Flow mechanisms in high pressure gas atomization

I. E. Anderson
Ames Laboratory, Ames, IA 50011 (U.S.A.)

R. S. Figliola and H. Morton
Clemson University, Clemson, SC 29631 (U.S.A.)

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Abstract

Very fine ($d < 10 \mu m$) metal and alloy powders can be produced efficiently by a high pressure gas atomization (HPGA) technique. Rapid solidification processing, metal injection molding, thermal spraying and other emerging powder-processing approaches benefit from the use of such fine powders. This paper reports on the results of an investigation of gas atomization process dynamics with emphasis on the high pressure operating regime. The direct benefit of a better understanding of the process dynamics will be to permit a more informed selection of atomizer design and operating parameters as well as to further improve HPGA performance.

1. Introduction

Interest in high pressure gas atomization [1] has been motivated by an initial study reported by Small and Bruce [2] which demonstrated that a powder size refinement was achievable with an increase in atomization gas pressure. It is reasonable to assume that the increased gas flow kinetic energy associated with high pressure atomization is in part responsible for this refinement, but the energy transfer mechanisms leading to melt break-up and droplet formation in gas atomization processes are still not well understood. In general, the physics used to describe the droplet formation mechanism in low velocity liquid fuel and water sprays has been applied to gas atomization of molten metals. Also, the resulting models originally developed for liquid sprays have been extended to high velocity atomization flows with ambiguous results.

Castleman [3] and Dombrowski and Johns [4] have described a two-fluid jet instability as a series of mechanisms that lead to droplet formation in planar sprays. The principle instability is thought to be brought about by the interaction between the liquid sheet and the surrounding gas at the gas-melt-coupling zone, whereby rapidly growing internal surface waves are amplified within the liquid. These waves continue to grow in amplitude until a critical size is reached and disintegration begins. The break-up process is characterized by the sheet breaking down into fragments which form into unstable ligaments brought on by surface tension effects. The ligaments subsequently break down into droplets. Experimental observations performed by See and coworkers (see e.g. refs. 5 and 6) at low gas pressures, using a free-fall gas atomizer having focused gas jets, generally support this model and imply that the melt break-up is initiated prior to the focal point of the gas stream. Bradley [7] proposed a two-dimensional, two-fluid instability model for droplet break-up in parallel flows which is more specific to the gas atomization of molten metals but still consistent with the disintegration mechanism proposed to occur in sprays.

The presumption in any of these models is that only those instabilities that arise between the two adjacent parallel flowing streams of gas and liquid play a significant role in droplet formation. Working correlations to predict the dominant droplet size produced depend only on the relative parallel gas-liquid slip velocity and surface tension [7]. The actual mechanism for energy exchange and, more importantly, process methods to bring about its enhancement for size refinement are not actually addressed by these models. We believe
that the specific flow behavior of both the gas and liquid in the gas-liquid-coupling zone controls the energy exchange necessary for droplet formation and that this flow behavior can be modified by atomizer design. If true, then both the atomizer geometrical parameters and the specific operating regimes for the atomizer can be adjusted for the control of powder size and its size refinement.

In conventional low and moderate pressure gas atomization practice, two types of nozzles are utilized. For applications where fine powder yields are not critical, a free-fall or unconfined melt-feeding configuration is common, as Fig. 1(a) illustrates. This free-fall configuration is characterized by a gap of several centimeters between the melt orifice at the bottom of the crucible or tundish and a concentric array of discrete gas jets. In the free-fall gap the melt stream is free to wander or oscillate and initiates the break-up instability, as noted by See and coworkers [5, 6]. Because the melt stream cannot be centered reliably with respect to the gas nozzle axis at the point of gas impingement and because the break-up instability and filming of the melt also cannot be controlled in this configuration, the free-fall nozzle is not a suitable candidate for development of a high efficiency, high kinetic energy gas nozzle.

