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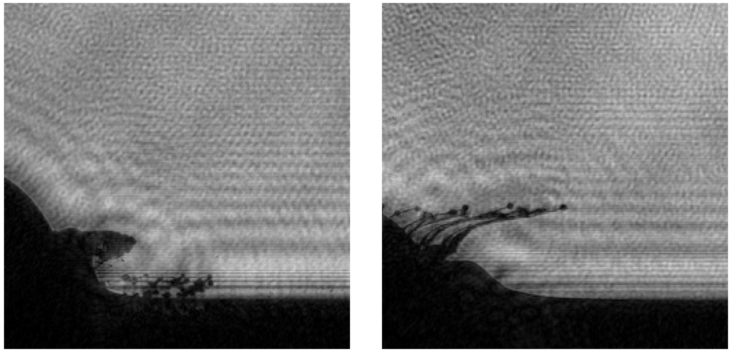

Viscous drops impacting thin liquid surfaces: experimental quantification of secondary fragment size and velocities

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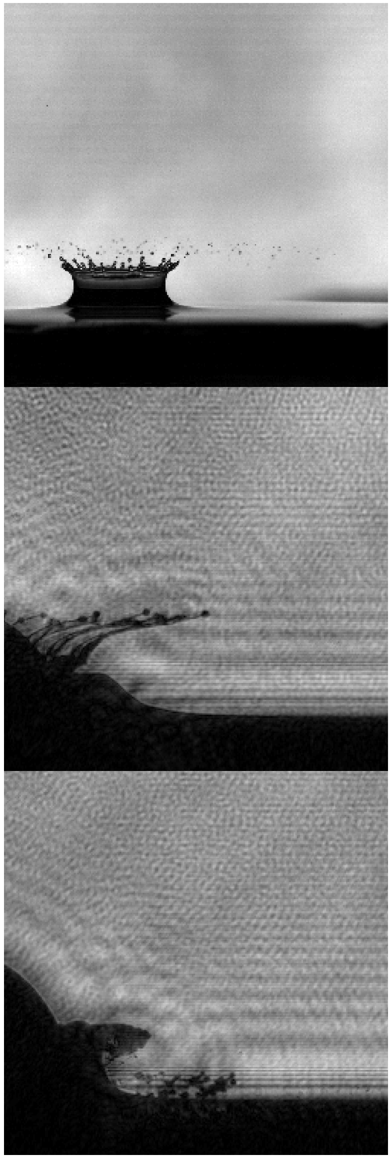
Drop impact on a thin film

Current status:

- There is disagreement as to the morphologies present as *We* and *Oh* are varied
- There has been very little treatment of non-Newtonian liquid behavior



Goal of this work:

- Originally to investigate the influence of shear thinning behavior on breakup dynamics
- Subsequently to study effect of Re variation on fragment size and velocity temporal behavior, as well as to identify morphologies
- Do so at high framing rates (20 kHz)

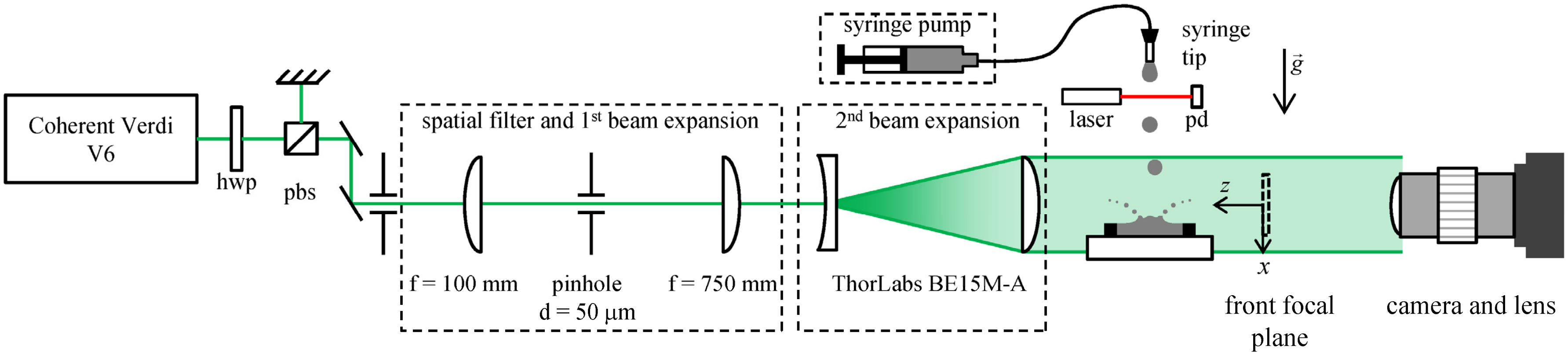
DIH setup

Configuration:

- Drop falling onto thin liquid film
- Images captured using Photron SAZ (20 kHz framing rate) camera with Infinity K2/Distamax long distance microscope and CF1 objective lens

