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**A SHEAR REVERSAL NOZZLE FOR
EFFICIENT GAS ATOMIZATION**

S. W. Brown

December 1992

**MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY**

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A SHEAR REVERSAL NOZZLE FOR EFFICIENT GAS ATOMIZATION

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Chemistry and Chemical Engineering Department
Development Division

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Prepared by the
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NOMENCLATURE

Upper case

A	Area, ft ²
B	Total number of divisions in a geometric progression
C _D	Aerodynamic drag coefficient
C _f	Boundary layer skin friction coefficient
C _p	Specific heat at constant pressure, BTU/lbm °R
C ₁	Atomization constant that relates the square of the velocity difference to particle size, ft/sec ²
C ₂	Atomization constant that relates the square of the velocity difference to particle size, ft/sec ²
D	Distance traveled in the finite difference model, ft
F _D	Drag force, lbf
M	Mach number
MASS _p	Mass of a single particle, lbm
MFR	Gas-to-liquid mass flow ratio
$\bar{M}$	Mach number based on the velocity difference between a particle and the gas
Mg	Mass flow rate of the gas, lbm/sec
N	Vortex sheading frequency, 1/sec
N _p	Number of particles
P	Gas static pressure, psia
Pr	Gas Prandtl number
PT	Gas Total Pressure, psia
Q	Bulk heat transfer rate from the particles to the gas, BTU/sec
R	Ideal Gas Constant, ft-lbf/lbm - °R
Re	Reynolds number
S	Total population of a geometric series
Stl	Strouhal number
T	Gas static temperature, °R
TT	Gas total temperature, °R
V	Velocity, ft/sec
VOL _p	Volume of a single particle, ft ³
Z	Potential energy height, ft

Lower case

a	Particle acceleration, ft/sec ²
d	Characteristic diameter, ft
dejector	Ejector exit diameter, ft
dp	Particle diameter, ft
D _{term}	Particle terminal diameter before the normal shock, ft
g	Acceleration of gravity, 32.17 ft/sec ²
ge	Force/mass conversion constant, 32.17 ft-lbm/lbf - sec ²

h	Gas convective heat transfer coefficient, BTU/sec-ft ² -°R
k	Gas conductive heat transfer coefficient, BTU/sec-ft-°R
$\dot{m}$	Mass flow rate, lbm/sec
$\dot{q}_p$	Heat transfer rate of a single particle, BTU/sec
r	Gas recovery factor
t	False time, sec
x	Distance from the leading edge of the acceleration section, ft

Greek symbols

∞	Number of offsprings in a geometric progression
β	Mach angle, radians
γ	Ratio of specific heats of the gas
Δ	Represents change in variable
$\delta,$	Boundary layer displacement thickness, ft
λ	Mach number eigenvalue
μ	Gas viscosity, lbm/sec-ft
ν	Prandtl-Meyer angle, radians
ρ	Density, lbm/ft ³
σ	Liquid/gas surface tension, lbf/ft
τ	Shear stress, lbf/ft ²
ϕ	Wall turning angle, radians
ω	Viscosity power law coefficient

Subscripts

c	Represents containment vessel conditions
CRIT	Represents condition beyond which division no longer occurs
e	Represents nozzle exit conditions
g	Represents conditions of the gas
i	Represents conditions at time increment i
l	Represents conditions of the liquid
MAX	Represents maximum conditions
MIN	Represents minimum conditions
o	Represents initial conditions
s	Represents initial conditions after the normal shock
w	Represents conditions at the wall
1	Represents conditions just before the normal shock
2	Represents conditions just after the normal shock

Superscripts

- * Represents sonic flow conditions
- ' Represents final particle conditions after the normal shock.

1. EXECUTIVE SUMMARY

The primary purpose of this report is to establish definitive rationale and technical drivers for atomizing nozzles that employ the shear reversal principle. In a shear reversing nozzle, the liquid to be atomized is introduced into a supersonic gas flow and is allowed to accelerate to a velocity near that of the gas before it exits the nozzle. The pressure conditions at the exit of the nozzle are managed in such a manner to produce a strong normal shock wave in the gas flow field. The shock wave causes a large reduction in the gas velocity at the exit of the nozzle. Because the liquid is traveling near the initial gas velocity as it exits the nozzle, it now encounters a relatively slow moving gas flow field, which causes further reductions in the particle size.

An elementary atomizing model is presented comprising two distinct processes: (1) particle divisions and (2) particle shearing. From the model, the primary process variables were identified and strategies were presented to maximize the production of fine diameter particles. In addition, an elementary finite difference model was presented to aid in the determination of the overall length of the shear reversing nozzle. Finally, a procedure was given to establish proper sizing of the components involved.

2. INTRODUCTION

Gas atomization nozzles have been under development at the Oak Ridge Y-12 Plant.* The work presented was conducted between 1989 and 1990 in support of the nozzle development efforts. One goal of this program has been to produce powders of minimum diameter for a given set of operating conditions. This goal effectively defines the most efficient nozzle configuration for a given energy input.

The nozzle development work has been pursued along three separate courses. The first course is described generically as conical flow field nozzles, which are prevalent in industrial gas atomization work today. The second course attempts to mechanically reduce the size of the liquid stream before contact with the high energy gas stream. The third course is termed shear reversal nozzles and is believed to be a new development in the gas atomization field. The purpose of this document is to describe the controlling factors and the design procedure for the definition of a flow reversal nozzle.

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3. PRECONDITIONS TO ATOMIZATION

3.1 MASS FLOW RATIO

A number of preconditions must exist to achieve efficient atomization. One of the more important preconditions in the mass flow ratio of the gas to liquid is defined as follows:

$$\frac{\dot{m}_{gas}}{\dot{m}_{liq}} = MFR = \frac{\rho_g A_g V_g}{\rho_l A_l V_l}, \quad (1)$$

where ρ is the density (lbm/ft³),
 A is the exit area (ft²),
 V is the velocity (ft/s),
 Subscript g is for the gas,
 Subscript l is for the liquid.

Not only does the atomizing gas have an effect on the liquid, the liquid also has an effect on the gas. In principle, the gas flow field should be maintained, intact, until all work is completed on the liquid. This state occurs when the liquid has been fully accelerated to the gas velocity and no further size reduction occurs. In practice, maintaining a gas flow field can be very difficult and requires precise geometric conditions, as will be discussed in Sect. 5, "Shear Reversal Nozzle."

Combining the momentum, continuity, and energy equations in differential form, Ref. 1 established the following general relationship for two-phase flow:

$$\frac{Cpl}{MFR} dT_l + C_{pg} dT_g + \frac{(V_l - V_g)}{MFR} dV_l = \frac{dP_g}{\rho_g}, \quad (2)$$

where C_p is the specific heat at constant pressure (BTU/lbm - °R),
 T is the gas temperature (°R),
 P is the gas pressure (psia).

Assuming that the particles are fully accelerated, as discussed in the preceding paragraph, and that both the gas and the liquid temperatures are equal, Eq. 2 reduces to the following:

assume $V_g = V_l$,
 $T_g = T_l$,

$$\left(\frac{Cpl}{MFR} + C_{pg} \right) dT = \frac{dP}{\rho_g}. \quad (3)$$

Integrating Eq. 3 from static to total conditions yields

$$\left(\frac{T_g}{TT_g} \right) = \left(\frac{P_g}{PT_g} \right)^n, \quad (4a)$$

$$n = \frac{(Rg/778.16)}{\left(\frac{Cpl}{MFR} + Cp_g \right)}, \quad (4b)$$

where T and P are the static temperature and pressure,
 TT and PT are the total temperature and pressure,
 R is the ideal gas constant (ft-lbf/lbm - °R).

As the mass flow ratio becomes very large (and losses within the nozzle are neglected), Eq. 4a reduces to the familiar isentropic pressure/temperature relationship defined by

$$\lim_{mfr \rightarrow \infty} \left(\frac{T_g}{TT_g} \right) = \left(\frac{P_g}{PT_g} \right)^{\frac{\gamma-1}{\gamma}}, \quad (5)$$

where γ is the ratio of specific heats.

Equation 4 was evaluated assuming a Mach 2.0 air nozzle atomizing pure aluminum and is shown in Fig. 1. This analysis indicates that for low values of the mass flow ratio (<10), the liquid can cause large flow behavior deviations from isentropic. For supersonic gas flow fields, this mass flow ratio range can cause even further deviation from isentropic gas flow as weak bow shock waves form in front of each particle. Characteristically, the weak shock waves coalesce causing the supersonic flow to jump rapidly to subsonic conditions in a nonisentropic manner. Analysis of the gas flow field for mass flow ratio in this range can be exceedingly complex and should be avoided.

Fig. 1. Effect of mass flow ratio.

At very high values of the mass flow ratio (>100), little deviation from isentropic behavior is observed. Once this state is achieved, little change in the particle size can be obtained by further increases in the mass flow ratio. For mass flow ratios >100, particle size control can be achieved only by varying either the characteristics of the gas flow field (e.g., Reynolds number, dynamic pressure, or Mach number) or the mixing methods at the gas/liquid interface (see Sect. 3.5, "Liquid/Gas Mixing").

Operation at moderate mass flow ratios (10 to 100) can be used as a means of controlling the particle size. Selection of an optimum mass flow ratio is largely a matter of economics, because gas consumption rates will vary considerably over the range. In addition, the target particle size also will be a factor. Only small deviations from isentropic flow are encountered over this range and, as a result, all further analysis reported will assume, unless otherwise stated, that isentropic flow equations apply.