A more efficient commercial approach [8] utilizes an annular slit nozzle to supply atomization gas and a confined melt feed configuration to feed molten metal directly to the atomization zone, as shown in Fig. 1(b). These annular slit-confined feed (AS-CF) nozzles typically operate at moderate gas pressures of 4–5.5 MPa and produce the commercial state-of-the-art yield of fine (\(d_p < 44 \mu m\)) powders [9]. Such an atomization gas pressure level has been viewed as a practical limit, in part because of the excessive rate of gas consumption of the AS-CF nozzle at higher pressures. Thus conventional wisdom states that an AS-CF atomizer can produce enhanced yields of fine powders but only at a significant penalty in gas consumption. The gas consumption rate often quoted is expressed as a ratio of the average mass flows of gas and melt, i.e. \(\dot{m}_g/\dot{m}_m\), and commercial systems rarely exceed a mass flow ratio of 2.0. An enhanced yield of fine powders can be achieved with an increased mass flow ratio, but this effect reaches a practical limit. With an economically dictated upper limit for atomization gas pressure using conventional technology fixed at about 5.5 MPa, the melt flow rate must be decreased to raise this ratio. Eventually, \(\dot{m}_m\) drops to a level where melt stream freeze-off occurs.

In fact, the increased refinement effect with increased \(\dot{m}_g/\dot{m}_m\) also appears to reach a more fundamental limit. Atomization experiments on iron alloys with an experimental AS–CF nozzle operated at 4.2 MPa [10] have shown that the increased size refinement effect with increased \(\dot{m}_g/\dot{m}_m\) saturates. Specifically, the mass mean diameter asymptotically approaches a level of about 20 \(\mu m\) for \(\dot{m}_g/\dot{m}_m = 5\) and remains unchanged even for ratios as high as 14.

A more promising approach to achieving production of fine powders with improved efficiency appears to lie with a discrete jet atomization nozzle with the confined melt feed configuration (DJ–CF). Both the annular slit and discrete gas jet nozzles employ a confined feed arrangement, also termed “close coupled,” which has long been recognized for efficient transfer of the kinetic energy of the atomization gas to the melt stream [8]. Research by Anand et al. [11] using a DJ–CF nozzle design, a so-called “ultrasonic” gas atomization (USGA) nozzle, indicated that a more promising trend of decreased particle size with increased gas pressure could be achieved through the use of elevated gas pressures beyond the commercial limit. Some early experimental results reported herein utilized the USGA nozzle design. However, later experiments employed a DJ–CF nozzle with an improved manifold and gas jet design [12].

In this paper we show supporting evidence for our hypothesis that the efficiency of a gas atomization process, i.e. the productivity of an atomizer for fine powder production, can be affected significantly by interactions of a supersonic gas flow with the melt. This hypothesis shifts the analysis of atomization mechanisms to a more pro-
found level than the simple comparison of mass flow ratios. Specifically, we show that the gas flow behavior in the vicinity of the melt tube orifice in a close-coupled nozzle, especially the DJ–CF type, can change the gas–melt coupling and can be used to control the efficiency by which the atomization energy is exchanged. We demonstrate that for a particular HPGA design an optimum operating condition for size refinement exists. Because of their effect on the flow field, both the atomizer melt tube tip geometry and the atomizer gas pressure are shown to be significant variables in gas flow behavior and to have a controlling influence on powder size.

2. Experimental procedure

2.1. Atomizer design

Two different versions of the DJ–CF atomization nozzle were used in this study. In the general design given in the central cross-section drawing of Fig. 2, a series of discrete atomization jets are arranged in an axial array around a melt pour tube. The gas jets are focused toward a point downstream of the melt orifice at fixed apex angle so as to impinge on the flowing melt to facilitate energy transfer from the gas to the liquid and initiate droplet formation within the atomization zone. The melt flow that feeds the melt pour tube originates in a bottom-tapped crucible. A series of gas-only tests were performed to attempt to understand the effects of the melt tube tip geometry and tip extension on high pressure operation of the atomization nozzle, as described below.

For initial work a DJ–CF nozzle of the USGA design was utilized. In this design 18 cylindrical gas jets are arranged at a 45° apex angle around the melt pour tube. The gas is supplied to each jet from a regular annular manifold through an angle-crossed passage, as shown in Fig. 3(a).

