Comparison of drag forces acting on different benthic body shapes in marine molluscs

Colton Skavicus, Petra Ditsche

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Contact Information:
Colton Skavicus
University of Washington
Skavicus@gmail.com

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Abstract:

The marine intertidal is an area prone to high wave energy and flow velocities, and the organisms living there are subjected to large hydrodynamic forces, such as drag. These forces acting to dislodge organisms may result in reduced foraging efficiency and depressed overall growth. In this study the body shape of a snail, chiton, and limpet are subjected to flume testing to observe how drag forces and drag coefficients change with a range of Reynolds numbers simulating currents up to 6 m/s. In higher flow velocities the snail body shape experienced drastically higher drag forces than the limpet and chiton body shape. The drag coefficients for the limpet and chiton both were relatively high at low flow velocity, and quickly decreased at higher speeds. The snail however experienced an opposite change in drag coefficient, with a lower drag coefficient at low flow speeds and increased with higher flow speeds. When compared to Reynolds number drag coefficients for the limpet and chiton show little change at higher Reynolds number, contrast to the snail body shape in which the drag coefficient appears to fluctuate with increasing Reynolds number.

Introduction:

The intertidal zone is often subjected to various flow forces, from the smashing waves to the constant ebb and flow of the tides. These flow forces can have an important impact on the organisms living there, as they risk being forced right off their substrate (Koehl 1984). Intertidal grazers that are dislodged by wave action are unable to forage and could lose their space to more competitive grazers that were once physical kept out (Connell 1972, Denny 1985). Additionally, a lack of a herbivore presence can result in unrestricted growth of certain algal species (Lubchenco and Menge 1978). How flow forces present in the intertidal affect vital benthic species could potentially have serious consequences on intertidal dynamics.

The flow and resistance of water over a fixed body will create two main forces; (1) skin drag (2) and pressure drag. Skin drag (also called friction drag) is a result of water molecules resisting the flow over the surface of an organism due to friction. This resistance creates a shear force, and is directed in the direction of the moving current. This part of drag force is proportional to the product of the surface area of the organism and flow velocity (Ditsche and Summers in press). Pressure drag (also called form drag) is caused by the turbulent wake formed downstream of the object. This turbulent wake creates a pressure zone lower than the pressure upstream, creating a downstream drag force (Koehl 1982). Pressure drag is proportional to the product of the organism's area in frontal projection and the square of the flow velocity (Ditsche and Summers, in press).

One way flow conditions are characterized are given by the Reynolds number:

$$Re = (\rho l U)/\mu$$

Reynolds number is a dimensionless unit that relates the length of an object to the speed of the moving fluid, and is a calculated function of seawater density (ρ), length of the object/organism (l), fluid velocity (U), and the dynamic viscosity (μ) (Vogel 1994). Reynolds number values have a very wide range, and indicate a lot about the major forces acting on an object. A relatively large Reynolds indicates that inertial forces are the major force acting on the object and, thus, pressure drag is the dominant part of drag. An example would be a large blue whale swimming through water. In contrast, a relatively low Reynolds number indicates that viscous forces are the major forces acting on the objects motion. So friction drag is the major force e.g. for drifting phytoplankton. The Reynolds number makes comparing flow forces among different organisms and conditions convenient, as a similar Reynolds number ensures that viscous and inertial forces are in the same proportions (Vogel 1994).

Previous literature has shown that pressure drag forces primarily affect macroorganisms, and must minimize the eddying wake behind it in order to reduce this force (Koehl 1984). Not only does the shape of the body affect the drag and determines the magnitude of stress, the volume (or size) of the body is also proportional to the drag forces experienced by the organism (Koehl 1982).

