Jetting instability mechanisms of particles from explosive dispersal

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Abstract. The formation of post-detonation ‘particle’ jets is widely observed in many problems associated with explosive dispersal of granular materials and liquids. Jets have been shown to form very early, however the mechanism controlling the number of jetting instabilities remains unresolved despite a number of active theories. Recent experiments involving cylindrical charges with a range of central explosive masses for dispersal of dry solid particles and pure liquid are used to formulate macroscopic numerical models for jet formation and growth. The number of jets is strongly related to the dominant perturbation during the shock interaction timescale that controls the initial fracturing of the particle bed and liquid bulk. Perturbations may originate at the interfaces between explosive, shock-dispersed media, and outer edge of the charge due to Richtmyer-Meshkov instabilities. The inner boundary controls the number of major structures, while the outer boundary may introduce additional overlapping structures and microjets that are overtaken by the major structures. In practice, each interface may feature a thin casing material that breaks up, thereby influencing or possibly dominating the instabilities. Hydrocode simulation is used to examine the role of each interface in conjunction with casing effects on the perturbation leading to jet initiation. The subsequent formation of coherent jet structures requires dense multiphase flow of particles and droplets that interact though inelastic collision, agglomeration, and turbulent flow. Macroscopic multiphase flow simulation shows dense particle clustering and major jet structures overtaking smaller instabilities. Late-time dispersal is controlled by particle drag and evaporation of droplets. Numerical results for dispersal and jetting evolution are compared with experiments.

1. Introduction
Particle jetting instabilities are widely observed in volcanic eruption, explosion of landmines, shallow underwater explosion (UNDEX), thermobaric explosion (TBX), and fuel-air explosion (FAE). All of these examples feature high dispersal speeds and exhibit multiple scales of jetting structures, with smaller instabilities often superimposed on larger structures. Experiments provide fundamental data for explosive dispersal of granular materials, liquids, and hybrid mixtures. Scientific testing has provided an up-to-date understanding on the phenomenology [1-3]. There are several generally-accepted facts for particle instabilities during explosive dispersal: large jetting structures are coherent and stable (e.g., see figure 1); jet instabilities are formed very early; jets form in the absence of an outer casing (e.g., landmines, UNDEX); and, particle jetting is not a Rayleigh-Taylor instability. Jetting instabilities remain a significant challenge for understanding the physical mechanisms of the origin and number of jets, and for multiphase numerical models.
Predicting the number of jetting structures has been an active area of research and previous studies have explored several possible mechanisms. Our early work [4] focused on the Richtmyer-Meshkov instability (RMI), which showed well-defined persistent jetting structures matching the number of prescribed outer surface perturbations. However, the timescale for formation was slow and the surface instability did not propagate into the bulk. Instead, a heuristic macroscopic particle attraction model demonstrated early-time fracturing of the powder bed with subsequent jetting structures. Our view remains that the number of jetting structures is established within the timescale of the shock propagating through the bulk. Milne et al. [5] counted the number of jets and suggested a possible connection with dynamic fragmentation theory. Frost et al. [6] evaluated jet number with a compaction Reynolds number to connect expansion inertia to viscous dissipation. The aforementioned counting studies have focused on spherical dispersal with count taken mainly in the early time. For cylindrical dispersal [3,4], the initial number of jets has been related to the Gurney velocity; it was further observed that the number of jets decreases at far distances.

Recent work has provided additional motivation on the origin of the jetting structures. Xu et al. [7] demonstrated using mesoscale simulations that the number of particle clusters/jets is dictated by the initial particle number on the inner layer at the explosive interface. In an attempt to link this finding to the macroscopic real world, the inner-layer “particles” were interpreted as particle agglomerates or fragments of a casing between the explosive and packed particle bed. Recent large-scale FAE tests by Zhang et al. [8] demonstrated the number of main jets can be traced back to the radial fractures in the bulk liquid. It was further hypothesized that the instability could be connected to the fragment number of the inner casing. Both small-scale (nominal 2 litre) [3] and large-scale (7103 litre) [8] data of Zhang are further analysed and interpreted in the present work. Numerical simulation using multiphase fluid dynamics is conducted to explore the instability mechanism for a layered dispersal configuration.

