SHAPED CHARGE JET VELOCITY & DENSITY PROFILES

B. Grove[1], I. Walton[1]

[1]*Schlumberger Reservoir Completions Center, 14910 Airline Road, Rosharon, TX 77583*

The velocity and density profiles of an oilwell perforating charge jet are presented. Oilwell perforators generally contain unsintered powder metal liners, and so produce finely particulated jets, which behave differently from those produced by traditional solid metal liners.

Jet properties were obtained via radiographic experiments, wherein charges were shot through varying thicknesses of a high-density target. Emerging jet velocities and diameters were measured. These results were then combined with numerical simulations of the mass distribution, to calculate the density profile.

The spatial velocity profile of the selected charge is approximately linear. Jet density generally decreases along its length at any given instant in time (being lowest at the tip), and the overall density profile decreases with increasing time (i.e. travel distance). To first approximation, jet density can be represented as a hyperbolic function of spatial position only.

INTRODUCTION

Oilwell perforators are small-caliber shaped charges used to create tunnels in reservoir rock, through which hydrocarbons subsequently flow. The finely particulated nature of oilwell perforator jets (they form from powdered – rather than solid – metal liners) can lead to a mass density profile which varies with time and or position, an issue not typically encountered with solid metal jets. Variable density jets have been investigated by some researchers (see Mayseless [1], Werneyer and Mostert [2], and Maritz, Werneyer, and Mostert [3]). More recently, compressibility effects for distended jets have also been considered in [4] and [5].

This paper presents a recent experimental effort undertaken to determine the velocity and density profiles of a powdered metal jet, with elementary supporting analytical treatments.

ANALYTICAL CONSIDERATIONS

Given a stretching jet, consider an infinitesimal element which originates at time t_0 with initial length l_0, as depicted in Figure 1.

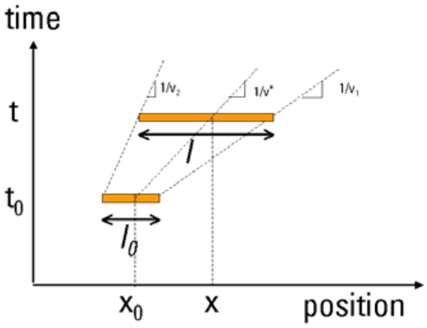


Figure 1. Evolution of an infinitesimal element on a stretching jet

At time t, element length l and characteristic position x are given by:

$$l - l_0 = (v_1 - v_2)(t - t_0) \tag{1}$$

$$x - x_0 = v^*(t - t_0), \tag{2}$$

where the various terms are defined in Figure 1. Note that x and x_0 refer to the point on the element travelling at some prescribed velocity v^*: $v_2 \le v^* \le v_1$. Combining equations (1) and (2) yields the relationship between element length and position:

$$l - l_0 = \frac{(v_1 - v_2)}{v^*}(x - x_0) \tag{3}$$

Equation (1) can be rewritten as:

$$\frac{l}{l_0} = a_t t + b_t : \quad \begin{cases} a_t = \dfrac{v_1 - v_2}{l_0} \\ b_t = 1 - a_t t_0 \end{cases} \tag{1'}$$

Equation (3) can be rewritten as:

$$\frac{l}{l_0} = a_x x + b_x : \quad \begin{cases} a_x = \dfrac{v_1 - v_2}{v^* l_0} \\ b_x = 1 - a_x x_0 \end{cases} \tag{3'}$$

Since element mass is constant, its average density ρ is given by:

$$\frac{\rho}{\rho_0}=\frac{d_0^2 l_0}{d^2 l}, \tag{4}$$

where *d* is diameter.