A new DJ–CF nozzle, the Ames HPGA nozzle [12], was designed and employed for the later series of visualization experiments and local pressure measurements. This nozzle has 20 cylindrical jets arranged around a melt pour tube at a 45° apex angle. The diameter of the melt pour tube is the same for either nozzle. The apex angle of the original USGA nozzle was maintained in the new Ames nozzle to simplify a direct comparison between the operating characteristics and performance of the two nozzles. Because this angle of impingement of the gas flows from opposing gas jets was maintained constant, the effect on the gas flow interactions, mainly the formation of supersonic flow patterns and their influence on powder size distributions, should be nearly equivalent. Some change in the uniformity of gas–melt interaction was expected from the slight increase in the total number of discrete jets from 18 to 20, since they were arranged annularly around the same diameter. The gas is supplied to each jet from an annular manifold directly to each cylindrical jet hole, as shown in Fig. 3(b). This simplified passage arrangement appears to provide an

![Fig. 2. General design of the DJ–CF nozzle with terminology.](image)

![Fig. 3. Nozzle designs shown with HPGA melt tube feed tip: (a) USGA nozzle with manifold; (b) Ames HPGA nozzle with manifold.](image)
increased efficiency relative to the complex arrangement USGA design, as described in Section 3.

2.2. Static pressure tests

The atomization of liquid metals using a high manifold gas pressure should result in a flow having a higher kinetic energy compared to low pressure operation. One should note that a problem can arise in high pressure atomizer operation when a static gas pressure near or above ambient exists at the melt tube orifice. Unless offset by a high metallostatic head or a pressurized crucible bath, a positive pressure at the melt orifice can allow a back flow of gas up the melt feed tube, leading to unstable melt feed operation and eventual melt flow freeze-up. The consequences of such unstable atomization can be catastrophic. Under high pressure conditions the stability of the melt feed can be better controlled if the atomizer nozzle or, specifically, the melt tube is designed to experience a subambient pressure at the melt orifice under the operating conditions of atomization [13, 14]. Operating in this intrinsic aspiration regime, the subambient (suction) pressure at the melt orifice should accelerate the melt stream towards the gas stream, providing for a stable melt feed operation.

The design of the melt feed tube was found to be crucial to stable operation and some critical aspects of its design were explored in a series of tests. In all tests the melt tubes used were constructed of identical materials and only the shape of the melt tip and the length of its extension into the gas flow field were varied. The various shapes tested are shown in Fig. 4. The extended melt pour tube shown as design 2 uses a conventional melt feed tube geometry common to many commercial and research low pressure atomizers. Tip design 1 provides a logical design control for comparison of alternative geometries because the melt tube position allows no direct contact between it and the flowing gas. Design 2 extends a square-edged melt tube into the flow field closer to the gas jet focal point. The extended tube tip essentially diverts the projected cores of the gas jets, thus providing for a strong interaction between the melt tip and the gas jet. Designs 3 and 4 use a taper on the exposed melt tube tip. The intent of design 4 is to align the melt tube taper with the gas jet angle to allow for an efficient flow expansion of the atomization gas at high operating pressures. As such, the taper of the melt tip of design 4 forms a 45° apex angle at its focus. To test the sensitivity between nozzle operation and this taper angle, design 3 is similar to design 4 but is designed to form a 63° apex angle, thus allowing for some off-axis spreading of the gas.

The static pressures developed at the melt orifice of the four alternative melt tube designs were measured during high pressure operation. A static pressure probe was positioned within the melt tube with the static port located at the melt orifice so as to sense melt tip (base) pressure during atomizer operation. The actual location of the static port was displaced radially 1.5 mm from the orifice center-line. The probe consisted of a 3 mm tube which was open at the orifice end and connected to a transducer. The transducer signal was observed during operation and recorded on a digital oscilloscope for subsequent analysis. All reported pressures are steady state values with the atomizer operated in a gas-only mode using argon, i.e. no melt flowed during these tests.

