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Liquid Metal Breakup and Fragmentation in a Shockwave-Induced Cross-Flow

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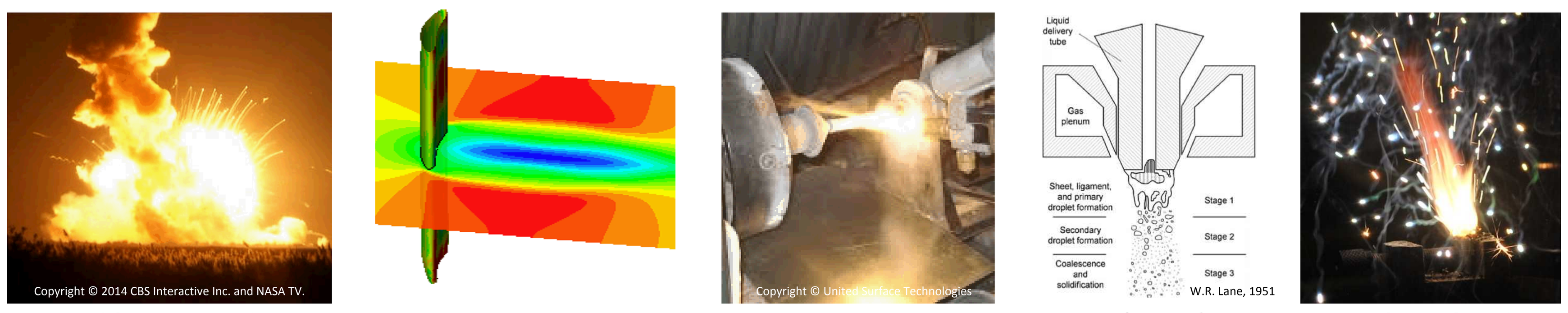
Problem

Liquid metal breakup processes are not well studied but are important for understanding metal powder formation, thermal spray coatings, fragmentation in explosive detonations and metalized propellant combustion processes. This knowledge is also essential for model validation and investigating accident scenarios.



Accident Scenarios | Model Validation | Thermal Spray Coating | Metal Powders | Metal Combustion

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Hypotheses and Approach

Liquid metals should share the same bulk breakup criteria as a typical fluid like water. However, the **high densities and fast oxide formation** of liquid metals will alter breakup morphology, acceleration properties, and droplet shape characteristics.

$$We = \frac{\rho_g u_g^2 d}{\sigma}$$

Weber number (inertial to surface tension forces)

$$\tau = \frac{t u_g}{d_c}\sqrt{\frac{\rho_g}{\rho_l}} = \frac{t u_g}{d_c}\frac{1}{\sqrt{\rho^*}}$$

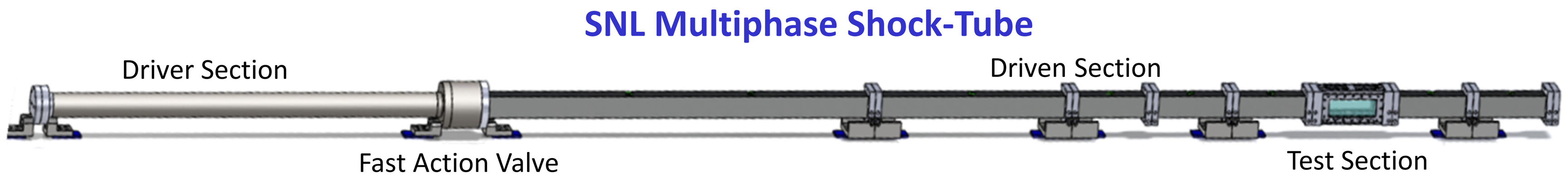
Non-dimensional time (constant acceleration due to drag)

