Mass Transfer Rate of Non-Spherical Particles in Turbulence

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Abstract

Planktonic organisms, or organisms that drift in water, raise the question of how one finds sustenance or excretes waste without self-propulsion. Using computational methods to solve the Navier-Stokes equations, which describe the flow of incompressible fluids, one can predict how organisms in both the Integral (large) scale and Kolmogorov (small) scale interact with their environment; however, solutions to the Navier-Stokes equations in the Taylor (middle) microscale region are currently too computationally intensive to solve. In order to understand how these organisms interact with their environment, an experimental model of their behavior needs to be created. Organisms are modeled using particles of different shapes and surface areas and are composed of sucrose, dextrose, and glass bubbles. This allows us to measure the mass transfer rate from the particle surface to the surrounding water and will help illustrate how nutrients may transport to and from an organism. It was found that thin rectangular-shaped particles have a higher mass transfer rate than cube-shaped particles, potentially due to their surface area to volume ratio. The particles studied serve as models to further our understanding of how planktonic organisms behave in turbulence.

Background

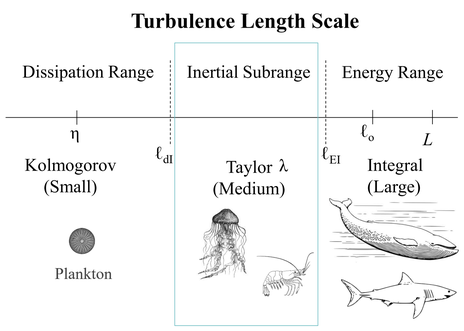
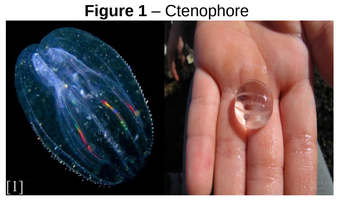


Figure 1 – Ctenophore


[1]

- Planktonic Organisms: Organisms that do not self propel
- Left: Similar to jellyfish this organism is native to the east coast of north and south America and lives in the inertial subrange
- Right: Ctenophore in hand for scale

Turbulence Tank

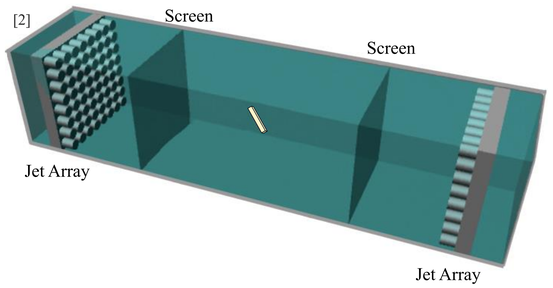


Figure 6 – Turbulence Tank Used to Conduct Experiments with Rod

- Particles are placed into turbulence tank filled with water
- Jets fire at random to produce turbulence
- Particles are removed and weighed in 60 second intervals to measure mass transfer rate

Integral length scale, L	80.0 x 10^{-3} m
Taylor length scale, λ_f	12.6 x 10^{-3} m
Kolmogorov length scale, $\eta = (\nu 3/\langle\varepsilon\rangle)1/4$	0.39 x 10^{-3} m
Turbulence Reynolds number, $Re_\lambda = u_T \lambda_f / \nu$	261 [3]

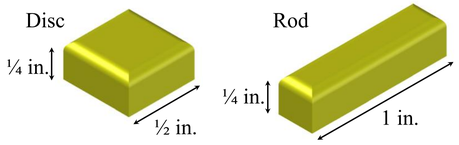
Discussion and Conclusion

Normalized Equation: $1 - \sqrt[3]{M/M_0} = k_0 t$ Hixon-Crowell Model Equation: $\sqrt[3]{M_0} - \sqrt[3]{M} = kt$

- Mass of particles decline as time increases
- Discs take 10-15 minutes to dissolve
- Rods take ~10 minutes to dissolve
- The green hollow circles from the rods in the Hixson-Crowell model have a much steeper slope in the positive direction, this means they have a higher mass transfer rate
- Data fits Hixson-Crowell model - we do not yet know why
- The rate (slope) looks shallower at the beginning of the Hixson-Crowell model, then jumps to a steeper slope after approximately 5 minutes this may be due to surface area to volume ratio falling below 1
- The dissolution rate, *k,* is shown with a solid line
- The confidence interval, or projected trend, is illustrated with a dashed line
- We are able to relate the rate at which waste is taken away from an organism to our model
- This matches previous experiments and shows reproducibility

Sugar Work

Figure 2 – Particle Shapes Used



Ingredients:

- Sucrose - Cane sugar
- Dextrose - Corn sugar
- 3M Glass Bubbles - Glass spheres added for buoyancy

Process:

1. Mix in 100mL beaker:
   - 4.9g Glass Bubbles
   - 24g Sucrose
   - 1.5g Dextrose
   - 1.5mL Water
2. Heat until mixture reaches 245-255 ˚F
3. Pour into mold
4. Wait until set
5. Demold and sand