In general, jet element diameter can decrease, remain constant, or increase. A solid metal jet's strength causes it to constrict as it stretches, maintaining constant density. Solid metal jet diameter varies according to:

$$\frac{d}{d_0}=\sqrt{\frac{l_0}{l}} \tag{5}$$

A powdered jet, on the other hand, has no tensile strength. Therefore, in the absence of any radial velocity component, diameter profile is constant, and element density varies inversely with length:

$$\frac{\rho}{\rho_0}=\frac{l_0}{l} \tag{6}$$

Combining equations (1') and (6) gives the element density evolution over time:

$$\frac{\rho}{\rho_0}=\frac{1}{a_t t+b_t} \tag{7}$$

Note the similarity with equation (1) in Reference [2]. Combining equations (3') and (6) gives the element density evolution with position:

$$\frac{\rho}{\rho_0}=\frac{1}{a_x x+b_x} \tag{8}$$

Equations (7) and (8) show that jet element density decreases hyperbolically with time (or, equivalently, distance). So far, however, they provide little insight into the density profile *along the entire jet*, at some given time *t*. The general question remains: *is jet density a function of time only, position only, or both?* Consider two possible scenarios:

1) Referring to equations (1’) and (7):
   - Partition the jet into elements sharing a common velocity differential (v_1-v_2).
   - If these elements are all formed at the same time and of equal initial length (i.e. all share common t_0 and l_0), then they share common values for a_t and b_t.

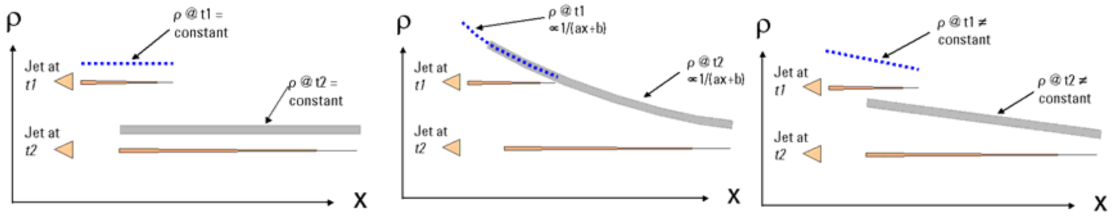
   Density is therefore uniform along the jet length at any given time. ρ=f(t) only, as shown in Figure 2a.

2) Referring instead to equations (3’) and (8)
   - Partition the jet into elements sharing a common velocity differential (v_1-v_2).
   - If these elements all share a common product ($v*l_0$), and a common origin location (x_0), then they share common values for a_x and b_x.

   Density therefore varies along the length of the jet at any given time, and all points on the jet traverse the same density-position trajectory. ρ=f(x) only, as shown in Figure 2b.

The first scenario above implies that the entire jet forms in accordance with the virtual origin assumption, although slightly after the V.O. time ($t_0 > t_{V.O.}$), since initial length $l_0 > 0$; each element therefore possesses its own unique formation position ($x_0 > x_{V.O.}$). However, it is well known that real jets form sequentially. For example, when the tail forms, the tip has long since formed and travelled downstream, presumably having distended to some reduced density. This suggests that density is not constant along the jet at any single instant in time, and that the first scenario is therefore not strictly valid.

The second scenario implies that the real jet does *not* form in accordance with a virtual origin (even if the eventual velocity profile is linear). The ensuing experimental results discussion will shed some light on the plausibility of this case. If this proves not quite representative of a real jet under investigation, then jet density would be a function of both position and time (Figure 2c).



(a) (b) (c)

Figure 2. Possible density profiles for a powdered metal jet: (a): ρ=f(t), (b): ρ=f(x), (c): ρ=f(x,t)

EXPERIMENTS

Technique

Velocity Profile

Assessing the velocity profile of a solid metal jet is straightforward: along the length of a given jet, several discrete particles are identified (via flash radiography) at two different times, and their velocities determined.

For powdered metal jets (which appear smooth and continuous on radiographic records), a different method is required. Our technique (Figure 3) was to shoot several charges, each through a different thickness target, then measure the velocity of the emerging "tip". The collection of several such points allows construction of the velocity profile.