2. Evolution of number of jetting structures

The time-dependence on number of jetting structures has not been thoroughly addressed previously. Figures 2 and 3 present the results from a manual counting of the number of jets throughout time using the overhead video frames for small-scale 114-mm-diameter cylindrical powder and liquid dispersal, respectively. The jet count results for powder dispersal show a dual overlapping jet structure in which both major jets and minor jets are evident beginning in the early time. The number of major jets in powder dispersal is nearly constant, while the number of minor jets decreases in later time as the instabilities are overtaken by the major jet structures. For the liquid dispersal results, all jets are counted for three burster sizes. For all cases, the initially high number of jets decreases with time and approaches a minimum in later times. The initial number corresponds to minor jets, which increases with burster size, and the asymptotic late-time number of jets represents the major jet structures.

The process of decreasing jet number through the emergence of major jets is illustrated in the video sequence in Figure 4 for liquid dispersal. Beginning at early times, a very high number of initial minor jets can be observed. A typical major jet begins to emerge and continues to grow, whereas the minor jets are overtaken by larger structures or dissipate due to evaporation. The major jet instability has higher momentum and appears to originate from the interior of the cloud, rather than being an outer surface perturbation.
2.1. Container fragmentation
Fragmentation of the outer container has been often contemplated as a possible instability source, despite the fact that jetting structures are observed in the absence of casing. Nonetheless, container fragmentation is considered briefly in connection to the number of minor jetting structures. Table 1 summarizes the number of initial jetting structures in the experiments and analytical estimates of the number of container fragments, using \( S = \left( \frac{24\Gamma}{\rho\dot{e}^2} \right)^{1/3} \). Here the container is 1.6-mm-thick polyethylene, and various models for container strain rate are employed. For a 10-mm-diameter burster, the experimental number of jets is similar for powder and liquid for the same approximate mass-to-burster ratio. This is in conflict with the strain-rate model based on experimental jet velocity, which does not match Gurney theory for powder [4]. Therefore the number of jets is most closely correlated with the burster size, and consequently the strain rate based on Gurney velocity. Thus, the number of initial minor jets appears to be a manifestation of the system configuration, namely the central buster size.

2.2. Phenomenology of jet evolution
As evidenced by a series of small-scale experiments, a large number of minor jets form very early. This initial jet number appears to be a function of system configuration and may be related to fragmentation theory near the outer surface. For both powder and liquid dispersal, the number of jets decreases later in time. For explosive dispersal of liquids, the dominant primary droplet jets overtake the smaller jets. Explosive dispersal of powders shows that the major jets are established early and merging of minor jets occurs through aerodynamic interaction. Therefore mechanisms for the number of jets need to distinguish between minor jets and the major jets in later time.
Table 1. Comparison of number of initial minor jets in the experiments with theoretical calculations for container fragmentation using various strain-rate estimates.

| Configuration | Experiment | \( \dot{\varepsilon} = \frac{V_{jet}}{R_0} \) | \( \dot{\varepsilon} = \frac{V_{g}}{R_0} \) | \( \dot{\varepsilon} = \sqrt{\frac{P}{\rho}} \frac{1}{R_0} \) |
|---------------|------------|---------------------------------|---------------------------------|---------------------------------|
| Trial Burster Fill | Number of Jets, \( N_{jet} \) | Number of Case Fragments, \( N_{frag} \) | Number of Case Fragments, \( N_{frag} \) |
| U04328B 10 mm Powder | 81 | 35 | 72 | 34 |
| U04281B 10 mm Liquid | 84 | 68 | 74 | 80 |
| U04239A 31 mm Liquid | 107 | 143 | 145 | 121 |
| U04238A 44 mm Liquid | 123 | 183 | 186 | 133 |

3. Large-scale dispersal experiment
Large-scale experimental data better distinguishes the major jets while providing another vantage point. High-speed cinematography was taken from the side (ground level). Therefore, one half of the dispersal circumference is visible. Figure 5 presents early- and late-time photographs of the liquid dispersal from Zhang et al. [8]. At 10.5 ms, vertical fracture lines are clearly visible (these are apparent as early as 2.5 ms after expansion to 1.5-2.0 times the initial container diameter). Nine fracture lines may be counted using this high-speed image. Also evident at the early time are a significant number of smaller perturbations imposed on the surface. Major jet structures are clearly visible at later times. The number of major jets is readily counted to be 10 in the half circumference, indicative of 18-20 total jets assuming symmetry in the circumference.