The gas was provided to the nozzle manifold from a standard high pressure (41.4 MPa, 6000 lbf in^-2) gas cylinder with gas pressure controlled by a regulator. In all tests the melt tip orifice was blocked except for the pressure port. The reported gas inlet pressures were measured on the downstream side of the gas regulator, such as would be monitored during a practical atomization run, but for comparison with other atomization systems, the gas inlet pressure at the nozzle manifold provides a more meaningful value since it eliminates the pressure drop due to tubing, couplings and the valve body of the gas delivery.
system. This pressure has been measured for both nozzle types for the several test configurations used in this study, and a maximum bias correction factor of \(-2.0\) and \(-0.34\) MPa can be applied to the inlet gas pressures reported with the USGA results and the Ames HPGA nozzle results respectively.

### 2.3 Hydraulic analogy tests

A surrogate flow system was implemented to study further the details of the effect of melt tip geometry on the gas flow field. This system uses the hydraulic analogy within the conservation equations for two apparently unrelated types of flows: (i) the frictionless, two-dimensional, free-surface flow of an incompressible fluid under the influence of gravity; (ii) the frictionless, two-dimensional, isentropic flow of a perfect gas under the influence of pressure forces [15]. The method is known to reproduce faithfully the main features of high velocity base flow systems [16, 17]. The hydraulic analogy provides for a direct correlation between a measured depth ratio \(h/h_0\), in a free-channel flow and a pressure ratio \(P/P_0\), in a gas stream which is given by

\[
\frac{P}{P_0} = \left(\frac{h}{h_0}\right)^2
\]

where \(P_0\) refers to the stagnation gas inlet pressure and \(h_0\) refers to an upstream stagnation reservoir depth.

As a direct consequence of the analogy, the gas Mach number becomes directly analogous to the Froude number for free-channel flows; a gas compression shock wave becomes analogous to a hydraulic jump. This similarity permits the simulation of complex gas flows with relative ease on a free-channel water table while maintaining the essential gas dynamic features.

The water table used in this study, depicted in Fig. 5, has a working channel 1.6 m long by 0.8 m wide. Water enters the working channel from a reservoir through an adjustable sluice which is used to control the reservoir depth. The working channel has a plate glass floor and sides 60 mm tall. Channel back pressure is controlled by a downstream weir and was maintained at 6.5 mm water depth for all reported tests, a depth found suitable to reduce capillary effects. The water is recirculated from a catch tank to the reservoir by a pump.

The test model consists of a symmetrical two-dimensional cross-sectional, 6.8:1 scaled replica of the actual Ames HPGA nozzle. The model can accommodate interchangeable melt tube tip designs. Shadowgraph photographic methods were used to record the flow patterns observed for each different melt tube tip design as a function of imposed pressure. More details on the test procedure can be found in ref. 18.

### 2.4. Schlieren tests

The atomization nozzle gas flow patterns for argon gas were observed using schlieren and high speed shadowgraph techniques. These techniques have been commonly applied to the study of supersonic gas flows. These tests supplement those reported earlier [14, 19, 20]. The straight, single-pass schlieren system used a 10 mW He–Ne laser light source. Images were recorded on Polaroid 55P/N film. Schlieren imaging is sensitive to the first spatial derivative of the gas index of refraction. In the photographs the brighter areas represent regions of the flow experiencing a change in refractive index and hence a density gradient. While interpretation of the images is complicated by the fact that the density gradient information of the entire three-dimensional flow is superimposed on a two-dimensional photo-

![Fig. 5. Water table schematic drawing.](image-url)
2.5 Particle refinement studies