The goal of this study is to compare the impact of the body shape on drag forces. Therefore, three different body shapes will be looked at in this experiment, comprised of common benthic organisms of the marine intertidal: a limpet, a chiton, and a snail. These organisms were chosen for both their high abundance in the intertidal and relatively simple shapes that can be easily converted into digital 3D models. Given the tall conical nature of the snail body shape, it is likely to experience the highest drag forces as a result of a larger turbulent wake. In addition, it is intuitive that given the more rounded and low profile body shape of the chiton and limpet, there is likely to be less of a turbulent wake and therefore less drag. However, how these flow forces actually vary over different flow velocities as well as body shape and may provide insight to organism's adaptations to living in high-energy environments.

Methods:

Animals

The organisms for this experiment were collected locally on San Juan Island. The snail specimen (*Calliostoma ligatum*) as well as the chiton specimen (*Tonicella lineata*) was taken from the collection tanks located in Lab 3 of Friday Harbor Laboratories. The limpet specimens (*Lottia pelta*) were collected from tires hanging off the docks of the Friday Harbor Research Station. These organisms provide a range of different body shapes, with the chiton having the lowest profile and being more rounded. The limpet is also relatively low profile, but cone shaped, while the spire of the snail body shape is not low profile at all, with a tall cone shaped spire. Once collected the organisms were kept in a plexiglass tank with continual seawater input.

Preparation of 3D models

Organisms were scanned into a 3D CAD program using the NextEngine 3D laser scanner. The 3D models were then transferred over to Cura, a 3d splicing program, where organisms were scaled to 1:1 and 2.5:1 sizes, and printed out using an ORION delta 3D printer (SeeMeCNC, Goshen, Indiana) with polyactide (PLA) plastic. The bases of printed models were drilled and 8-32 thread screws were glued head first into the holes using 2-ton epoxy (Devcon, Danvers, MA). In the 1:1 scale models a nylon flat head screw was used and in the 2.5:1 scale models a stainless steel flathead screw was used. The length of exposed screw was measured and cut down to be approximately 14mm.

The remaining hole in the base of the model not filled in with epoxy was plugged up using play-doh, to ensure a solid base for the model organisms.

Figure 1. 3D printed 2.5:1 scale models the chiton (*Tonicella lineata)*(left), the limpet (*Lottia pelta)*(middle), and the snail (*Calliostoma ligatum)*(right).

High Speed Flume Measurements

The high speed flume capable of speeds up to 2.5 m/s was used to test the drag forces experienced by the 3D models. The flume itself is comprised of a plexiglass channel, 2 hp 180v motor, and approximately 9" diameter PVC tubing which cycles the water back to the other end of the plexiglass channel. A rectangular cutout at the top of the plexiglass allows access for the force transducer into the flume channel. The force transducer used in this experiment measures forces in the X and Y planes and was mounted onto a rectangular piece of plexiglass that sits flush within the cutout on the flume. The printed models were screwed into the transducer such that model base was flush with plexiglass wall, then placed into the flume (upside down), mimicking the flow experienced by a benthic organism. The transducer is connected to a USB-6009 data acquisition device (National Instruments, Austin, Texas), which transmits data to LabView software. The transducer was calibrated to accurately convert measured volts to Newtons (force). Calibration was done by hanging a series of known weights (1,2,5,10,20, and 50 g) in each the X and Y planes and calculating a linear regression of force vs. voltage. Because the center of mass in the 1:1 and 2.5:1 scaled models were different, separate calibrations were made for each scale, using screws of similar length to the models.

Figure 2. High speed flume capable of speeds up to 2.5 m/s. Organisms attached to force transducer access flume from a cutout at the top of the plexiglass channel.

Calculating Reynolds Number and Drag Coefficients

Reynolds numbers were calculated using the previously described formula:

$$Re = (\rho l U)/\mu \qquad \text{(Eq. 1)}$$

where ρ is water density, l is the characteristic length of the model, flume speed U, and dynamic viscosity μ. The flume was filled with freshwater, giving the water density a value of 1000 kg/m^3. The characteristic length of each model was measured using calipers and photos of the organisms in the flume were used to verify the orientation and accurately measure the length. A textbook value of 1.01×10^{-3} N s m^{-2} was used for the dynamic viscosity of fresh water (List 1958).