Analysis Hardware:

- Discussed in earlier talk today



Initial conditions

Table 1. Initial conditions, given as the mean from all videos±the standard deviation of the mean from each video.

wt.% CMC	Fall height (mm)	Number of videos analyzed	Initial diameter, d_0 (mm)	Impact velocity, v_0 (m/s)	Dimensionless film thickness, δ	Impact Weber number, We	Impact Reynolds number, Re
0.00	1250	13	2.645 ± 0.009	4.48 ± 0.01	0.889 ± 0.003	737 ± 6	11800 ± 61
0.00	2250	20	2.648 ± 0.006	5.62 ± 0.02	0.888 ± 0.002	1160 ± 10	1490 ± 74
0.125	1250	20	2.667 ± 0.005	4.48 ± 0.02	0.881 ± 0.002	744 ± 5	2600 ± 10
0.125	2250	20	2.647 ± 0.005	5.62 ± 0.02	0.888 ± 0.002	1160 ± 9	3200 ± 13
0.25	1250	20	2.665 ± 0.012	4.49 ± 0.02	0.881 ± 0.004	744 ± 8	1900± 13
0.25	2250	22	2.648 ± 0.005	5.61 ± 0.02	0.888 ± 0.002	1160 ± 8	2360 ± 9

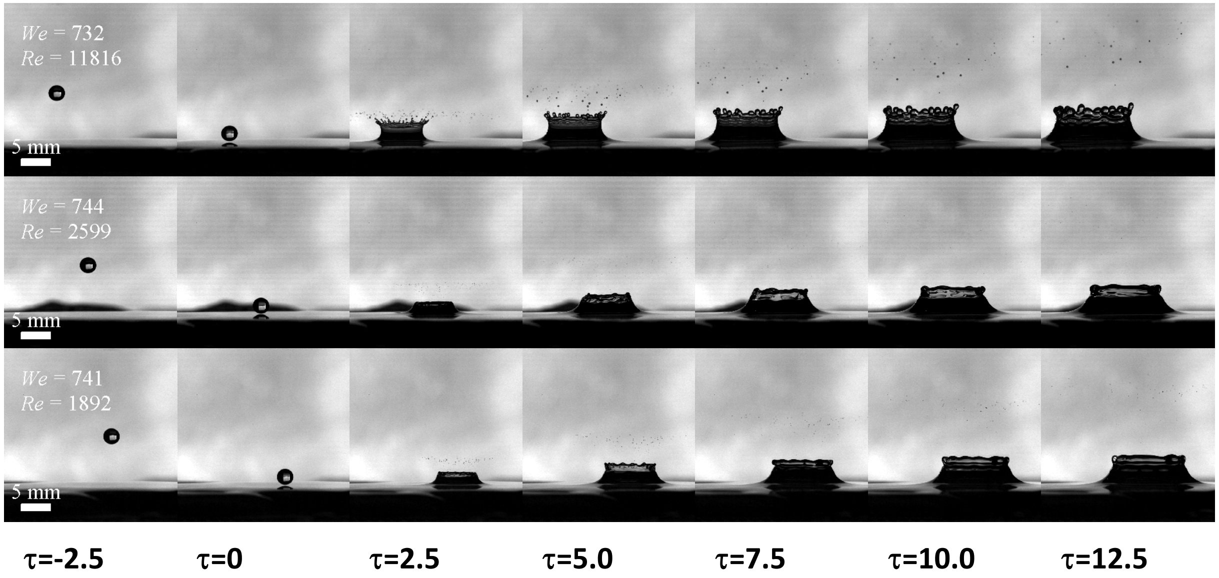
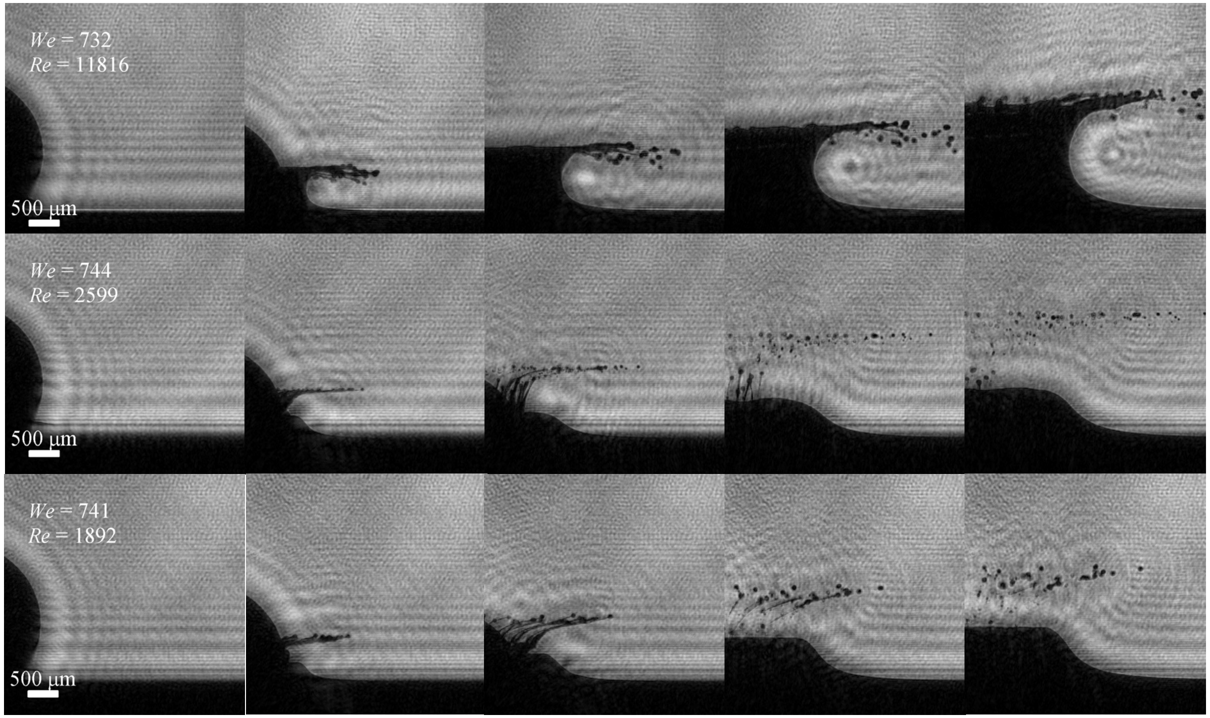