The Naval Research Laboratory (NRL) high pressure gas atomization (HPGA) system was used for the initial study of the dependence of powder size distribution on inlet gas pressure. The HPGA system at NRL, shown in Fig. 6, consisted of a single chamber containing an induction-melting furnace with the atomization nozzle mounted beneath it. The atomization spray was created at the nozzle and the resulting powder was transported, as shown in Fig. 6, to the powder collection system through pneumatic transport by the expanding atomization gas. For atomization, a DJ–CF nozzle of the USGA design described above was used with a melt tube geometry of design 4 in Fig. 4. The atomization crucible was filled with 1.5 kg of a Sn–5wt.%Pb alloy and the molten charge heated to 550 °C prior to each atomization run. The graphite crucible was bottom tapped and the melt flow was controlled by a stopper rod. A programmable process controller allowed reproducible actuation of all atomizer control devices during a run. The Sn–Pb alloy was atomized using argon gas supplied to the atomization nozzle at regulated inlet pressures of 10.3, 12.4 and 17.2 MPa. Powder collection was accomplished by separation of the powder–gas exhaust stream in a cyclone cendifugal dust separator and by retention in a valved powder can, as shown in Fig. 6.

3. Results

3.1 Static pressure tests

The static pressure test results for the USGA nozzle using the various melt tip geometries are shown in Fig. 7. Inspection of these data reveals that designs 2 and 4 produce an aspirating (suction) pressure at the melt tube tip over a wide range of high operating pressures. While the other designs might produce such an effect, it must be developed at substantially lower pressures, seemingly excluding them from high pressure atomization use. The suction pressure measured for design 2 tended to decrease with increasing inlet gas pressure, perhaps reaching an asymptotic value near 15 MPa. Design 4 was found to possess a minimum pressure that occurred near 12 MPa, with a gradual recovery at higher pressures.

It is interesting to note that designs 1 and 3 each failed to produce an aspirating effect at high pressures. In fact, Anderson and Rath [13] report that early efforts to use design 1 at high pressures resulted in unstable atomization and expulsion of the melt from the crucible. Therefore designs 1 and 3 were eliminated from further consideration.

The aspirating effect found to occur with design 2 appears to be consistent with the anticipated flow behavior of this shape, i.e. a large, low pressure wake attached downstream of the melt tip. Commercial operators often cite that a stable atomization condition results with design 2,
which is rather insensitive to minor variations in inlet gas pressure. However, this design is also known to be rather inefficient for producing very fine powders, especially at high operating pressures. The straight cylindrical wall of tip design 2 obstructs and diverts the high velocity core of each gas jet, as indicated in Fig. 4, which would significantly reduce the amount of energy available in the atomization zone for transfer to the melt stream. Furthermore, there is a known tendency for erosion of the exterior of the tip with this design owing to the high impact energy imparted by the gas jets on the tube wall. Erosion is especially a problem for the monolithic ceramic pour tubes in common usage. With erosion, ceramic particulate will be collected with the powder yield and may lead to microstructure defects in consolidated parts. For these two basic reasons, tip design 4 was selected for extensive atomization studies, but further comparisons were also made with tip design 2, especially to explore atomization energetics issues.

3.2. Comparison of performance of DJ--CF nozzles

The results of a series of static pressure tests indicate that a significant difference exists between the efficiency of the two designs of DJ--CF nozzles used in this study, although the primary features of their operation in the HPGA regime is remarkably similar. The similarity in operation is further demonstrated in gas flow visualization results discussed in a following section. A summary of the effect of gas inlet pressure on the melt orifice suction pressure is presented in Fig. 8, where the results pertain to gas-only flow using argon gas and a melt tip of design 4. With increased inlet gas pressure, both DJ--CF nozzles exhibit an initial decrease in orifice pressure, a minimum in orifice pressure of about 0.4 times ambient pressure and a subsequent increase in orifice pressure. While their trends are similar, there is an obvious shift to lower inlet pressures for the Ames HPGA nozzle compared to the USGA nozzle. Because these tests were performed on a test bench using very similar gas delivery systems, this shift of about 5 MPa in gas inlet pressure required to reach the minimum in melt tube orifice pressure must be principally due to nozzle design.