Calculating drag coefficients was done using the formula:

$$Cd = (2F)/(\rho U^2 A) \qquad \text{(Eq. 2)}$$

where F is the force in Newtons, ρ is the water density, U is the flume speed, and A is the frontal area in flow (calculated using ImageJ software).

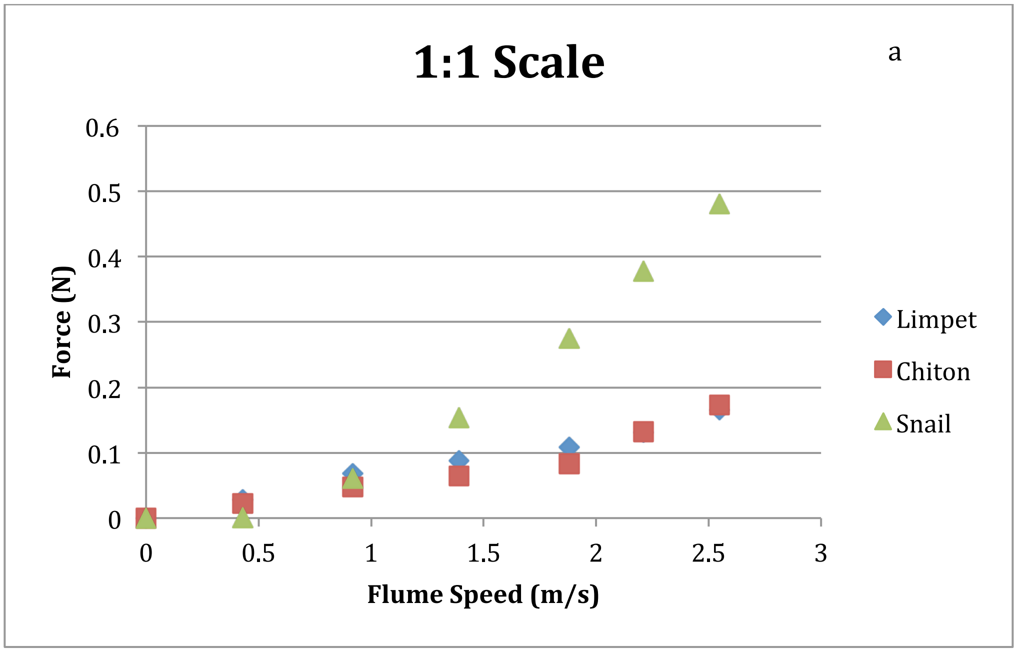
Results:

Frontal area in flow was highest in the snail body shape for both size models (Table 1). In the 1:1 scale models the limpet had the second largest area, and the chiton the least. This changes in the 2.5:1 models as the chiton has a slightly larger area than the limpet.

Table 1. Table showing the frontal area projection, A, of the limpet (*Lottia pelta*), chiton (*Tonicella lineata.*), and snail (*Calliostoma ligatum*) in both scale models.

Organism	Scale	A (m^2)
Limpet	1:1	1.27×10^{-4}
	2.5:1	5.36×10^{-4}
Chiton	1:1	1.03×10^{-4}
	2.5:1	5.62×10^{-4}
Snail	1:1	1.35×10^{-4}
	2.5:1	7.49×10^{-4}

Drag forces acting on both the 1:1 and the 2.5:1 scale models increased with increasing flume velocity (Fig. 3). The snail, in both scales, yielded the highest drag forces compared to the chiton and limpet. With increasing flume speed the chiton and limpet experienced very similar drag forces. In the largest models (2.5:1 scale) at the highest velocities (approximately 2.5 m/s) the chiton experienced almost double the drag force of the limpet.