Mass Density Profile

Powdered jet density can be determined experimentally via one of the following:

1) infer density profile directly from radiographic records (i.e. "brightness" of jet image, from a well-calibrated film exposure)
2) determine jet volume profile from radiographic records, and combine with mass information from some other source (i.e. numerical simulations) to construct density profile

The latter method was chosen for the present work. Knowledge of the velocity profile enables partitioning of the jet into discrete regions, bounded by points of known velocity. The length evolutions can then be determined. The diameters at various points along the jet are also measured, allowing construction of the diameter profile(s, which may vary over time). Length and diameter measurements yield the volume evolution of each jet region. This is combined with the mass profile (obtained from numerical simulations) to construct an average density profile evolution over time.

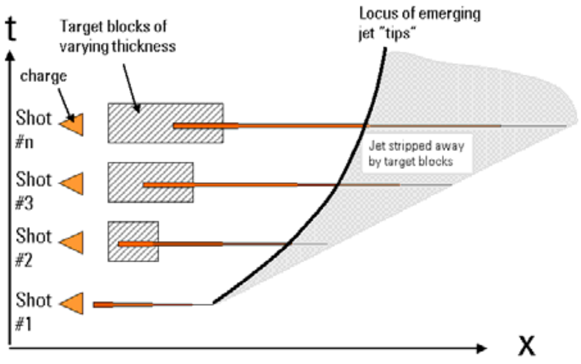


Figure 3. Velocity profile determination technique, for powdered metal jet.

Results & Discussion

The technique described above was applied to the analysis of an oilwell perforating charge. We shot several charges from the same box of a single production run, for an intermediate-sized charge design. Results of this experimental effort are presented in Figures 4 through 7. Details regarding the numerical simulation are omitted here, as are intermediate results such as raw diameter measurements, element length evolutions, etc. Emphasis is placed on the qualitative features of the velocity and density profiles.

Velocity Profile

Figure 4 is a "fan plot", showing time-position trajectories for several points along the jet (each trajectory was obtained from a different shot). These trajectories nearly converge at a single point (the tail region being the primary exception). This indicates that the resulting velocity profile is nearly linear in space.

Figure 5 shows the jet velocity-position profile, at two arbitrarily selected times. Consistent with the fan plot, this profile is substantially linear. Certain shots were repeated for statistical purposes, and are included in Figures 4 and 5.

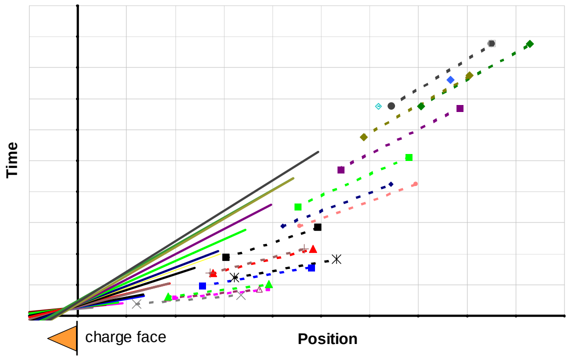


Figure 4. Jet fan plot: constructed from several shots.

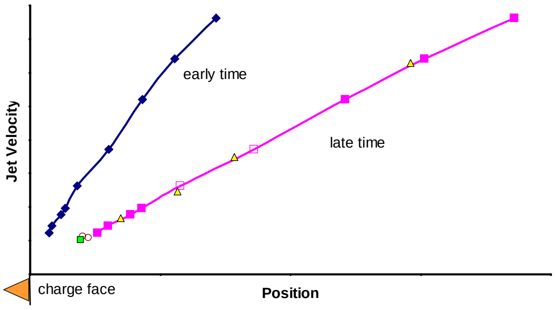


Figure 5. Jet velocity profile: constructed from several shots.

Density Profile

Figures 6 and 7 show the density profile, plotted against velocity and position, respectively. Each curve in Figure 6 represents a density vs. velocity “snapshot” at a single instant in time. We observe the expected reduction in overall jet density with increasing time. Furthermore, it is clear that density is *not* constant along jet length at any given time. Rather, jet density tends to be lowest at the tip, and increases toward the tail. This confirms our earlier expectation that density would not be uniform along jet length. In other words, equation (7) does not generally apply to the entire jet, and Figure 2a is not representative of actual jet density evolution.