The simplified gas passage design of the Ames HPGA nozzle relative to the USGA design, as Fig. 3 indicates, as well as some modifications to the gas manifold inlet, described elsewhere [12], appear to contribute to a reduction in nozzle gas flow resistance, manifested as a reduction in pressure drop through the nozzle. This reduction translates directly to a drop in the gas pressure for optimum disintegration performance by argon atomization to between 6.9 and 7.6 MPa. The high performance operating pressure range of the new Ames HPGA nozzle now falls just above the maximum pressure range of 5.5 MPa of many existing commercial AS--CF inert gas (argon) atomization nozzles which have reduced performance. Because only a small elevation of established atomization gas supply pressures would be required to achieve a significantly enhanced yield of fine powders, the process of technology transfer of the HPGA approach into industry would not require a major change in safety limits on the part of powder plant design engineers.

3.3. Hydraulic analogy tests

In all water table tests the upstream water depth was varied between depths equivalent to manifold gas pressures of 1.8 through at least 10 MPa. Representative flow patterns for the four designs shown in Fig. 4 are presented in Fig. 9. For all designs at these elevated pressures the underexpanded nature of the gas jet flow is demonstrated by expansion waves and the shape of the external jet boundaries. Each design gives rise to an attached conical recirculation region downstream of the melt tip and a well-defined dissipative mixing later. The shadowgraphs reveal that the conical region is broader for the straight melt
tip in both its retracted (design 1) and extended (design 2) positions relative to either the 63° (design 3) or 45° (design 4) tapered tips and is the narrowest with the 45° taper.

With increasing pressure, a normal shock wave or Mach disk, evidenced as a large sudden jump in water depth, was observed to appear within the neck of the conical region with designs 2–4. This jump moved downstream and eventually became diffuse with increased reservoir pressure. The remaining wave patterns indicate reflective shocks forming a diamond pattern downstream of the normal shock. In fact, the flow pattern observed with design 4 is very similar in many respects to a high Mach number, underexpanded plug nozzle flow found in certain rocket nozzles which were studied with great intensity in the 1960s (see e.g. refs. 16 and 21). These base flow characteristics and particularly the strength of recirculation are believed to have a significant impact on melt break-up [14].

3.4. Schlieren tests

Schlieren-imaging tests of argon gas flow from the Ames HPGA nozzle were performed using melt tip designs 2 and 4. These visualization
results on the Ames nozzle have improved resolution over results previously reported for the USGA nozzle [14] which used a less intense strobbed xenon flash lamp light source and a longer shutter-opening time. Despite these differences in resolution, the trends in gas flow pattern evolution for melt tip design 4 are reproduced for either DJ-CF nozzle design. For both clarity and brevity, only the Ames nozzle results are reported here.

There is a close similarity between the schlieren images and those generated on the water table. For design 4, three distinct gas flow regimes—a low pressure, a high pressure and an overpressure regime—were identified within gas inlet pressures ranging from 0.7 to 17 MPa. As can be noted from the progression of inlet pressures shown as Figs. 10(a)–10(f), the gas flow field is defined by an external constant-pressure boundary that is directed inward toward the center-line. The volume defined by this boundary narrows to a minimum downstream of the melt tip at the focus of the internal shock. The boundary then expands as the reflected shock emanates outward from the focus.

The low pressure regime from 0.7 to about 4.1 MPa consists of a symmetrical array of 20 individual underexpanded gas jets each characterized by a pressure-dependent diamond shock wave pattern. The bright horizontal layers noted in Figs. 10(a) and 10(b) actually correspond to many discrete regions where reflected waves from neighboring jets meet and again reflect to form these diamond patterns. By 4.1 MPa (Fig. 10(c)) the positions of the discrete layers have expanded to the point that the discrete gas jets begin to

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Fig. 10. Schlieren results for Ames HPGA nozzle with tip design 4 using argon gas: (a) 0.7 MPa; (b) 2.1 MPa; (c) 4.1 MPa; (d) 6.9 MPa; (e) 9.0 MPa; (f) 13.1 MPa.
merge into a unified flow field. Using the diameter of the melt tip, \( B \), as a reference length, it can be seen that an abrupt increase in gas density develops along the horizontal plane located at distance \( B \) downstream of the melt tip orifice. Coincident with this position is the minimum in the volume defined by the external boundary. Also apparent, the apex of axisymmetric reflected shock waves is located at \( 2.3B \).