Note that a great majority of modern atomizing nozzles have fixed geometry gas and liquid flow sections. As a result, only one method—changing the liquid flow rate—is available for independently adjusting the mass flow ratio. Changes in the gas operating pressure will change not only the gas mass flow rate but also the Reynolds number and the dynamic pressure, which will be shown to influence primarily the final particle size. Considering that the liquid ejector area is normally fixed, changes in the liquid flow rate can be achieved by varying the ejector differential pressure and is related through the following Bernoulli equation:

$$\frac{g}{g_c}(\Delta Z) + \frac{\Delta P l}{\rho l} + \frac{\Delta V l^2}{2 g_c} = 0 , \quad (6)$$

where ΔZ is the change in the potential energy height (ft).

Finally, the second assumption in Eq. 3 generally does not hold because the molten liquid typically freezes at the low gas temperatures. This factor will be fully accounted for during discussions of Rayleigh flow in Sect. 6, "Time-Dependent Acceleration and Heat Transfer Model."

3.2 SUPER HEAT

Maintenance of an adequate amount of super heat in the molten liquid also is a critical precondition for proper atomization. At low super heat values, the particles will freeze prematurely, preventing further atomization. As such, it is critical that the liquid particle remain molten until all work is completed. As in the preceding section, this state occurs when the liquid has been fully accelerated to the gas velocity.

Excessive super heat also can be detrimental to the atomization process. At very large values of super heat, the particles reach the walls of the containment vessel in a molten state where freezing occurs. As the atomization process proceeds, layer upon layer of molten particles are deposited on the containment walls.

At more moderate levels of super heat, the particles can reach the containment walls in a solid state and elevated temperatures. At the elevated temperature, sintering of the powder can occur, causing bonding between particles. In this situation, the powder collected very nearly resembles a solid mass. Based on these arguments, selection of the super heat is critical for proper atomization. Systematic methods for determining the super heat level are discussed in Sect. 6.

It is important to note that the selection of the proper super heat is very much a time-dependent process. During the initial stages of atomization, the containment system is generally cold, which leads to rapid quenching of the particles. As the atomization process continues, heat builds inside the containment system, which can move the super heat level into the undesirable range. As a result, extreme care must be exercised to ensure that the heat transfer rates (convection, conduction, and radiation) and the containment system surface area are adequate to remove the steady-state heat load provided by the molten liquid.

3.3 GAS FLOW FIELD DETERIORATION

The ejection of a high-velocity gas jet into still air has been studied in a number of different applications. In general, a boundary called a slip stream (Refs. 2 and 3) is formed between the high-velocity gas and the gas at rest. No pressure gradients exist across a slip stream, but the temperature, density, and velocity gradients are discontinuous. In the limiting case, the slip streams become vortex sheets, which produces nonisentropic mixing and entropy gains. This concept is extremely complex and involves simultaneous solutions to potential flow and boundary layer theories. As a result, detailed discussions of this concept are beyond the scope of this document. However, it is important to note that the vortex shedding occurs at a predictable frequency and is based upon the Strouhal number (Ref. 4, p. 32):

$$Stl = \frac{Nd}{V}, \quad (7)$$

where N is the frequency of vortex shedding (1/s),
 d is a characteristic dimension (ft).

The vortex generation causes two distinct problems in gas atomization. First, a circular flow pattern is generated in the containment system. This causes already atomized particles to move to the top of the containment system where they are either deposited or re-entrained by the gas field. Second, and more profound, the vortex formation causes a mass and momentum transfer across the slip stream. This process leads to viscous mixing of the jet with the containment gas. Specifically, the viscous mixing can cause a rapid deterioration in the gas flow field. In this case, incomplete atomization occurs. As a result, efforts to isolate the gas jet from the still gas can be beneficial provided no other disturbances are present in the gas jet.

A number of modern atomizing nozzles employ a choked exit condition (sonic velocity) in which the high-energy gas is allowed to expand to exhaust conditions. In this situation, a number of expansion (isentropic) and compression (nonisentropic) waves develop to produce a complex supersonic flow field. Three separate problems are associated with these nozzles. First, the wave formation pattern can be exceedingly complex, making these solutions tedious and time consuming. When supersonic flow fields are desired, other more appropriate measures exist to generate and cancel the wave formation. These measures will be discussed in Sect. 5. Second, a problem develops when the liquid to be atomized is subjected to a complex and constantly changing gas-flow condition. Calculations of particle shearing and heat transfer rates become nearly impossible under these circumstances. Third, the generation of the weak compression wave will ultimately produce a terminal shock system yielding incomplete atomization. As a result, the methods discussed in Sect. 5 for developing and controlling the supersonic gas flow field are superior to using a choked exit nozzle.

3.4 LIQUID EJECTOR FREEZING

A common problem in atomization is freezing of the liquid at the ejector tip, thereby stopping the atomization process. Correcting this problem can take several routes. The first measure normally taken is to increase the super heat in the melt. This correction method is undesirable because it may move the super heat level off of the optimum value, which will be discussed in Sect. 6. Other problems with this approach were discussed in Sect. 3.2.

A different approach employs a heated atomizing gas that is impinged directly on the liquid ejector tip. Although this approach provides for close coupling of the liquid and gas streams, it is also undesirable. First, the heated gas adds to the steady-state heat load burden of the containment system discussed in Sect. 3.2. Second and more important, heated atomizing gas reduces the Reynolds number by the square root of the absolute temperature (see Sect. 4.4). As will be shown in Sect. 4.4, the Reynolds number is one of the dominant variables in the atomization process and should be maximized.

The most desirable method for alleviating a liquid ejector freezing problem is to provide for secondary heating of the ejector tip. A number of methods exist to provide secondary heating, including resistance heating (ultrahigh-temperature elements) and RF field generation. When this situation is encountered, care should be exercised to minimize all heat transfer elements in the vicinity of the ejector tip. Alternate construction materials with lower conductive heat transfer rates should be explored. Shielding of the ejector tip from the atomizing gas should be investigated as a means of reducing convective heat transfer losses. Finally, attention should be given to the absorption and reflection rates of materials surrounding the ejector tip to minimize radiation losses.

3.5 LIQUID/GAS MIXING

Recent studies (Ref. 5) have used high-speed cinematography to investigate the initial mixing zones of the gas and liquid. This study has identified three separate stages in the initial mixing zone as depicted in Fig. 2. Initially, the liquid flows from the ejector to cover the full frontal tip area. In Stage 1, liquid is entrained by the gas at the outer edge of the tip to form a sheet. The liquid sheet is broken into oblong ligaments in Stage 2, and finally, the ligaments are divided into near-spherical shapes in Stage 3.

It is suggested that influencing the initial mixing zone can have a pronounced and dramatic effect on the ultimate particle size produced. Consider supersonic gas flow field with fixed energy content impinging on the ejector tip in Fig. 2. For relatively large ejection-tip diameters, the liquid sheet and ligaments formed during Stages 1 and 2 will tend to be relatively large, and these effects will extend farther downstream. In such a case, relatively large final particle sizes would be expected. On the other hand, relatively small liquid sheets and ligaments would be expected for smaller ejection-tip diameter. In such a case, a reduction in the final particle size would be expected.

Fig. 2. Initial liquid/gas mixing zone.

A complicating factor is that the liquid sheet and ligaments have a series of detrimental effects on the gas flow field through the formation of bow shock systems, as discussed in Sect. 3.3. As a result, efforts should be made to minimize the development of Stages 1 and 2 by keeping the ejector-tip diameter as small as possible. Arguably, small ejector-tip diameters imply small liquid flow rates and limited production capacity. However, even for small ejector-tip diameters, the liquid mass flow rate can be increased to reasonable levels by adjusting the ejector differential pressure. The relationship between the liquid velocity and the ejector differential pressure is defined by the Bernoulli equation in Sect. 3.1.

4. ATOMIZATION MECHANICS

4.1 ATOMIZING PHASES

No two-phase flow model is known to exist that adequately describes the complete atomization process. Ref. 5 suggests that the initial atomizing phase occurs in three distinct stages. The purpose of this section is to provide an elementary model for the atomization process that is based on a division and shearing model.

4.2 PARTICLE DIVISION

Consider a solid sphere in potential flow as shown in Fig. 3(a). Because no boundary layer exists, the stagnation or total pressure of the gas is achieved at the polar regions ($\theta = 0^\circ$ and 180°). The static pressure exists all along the equator ($\theta = +90^\circ$ and -90°). If this solid sphere is a liquid, these pressure differences will tend to flatten the sphere in the polar regions and to elongate the sphere at the equator until division of the sphere occurs as shown in Fig. 3(b).

Fig. 3. Particle division based upon potential flow.

This division is three-dimensional in nature; therefore, each sphere would tend to divide into multiple ellipsoids (more than two). As such, the division would proceed at a rate faster than that predicted by a simple geometric division. The final number of particles attributed to this atomizing mode can be predicted using the following series equation of a geometric progression (Ref. 6):

$$S = \left(\frac{1}{1-\alpha} \right) - \left(\frac{1}{1-\alpha} \right) \alpha^B, \quad (8)$$

where S is the total number of particles in B divisions,
 α is the number of offsprings from each generation,
 B is the total number of divisions.

It would seem reasonable that a likely appropriate value for ∞ is -4 based upon the three-dimensional symmetry of the problem. Assuming a value of 4 , a total of 5.36×10^{59} particles are present after only 100 divisions. Clearly, the division of particles proceeds at an extremely rapid pace.

