loading = 28%, $\overline{q}$ = 4.3

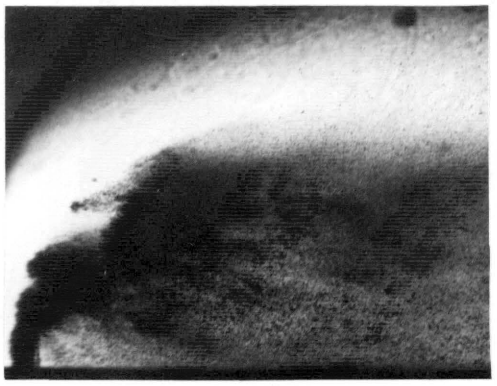


b) Loading = 56%, $\overline{q}$ = 12.1

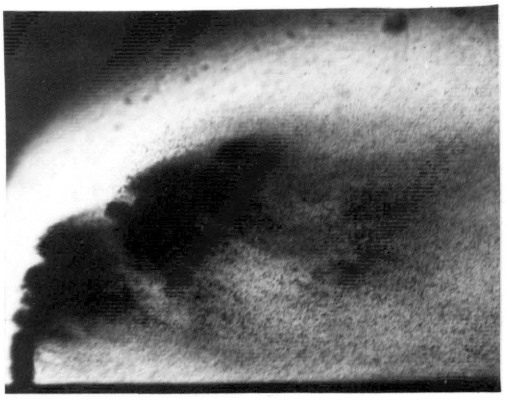
FIGURE 7 - SEPARATION OF PARTICLES FROM THE LIQUID PLUME
- STREAK PHOTOGRAPH



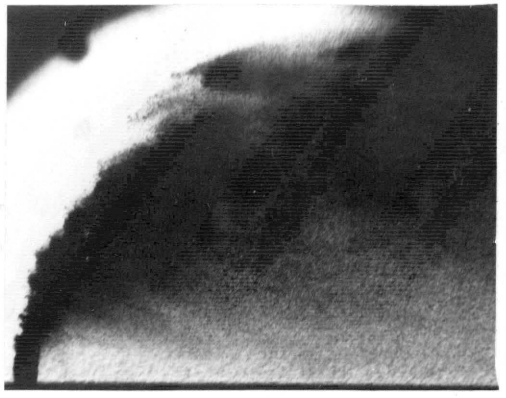
a) Loading = 36%, $\overline{q}$ = 2.8



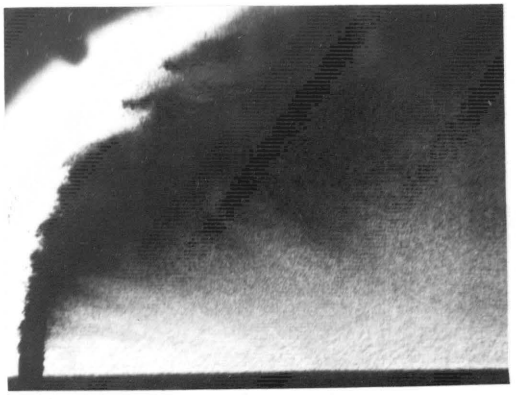
b) Loading = 33%, $\overline{q}$ = 3.2



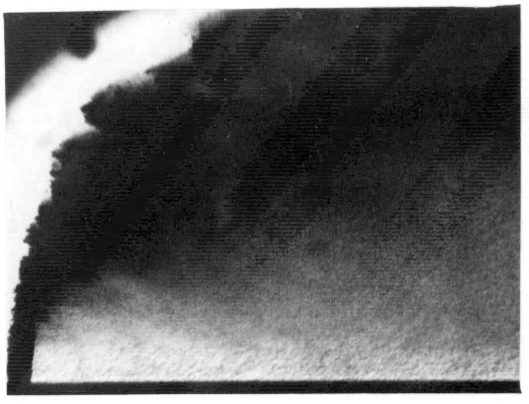
c) Loading = 33%, $\overline{q}$ = 4.7