The high pressure regime was observed for inlet gas pressures over the range of 6.2–10.3 MPa. In the gas flows at these pressures a normal circular shock wave or Mach disk becomes apparent and is located at the minimum in the volume defined by the external boundary. That is, it is formed at the focus of the incident shock wave. As demonstrated in Figs. 10(d) and 10(e), the position of the Mach disk moves downstream with increased inlet pressure from \( B \) to \( 1.55B \). The external jet boundary becomes the most constricted in this range of pressures. The reflected shock waves downstream of the Mach disk remain visible.

The overpressure regime was observed at pressures beyond 11 MPa. As characterized in Fig. 10(f), the Mach disk has dissipated in this regime, the interior of the unified flow field develops a low density core below the incident shock reflections and the external boundary becomes nearly vertical without the constriction noted at lower inlet pressures.

For design 2, two distinct regimes were apparent within the 0.7–14.5 MPa gas inlet pressure range tested, as shown in Figs. 11(a)–11(d). At low pressures between 0.7 and 2.1 MPa the external gas flow boundaries are initially directed vertically downward as they exit the gas jets but then bend toward the flow center-line as the flow passes the edge of the extended melt tip (Fig. 11(a)). As the inlet pressure is increased (Figs. 11(b) and 11(c)), the individual underexpanded gas jets become visible, each characterized by a pressure-dependent diamond shock wave pattern. However, the internal shock wave which defines the external gas flow boundary is deflected outward from the center-line; this is distinctly different from the behavior of design 4. Only when the inlet pressure was increased to 11.7 MPa and for higher pressures tested did the flow finally become unified and a Mach disk form (Fig. 11(d)). Both incident and reflection shocks are clearly visible within the Mach disk region.

The schlieren results reveal both similarities and differences in the highly energetic, compressible gas flows generated by these two different designs for an HPGA nozzle. This suggests a strong relationship between melt tube tip design and its resulting flow field under high pressure operation. The schlieren results complement the static pressure results. For the 45° apex angle design the aspirating effect occurs at gas inlet pressures residing in the high pressure flow regime, a flow regime that is represented by very distinct flow characteristics. The taper angle associated with this design allows the supersonic gas flow to persist along the length of the melt tip and without any significant loss of energy to the melt tip through direct impingement. From momentum considerations the aspirating effect also requires the presence of a gas recirculation region attached to the melt tip.

Gas recirculation could play a significant role in energy transfer and droplet break-up in HPGA by forcing the melt to flow radially outward, carrying it toward contact with the high velocity gas flow, a mechanism initially described and supported in ref. 14. Secondary disintegration could also occur as the droplets pass through the focal region containing the Mach disk, but this could not be verified. A model of the gas flow field has been constructed in Fig. 12.

### 3.5. Powder refinement tests

The results of the powder-processing tests [13] using the 45° apex angle melt tip of design 4 are shown in Fig. 13 for three inlet pressures. These pressures cover the high pressure and overpressure flow regimes identified by schlieren imaging [14] and the static pressure tests (Fig. 8) for the USGA nozzle. It is clear that an enhanced refinement in particle size occurs as the pressure is increased within the high pressure operating regime of this design from 10 to 12 MPa. Such refinement is in agreement with the suggestion of Small and Bruce [2]. The gas velocities developed within the underexpanded jet boundaries will increase with inlet gas pressure and a decrease in dominant particle size with increasing gas velocity is in agreement with the model proposed by Bradley [7]. This pressure range also coincides with the appearance of the Mach disk in the schlieren tests performed with the USGA nozzle with the extended 45° tip [14]. However, a further increase in gas inlet pressure into the overpressure operating regime of this nozzle from 12 to 17 MPa actually produced larger particles, a
result that is in contrast to existing models. This behavior has been reproduced numerous times within our laboratories with both the USGA nozzle and the more recent Ames nozzle.