Consider now a solid sphere in viscous flow, as shown in Fig. 4(a). Because of the boundary layer, the flow separates from the sphere at a position below the equator. The exact point of separation is a function of the Reynolds number and the condition of the boundary layer (laminar or turbulent). Because of the separation, the total pressure condition is not achieved in the lower polar region in the area of the wake. However, because the flow is attached below the equator, an adequate pressure field exists that will tend to divide each sphere into at least four parts [(see Fig. 4(b)] rather than two parts suggested by potential flow. Because of the three-dimensional nature of the problem and the symmetry involved, each sphere should have a minimum of eight offsprings. At this propagation rate, a total of 2.91×10^{69} particles would be present after 100 divisions.

Fig. 4. Particle division based upon viscous flow.

Because the division rate is so fast, it is suggested that insufficient time is available to form a complete boundary layer around a sphere. As such, the model offered by the potential flow condition may more closely resemble the physical behavior of the process. It is further suggested that the ligament formation observed in Stage 2 by Ref. 5 is evidence of this divisional process.

The particles cease to divide when the forces that tend to hold the particle together exceed the forces of division. The forces that hold the particle together are related to the surface tension of the liquid and the diameter of the particle. The divisional forces are much more complex. A first approximation to the divisional forces would be the difference between the total and the static pressure times the frontal area, as discussed earlier. However, in a supersonic gas stream, a bow shock wave system may be present in front of each particle, depending on the relative velocity between the gas and the particle. As a result, evaluation of the total to static pressure relationship should be made after traversing a near-normal shock for these conditions. To further complicate the problem, the particles have been accelerated by the gas stream.

Because the forces that hold a particle are relatively small, division of the particles will continue until the velocity of each particle is very near that of the gas. When the velocity difference becomes very small, the flow around each particle is best described in incompressible terms. In such a situation, the best estimate of the divisional forces is related to the dynamic pressure developed by the velocity difference between the gas and the liquid particles. Based on these arguments, the critical particle diameter beyond which division no longer occurs is defined by

$$\sigma l(\pi d_{crit}) = \pi (D_{crit})^2 \left[\frac{g_c}{2} \rho g (V_{g_i} - V_{l_i})^2 \right], \quad (9)$$

where σ is the surface tension of the liquid (lbf/ft),
 d_{crit} is the critical diameter beyond which no division occurs,
 i indicates position in time.

Solving for the critical diameter yields

$$d_{crit} = \frac{2\sigma l}{g_i \rho g (V_{g_i} - V_{l_i})^2}. \quad (10)$$

In theory, d_{crit} becomes very large as the velocity difference between the particle and gas becomes small. However, the division of the particles is very rapid, as was noted earlier. Determination of the actual minimum particle diameter from division requires a time-dependent model for this process. As the particles are first introduced into the gas stream, the velocity difference is very large and the critical diameter is very small. The difference between the actual particle diameter and the critical diameter is also very large. As the particles divide and accelerate, the gap between the particle diameter and the critical diameter closes rapidly until they are equal. As such, the ultimate minimum particle size available through division is a strong function of time.

Given its limitation, Eq. 10 still provides powerful insight into atomization by division. This equation suggests that the particle size produced by a nozzle should be a square function of the initial gas velocity. As a result, attempts should be made to maximize the gas velocity when fine-diameter particles are desired. In addition, this equation suggests that higher-density gases produce smaller-diameter particles. Finally, the time-dependent aspects of this process discussed in the preceding paragraph suggest that finer-diameter particles are produced from higher-density liquids. This observation arises from the fact that the higher-density liquids require longer to accelerate in a given gas field, which provides for a longer period of time before the actual particle diameter is equal to the critical diameter.

4.3 PARTICLE SHEARING

A secondary influence in the atomization process is particle shearing caused by the local skin friction coefficients developed by the boundary layer. Initially, the local skin friction coefficient is zero at the upstream pole on a sphere. However, as the boundary layer grows, the skin friction coefficient continues to rise until the point of separation is reached. When the forces exerted by the local skin friction exceed those generated by the surface tension, a portion of the particle is sheared away. Because the skin friction forces are small (of the same order as the surface tension), an

adequate level for shearing will not be developed until the boundary layer nears the equator of the sphere. As a result of geometry consideration, the offspring particle generated by this mechanism will be substantially smaller than the offsprings generated by division.

Because insufficient time is available to generate a fully developed boundary layer during division, it is likely that the offsprings produced by the shearing mechanism are only a small fraction of the total population obtained during atomization. However, with a basic understanding of the controlling mechanisms and tailoring of the aspects that generate the shearing mechanism, atomization by shearing offers the potential to produce exceedingly small diameter particles. The size of these sheared particles would be substantially smaller than would be expected by the division process. The remainder of this section is devoted to understanding the boundary layer development and subsequent generation of shear stress and assumes that no other mechanisms are present in the atomization process.

Because high-pressure gas streams are used in modern atomizing processes, the gas/particle boundary layer must move through several different flow regimes. Initially, the boundary layer can be described using a compressible flow, turbulent approach. As the particles shear and accelerate, reducing the velocity difference between the gas, the boundary layer conditions will move through compressible flow, laminar conditions; incompressible flow, turbulent conditions; and finally, incompressible flow, laminar conditions. The mechanisms that move the boundary layer development from one flow regime to another will be a function of the circumstances affecting the boundary layer formation. No known general, time-dependent solution to the Navier-Stokes equations involving two-phase flow exists that covers all of these flow regimes. As such, each flow regime must be examined independently. Furthermore, the geometry of the liquid changes during each flow regime, as suggested by Fig. 2.

Initially, a sheet of liquid is formed at the tip of the liquid ejector. Because the gas velocity is very high (i.e., high Reynolds number), a turbulent boundary layer quickly forms on the sheet. The shearing action of the gas during this stage is best described in terms of a flat-plate solution in compressible, turbulent flow. Using a Prandtl's mixing length hypothesis, the skin friction coefficient of a flat plate as given in Ref. 4 (p. 670) takes the following form:

$$\frac{0.242}{\sqrt{C_f}}(1 - \lambda^2)^{1/2} \frac{\arcsin \lambda}{\lambda} = \log(Re_g C_f) + \frac{1 + 2\omega}{2} \log(1 - \lambda^2) , \quad (11a)$$

$$1 - \lambda^2 = \frac{1}{1 + \frac{\gamma - 1}{2} M^2} , \quad (11b)$$

$$\frac{\mu g}{\mu g_w} = \left(\frac{Tg}{Tg_w} \right)^\omega \text{ with } 0.5 < \omega < 1.0 , \quad (11c)$$

where M is the local free stream Mach number,

$$C_f = \frac{\tau_W}{\frac{1}{2}\rho g V_g^2}, \quad (11d)$$

$$Re_g = \frac{\rho g V_g X}{\mu_g}, \quad (11e)$$

τ_W is the local shear stress at the wall (lbf/ft²),
 x is the position from the leading edge of the ejector tip (ft),
subscript W indicates conditions at the surface or wall,
 ω represents the simple power law for the viscosity variation across the boundary layer (in most fields, $\omega = 1$ provides good approximation),
 Re is the Reynolds number,
 C_f is the skin friction coefficient.

Equation 11a suggests that three variables are important to the initial stages of atomization: the free stream Mach number, the Reynolds number, and the ratio of specific heats of the working gas. [See Figs. 5(a), (b), and (c).] Insight can be gained as to the relative importance of each variable by incrementally fixing two and observing the change in the skin friction coefficient caused by variations in the third. The conditions assumed for this sensitivity analysis are as follows, and the results are shown in Fig. 5.

Sensitivity Analysis Assumptions

$$\begin{aligned}
 M &= 1.0 \\
 Re_g &= 10^6 \\
 \gamma &= 1.4 \text{ or } 1.66 \text{ (diatomic and monatomic)}
 \end{aligned}$$

(Note that ω is a physical constant once the working gas is selected and operating condition defined and was assumed as 1.0 for this analysis).

Fig. 5(a). Shear stress coefficient vs Mach number.

Fig. 5(b). Shear stress coefficient vs Reynolds number.

Fig. 5(c). Shear stress coefficient vs ratio of specific heat.

The results of the sensitivity analysis indicate that the skin friction coefficient decreases as the Mach number, Reynolds number, and ratio of specific heats increase. The most predominant variation occurs with the Reynolds number followed by the Mach number and with little change observed with the ratio of specific heats. As such, the Reynolds number is the primary dominant variable during the initial stages of atomization with the Mach number being of secondary importance. Although the geometry changes from a flat plate to a spherical approximation in Stage 3, it is suggested that this sensitivity analysis also is valid once the particles take a more spherical shape.

It is imperative to understand that this sensitivity analysis does *not* suggest that the smallest diameter particles are produced with the lowest Reynolds and Mach numbers. The converse is true because the shearing of a particle into a smaller diameter is an integrative process. As the liquid is first introduced into the gas stream, the Reynolds and Mach numbers are relatively high, which

produces low shear stress coefficient. As the particles shear to finer diameters, the Reynolds number is reduced by a linear ratio. Furthermore, the drag forces exerted on the liquid by the gas cause it to accelerate, thereby reducing the relative velocity difference between the liquid and the gas. This reduction in relative velocity also works to reduce the Reynolds number in a linear fashion. The combined effects of shearing and acceleration produce a quadratic reduction in the Reynolds number. As a result, the shear stress coefficient rises because of a rapid reduction in the Reynolds number as the particles continue to shear. It is the cumulative action of these forces and dimensionless variables that ultimately determines the final particle diameter. As such, the final particle diameter is more closely related to the area under the curves in Fig. 5 rather than to the absolute value of the shear stress at any moment in time. Based on these arguments, higher Reynolds and Mach numbers produce smaller final particle sizes. However, the sensitivity analysis does serve to show that higher gains in particle size reduction can be achieved by increasing the Reynolds number rather than the Mach number.