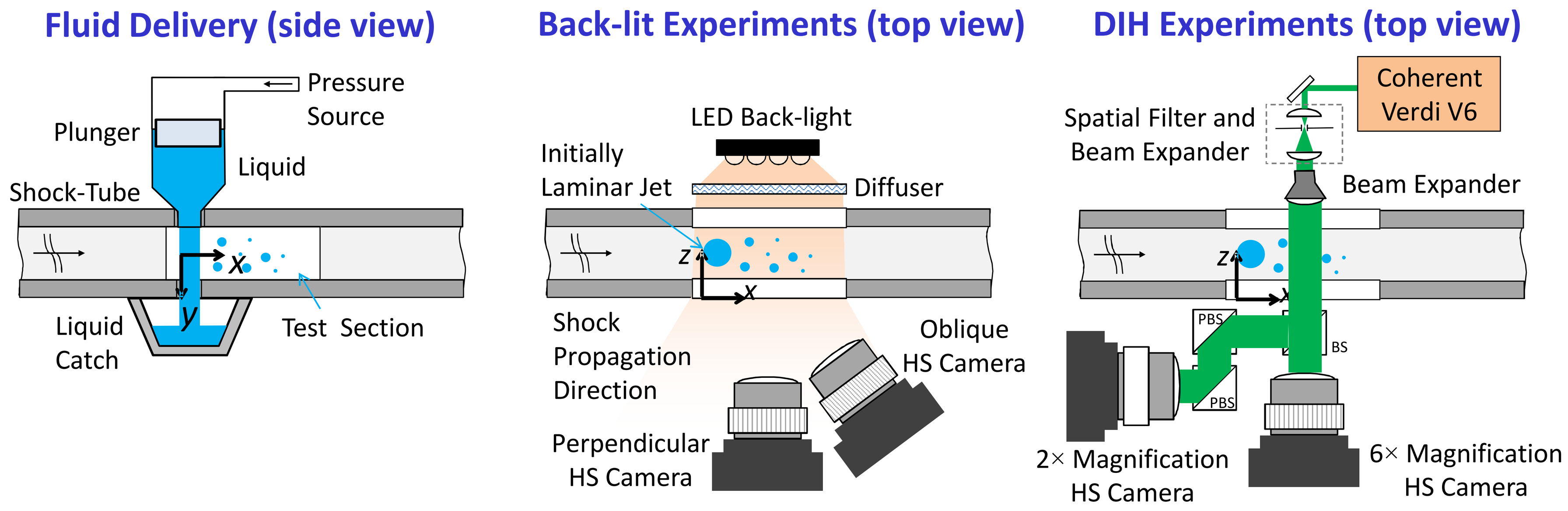
We compare the breakup of **water with Galinstan**, a room-temperature eutectic liquid metal alloy (gallium 68.5%, indium 21.5% and tin 10%) with elastic oxide skin properties similar to aluminum. Temperature gradient and combustion effects can be ignored.

Properties	Water	Galinstan
Density	1000 kg/m^3	6440 kg/m^3
Surface Tension	0.073 N/m	0.718 N/m
Bulk Viscosity	0.89 mPa·s	2.4 mPa·s

Experimental Methods

SNL Multiphase Shock-Tube





- Shockwaves with a step change in velocity are produced in a shock-tube (76×76 mm cross section, 5.2 m long) using a pressurized nitrogen source actuated by a fast action valve.
- Mach numbers range from 1 to 1.5 and test times range from 5 to 10 ms.
- Back-lit imaging with Photron SA-Z high speed cameras is used to compare breakup morphology.
- Digital in-line holography (DIH) at 100 kHz is used to quantify particle size and velocity properties.

Digital In-line Holography

- Holography is ideal for mapping 3D positions on a 2D sensor and quantifying particles that may be out-of-focus at high magnifications.
- The diffraction integral equation describes light propagation. Convolution is used to numerically refocus holograms by selecting z.

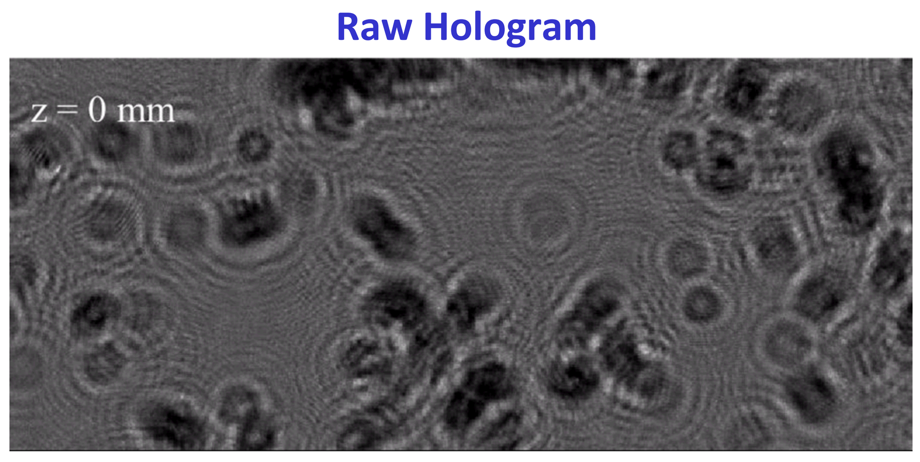
$$E(x,y,z) = \frac{1}{\lambda}\iint E(\xi,\eta,z=0)\frac{e^{-jkr}}{r}d\xi d\eta$$