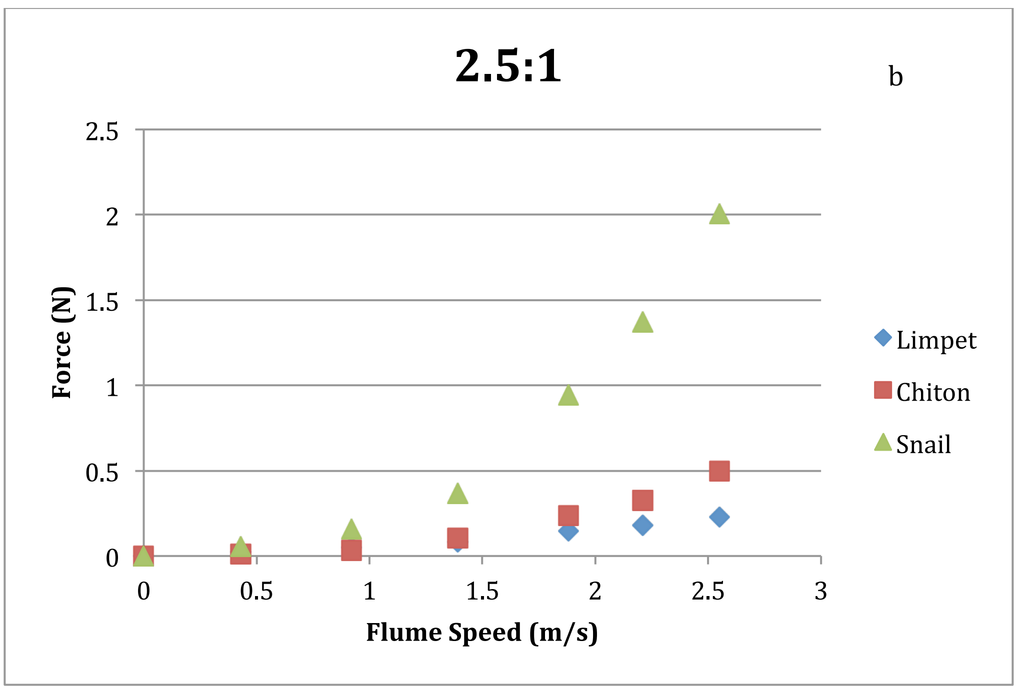
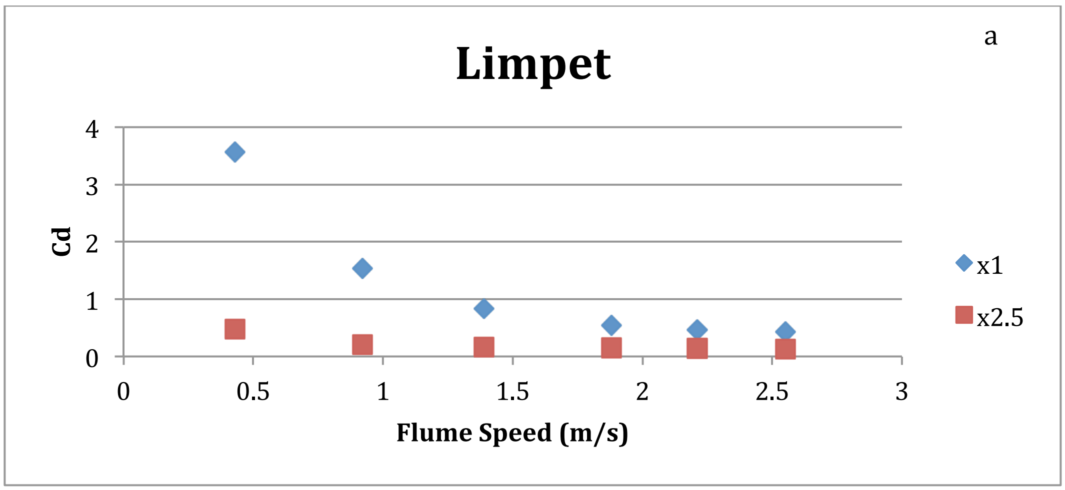
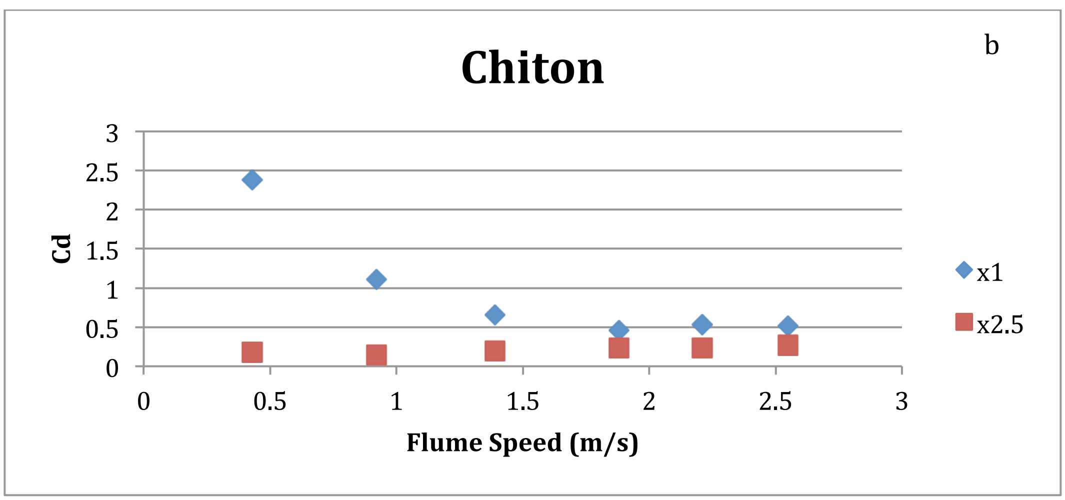