It is also appropriate to examine the opposite end of the spectrum, namely, compressible laminar flow. In this situation, the particles are more appropriately described as spherical geometries, as discussed earlier. However, closed-form solutions for any geometry in compressible laminar flow are lengthy and cumbersome. Again, insight can be gained by making the simplifying assumption of a flat plate. Schlichting (Ref. 4, p. 344) indicates that the boundary layer development is a function of not only Reynolds and Mach numbers but also the Prandtl number. The primary mechanism that evolves from the Prandtl number (Pr) is an entropy gain across the boundary layer, which reduces the total temperature of the working gas. Intrinsically, the loss in total temperature works to reduce the overall energy content of the working gas and, thus, its ability to shear the liquid particles. Specifically, the loss in total temperature works to change the physical properties of the gas (e.g., viscosity, density, and pressure), which are temperature dependent, and to reduce the Mach number because the speed of sound is also a function of temperature. The gas total temperature at the gas/liquid interface can be described in terms of a recovery factor, r , given by the following relationship:

$$T_w = T \left(1 + r \frac{\gamma - 1}{2} M^2 \right), \quad (12a)$$

where

$$r = \sqrt{Pr}. \quad (12b)$$

This relationship indicates that the energy loss of the gas can be minimized by selecting a working gas with a Prandtl number near unity. In practice, however, very little gain can be realized because there is little difference in the Prandtl numbers for various working gas, as the following indicates:

<u>Working Gas</u>	<u>Prandtl Number (72°F)</u>
Air	0.709
Helium	0.700
Nitrogen	0.714
Argon	0.675

Before moving to the next flow regime, it is critical to understand the relative importance of compressible laminar flow. A typical atomizing nozzle produces powder with diameters on the order of $\leq 100\text{-}\mu\text{m}$. Even for the relatively high gas velocities that are produced at sonic or supersonic conditions, the Reynolds number based upon a $100\text{-}\mu\text{m}$ diameter and the relative gas velocity can be in the laminar range. As a result, it is likely that the majority of the shearing of an individual particle is controlled by the relationships established in this regime.

A large body of empirical data exists for both laminar and turbulent incompressible flow (Refs. 4, 7, and 8). These data indicate that the drag coefficient (integral of skin friction over the surface area) on a spherical geometry is solely a function of the Reynolds number, as illustrated in Fig. 6. As a result, in both the laminar and the turbulent flow regimes, the Reynolds number is the single variable that controls the shearing action of the working gas.

Fig. 6. Drag coefficient vs Reynolds number.

4.4 MAXIMIZING SHEAR

As noted earlier, maximizing the effects of shear on a particle will likely result in exceptionally fine diameter particles. As such, it is appropriate to examine methods to influence the dimensionless parameter identified in the preceding section to enhance the generation of shear. Over each of the boundary layer flow regimes investigated, the Reynolds number based on the liquid particle-to-gas velocity difference was determined to be the dominate variable with the Mach number playing a secondary role for only the compressible flow regime. The free stream Reynolds number and the Mach number can be used as initial values to approximate the relative Reynolds number and Mach numbers. In effect, these initial free stream values determine the starting position of the integrative process of atomization. Expressing the free stream Reynolds number and the Mach number in terms of the design and operating variables yields the following results:

$$Re = \sqrt{\frac{gc\gamma}{R\mu g^2} \frac{PT}{\sqrt{TT}} \frac{Mx}{(1 + \frac{\gamma - 1}{2} M^2)^{1/\gamma - 1}}}, \quad (13a)$$

$$\bar{V} = \sqrt{\frac{\gamma R_g T T}{1 + \frac{\gamma - 1}{2} M^2}} M \quad (13b)$$

The relationship between the free stream Reynolds number and the total pressure and the total temperature is apparent. The free stream Reynolds number increases linearly with the total pressure and decreases as a function of the square root of increasing total temperature. As a result, efforts to maximize shear should use high gas pressures and low gas temperatures. The first term in Eq. 13a relates specifically to the selection of the proper atomizing gas. Values for the gas-specific term are listed in Table 1. The data indicate that the highest free stream Reynolds numbers are produced with either argon, nitrogen, or air, and, thus, define the set of efficient atomizing gases. The free stream Reynolds number produced with helium or hydrogen will be two to three times smaller than the set of efficient atomizing gases at comparable pressures and temperatures. The free stream Reynolds number produced by steam is roughly two orders of magnitude lower than the set of efficient gases and indicates that atomization by water is a grossly inefficient process.

Table 1. Gas-specific Reynolds number term

Gas	Gamma	R ($\frac{\text{ft-lbf}}{\text{lbm-R}}$)	Mu ($\frac{\text{lbm}}{\text{sec-ft}}$)	Rey No. ($\frac{\text{ft} \cdot \sqrt{R}}{\text{lbf}}$) term
Air	1.40	53.34	1.2252 E-5	7.500 E4
Argon	1.66	38.66	1.5052 E-5	7.808 E4
Helium	1.66	386.00	1.3394 E-5	2.777 E4
Hydrogen	1.40	766.40	0.5961 E-5	4.067 E4
Nitrogen	1.40	55.15	1.1844 E-5	7.630 E4
Steam	1.33	85.76	1.8022 E-3 ^a	3.919 E2 ^a

Note: Values listed are at 72°F and 14.14 psia unless noted.

^a Value for dry saturated steam at 212°F, 14.504 psia.

The effects of free stream Mach numbers on free stream Reynolds numbers are shown in Figs. 7(a) and 7(b) for various pressure and temperature conditions of air. The analysis indicates that a peak free stream Reynolds number is obtained for a free stream Mach number of roughly 1.20. The exact position of this peak can be obtained from Eq. 13a. Because PT, TT, and the gas-specific constant are fixed for any given operating condition, the derivative of the free stream Reynolds number with the free stream Mach number becomes

$$\frac{dRe}{dM} = \frac{\left[1 + \left(\frac{\gamma - 1}{2} \right) M^2 \right]^{1/(\gamma-1)} - M^2 \left[1 + \left(\frac{\gamma - 1}{2} \right) M^2 \right]^{\frac{(2-\gamma)}{(\gamma-1)}}}{\left[1 + \left(\frac{\gamma - 1}{2} \right) M^2 \right]^{2/(\gamma-1)}} \quad (13c)$$

Setting the derivative to zero, and solving for the free stream Mach number at peak free stream Reynolds numbers yields

$$M|_{Re-\max} = \sqrt{\frac{2}{3 - \gamma}} \quad (13d)$$

For diatomic ($\gamma = 1.40$) and nonatomic ($\gamma = 1.66$) gases, the free stream Mach number at the peak free stream Reynolds number becomes 1.118 and 1.222, respectively.

As in Sect. 4.3, the presence of a maximum free stream Reynolds number does not imply that the finest particle size is produced at a specific free stream Mach number. Because atomization is more an integrative process, higher free stream Mach numbers will produce finer particles. However, Fig. 7(a) does show that larger reductions in particle size would be expected with increases in total pressure as opposed to increases in the free stream Mach number. In addition, this analysis shows that all atomization nozzles should be designed to produce a free stream Mach number of 1.2 or larger to take advantage of the peak free stream Reynolds number.

Fig. 7(a). Reynolds number vs Mach number and pressure.

The data shown in Fig. 7(b) indicate the inverse relationship between free stream Reynolds numbers and temperature. These data suggest that the temperature of the gas should be reduced as low as reasonably possible to increase the free stream Reynolds number. This is the prime reason for not recommending the use of heated gas as a means of keeping the ejector tip hot as discussed in Sect. 3.4.

The last subject for shear maximization involves timing. Although time-dependent models have not been presented, it is suggested that the timing aspects of boundary layer development are the dominant variable in shear maximization. The division model presented in Sect. 4.2 indicated that the process was extremely rapid. As such, it is unlikely that a boundary layer has sufficient time to develop on a single particle before that particle divides. Once the particle divides, the boundary layer must re-form on the offsprings, which ultimately will undergo a division process themselves. As a result, the effects of shearing will not be realized to any significant degree until the division process is near completion.

Fig. 7(b). Reynolds number vs Mach number and temperature.

To take advantage of particle shear, the division process must be allowed to go to full completion. As such, the gas flow field must be maintained free of disturbance (expansion or compression waves) or other factors that tend to deteriorate the flow (see Sect. 3.3). Particle acceleration also occurs during the division process, and the particle velocity likely will be near the gas velocity once the division process is complete. Minimal shearing will occur with these low-velocity differentials. Methods will be given in Sect. 5.1 to change the gas velocity abruptly once division is complete, thereby prompting the shearing action of the gas.

5. SHEAR REVERSAL NOZZLE

5.1 SUPERSONIC NOZZLE OPERATION AND THE SHEAR REVERSAL PRINCIPLE

Once the geometry of a supersonic nozzle is fixed, the nozzle can operate in three distinct modes that are a function of the gas exit static pressure and the containment vessel pressure. These three modes are on underexpanded, perfectly expanded, and overexpanded states and are shown in Fig. 8 (Ref. 9, p. 128).

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Fig. 8. Nozzle operating modes.