$$\text{where: } r = \sqrt{(\xi - x)^2 + (\eta - y)^2 + z^2}$$

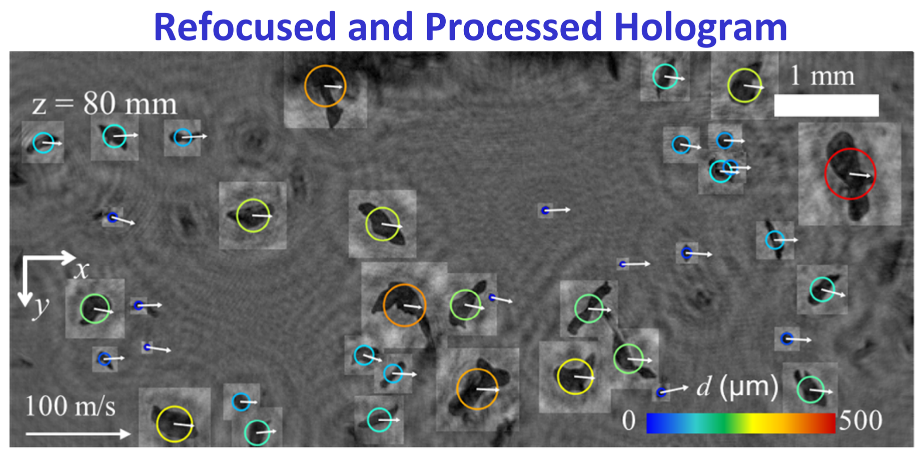
E(x,y,0) = h(x,y)·Er* is the complex amplitude at hologram plane, h(x,y) is the hologram, Er* is the planar reference wave, E(x,y,z) is the refocused complex amplitude at optical depth z

- Particle z-locations identified with minimum amplitude maximum Tenengrad method.
- Velocities are tracked using nearest neighbor and particle size cost functions on data from multiple frames. Processing was conducted on the SNL ODIN cluster.