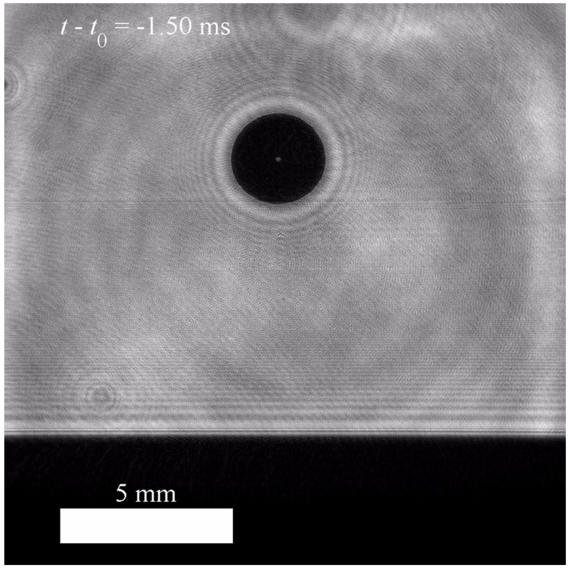
Figure 1. Select results from high-speed backlit imaging of the impact of a drop on a thin film at *We* ≈ 740. Top row shows pure DI water; middle row is water plus 0.125% CMC-Na; bottom row is water plus 0.25% CMC-Na.

DIH raw results



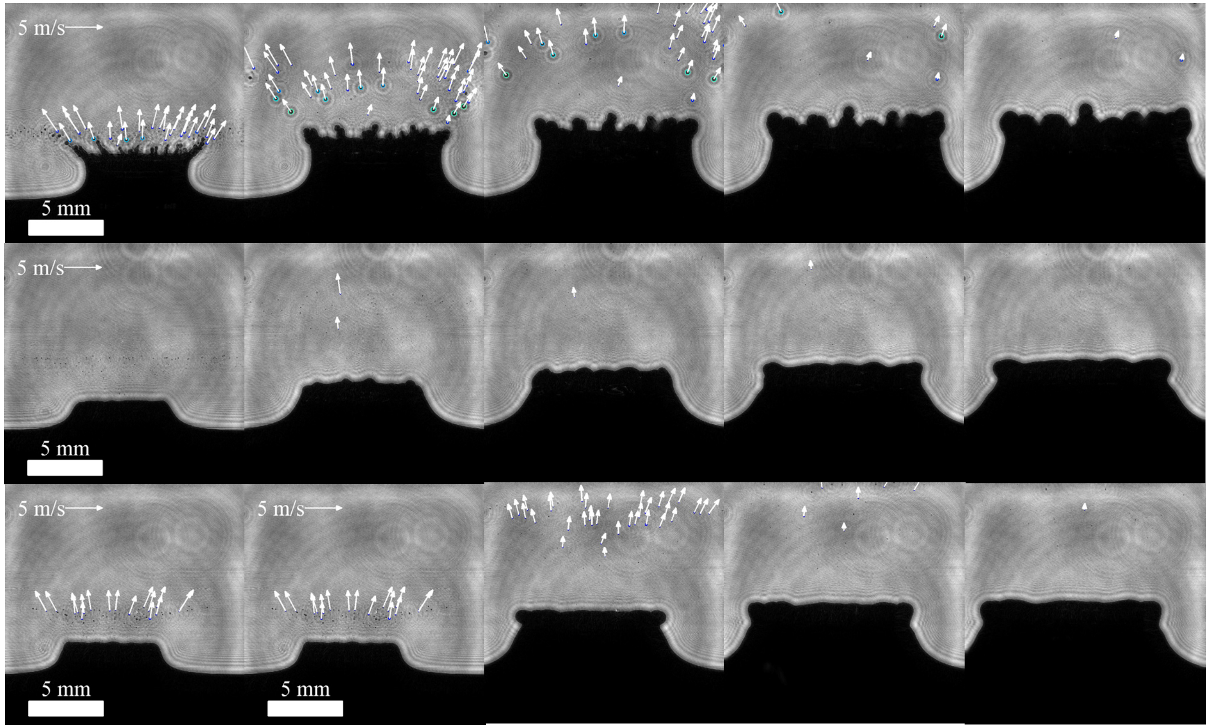
(a) τ = 0.2 **(b) τ = 0.4** **(c) τ = 0.6** **(d) τ = 0.8** **(e) τ = 1.0**