When the exit static pressure of the gas is greater than the containment vessel pressure, the exit gas must expand to the containment pressure through the generation of weak expansion waves. As the gas expands through the weak waves, the Mach number increases. The increase in Mach number always causes an increase in the gas velocity. However, the rate at which the gas velocity increases will decrease substantially as the Mach number increases. An example of this situation is shown in Fig. 9 for the expansion of room-temperature air and shows that an expansion from a Mach number of 2 to 3 causes only a 20% increase in the gas velocity. These relatively small velocity changes occur over a relatively large distance and, as a result, provide only a small impulse function for the generation of particle shearing. Operation of a nozzle in this mode is termed underexpanded because the gas static pressure has not been allowed to fully expand to the containment pressure.

Fig. 9. Gas velocity vs Mach number.

When the gas exit static pressure is equal to the containment pressure, no forces exist that act to change the gas velocity. Because of small perturbations at interfaces, Mach waves exist in the flow but are infinitesimally weak. Provided that a particle is at the free stream velocity, it will remain so until the forces described in Sect. 3.3 cause the gas field to deteriorate. In this situation, further particle division is not possible, but the forces controlling particle shearing may have time to develop. Operation of a nozzle in this mode is termed perfectly expanded because the gas exit static pressure is equal to the containment pressure.

When the gas exit static pressure is less than the containment pressure, a series of relatively strong shock waves must be present to recompress the gas to the containment pressure. Depending on the pressure conditions, the recompression of the gas can occur either internally or externally to the nozzle. When the ratio of the exit to the containment pressure is ~ 0.85 , a series of oblique shock waves and corresponding reflected expansion waves will develop along the centerline of the flow (see Fig. 8). Further reductions in the pressure ratio to ~ 0.66 will cause the formation of a complex curved shock system. Operations at a pressure ratio of ~ 0.4 will cause the formation of a strong normal shock wave. Additional reductions in the pressure ratio will force the normal shock wave internal to the nozzle to match the boundary conditions.

The exact solution for the pressure ratio that places the normal shock at the exit of the nozzle is a function of the exit Mach number of the nozzle and the ratio of specific heats of the gas. The equations that determine the value of the ratio (Ref. 10, p. 63) are as follows and are illustrated in Figs. 10(a) and 10(b):

$$M_2 = \frac{M_1^2 + \frac{2}{\gamma - 1}}{\left(\frac{2\gamma}{\gamma - 1}\right)M_1^2 - 1}, \quad (14a)$$

$$\frac{P_2}{P_1} = \frac{(1 + \gamma M_1^2)}{(1 + \gamma M_2^2)}, \quad (14b)$$

$$\frac{PT_1}{P_2} = \frac{(1 + \gamma M_2^2) \left[1 + \left(\frac{\gamma - 1}{2}\right)M_1^2\right]^{\frac{\gamma}{\gamma - 1}}}{(1 + \gamma M_1^2)}, \quad (14c)$$

where M is the Mach number,
P is the static pressure (psia),
PT is the total pressure (psia),
subscript 1 indicates the conditions ahead of the shock or at the exit of the nozzle,
subscript 2 indicates the conditions behind the shock or containment conditions.

Fig. 10(a). Static pressure ratio across exit shock.

Fig. 10(b). Total/static pressure ratio across shock.

The strong normal shock wave generated at the proper exit pressure ratio causes the Mach number behind the shock to jump to subsonic conditions in a near-discontinuous fashion. The strength of the shock in terms of velocity change is a function of the nozzle exit Mach number and the gas total temperature. This relationship is illustrated for air in Fig. 11 and was computed from the normal shock relationships given in Ref. 10. The analysis indicates that substantial velocity changes will occur at even modest Mach number/temperature conditions as a particle moves across a normal shock. Furthermore, larger Mach numbers and temperatures produce higher velocity changes. Assuming that a particle is traveling at the gas velocity ahead of the normal shock, this abrupt change in the gas velocity will act as a strong impulse function to re-establish both the division and shearing of the particles. As such, nozzles that use the overexpanded design principle have the potential to produce particles with diameters far smaller than another nozzle.

Fig. 11. Velocity change across a normal shock.

It is also appropriate to examine the change in gas flow conditions across a shock in terms of the impulse Reynolds number change that is generated. The Reynolds number change will be a function of not only the exit Mach number and total temperature but also of the exit total pressure. Again, the change in Reynolds number was determined based on the normal shock relationships given in Ref. 10 and is shown in Figs. 12(a) and 12(b). The data indicate that a local maximum Reynolds number change is obtained at an exit Mach number of ~2.0. Increases in total pressure tend to increase the

local maximum Reynolds number change whereas increases in total temperature tend to decrease the local maximum Reynolds number change. This total pressure/total temperature trend is consistent with Eq. 13a and can be shown to be directly related to Eq. 13a once the normal shock equations are introduced.

Fig. 12(a). Reynolds number change vs Mach number and total pressure (PT).

Fig. 12(b). Reynolds number change vs Mach number and total temperature (TT).

As indicated in preceding sections, the presence of a maximum Reynolds number does not imply that the finest particle size is produced at a specific Mach number. Fig. 11 indicates that the velocity change across a normal shock continues to rise as the Mach number increases. Above a Mach number of 2.0, lower Reynolds numbers are experienced because the velocity increase is offset by a density decrease. As a particle begins to decelerate as a result of the reverse shear field, the Reynolds number will increase along a constant total pressure line until it reaches a maximum value. However, this analysis does show that shear reversal nozzles should be designed for Mach 2.0 operation and above.

5.2 OPERATING CONSTRAINTS

To achieve an overexpanded nozzle condition, supersonic flow must be established throughout the nozzle, an action known as "nozzle starting." The most efficient method for starting the nozzle is to place the nozzle just slightly past the perfectly expanded conditions into the underexpanded region shown in Fig. 8. Nozzle starting is achieved by either raising the total pressure for a constant containment vessel pressure or by lowering the containment pressure at a constant nozzle total pressure. Assuming a perfectly expanded nozzle condition, the minimum starting conditions can be defined by

$$P_{C_{MAX}} = \frac{P_{T_{MIN}}}{\left[1 + \left(\frac{\gamma - 1}{2}\right)M_e^2\right]^{\frac{\gamma}{\gamma - 1}}}, \quad (15)$$

where $P_{C_{MAX}}$ is the maximum containment vessel pressure during nozzle starting (psia),
 $P_{T_{MIN}}$ is the minimum nozzle total pressure during nozzle starting (psia),
 M_e is the design exit Mach number of the nozzle.

The relationship established by Eq. 15 is shown in Figs. 13(a) and 13(b) and indicates that the nozzle starting pressure will exceed 1000 psia at ambient exhaust conditions once the nozzle exit design Mach number moves into the 3.5 to 4.0 range. Using a containment vessel pressure-control strategy at a nozzle total pressure of 100 psia, the containment vessel pressure level will move into the vacuum range once the nozzle exit design Mach number exceeds ~1.8. Note that the use of vacuum conditions in the containment vessel is not generally recommended because many materials become oxygen and/or moisture sensitive, especially at the fine particle diameters produced by this approach. It is important to note that the nozzle-starting requirement imposes additional burdens on the atomizing support equipment. As such, sizing of the pressure supply equipment and containment vessel exhaust system and equipment must be accomplished at pressure conditions and flow rates defined by the starting conditions.

Fig. 13(a). Starting pressure for ambient exhaust.

Fig. 13(b). Exhaust pressure for nozzle starting.

5.3 SUPERSONIC NOZZLE DESIGN FOR SHEAR REVERSAL

The supersonic nozzle design approach is a critical element for successful use of the shear reversal principles. This approach employs the unique geometrical setup shown in Fig. 14. The shear reversal nozzle consists of three basic components: the nozzle body, the gas shield, and the acceleration section. The shear reversal nozzle is more efficient because it can generate the same velocity change produced by current atomization nozzles while operating at substantially lower pressures and gas consumption rates.

The gas supply enters the upper part of the nozzle body into a relatively large area stilling chamber. The gas velocity in the stilling chamber generally should be kept below 50 to 100 ft/sec to avoid the generation of significant pressure losses. The gas flow is accelerated to supersonic speed by the converging/diverging geometry along Surface A. The coordinates of Surface A can be determined precisely using the method of characteristics presented in Sect. 5.4. The lower portion of the nozzle body has a converging shape along Surface B to compensate for the removal of the gas shield. The coordinates of Surface B also can be determined precisely using the methods of Sect. 5.4. Finally, the gas flow field exits the lower portion of the nozzle body and enters the particle acceleration section.

Fig. 14. Shear reversal nozzle components.

The purpose of the gas shield is to prevent depositing the molten liquid on the internal surfaces of the nozzle. As such, it is a "keyhole" through the gas flow field that is removed once the gas has been fully accelerated. This is especially important in the stilling chamber area, where the swirling effects of the gas supply can cause large deviations in the molten liquid velocity vector. At the

supersonic velocities at which the gas shield is removed, deviations sufficient to allow deposition of molten liquid on the internal surfaces of the nozzle body are generally impossible as a result of vectoring considerations.

The outside surface of the gas shield can be either square, rectangular, or circular in cross section but a square or a rectangular approach is preferred, as explained in Sect. 5.4. The thickness is equal to or exceeds the height of the nozzle shown in Fig. 15. The gas shield is removed along Surface C, which is the final aerodynamic contour defined by the Method of Characteristics. The design coordinates of Surface B must be positioned precisely with those of Surface C. The supersonic wave forms generated by Surface B are canceled by the contour along Surface C, yielding a uniform, wave-free supersonic flow stream in the acceleration section of the nozzle. Using this approach takes advantage of many of the factors discussed in Sect. 3.4.