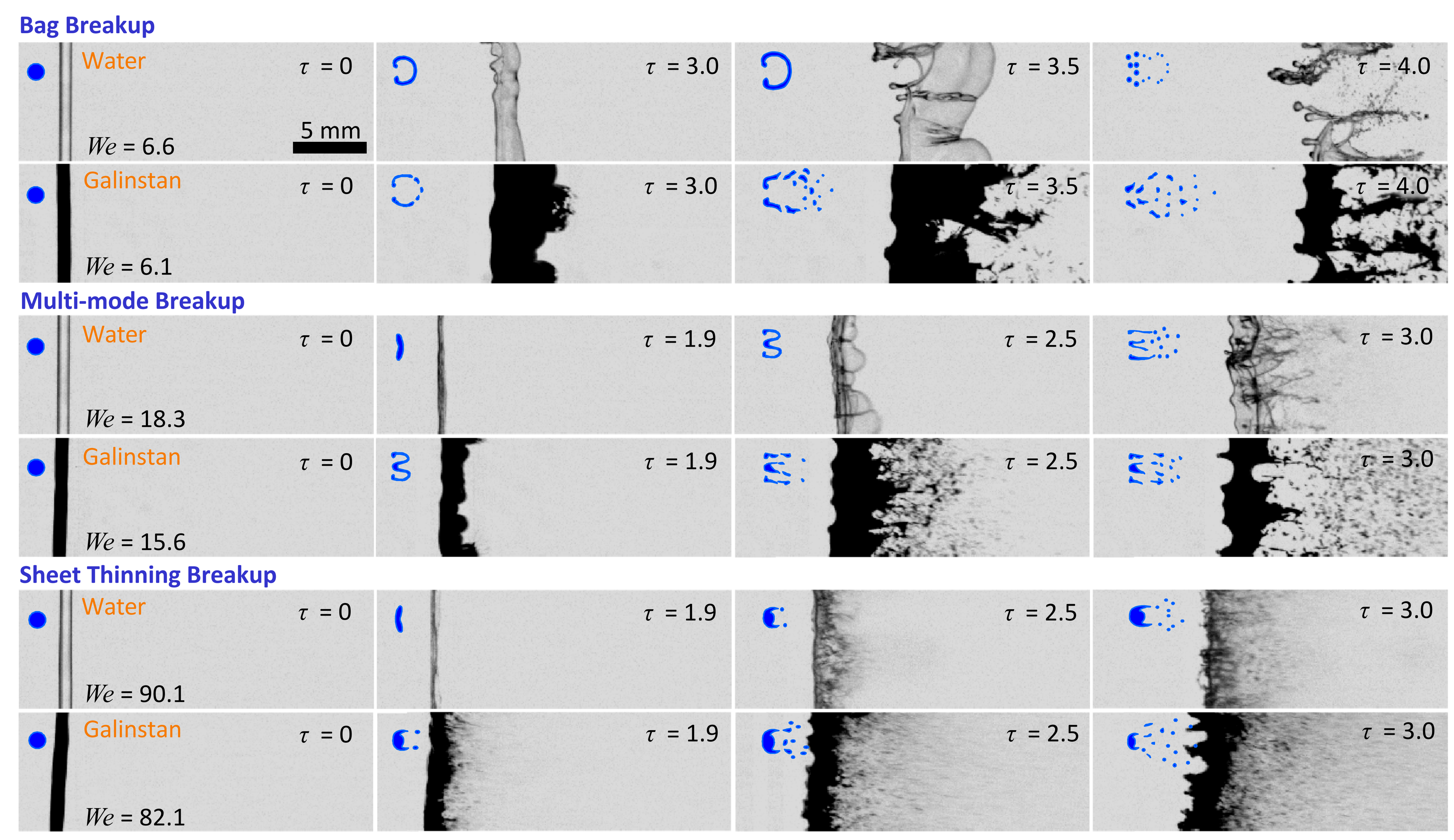
Raw Hologram



Refocused and Processed Hologram

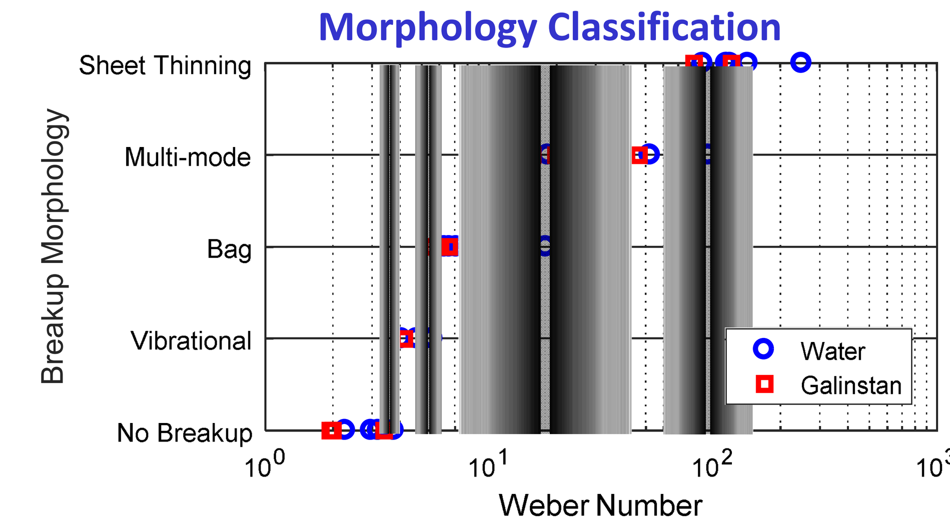


Breakup Morphology Results



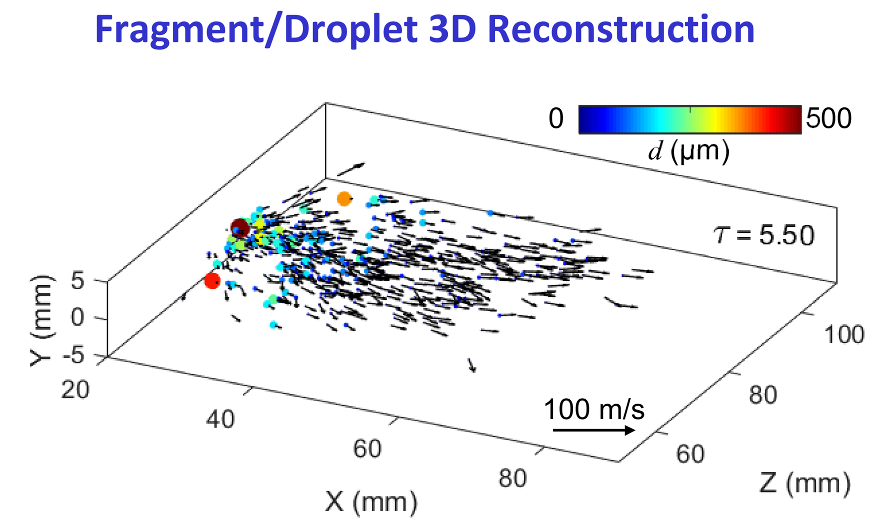
- The fluids motions align as a function of τ due to the inclusion of the density ratio.
- Galinstan and water have similar breakup morphology maps as a function of *We*.
- Galinstan fragments are jagged due to fast oxide formation.
- Galinstan break up occurs earlier due to its higher density by at least $\tau \approx 0.5$.