Figure 5. Evolution of number of jets in large-scale liquid dispersal [8].

The cinematography was analysed to count the total number of jets in time, with the results plotted in figure 6. The jets were counted within a cylindrical volume with a height matching the length of the central burster. The total number of jets consists mainly of minor jets in the early stages, decreasing to a dominant major jet number later in time. The major jet number can be traced back to the initial fracture number, thus indicating that the major jet number is established at the beginning.

3.1. Observations from jets and fractures
Several key observations can be made from the high-speed cinematography. The liquid fracture is aligned with the initial longitudinal container failure points and the primary droplet jets are contained between the fractures and behind fragments (therefore jetting does not occur through gaps). It is surmised that the liquid fracture locations coincide with the initial container failure points which form long strips. The outer container fragment number is different than the major jet number later in time. The primary jet number must be established before the outer surface instability. The large-scale jet structure is initially planar within the burster length, and later overtakes smaller surface instabilities.
3.2. Concept for dominant jet mechanism
A hydrodynamic instability is considered for the dominant mechanism for major jets. As the detonation shock transmits into the bulk dispersant, an RMI may form at the inside interface. As the driven shock reaches the outside boundary, it transmits into air and a rarefaction wave travels inward. This expansion wave accelerates and stretches the RMI followed by recompression at the inner interface. The bulk dispersant fractures at locations of maximum strain which occur in front of the RMI tips; the resulting jet structures are thereby formed between RMI structures. We have a similar view for powder and hybrid dispersal, in which the inside instability dictates the fracture length scale. This concept admits smaller surface perturbations to be superimposed on the large structures and casing fragments to ride on the surface of the dispersant. The outside casing may also fracture in front of the RMI instability tips, and the resulting jet structures are then located behind the casing fragments. Therefore the number of bulk fractures and major jets defines a lower limit on the initial number of container fragments, and importantly, not vice versa.

4. Numerical results
In order to explore the fracture mechanism concept, numerical simulation was undertaken. The calculations focus on liquid dispersal to avoid the dissipative mechanisms that exist in dense multiphase flow. Owing to the longitudinal fracture of the container and the planar dispersal pattern observed in experiments, a two-dimensional simulation was appropriate. The shock process was simulated in an Eulerian hydrocode using a modified Tait equation of state for the liquid. The burster casing was pre-fragmented and responded to the flow in a conservative fully-coupled manner as rigid bodies. A scaled-down cylindrical configuration 100 mm in diameter was simulated using TNT explosive (ρ = 1.6 g/cc) to disperse water (ρ = 1 g/cc). A one-quarter symmetric domain was used with a 200 µm mesh resolution.

4.1. Hydrocode modelling of shock and casing fragments
Equal-size 2-mm-wide burster casing fragments were employed. For 10 mm and 20 mm diameter bursters, this corresponded to 16 and 32 fragments respectively around the circumference. Figures 7 and 8 illustrate the continuum flow process. Following detonation of the burster, the casing fragments are accelerated and drive a cylindrical shock into the liquid. The wave reflects from the outer boundary as an inward-travelling rarefaction wave that further accelerates the liquid while the cylindrical divergence leads to circumferential stain. The inner boundary continues to travel radially and builds a ‘ρ-layer’, or accretion layer, that is wrinkled due to the inner instability. The interaction of the expansion wave and the driving accretion layer leads to locally-high circumferential strain ahead of the burster fragments. Modelling of the incipient liquid fracture was not explicitly represented.
4.2. Multiphase modelling of droplet dynamics

Fracturing of the liquid is a complex process and was not simulated in detail. Instead, a simple cavitation damage model employs ‘instantaneous fragmentation’ [9] upon the condition of continuum tension matching dense-packed spheres (i.e., $\phi < 0.74$). Thus the breakup criterion is essentially strain-based for the bulk (i.e., $P_{\text{cav}} < 5000$ Pa). The accretion layer remains dense and is later fragmented at a prescribed time. Prescribed normal size distributions were employed for the droplet particles: 26 – 307 µm for the bulk liquid, and 58 – 490 µm for the accretion layer (sheet and filaments). Physically, the spray droplet sizes are defined by spall theory, whereas the larger droplet size is proportional to the sheet thickness and the delay time corresponds to sheet instability and breakup timescales.