Fig. 15. Rectangular cross section resulting from one-dimensional Method of Characteristics.

The center of the gas shield is hollow, which allows the liquid from the ejector tip to fall through undisturbed by gas flow fields. The gas shield must be sealed at the ejector tip to prevent pressure difference between the upper and the lower sections from generating a gas flow pattern that ultimately will lead to deposition of molten liquid on the internal surfaces. As such, the upper portion of the gas shield may require heating to keep the ejector tip at the proper temperature. Placement of the containment vessel is arbitrary, and it can be attached to the lower portion of the acceleration section, to the nozzle body, to the gas shield in the area between the nozzle and the melt vessel, or to any position along the melt vessel, including full encapsulation.

The purpose of the acceleration section is to allow the particles to accelerate in a uniform, disturbance-free flow field. As such, it creates a buffer zone that allows the particles to divide, shear, and accelerate before crossing the normal shock and encountering the reverse shearing action of the nozzle. The length of the acceleration section is critical, and methods to determine the length are given in Sect. 6.

The design of the acceleration section is detachable for a number of reasons. First, the length of the acceleration section can be relatively long under certain conditions, which can allow molten liquid deposits on the internal walls after prolonged use. The detachable feature allows removal of the acceleration section for cleaning or replacement. As such, the acceleration section also is split along the centerline as a cleaning aid. Second, the length determination procedure given in Sect. 6 is an iterative process requiring, at a maximum, an initial and a final set of hardware. Finally, the most important reason for the detachable feature is that it provides flexibility for atomizing materials of different densities. As atomization materials are changed, the only modification necessary for this approach is the selection of the proper length for the acceleration section.

The cross-sectional area for the flow in the acceleration section is constant for short lengths. For longer lengths, the flow area must slightly increase as a function of position to account for the boundary layer displacement thickness buildup on the internal walls. The boundary displacement thickness can be estimated from relationships established in Ref. 4. (pp. 599-603) for compressible

flow at zero pressure gradient over a flat plate. The following relationship accounts for the virtual origin effect caused by the transition from a laminar to a turbulent boundary layer and assumes a critical transition Reynolds number of 5×10^5 :

$$\delta_1 = 2.571(X) \left[\frac{0.45}{(10gRe_x)^{2.58}} - \frac{1,700}{Re_x} \right], \quad (16)$$

where δ_1 is the displacement thickness (ft),
 X is the distance from the upper edge of the acceleration section (ft).

Note that laminar flow conditions result in a negative value of the displacement thickness from Eq. 16. In these cases, the displacement thickness should be assumed to be zero. Displacement thickness calculations for laminar compressible flow conditions are exceedingly complex as a result of the failure of the velocity power law distribution. As such, displacement thickness calculations are not provided in the laminar compressible flow range.

The final subject of this section deals with the design of the liquid ejector. It is essential that the molten liquid travel in a continuous stream throughout the length of the gas shield to avoid deposits on the internal wall. As such, the ejector tip must be designed to promote the development of laminar flow between the molten liquid and the ejector tip walls. The length of a constant area flow section internal to the ejector tip must exceed 7 to 8 times the diameter of the flow section to ensure fully developed laminar conditions. The exit conditions at the ejector tip should provide for a sharp lip to avoid the accumulation of material, which can cause a dripping action. Finally, the ejector tip should be tested before installation using surrogate fluids. It is especially important to simulate the pressure differential conditions expected at operating conditions during acceptance testing because the shear reversal nozzle tends to generate high suction conditions. A scaled sketch of a design for a Mach 2.0 shear reversal nozzle is shown in Fig. 16 and indicates the relative size of the nozzle body, the gas shield, the acceleration section, and the melt vessel system.

Fig. 16. Mach 2.0 shear reversal nozzle.

5.4 METHOD OF CHARACTERISTICS

The Method of Characteristics is a pseudonumerical technique for computing gas flow fields at supersonic conditions. It is based upon the turning angle relationships developed from the Prandtl-Meyer flow equations. The Method of Characteristics can take the conical form (two-dimensional) for circular cross sections or the pseudo one-dimensional form (in reality, a simplified two-dimensional form) for rectangular or square cross sections. Because of a reduced computational burden, the pseudo one-dimensional approach is preferred, which results in nozzle designs with varying rectangular cross sections at constant height, as shown in Fig. 15. Another advantage of the pseudo one-dimensional

approach is that nozzle fabrication techniques are simpler because contoured inserts can be machined from plates of constant thickness. This approach also allows for a higher degree of tolerancing in the fabrication setup. The contoured inserts are bounded on either side by flat plates that are sealed by a number of means. This method of construction is depicted in Fig. 16.

In one-dimensional supersonic flow, the Prandtl-Meyer angle is equivalent to the angle of a sharp corner, which accelerates the flow, as shown in Fig. 17. An expansion fan develops at the sharp corner, which consists of a series of weak isentropic waves. The flow ahead of the sharp corner possesses a Prandtl-Meyer angle that is a function of the Mach number and the ratio of specific heats of the gas. The Prandtl-Meyer angle behind the expansion fan is simply the Prandtl-Meyer angle ahead of the turn plus the turning angle of the corner. From the Prandtl-Meyer angle behind the expansion fan, the Mach number and flow conditions can be determined. The relationship for the Prandtl-Meyer angle is as follows and was obtained from Ref. 10 (p. 125):

Fig. 17. Prandtl-Meyer flow at a sharp corner.

$$v = \left[\sqrt{\frac{\gamma + 1}{\gamma - 1}} \text{ARCTAN} \sqrt{\frac{\gamma - 1}{\gamma + 1}} (M^2 - 1) - \text{ARCTAN} \sqrt{M^2 - 1} \right], \quad (17)$$

where v is the Prandtl - Meyer angle (radians).

Another important concept in the Method of Characteristics is a Mach wave. Disturbances propagate in supersonic flow along Mach wave lines that have incident angles defined by

$$\beta = \text{ARCSIN} \left(\frac{1}{M} \right), \quad (18)$$

where β is the Mach angle (radians).

The initial expansion wave propagates at an angle β_1 based on M_1 in Fig. 18. The final expansion wave propagates at an angle of β_2 based upon M_2 . The expansion fan angle is then $\beta_2 - \beta_1$.

The Method of Characteristics is based on these relationships and assumes small turning angles, Φ . For small turning angles, the incident angle of the expansion fan can be approximated by the average Mach angle ahead of and behind the sharp corner. When this procedure is expanded to cover the large Prandtl-Meyer angle ranges that occur between the sonic condition at the nozzle throat and the nozzle exit Mach number, a mesh system of Mach waves and their interactions develop. Detailed descriptions of this procedure are given in Refs. 2, 9, 10, and 11.

Fig. 18. Interaction of surfaces B and C.

The turning angle increment used in this procedure should not exceed a value of 0.5° for a nozzle exit Mach number of 2.0. For a higher nozzle exit Mach number, the turning angle increment should be reduced accordingly to retain accuracy. Note that the use of the Method of Characteristics is not a trivial exercise. For a nozzle exit Mach number of 2.0 and an incremental turning angle of 0.5° , a 275-element mesh system develops in which four flow parameters must be computed for each element. In addition, analytic geometry must be used to solve the coordinate position of each of the four node points of each element. However, this procedure does serve to provide a uniform, disturbance-free supersonic gas flow stream consistent with the requirements discussed in Sect. 3.3.

The use of this procedure is recommended for the design of the contour of surface A in Fig. 14. It also should be used for the design of the contour for Surfaces B and C. However, other factors involved in the contour of surfaces B and C are worth noting. The purpose of these contours is the removal of the gas shield so that the molten liquid can be exposed to the supersonic flow. Because the flow is supersonic, the removal process must begin on surface B by introducing a sharp inward corner, as illustrated in Fig. 18. The sharp inward corner generates an oblique, non-isentropic shock wave, which can be computed by the methods given in Ref. 10. The flow direction after the oblique shock wave is equal to the turning angle of the inward corner. The value of the turning angle of the inward corner should be kept below 10° for a Mach 2.0 condition as a means of minimizing the loss in total pressure and entropy gains across the oblique shock. As the Mach number increases, the inward turning angle of the corner must decrease to avoid unnecessary losses.

The contour of Surface C also begins with a turning angle equal to the inward turning angle of Contour B. However, the position of the corner on Surface C must be strategically placed so that the oblique shock wave generated from Surface B impinges directly on it. In this manner, the oblique shock wave is canceled and no reflection occurs. The flow directly behind the oblique shock wave is at an incident angle relative to the centerline equal to the turning angle of the corner. As a result, the flow must, once again, be turned so that it is parallel to the centerline. This procedure again is accomplished using the Method of Characteristics with the turns initiated on Surface B strategically canceled by equal turns on Surface C at the proper position. Using this approach, a uniform, disturbance-free flow field is re-established for atomization. Note that the condition used in the design of Surfaces B and C must be based on the isentropic properties that develop after the nonisentropic event of the oblique shock wave.

6. TIME-DEPENDENT ACCELERATION AND HEAT TRANSFER MODEL

6.1 FINITE DIFFERENCE EQUATIONS

An elementary finite difference model of the particle acceleration and heat transfer are presented in this section. This model is required to determine the length of the acceleration section and the proper super heat of the molten material.