d) Loading = 36%, $\overline{q}$ = 6.7



e) Loading = 36%, $\overline{q}$ = 9.7



f) Loading = 36%, $\overline{q}$ = 11.0

FIGURE 8 - NANOFLASH PHOTOGRAPHS FOR VARIOUS $\overline{q}$

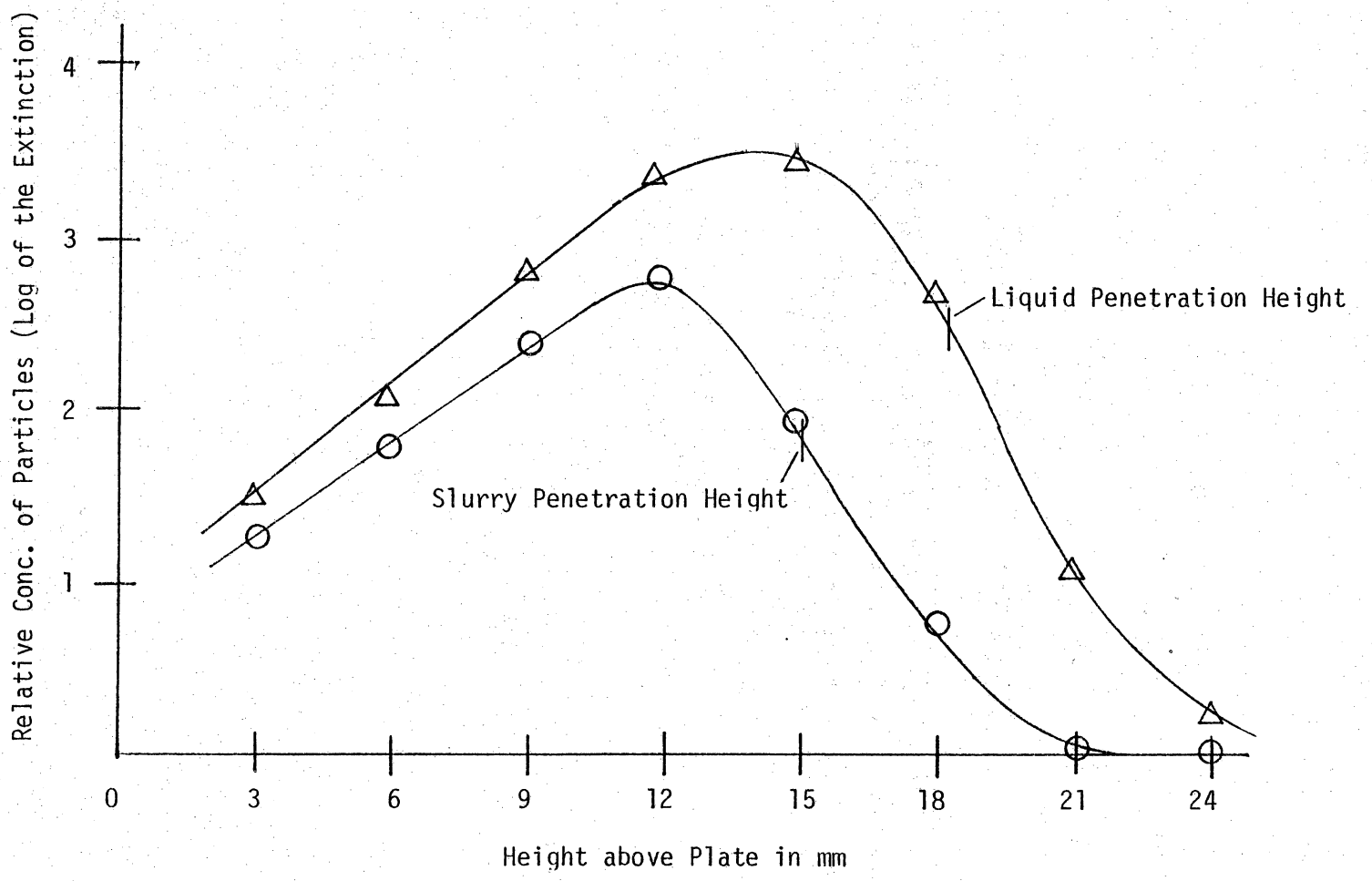
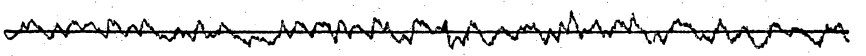
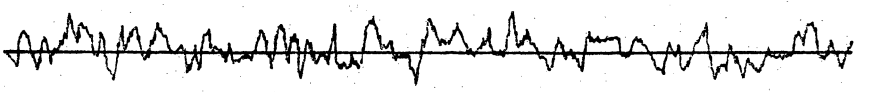
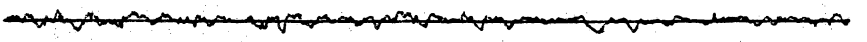


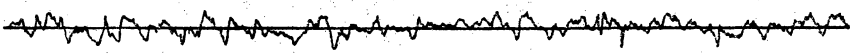
FIGURE 9 - EXTINCTION CURVES FOR SLURRY AND LIQUID

a) 

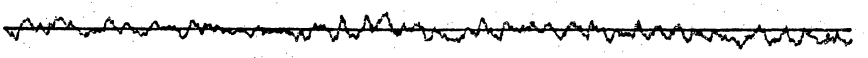
b) 