Figure 2. Selected DIH results at early times after drop impact on a thin film at *We* ≈ 740. Top row is pure DI water; middle row is 0.125-wt.% CMC-Na in DI water; bottom row is 0.25-wt.% CMC-Na in DI water.



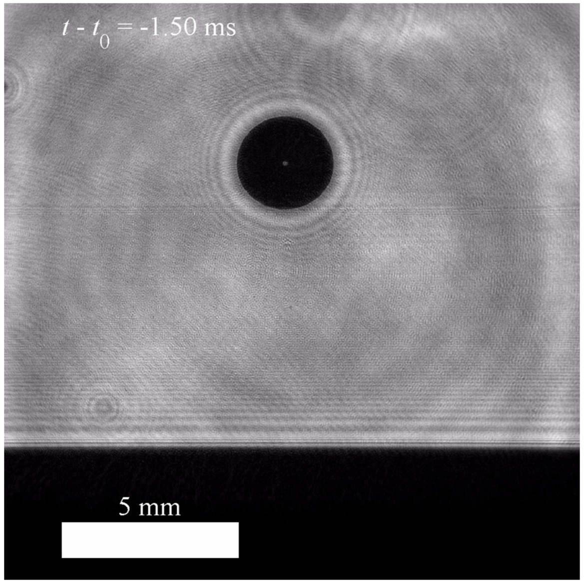
Motzkus *et al.*, 2008: water and water+C_2H_5OH observe both crown ($d_{fragment}/d_0$~0.7) and "micro" ($d_{fragment}/d_0$~0.1) droplets when *We*>200