Figure 3. Plot showing flume speed (m/s) v. drag force (N) for (a) the 1:1 scale models of the organisms and (b) the 2.5:1 scale organisms.

Drag coefficients for the 1:1 scale limpet and chiton decreased with increasing flume speed (Fig. 4a,b), however the drag coefficient for the 1:1 snail increased until approximately 1.5 m/s, at which point it began to slowly decrease (Fig. 4c). Contrast with the 2.5 scale models, which were significantly lower in the chiton and limpet. The larger snail model initially had the higher drag coefficient, however at around 0.75 m/s the 1:1 scale model's drag coefficient becomes greater than the larger model.





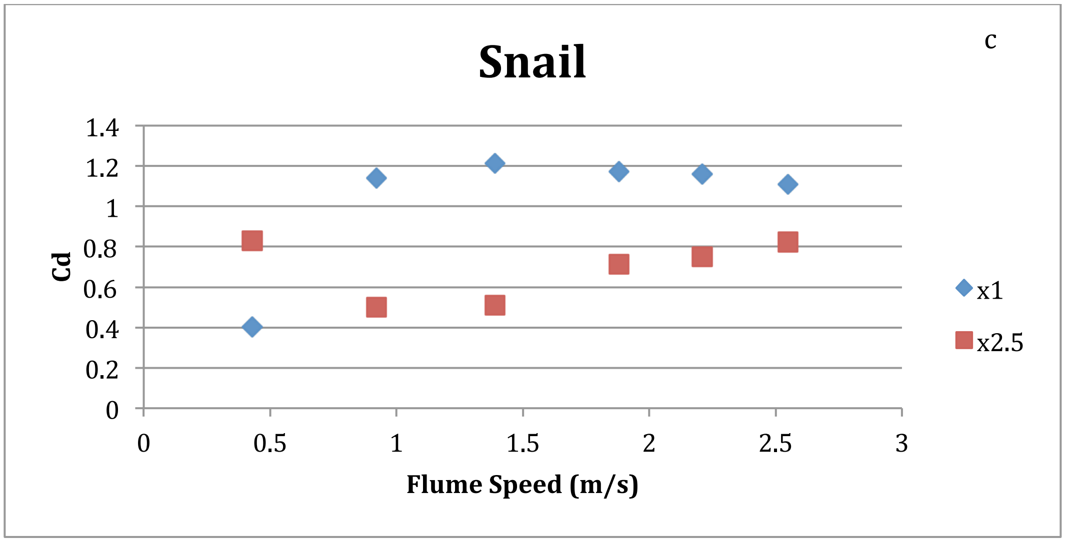


Figure 4. Plots of flume speed (m/s) vs. Drag Coefficient for a) the limpet species *Lottia pelta*, b) the chiton species *Tonicella lineata* and c) the snail specie *Calliostoma ligatum.*