4. Discussion

It is notable that the maximum powder size refinement was found to occur at a value of inlet pressure near that which produced the maximum aspirating effect with the 45° apex angle design. This would suggest a strong correlation between the results of the static pressure tests, the hydraulic analogy tests, the schlieren tests and actual powder refinement tests. Such a strong correlation would also suggest that a wide range of major nozzle modifications, including the apex angle, could be explored very conveniently using...
hydraulic analogy tests to further improve the efficiency and stability of an HPGA nozzle. These rapid, inexpensive, preliminary tests should indicate if, for example, the stable pressure range of nozzle operation could be extended while still maintaining a well-defined shock field along the central axis of the flow for optimum performance. Of course, encouraging results from such preliminary tests would then need to be confirmed by construction of an actual nozzle and the battery of static pressure, schlieren and powder production tests.

This investigation demonstrates that fairly profound differences exist in the gas flow pattern of a gas atomization nozzle as elevated atomization pressures are utilized, particularly in the high pressure regime. This implies that an analysis of the particle size refinement capability of a gas atomization nozzle should not be restricted to a simple comparison of $r_{m}/r_{m}$ ratios but must include an understanding of the influence of supersonic gas flow on the melt break-up process. Future investigations will be extended to include significant modifications in the melt-feeding dynamics and melt feed rate to explore additional variables which may improve atomization efficiency and control.

Additional insight into the HPGA flow field can be gained by relating it to the similar flow field of an annular truncated plug nozzle, illustrated in Fig. 14. The extensive research performed on these altitude-compensating rocket nozzles provides a comprehensive description of their basic flow characteristics. A difference between the flow fields of the HPGA and the plug nozzle is that the HPGA flow field is three dimensional and axially discontinuous about the gas orifices. However, once the discrete underexpanded gas jets have mixed, the HPGA flow field becomes essentially axisymmetric, as in the plug nozzle flow.

A flow model developed for a truncated plug nozzle during high altitude operation [21] contains the same basic flow characteristics seen in the HPGA gas flow field. The basic flow model shown in Fig. 14 divides the flow into a base region containing recirculating flow, a dissipative mixing layer and an inviscid adjacent stream. In addition, a strong internal shock originating in the vicinity of the shroud, which can give rise to a normal Mach disk and a recompression shock, was identified. Studies introducing mass addition into the near wake [22] are of interest because the base bleed of rocket nozzles is similar to the addition of melt to the HPGA flow field. An increase in the wake neck thickness, the conical region in HPGA flow, has been observed in both processes. Another effect is that the peak stream pressure on the nozzle center-line, which normally occurs at the tip of the recirculation region, is shifted further downstream. This effect implies
that the recirculation region of the HPGA flow field can be expected to lengthen somewhat as liquid melt is introduced.

5. Conclusions

An experimental investigation into the flow mechanisms associated with melt break-up in high pressure gas atomization has been reported. An improvement in nozzle operating efficiency in the high pressure regime was demonstrated through nozzle design modifications. The effect of melt tube tip geometry on the resulting atomizer gas flow field was also studied. It was shown that the melt tube tip geometry plays a significant role in determining the resulting HPGA flow field. Specifically, for optimum performance in the HPGA operation regime the exterior surfaces of the nozzle feed tube should align exactly with the interior dimension of the discrete jet array. Further, the taper of the feed tube should match the extended flow direction of the high energy cores of the gas jets, i.e. the interior of the supersonic gas flow “curtain.” These tight geometric constraints minimize gas flow energy losses in the short free-expansion region along the exterior of the feed tube tip and thereby promote the persistence of supersonic laminar gas flow all the way to the point of first impact of the gas with the melt. These effects ensure the maximization of atomization energy transfer in the initial atomization event at the edge of the pour tube and encourage the full development of an intense Mach shock disk which may also perform an effective secondary atomization function.

The physical extension of the melt feed tube tip into the atomization region can produce an aspiring effect that can stabilize melt feed and generate a strong recirculation region. Under proper conditions an intense downstream normal shock disk can appear which was correlated to the measurements of a maximum in nozzle aspiration effect. For one design tested, an optimum operating condition was found to occur which was shown to be correlated to particle size refinement.

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References