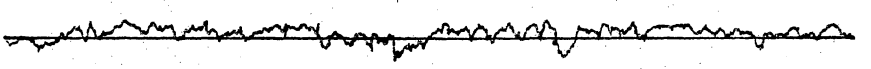
Slurry (a) and Liquid (b) at the Penetration Height

c) 

d) 

Slurry (c) and Liquid (d) at 3 mm above the Penetration Height

e) 

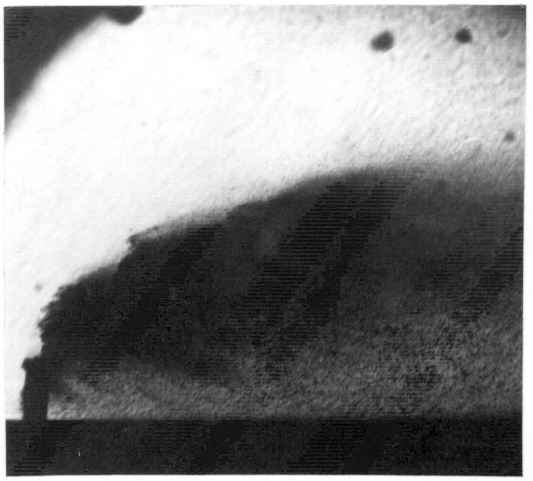
f) 

Slurry (e) and Liquid (f) at a height half the Penetration Height

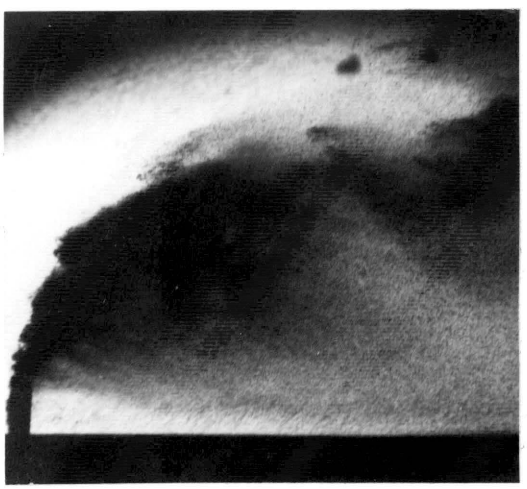
All data taken 30 mm downstream of the injector at a $\bar{q}$ = 7.