Figure 9 illustrates the early droplet dynamics. The outer edge of the cloud features random perturbations due to the droplet size distribution. The dense regions originally in between the burster casing fragments are identified by arrows in the plots. These droplet groups are accelerated by a squeezing mechanism of the burster detonation products gases. This is analogous to a low-pressure shaped-charge dispersal mechanism. Frost et al. [10] explored a traditional shaped-charge dispersal of powders which showed coherent jets that were consistent with Gurney velocity.

The dense particle groups have higher momentum during their dispersal and eventually overtake the slowing outer boundary and surface instabilities of the cloud. Figures 10 and 11 show the results at 100 ms for the 10-mm and 20-mm diameter bursters, respectively. The results have been mirrored from the quarter-symmetric solution to illustrate the full circumferential dispersal. Distinct late-time major jet structures are clearly evident matching the internal boundary instability number established by the casing fragment number. The emergence of the major jets occurs later in time as compared with experiments due to insufficient dense drag on the particle groups. Aerodynamic interaction between droplet groups [4] is expected to refine the jets structure. The increasing number of major jets with burster size is consistent with experimental observations (see figure 3).
5. Modelling challenges

Dispersal of solid particles features dissipative and non-equilibrium mechanisms in the dense and granular flow regimes. Dynamic stress bridging, shock sintering, particle damage/fragmentation, inelastic particle collision, turbulent wake interaction, and agglomeration are known as some of the challenging salient features.

For liquid dispersal, mechanisms and criteria for liquid fracture, tensile failure, and cavitation remain as difficulties for hydrocodes. Fracture surfaces necessitate special treatment through the use of boundary conditions, material interfaces, and free surfaces. Solid mechanics of the burster casing and outer container require appropriate constitutive and failure models. The droplet formation and droplet size distribution remain as a significant gap in the field of explosive liquid dispersal. Although evaporation and aerodynamic breakup of droplets are well established for pure materials, application to hybrid dispersal of mixtures of powders and liquids involves interacting phenomena such as stripping of liquid coatings from solid particles and breakup of liquid/powder agglomerates.

Explosive dispersal of granular materials and liquids features multi-material, multi-scale, multi-physics phenomena. Many of the above mechanisms need to be further explored at the mesoscale to develop macroscale models required for practical 3D simulation. The multiphase RMI at macroscale is one emerging concept and may contribute to the understanding of explosive particle instabilities, but a rigorous definition of the concept will need the help of microscale simulations as well.
6. Conclusions
Interaction of explosively-dispersed particles with surrounding structures and combustion of so-formed fuel clouds has motivated a better understanding of the jetting instability mechanism, the structure and number of jets, and related dispersal phenomena. This work has focused on the origin and number of jets. Perturbations on the inside and outside of the charge originate as Richtmyer-Meshkov instabilities for bulk liquid, and as micro jets and particle collisions for granular powder. Particles, casing fragments, and other imperfections influence the length scale. The instability dictates a length scale for bulk fragmentation of the expanding shell into discrete segments of dispersant that later define the jetting structures.

Analysis of experimental trials has provided phenomenological and quantitative information on the number of jets. A dual jetting instability hierarchy has been presented, both of which form very early. Small jet instabilities are formed at the outside boundary, whereas primary jet instabilities are formed from the interior boundary. Major jets later overtake smaller outside perturbations.

Numerical modelling was used to explore the fracture mechanism concept leading to the formation of major jet structures. The instability induced by the fragments from the inner boundary dictated the later-time number of major jet structures. The simplified calculation approach demonstrated the dual jetting instability. Consistent with our premise, the internal interface instability defines the primary jetting structures. Modelling has shown the major jet mechanism without external surface perturbation. As such, the methods are further applicable to particles premixed with explosive, which are known to form jets mainly with an external interface. The impedance ratios of the explosive, burster casing, and bulk dispersant remain as parameters to be investigated. A brief review of the modelling challenges shows that much work remains in this active area of research.

Acknowledgements
The authors would like to acknowledge the assistance of the DRDC Suffield Advanced Energetics Group and Field Operations Section, and Martec’s Chinook Development Team; and the support from DRDC Projects and DTRA Advanced Energetic Program (Dr. William Wilson).

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