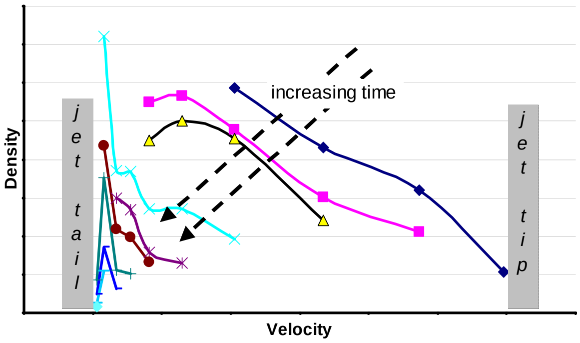


Figure 6. Density profile(s) of a powdered metal jet.

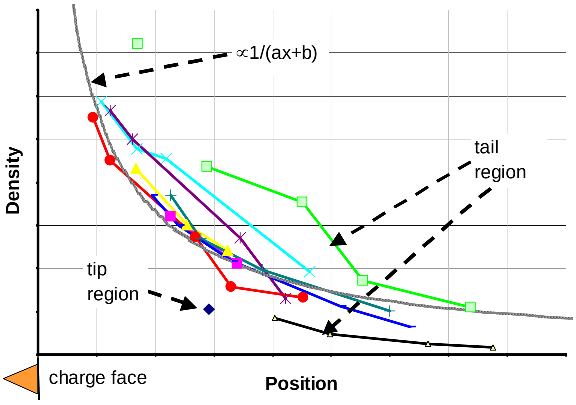


Figure 7. Density profile(s) of a powdered metal jet.

Figure 7 shows density-position trajectories for several points on the jet, superimposed on a reference curve of the form *1/(ax+b).* The general agreement between the shapes of each curve and the hyperbolic reference indicates the validity of equation (8) in describing the density evolution of each individual point. Furthermore, many of these curves approximately collapse onto one another (the extreme tip and tail regions being the primary exceptions). To the extent that these trajectory curves do coincide, jet density is found to be *a function of spatial position only*. This suggests that equation (8) is generally applicable to the *entire jet*, whose density evolves approximately as indicated in Figure 2b.

CONCLUSIONS & RECOMMENDATIONS

We have presented results of an experimental effort to determine the velocity and density profiles of a powdered metal shaped charge jet.

Jet characteristics were obtained via radiographic experiments, wherein several charges were shot through varying thicknesses of a high-density target. Emerging jet velocities and diameters were measured. These results were combined with the numerically-determined mass distribution, to calculate the density profile.

The spatial velocity profile of the selected charge is approximately linear. Jet density generally decreases along its length (from tail to tip) at any given instant in time, and this overall density profile decreases with increasing time. These various profiles approximately collapse onto a single hyperbolic curve in velocity-position coordinates. To a first approximation, therefore, jet density can be represented as a function of spatial position only. This observation is consistent with theoretical arguments based on a sequentially-forming jet whose diameter profile is time-invariant.

It is recommended that this work be extended to other charges, with emphasis on validating the technique, and more rigorously addressing statistical issues and experimental uncertainty. Ultimately, it would be valuable to combine this present and future work with analytical penetration model development efforts.

REFERENCES

[1] M. Mayseless, “Penetration of Porous Shaped Charge Jets”, *16th International Symposium on Ballistics,* 317-26 (1996)

[2] K.D. Werneyer, F.J. Mostert, “Analytical Model Predicting the Penetration Behavior of a Jet with a Time-Varying Density Profile”, *21st International. Symposium on Ballistics,* 390-97 (2004)

[3] M.F. Maritz, K.D. Werneyer, F.J. Mostert, “An Analytical Penetration Model for Jets with Varying Mass Density Profiles”, *22nd International Symposium on Ballistics,* 622-29 (2005)

[4] B.Grove, “Oilwell Perforators: Theoretical Considerations”, *22nd International Symposium on Ballistics*, 585-92 (2005)

[5] B. Grove, “Theoretical Considerations on the Penetration of Powdered Metal Jets”, *International Journal of Impact Engineering* **33**, 316-325 (2006)