The equations of motion for a single particle are given by

$$V = \int a dt , \quad (19a)$$

$$D = \int dt . \quad (19b)$$

In a finite difference approach, Eq. 19 becomes:

$$V_{pi+1} = a_i \Delta t + V_{pi} , \quad (20a)$$

$$D_{pi+1} = \frac{1}{2} a_i (\Delta t)^2 + \frac{1}{2} (V_{pi+1} + V_{pi}) \Delta t + D_{pi} . \quad (20b)$$

The velocity conditions of the gas are determined from aerodynamic principles. The reference conditions of the gas can be determined at any false-time increment from the isentropic relationship (see Refs. 2, 9, 10, and 11) defined by

$$\frac{P_i}{P_{Ti}} = \frac{1}{\left(1 + \frac{\gamma - 1}{2} Mi^2\right)^{\frac{\gamma}{\gamma - 1}}} , \quad (21a)$$

$$\frac{T_i}{T_{Ti}} = \frac{1}{\left(1 + \frac{\gamma - 1}{2} Mi^2\right)} , \quad (21b)$$

$$Mi = \frac{V_{gi}}{\sqrt{\gamma R g_c T_i}} . \quad (21c)$$

The concept of a relative Mach number must now be introduced that results from the velocity difference between the gas and a particle:

$$\bar{Mi} = \frac{|V_{gi} - V_{pi}|}{\sqrt{\gamma R g_c T_i}} . \quad (22)$$

When the relative Mach number is > 1.0 , a bow shock wave will develop in front of each particle. This nonisentropic event causes a change in the gas total pressure and the Mach number but does not change the gas total temperature. The bow shock wave can be approximated using the normal shock relationships:

$$M_{2,i} = \frac{(\overline{M}_{1,i})^2 + \left(\frac{2}{\gamma - 1}\right)}{\left(\frac{2\gamma}{\gamma - 1}\right)(\overline{M}_{1,i-1})^2}, \quad (23a)$$

$$\frac{P_{2i}}{P_{1i}} = \frac{(1 + \gamma(\overline{M}_{1,i})^2)}{(1 + \gamma(M_{2,i})^2)}, \quad (23b)$$

$$\frac{T_{2i}}{T_{1i}} + \frac{1}{\left(1 + \frac{\gamma - 1}{2}(M_{2,i})^2\right)}. \quad (23c)$$

A time-dependent model for the particle diameter is unavailable. However, two boundary conditions are known. At the false-time step equal zero (end of the gas shield), the particle diameter is equal to the diameter of the ejected liquid stream. For steady-state conditions, this diameter is equal to the ejector tip diameter, and this relationship can be demonstrated using the Bernoulli and continuity equations at constant density. The second boundary condition occurs at the end of the acceleration section. At this point, the particle diameter must equal the terminal value. Initially, the terminal diameter must be assumed. However, the actual value can be determined experimentally by operating the nozzle at perfectly expanded conditions (see Fig. 8) and by measuring the particle size produced. If the actual terminal particle size is substantially different from the assumed value, the acceleration section can be replaced easily because the component is detachable.

In lieu of a time-dependent model, the particle diameter at a given false-time increment is assumed to be a function of the square of the difference between the gas and the particle velocity. The square term arises from the dynamic pressure developed by the gas as presented in Eq. 10 of the division model. In functional form, this relationship is

$$dpi = \left(\frac{d_{ejector} - d_{term}}{[V_{g_0} - V_{p_0}]^2} \right) (V_{gi} - V_{pi})^2 + d_{term}, \quad (24)$$

where V_{g_0} is the initial gas velocity at the end of the gas shield (ft/s),
 V_{gi} is always evaluated using isentropic relationships (ft/s).

Assuming a spherical shape, the volume and mass of a single particle is determined by

$$VOL_{pi} = \frac{\pi}{6}(dpi)^3, \quad (25a)$$

$$MASS_{pi} = \rho_i(VOL_{pi}). \quad (25b)$$

The number of particles that must be present at any given time can be determined by

$$N_{pi} = \frac{(\dot{m}_i)(\Delta t)}{MASS_{pi}}. \quad (26)$$

The density of the gas is computed from the ideal gas equation as follows:

$$\rho_{gi} = \frac{P_{gi}(144)}{R T_{gi}}, \quad (27)$$

where P_{gi} and T_{gi} are obtained from either Eq. 21 or Eq. 23, depending on the value of $\bar{M}_i$ in Eq. 22.

The viscosity of the gas is a function of temperature. The specific relationship is a function of the selected atomizing gas. It is suggested that a least-squared approach be used to determine the functional relationship of the selected gas. The appropriate temperature for evaluating the gas viscosity is the recovery temperature as defined in Eq. 12. In finite difference terms, these relationships become

$$T_{wi} = T_i \left(1 + r \frac{\gamma - 1}{2} \bar{M}_i^2 \right), \quad (28a)$$

$$\mu_{gi} = f(T_{wi}). \quad (28b)$$

The relative Reynolds number is obtained from

$$Re_i = \frac{\rho_{gi} |V_{gi} - V_{pi}| dpi}{\mu_{gi}}, \quad (29)$$

where V_{gi} is evaluated based on Eq. 21.

The bulk drag coefficient on a sphere was obtained from Ref. 7 and is given in functional form based on the methods of least squares:

$$\begin{aligned} \log(C_{di}) = & 2.547687 \times 10^{-4} [\log(Re_i)]^4 \\ & - 3.20910 \times 10^{-6} [\log(Re_i)]^3 + 0.1048731 [\log(Re_i)]^2 \\ & - 0.8934420 [\log(Re_i)] + 1.4150224 \end{aligned} \quad (30)$$

The behavior of this least-squares function is compared with the empirical data in Fig. 19 and indicates adequate agreement for this analysis.

Fig. 19. Least square function for drag coefficient.

The acceleration forces experienced on a single particle can be determined by

$$F_{di} = \frac{\pi}{8} (C_{di}) (d_{pi})^2 (\rho_{gi}) (V_{gi} - V_{pi})^2 / g_c, \quad (31a)$$

$$a_i = \frac{g_c (F_{di})}{MASS_{pi}}. \quad (31b)$$

The particle acceleration determined in Eq. 31 is used to determine the conditions for the next false time increment in Eq. 20.

The particles are not only accelerating but also transferring heat to the gas. One of the major heat-transfer mechanisms that evolves is the convective force that develops between the gas and a particle. The convective heat transfer coefficient for heated spheres in crossflow is obtained from Ref. 8 and is given as follows:

$$h_i = 0.37 \frac{K_{gi}}{d_{pi}} (Re_i)^{0.6} \quad (32a)$$

for $25 < Re_i < 100,000$,

$$h_i = C_{pg}(V_{gi} - V_{pi})\rho_{gi}\left(\frac{2.2}{Re_i} + \frac{0.48}{Re_i^{0.5}}\right) \quad (32b)$$

for $1.0 < Re_i < 25$.

The heat transferred from a single particle is

$$\dot{q}_{pi} = 4\pi(d_{pi})^2(h_i)(T_{pi} - T_{wi})/3600. \quad (33)$$

The fall in temperature of a single particle is computed from

$$T_{pi+1} = T_{pi} - \frac{(\dot{q}_{pi})(\Delta t)}{C_{pi}(MASS_{pi})}. \quad (34)$$

The bulk heat transferred from the particles to the gas takes the form

$$\dot{Q}_{gi} = N_{pi}(\dot{q}_{pi}). \quad (35)$$

The bulk rise in the total temperature of the gas is determined by

$$TT_{i+1} = TT_i + \left(\frac{\dot{Q}_{gi}}{C_{pg}\dot{M}_g}\right), \quad (36)$$

where $\dot{M}_g$ is the mass flow rate of the gas (lbm/s).

The results of Eq. 36 indicate that the heat transferred from the particle to the gas act to increase the total temperature of the gas, which changes the Mach number/temperature relationships established in Eqs. 21 and 23. Gas flow with heat addition is called Rayleigh flow (see Ref. 10). Because the cross-sectional area of the acceleration section is constant (note that corrections are made for boundary layer displacement thickness), the Rayleigh flow equations at constant area can be used. In finite difference form, these equations are as follows

$$\left(\frac{P}{P^*}\right)_i = \frac{1 + \gamma}{1 + \gamma M_i^2}, \quad (37a)$$

$$\left(\frac{T}{T^*}\right)_i = \frac{(1 + \gamma)^2 M_i^2}{(1 + \gamma M_i^2)^2}, \quad (37b)$$

$$\left(\frac{TT}{TT^*}\right)_i = \left[\frac{(1 + \gamma)^2 M_i^2}{(1 + \gamma M_i^2)^2}\right] \left[\frac{(1 + \frac{\gamma - 1}{2} M_i^2)}{(1 + \frac{\gamma - 1}{2})}\right], \quad (37c)$$

where the superscript * represents the sonic reference conditions.

The change in the Rayleigh reference conditions can be obtained by

$$\left(\frac{TT}{TT^*}\right)_{i+1} = \left(\frac{TT_{i+1}}{TT_i}\right) \left(\frac{TT}{TT^*}\right)_i. \quad (38)$$

The Mach number at the new sonic reference conditions (M_{i+1}) can be obtained from a numerical solution to Eqs. 37 and 38. The value of the M_{i+1} should be used in Eqs. 21 and 23 for computing the flow conditions at the next false-time increment.