When Drag coefficient is plotted against Reynolds number the drag coefficient of the limpet steadily decreases with increasing Reynolds number, for both the 1:1 and 2.5:1 scale models (Fig. 5a). The chiton, similarly to the limpet, had very high drag coefficients at low Reynolds number, but quickly decreased with increasing Reynolds number. The 2.5:1 scale model of the chiton extended to a much higher Reynolds number than the 1:1 scale model, slightly increasing drag coefficient with increasing Re (Fig. 5b). The drag coefficient of the snail, initially, was the lowest of the 1:1 scale models (Cd = 0.4, Fig. 3c). However, with increasing Re the drag coefficient more than doubled, reaching a maximum around a Re of $2.5x10^4$, before declining again. In contrast, The 2.5:1 scale snail model had the highest drag coefficient at the lowest Re number, and decreased with increasing Re number until approximately $5.0x10^4$ Re, at which point it the drag coefficient increased with increasing Re number (Fig. 5c).

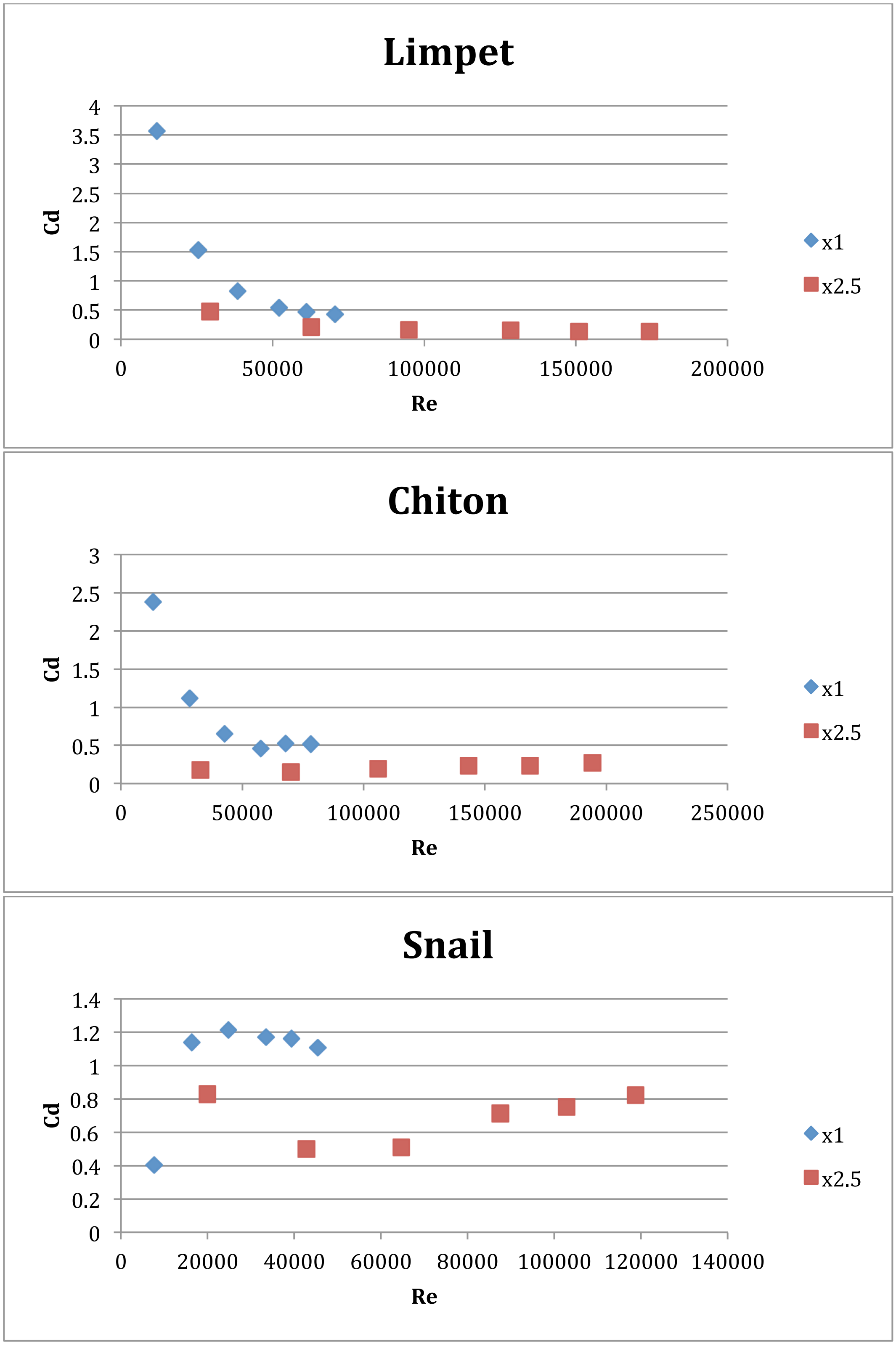


Figure 5. Plots of Reynolds number (x-axis) vs. Drag Coefficient (Y-axis) for a) the limpet species *Lottia pelta*, b) the chiton species *Tonicella lineata.* And c) the snail specie *Calliostoma ligatum.*

Discussion:

The 2.5:1 scale models all experienced higher drag forces than the smaller 1:1 scale counterparts, which is most likely a combination of larger volume (Koehl 1982) and greater frontal projection area (Ditsche and Summers, in press). The increasing force observed in the snail and chiton on Figure 3 follows an exponential pattern, which is was expected as the form drag is proportional to the square of flow velocity (Ditsche and Summers, in press). Contrast with the limpet, which does not appear to increase in drag force exponentially with increasing flow velocity like the snail and chiton body shapes. The two different size scale models also do not seem to experience drag in different patterns, as both the snail and chiton increase exponentially while the limpet increases what appears to be linearly in both scale sizes. The snail by far experiences the highest drag force overall, likely due to the larger frontal projection area (Table 1).