DIH raw results

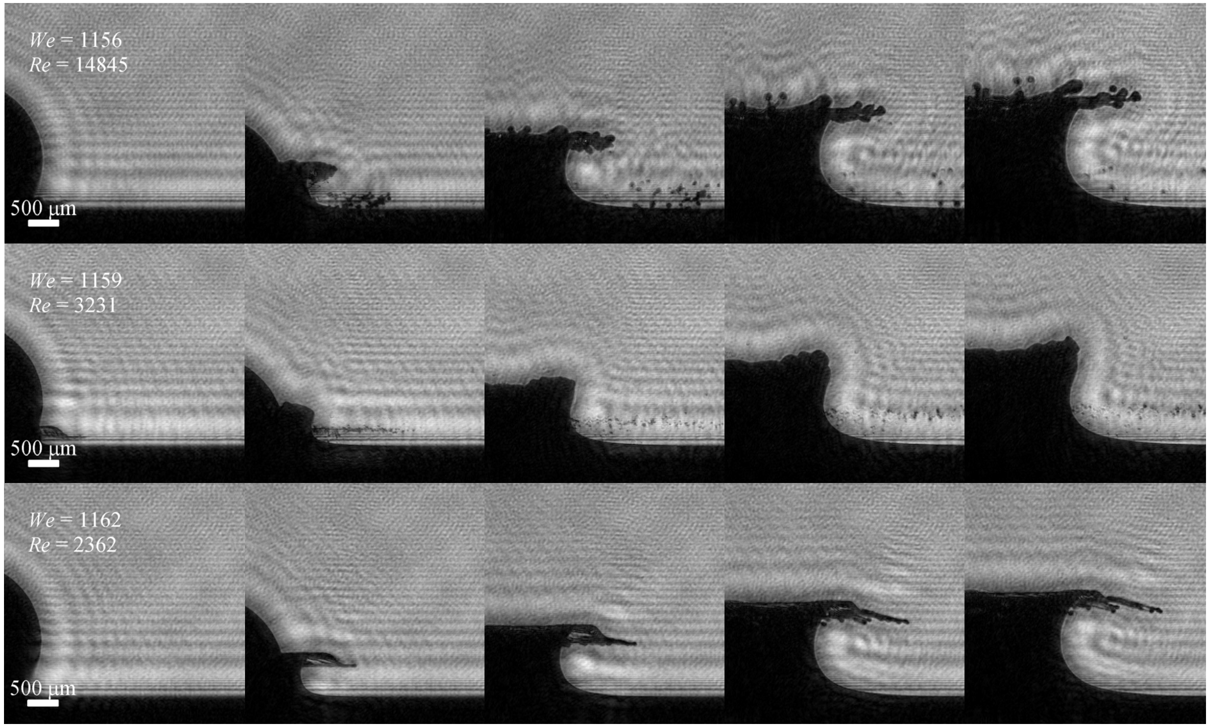


(a) $\tau = 2.5$ **(b)** $\tau = 5.0$ **(c)** $\tau = 7.5$ **(d)** $\tau = 10.0$ **(e)** $\tau = 12.5$

Figure 3. Selected DIH results at late times after drop impact on a thin film at *We* ≈ 740. Top row is pure DI water; middle row is 0.125-wt.% CMC-Na in DI water; bottom row is 0.25-wt.% CMC-Na in DI water.



DIH raw results



(a) τ = 0.2 **(b) τ = 0.4** **(c) τ = 0.6** **(d) τ = 0.8** **(e) τ = 1.0**

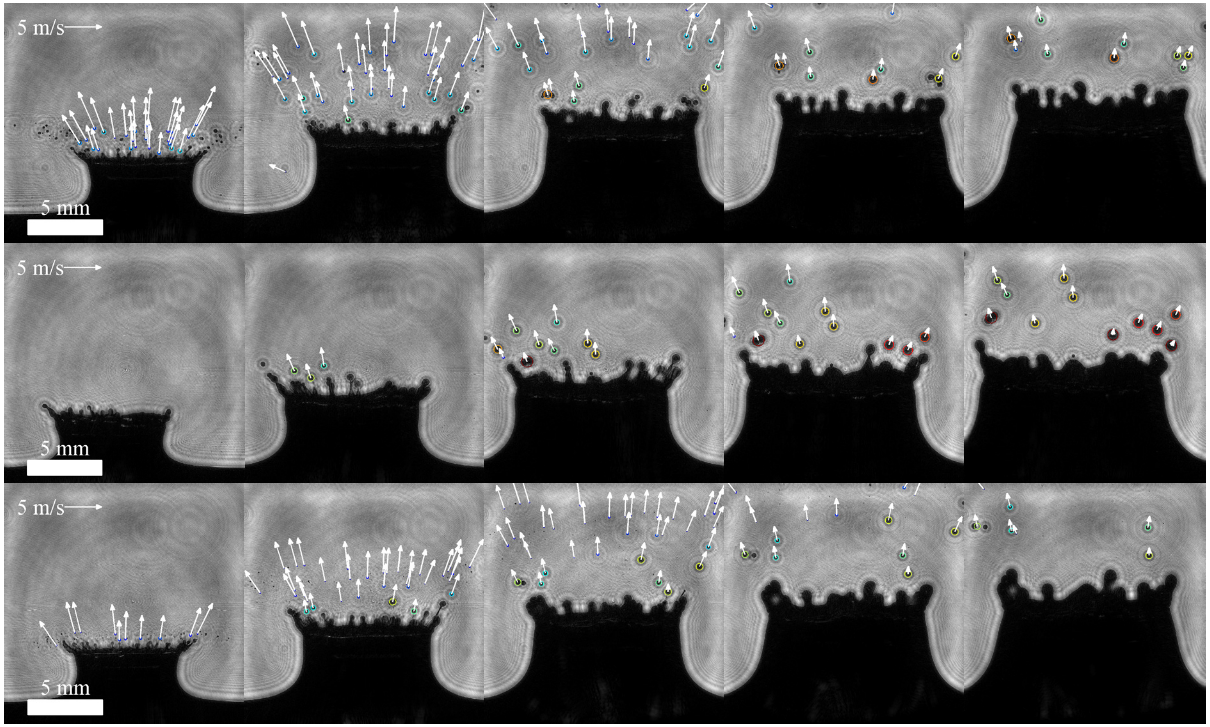
Figure 4. Selected DIH results at early times after drop impact on a thin film at *We* ≈ 1160. Top row is pure DI water; middle row is 0.125-wt.% CMC-Na in DI water; bottom row is 0.25-wt.% CMC-Na in DI water.