FIGURE 10 - EXTINCTION DATA FOR VARIOUS HEIGHTS

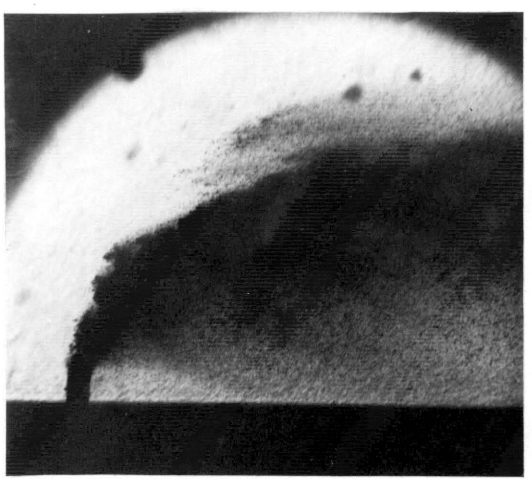
a) Loading = 16%, $\overline{q}$ = 4.2



b) Loading = 52%, $\overline{q}$ = 4.2



c) Loading = 16%, $\overline{q}$ = 9.0

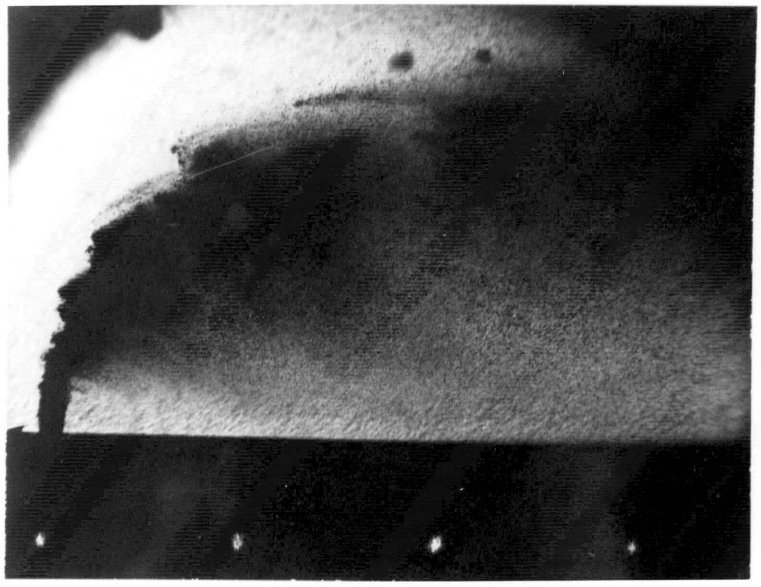


d) Loading = 48%, $\overline{q}$ = 9.2

FIGURE 11 - NANOFLASH PHOTOGRAPHS FOR VARIOUS LOADINGS

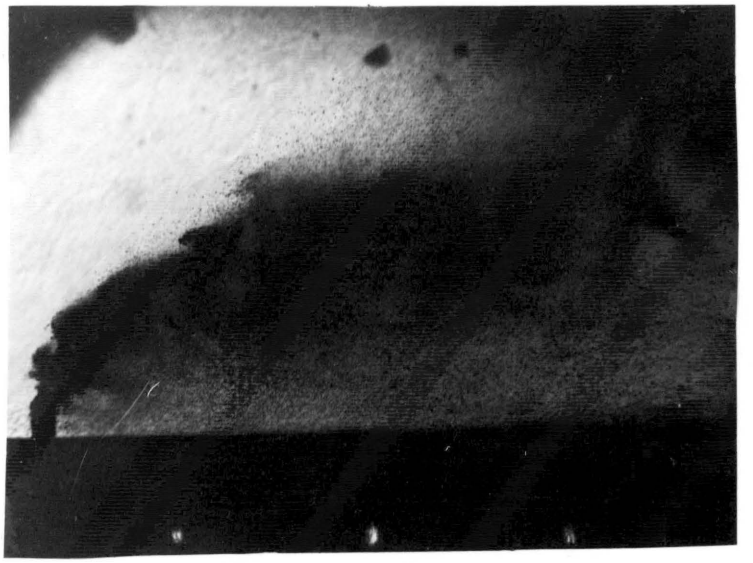
Loading = 68%, $\overline{q} \simeq 15$

FIGURE 12 - AGGLOMERATES IN LIQUID PLUME

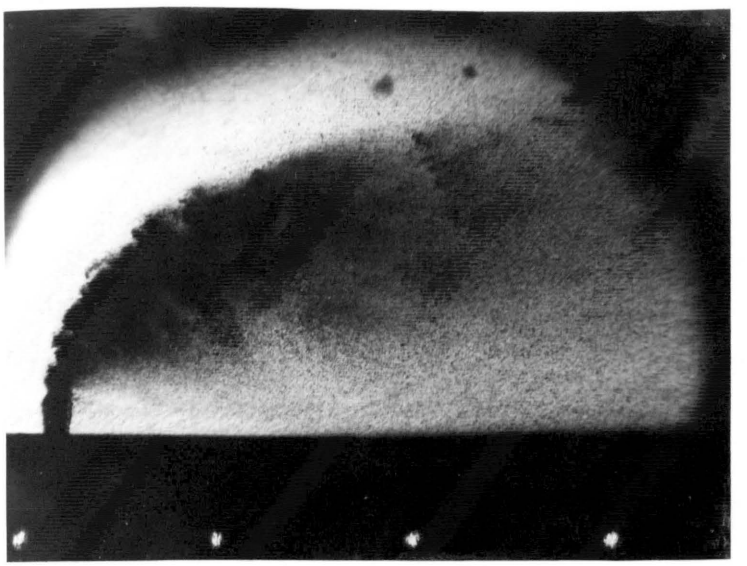


Loading = 52%, $\overline{q}$ = 10.0

FIGURE 13 - SHEARING OF LIQUID OFF AGGLOMERATES



a) Loading = 52%, $\overline{q}$ = 6.7



b) Loading = 59%, $\overline{q}$ = 6.7

FIGURE 14 - HIGH-LOADING EFFECTS

Loading = 59%, $\bar{q} \simeq 10$

FIGURE 15 - WAVE ACTIVITY ON HIGHLY-LOADED JET

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TRANSVERSE INJECTION OF A PARTICLE-LADEN LIQUID JET INTO A SUPERSONIC AIR STREAM

by

David Matthew Less

(ABSTRACT)

An experimental study of the transverse injection of a particle laden liquid jet into a supersonic air stream was conducted. Five micron diameter silicon dioxide particles with a specific gravity of 2.35 were suspended in water and injected across a Mach 3.0 air stream. A stagnation pressure of 4.2 atm. and a stagnation temperature of 15^{o} C were maintained throughout the tests. Particle loadings of up to 68% by mass were injected. The penetration and behavior of the jets were examined through a light extinction survey and through a series of streak and nanoflash photographs. Some of the particles were found to agglomerate into clumps ranging up to 40 microns in diameter. The clumps separated from the liquid plume and penetrated up to 45% further into the air stream than the liquid. For mass loadings greater than 55%, the jet column appeared more rigid than those of lower or zero particle loadings.