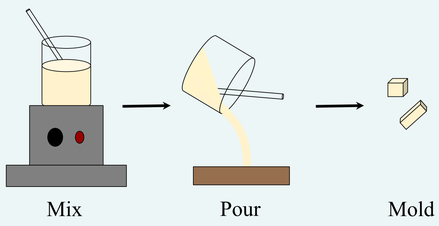


Figure 3 – Process of Creating Particles

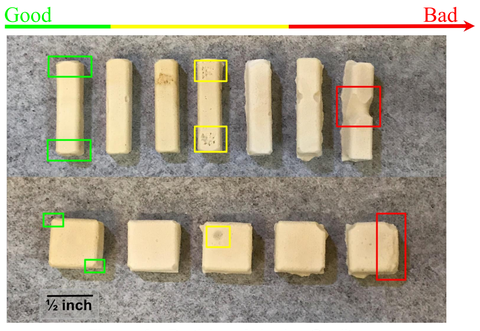


Figure 4 – Particles of Varying Quality

Quality Control:

Left:

- Consistent color
- No air bubbles, filled corners
- Ideal

Center:

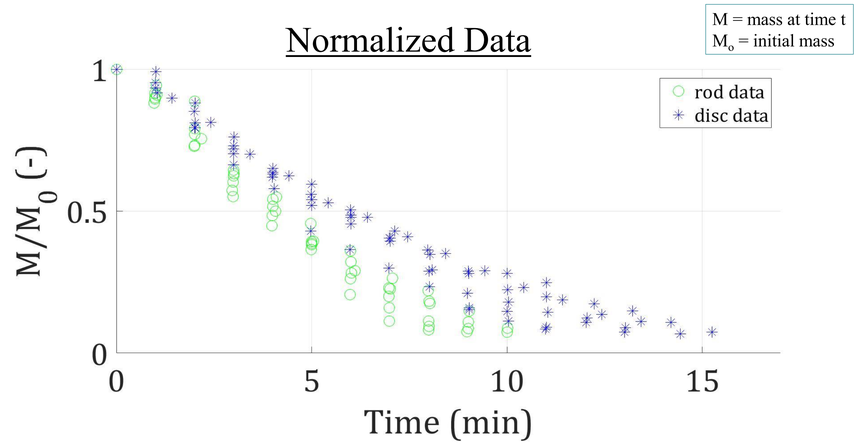
- Inconsistent color
- Air bubbles, some unfilled corners
- Unusable

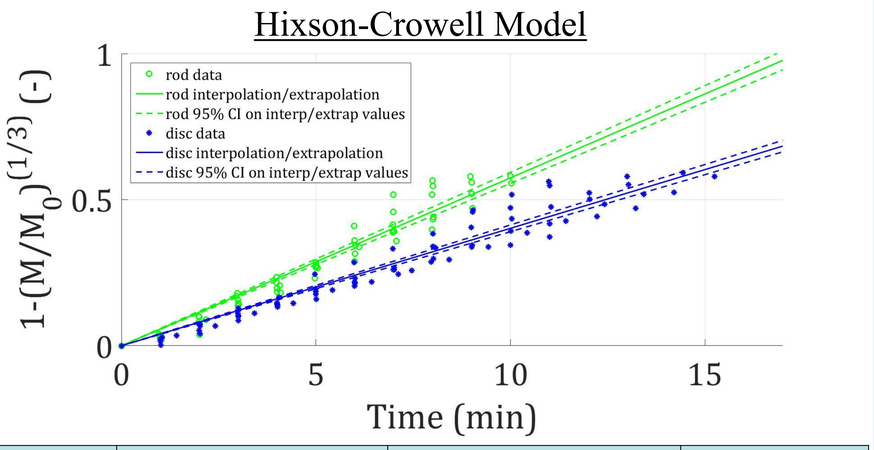
Right:

- Large air bubbles
- Unfilled corners
- Unusable

Figure 5 – Particle Dissolving as Time Increases

Results





Shape	Rate constant, k [$M^{1/3}/T$]	Confidence Interval Upper	Confidence Interval Lower	R^2 value
Rod	0.0575	0.0556	0.0594	0.9543
Disc	0.0402	0.0390	0.0414	0.9482

Future Work

- Create surface area matched particles with different volumes (results presented are volume matched)
- Test how the volume-to-surface area ratio influences the mass transfer rate

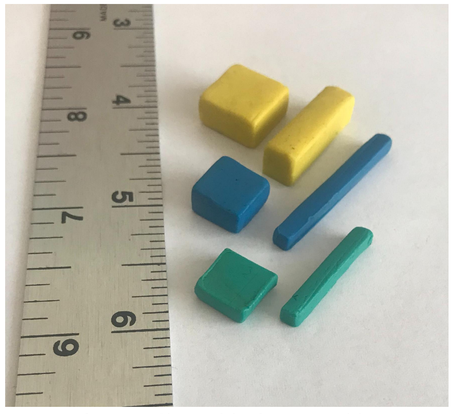


Figure 7 – Clay Models of Future Particles

Aspect Ratio
largest to smallest dimension

Yellow Disc
- 2:1

Yellow Rod
- 7:2

Blue Disc
- 3:2

Blue Rod
- 10:1

Green Disc
- 3:1

Green Rod
- 7:1

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References

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