- A small change in composition can have a considerable impact on rheology
- For shear thinning rheology:
  - K= 6.32e^{-03} Pa-s$^{0.966}$, n=0.966 and K=4.86e^{-03} Pa-s$^{0.978}$, n=0.978
- For Newtonian rheology:
  - $<\mu>$=0.00391 and $<\mu>$=0.00500 Pa-s

Thoroddsen (2002) has *We*~2200, *Re*~650, μ>0.0035 Pa-s

Zhang *et al*. (2012) show ejecta sheet and second jet

DIH raw results



(a) τ = 2.5 **(b)** τ = 5.0 **(c)** τ = 7.5 **(d)** τ = 10.0 **(e)** τ = 12.5

Figure 5. Selected DIH results at late times after drop impact on a thin film at *We* ≈ 1160. Top row is pure DI water; middle row is 0.125-wt.% CMC-Na in DI water; bottom row is 0.25-wt.% CMC-Na in DI water.

DIH processed results

Table 2. Characteristic sizes of the fragments for *We* ≈ 1160, given as the mean from all videos ± the standard deviation of the mean from each video.

wt.% CMC-Na	Number of measured fragments	D_{10} (mm)	D_{30} (mm)	D_{32} (mm)
0.00	59 ± 6	209 ± 17	286 ± 20	382 ± 42
0.125	32 ± 14	251 ± 108	330 ± 108	423 ± 104
0.25	41 ± 7	138 ± 30	248 ± 58	422 ± 108

Measured total drop volume ranges from 0.6 to 3% of initial drop volume, about twice that reported by Motzkus *et al.*, J Colloid Interf Sci **362**, 540-552 (2011)

Comparison with previous results

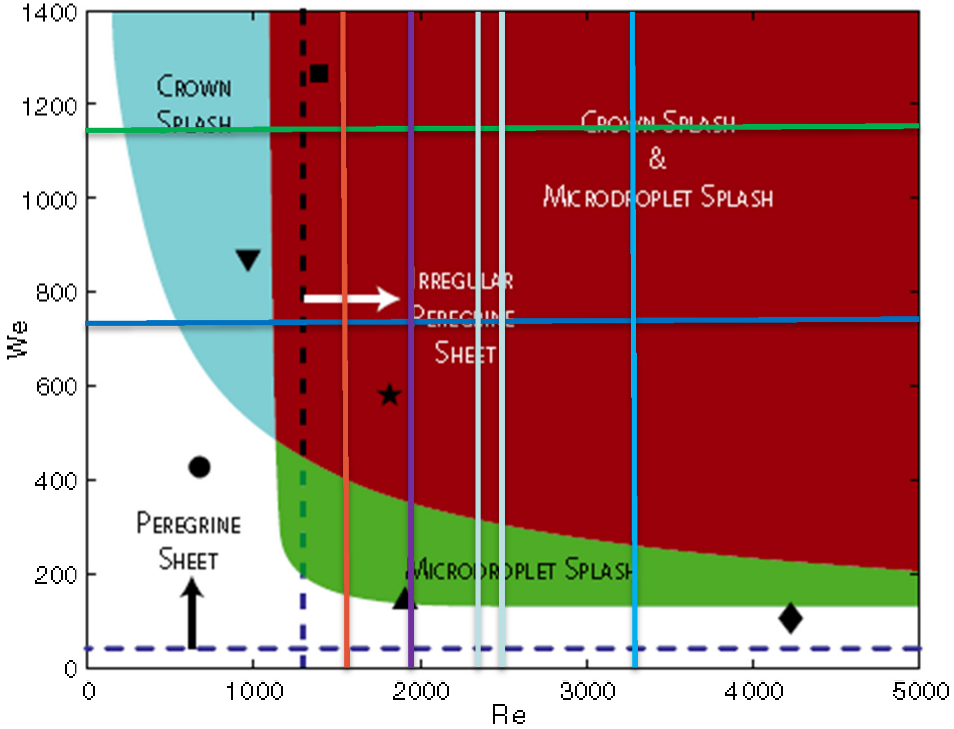


Figure 3. Phase diagram indicating the qualitatively different regimes of drop impact. The dashed vertical line indicates the Re beyond which the Peregrine sheet is disordered, and the horizontal dashed line indicates the We number above which a Peregrine sheet forms.

Deegan *et al*., Nonlinearity, **21:**C1-11, 2008.