The procedures defined by Eqs. 20 through 38 are performed for each successive false-time increment until the velocity difference between the gas and the particle is relatively small. Note that the length of the acceleration section becomes excessively long as the differential velocity cut-off value approaches zero. In most cases, a value of 50 ft/sec is recommended for the velocity cut-off value. In essence, the velocity of the particle is 50 ft/sec lower than the gas velocity at this level. However, once the particle moves past the normal shock wave at the exit of the acceleration section, the particle will encounter a relatively slow-moving gas stream. For a Mach 2.0 exit condition, 200°F total temperature nozzle (note that the gas total temperature has been increased by the heat transfer from the particle), the gas velocity drop across the normal shock is roughly 1200 ft/sec (Fig. 11), which is relatively large compared with a 50-ft/sec velocity cut-off value.

6.2 INITIAL CONDITIONS AND TIME CONSTANT

The initial conditions for the gas can be determined from the isentropic relationship at the exit of the nozzle body. The initial temperature of the molten liquid will be the melt vessel temperature. The initial velocity of a particle can be assumed to be zero with little resulting error or can be determined from the melt vessel/nozzle body exit differential pressure using the Bernoulli equation given in Eq. 6.

The optimum false-time constant (Δt) must be obtained through a series of iterations of the finite difference equations. An initial false time constant is assumed, and the acceleration section length is determined. The initial false-time constant then is reduced by a factor of ten, and the length of the acceleration section is determined with the new false-time constant. A factor-of-ten reduction is continued in the false-time constant until the change in the acceleration section length is less than the desired accuracy. Note that the time constant required for a stable solution is particularly sensitive to the terminal particle size. For terminal particle sizes in the 10- to 50- μ m range, the stable false-time

constant is in the 10^{-6} - to 10^{-7} -s time range. However, for terminal particle sizes in the 0.1- to 1-micron range, a stable-false time constant in the 10^{-10} - to 10^{-11} -sec range is required.

This procedure also can be repeated after the position of the normal shock. The initial conditions must be re-established with a new value for the gas velocity and temperature. The temperature and velocity of the particle also must be initialized. The ejector diameter in Eq. 24 now becomes the terminal diameter of the particle, and a new value for the terminal diameter must be estimated. One method for estimating the new terminal diameter is based on the square of the relative velocity change across the shock wave and is given as follows:

$$d_{term} = C_1 \frac{dejector}{V_{go} - V_{po}^2}, \quad (39)$$

$$d_{term}' = C_2 \frac{d_{term}}{(V_{gs} - V_{ps})^2}, \quad (40)$$

where V_{go} and V_{po} are the initial values of the gas and particle velocity (ft/s),
 V_{gs} and V_{ps} are the gas and particle velocity just after the normal shock (ft/s),
 C_1 and C_2 are constants that reflect the atomization processes that occur.

Dividing Eq. 40 by Eq. 39 and rearranging terms yields

$$d_{term}' = \left(\frac{C_2}{C_1} \right) d_{term} \left(\frac{d_{term}}{dejector} \right) \left(\frac{V_{go} - V_{po}}{V_{gs} - V_{ps}} \right)^2. \quad (41)$$

Provided the atomization processes are equivalent before and after the shock, the values of C_1 and C_2 should be equal and, therefore, cancel one another. In such a case, the final terminal particle size can be estimated by

$$d_{term}' = d_{term} \left(\frac{d_{term}}{dejector} \right) \left(\frac{V_{go} - V_{po}}{V_{gs} - V_{ps}} \right)^2. \quad (42)$$

The value of this approach is that it allows the computation of the particle temperature at the final terminal diameter. If the computed temperature is below the freezing temperature of the product, the super heat of the melt can be adjusted upward. If the computed temperature is substantially above the freezing temperature, the super heat of the melt can be lowered. A positive margin between the computed temperature and the freezing point should be maintained to account for the radiation heat transfer losses, which were ignored in this analysis. As a result of the performance of this procedure, the particles should be molten through most of the flow range, allowing the atomization process to continue. Note that the length of the acceleration section must be recomputed at the new values of super heat because of the Rayleigh flow changes that occur.

7. EQUIPMENT SIZING

Considering all of the other computations necessary to define the geometry, sizing of a shear reversal nozzle may be considered a simple exercise. However, improperly sized nozzles can either severely restrict operational flexibility (i.e., particle size) or be inefficient by consuming large amounts of atomizing gas. As such, it is appropriate that a sizing method be defined for efficient operation. The subsequent steps should be followed for proper sizing.

1. From the production capacity requirement, determine the molten liquid flow rate required.
2. From Fig. 1, select a mass flow ratio based on the economic factors involved. The operating gas flow rate is determined from the selected mass flow ratio and the liquid flow rate from Step 1.
3. Select a containment vessel operating condition. Note that a factor-of-10 increase in containment vessel pressure results in roughly a 20-fold increase in the Reynolds number because of the isentropic relationships. Further note that the primary variable that influences final particle size was a Reynolds number. As such, operations above ambient exhaust are recommended.
4. Select an atomizing gas. Note that argon, nitrogen, and air had the largest gas-specific Reynolds number term.
5. Select an exit Mach number for the acceleration section. Note that a Mach number of 2.0 produced a maximum Reynolds number change across the exit shock. As such, the design exit Mach should be ≥ 2.0 to take advantage of the peak Reynolds number change.
6. Select a gas operating temperature. Note that colder gases produced higher Reynolds numbers.
7. Based on the isentropic and normal shock relationships, determine the gas density and velocity at the nozzle throat.
8. Based on the continuity equation, determine the flow area of the throat from results in Steps 2 and 7.
9. Select the height of the flow area cross section shown in Fig. 15. From the area (Step 8) and height determination, determine the width of the nozzle throat.
10. Divide the width of the nozzle throat by two (half of the flow on either side of the gas shield).
11. Determine the coordinates for the nozzle based on the half width and the methods outlined in Sect. 5.4.
12. Select an ejector-tip diameter. Note that smaller ejector-tip diameters produced smaller particle size and that the higher molten liquid flow rate can be achieved by adjusting the differential pressure through the Bernoulli equation.
13. Determine the initial length of the acceleration section. Note that the final length may be determined by operating the nozzle at perfectly expanded conditions.
14. Determine the geometry of the gas shield and position the coordinates of the nozzle accordingly.
15. Size the pressure delivery equipment and exhaust system for the pressure and flow rate conditions that develop under the nozzle starting conditions.

8. SUMMARY AND CONCLUSIONS

The prime purpose of this report is to establish definitive rationale and technical drivers for atomizing nozzles that employ the shear reversal principle. The shear reversal nozzle principles presented are believed to be a new development in the field of gas atomization. A number of observations and conclusions result from these principles and are summarized as follows.

1. A number of preconditions and preferred methods exist for efficient gas atomization. The preconditions required include an adequate gas-to-liquid mass flow ratio (between 10 and 100), proper positioning of the super heat value, avoidance of phenomenon that deteriorate the gas flow field, strict use of auxiliary heating to prevent ejector freezing as necessary, and the positive effects on the initial gas/liquid mixing zone that result from reduced liquid ejector diameters.
2. An elementary atomization model was presented consisting of two distinct processes. The first process was particle division resulting from pressure forces that develop on a particle. The second process was particle shearing resulting from skin friction forces that develop because of the gas boundary layer.
3. The prime variables controlling particle division were the surface tension that develops between a liquid particle and the atomizing gas, the density of the gas, and the square of the time-dependent velocity difference between the gas and a particle.
4. Smaller final particle sizes by division are expected as the surface tension decreases, the density of the gas increases, the initial gas velocity increases, and as the density of the liquid increases.
5. Particle shearing is the primary function of the Reynolds number and a secondary function of the Mach number, Prandtl number, and ratio of specific heats of the gas.
6. Attempts to maximize particle shearing should focus first on higher gas total pressure. Because the atomization is more an integrative process, finer particle sizes also will be obtained through increases in the Mach number.
7. Based on Reynolds number maximization, an efficient set of atomizing gases is either argon, nitrogen, or air.
8. A shear reversal strategy was presented that provides a strong impulse change in the gas velocity and subsequent Reynolds number change by strategically placing a normal shock wave in the gas stream at a position where the particles are traveling near the gas velocity.
9. Shear reversal nozzles should be designed for an exit Mach number of ≥ 2.0 to take advantage of a maximum in the impulse Reynolds number change.
10. The three components of a shear reversal nozzle are a nozzle body, a gas shield, and an acceleration section. Basic requirements for each of these components were presented.
11. The requirements for the nozzle body were as follows:
 - a rectangular cross section with constant height;
 - the use of pseudo one-dimensional Method of Characteristics for the coordinate definition of the nozzle to produce a uniform, disturbance-free flow field; and
 - coordination of the nozzle body coordinate design in the region where the gas shield is removed.

12. The requirements for the gas shield were as follows:

- a rectangular cross section with constant height that is equal to or greater than the height of the nozzle body;
- the use of pseudo one-dimensional Method of Characteristics for the coordinate definition in the region where the gas shield terminates,
- sealing of the gas shield at the ejector tip to prevent flow fields from prematurely disturbing the liquid stream; and
- design of the ejector tip to promote laminar liquid flow.

13. The requirements for the acceleration section were as follows:

- a detachable feature that provides for cleaning, calibration of the proper length, and use with different atomizing materials;
- a constant rectangular flow section that is corrected for only boundary layer displacement thickness growth; and
- a definable length based on the velocity difference between the particle and the gas.

14. An elementary finite difference model for determining the length of the acceleration section was presented. The finite difference model contained particle velocity and acceleration components and methods to compute the heat transfer between the particles and the gas.

15. A method for extending the finite difference model past the normal shock was presented as a means for determining the proper super heat of the melt.

16. Methods for sizing the flow reversal nozzle and associated support equipment were defined.

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