Morphology Classification



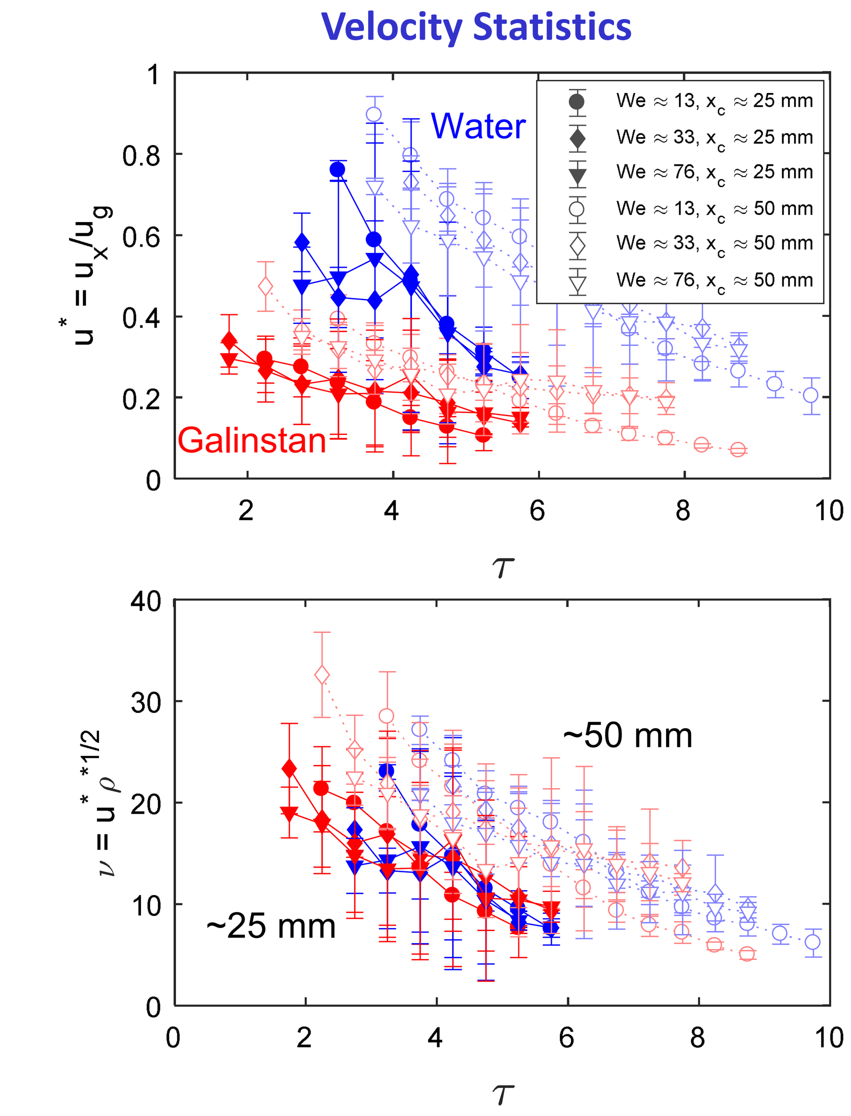
Droplet Size and Velocity

Fragment/Droplet 3D Reconstruction

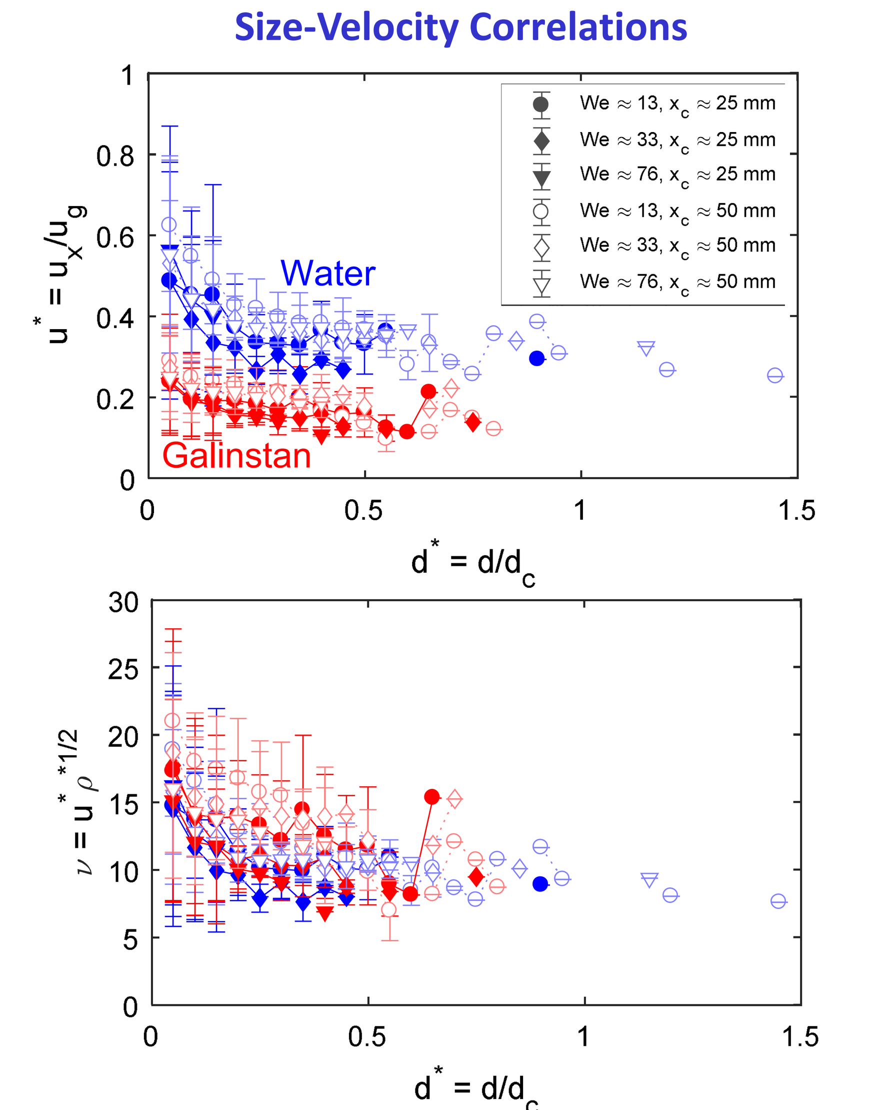


- Experiments at multiple downstream positions can be stitched together to create 3D reconstructions of the droplet distribution.
- Statistics are gathered from multiple experiments at each downstream position.
- Non-dimensionalization by the density ratio allows the fluid velocities to be compared.
- Galinstan generates particles earlier in non-dimensional time but creates fewer large droplets due to the elastic surface oxide .

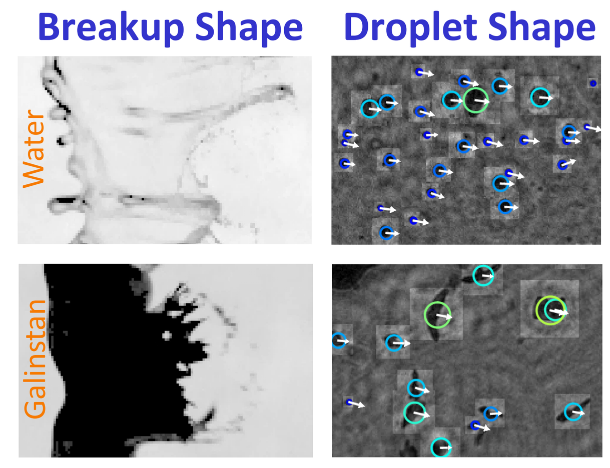
Velocity Statistics



Size-Velocity Correlations



Conclusions



- We validated our hypotheses showing that although liquid metals have bulk behaviors similar to typical fluids like water, higher densities and fast oxide formation affect various properties.
- Galinstan non-dimensional time, non-dimensional velocity, and breakup initiation time are affected but its higher density.
- Galinstan breakup and droplet shapes are jagged due to fast surface oxide formation. This affects droplet sizes at low *We*.
- Morphology, time-profile and statistical results are being used for model development and validation.

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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References:
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