Comparison with previous results

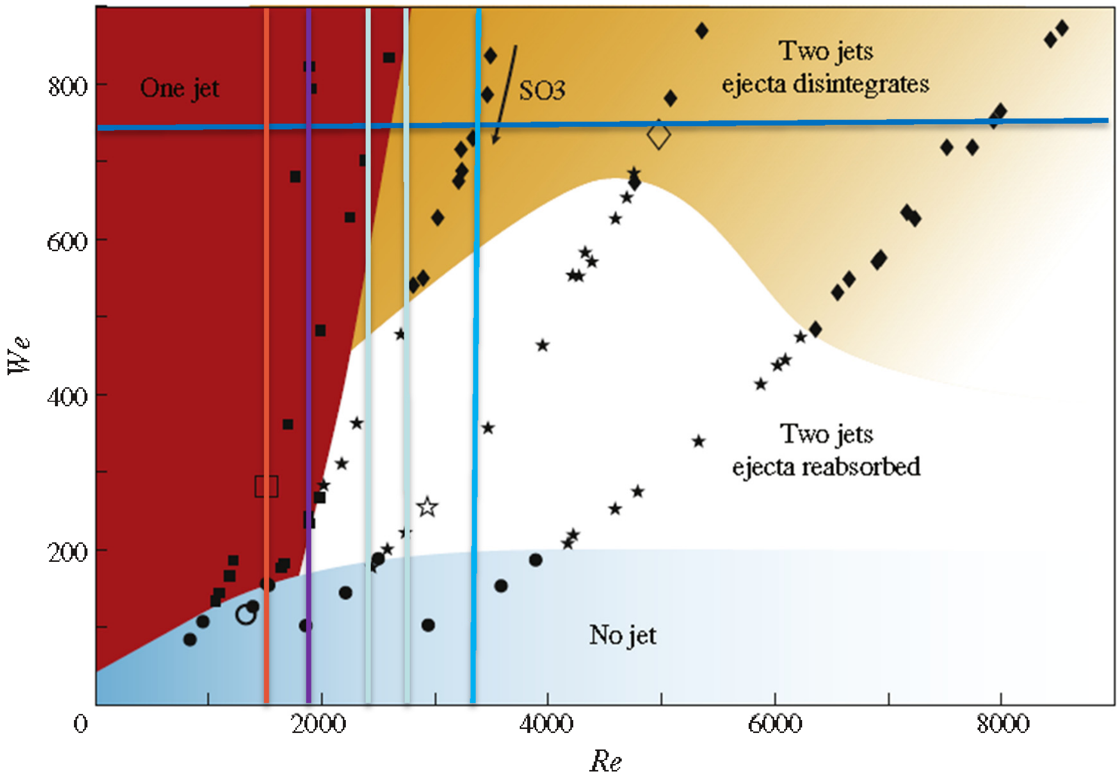


FIGURE 3. (Colour online available at journals.cambridge.org/flm) Phase diagram as a function of *We* and *Re* indicating number of jets resulting from drop impact. The behaviour of each experiment is indicated with a symbol: circles for a non-cresting capillary, squares for a single jet comprising both the ejecta and lamella sheet, stars for separate ejecta and lamella, and diamonds for separate ejecta and lamella when the ejecta dissociates into secondary droplets. Open symbols correspond to the particular experiments depicted in figure 2.

Zhang et al., JFM **690**, 5-15 (2012)

Results

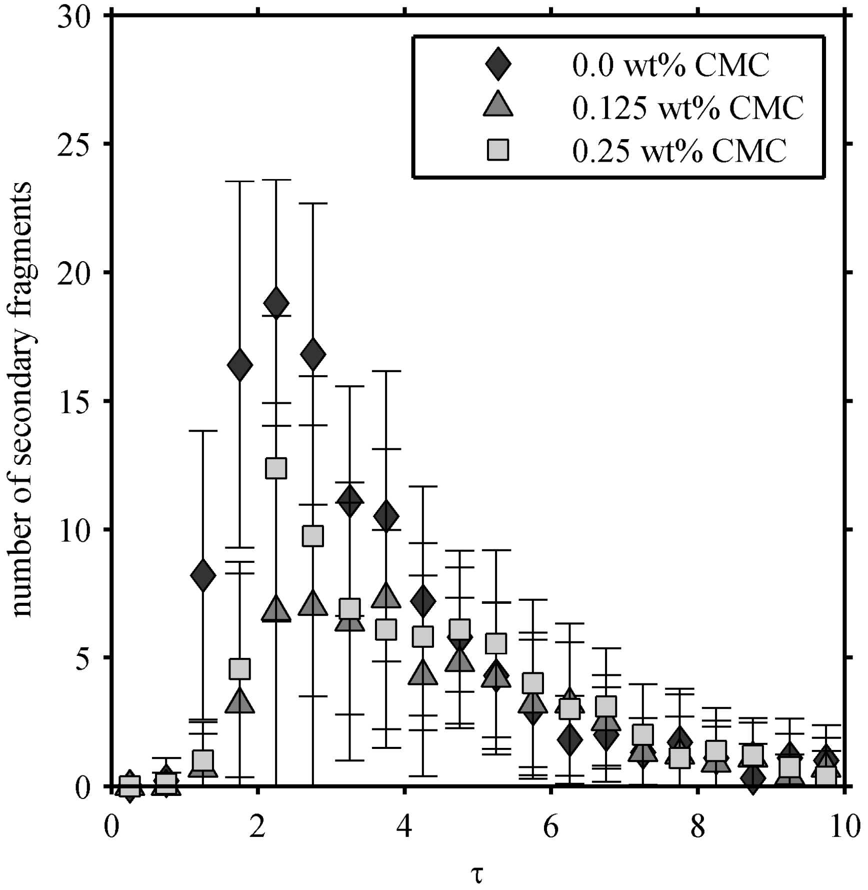


Figure 6. Measured number of secondary fragments for *We* ≈ 1160 and three concentrations of CMC-Na in DI water.

Number of water fragments produced is consistent with Motzkus *et al*., Aerosol Sci **40**, 680-692 (2009)

Comparison with previous results

- Regime maps from the Deegan group are not consistent with results presented here (perhaps due to slight shear thinning behavior?)

- Drop fractional mass collected, and number of fragment drops observed, are consistent with work by Motzkus *et al*.
    - This gives some confidence in our experimental data

Results

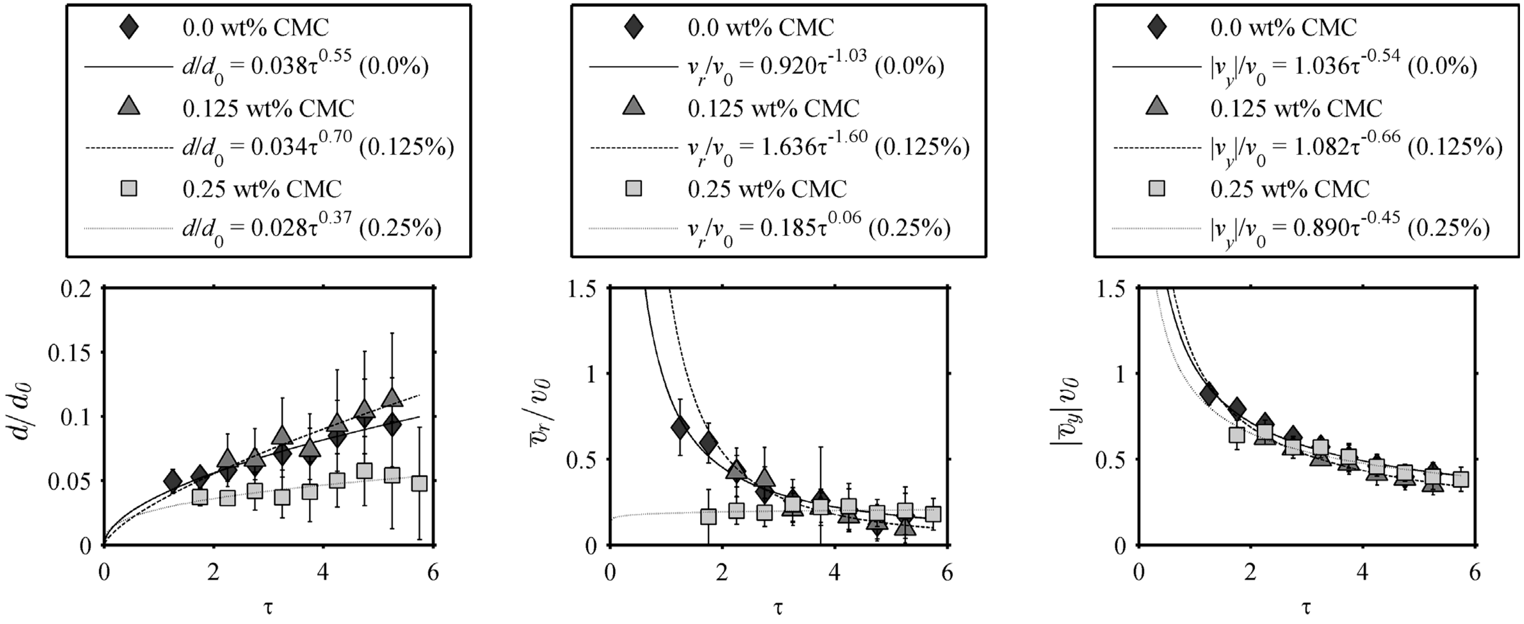


Figure 7. Comparison of (a) measured fragment sizes, (b) measured fragment radial velocities, and (c) measured fragment *y*-velocities for three concentrations of CMC-Na in DI water, all at *We* ≈ 1160.

Discussion

Temporal behavior of fragment size and velocity data show that

- Dimensionless diameter decreases with dimensionless time, as expected
  - The effect diminishes as *Oh* increases
- Dimensionless vertical velocity shows the expected decrease with dimensionless time
  - There is no influence of *Oh*
- Dimensionless radial velocity exhibits mixed behavior—it decreases with dimensionless time for lower *Oh*, but is essentially constant at the highest *Oh* considered during this study

Conclusions

- Even weakly non-Newtonian behavior may lead to new drop impact morphologies
- Existing regime maps for breakup morphology don’t seem to be accurate for even weakly non-Newtonian substances

Questions?