Drag coefficients for the 1:1 scale chiton and limpet both started drastically high, approximately 2.5 and 3.5 respectively, and were quickly reduced and level off around a flume speed of 1.5 m/s (Figure 4a,b). The 1:1 scale snail, however, followed an opposite curve. This drastic difference in drag coefficients between the snail and the limpet and chiton could be the result of the limpet and chiton experiencing very high drag forces that are not in proportion to the flow velocity, yielding a very high initial drag coefficient (Eq. 2). Given that these high drag coefficients occur at relatively low flume velocities, it is debatable whether skin drag or pressure drag is the dominating drag force. The 2.5:1 scale models are varied in how the drag coefficient changed with flume speed compared to their 1:1 scale counterparts. However, when drag coefficient plotted against flume speed for the 2.5:1 scale models is compared to that of the 1:1 scale models and interesting pattern emerges. Despite the observed differences in drag coefficients at low flow velocities, at higher flow velocities drag coefficients appear to converge on a specific value, 0.4 for the limpet and chiton and 1.0 for the snail. This is an interesting result, as it suggests that at higher flow speeds the size/scale of the body shape becomes unrelated to the drag coefficient.

When drag coefficients are compared to Reynolds numbers it is easier to visualize what drag coefficients might be like for the 1:1 scale models in higher flow velocities. The 2.5:1 models of the limpet and chiton both have little variance with increasing Reynolds number. The drag coefficients observed are in line with previous studies on drag forces of *L. pelta* at similar Reynolds numbers (Denny 1989). It is likely that there is a greater change in drag coefficients for the chiton and limpet at lower Reynolds number, as the 1:1 scale models show the biggest changes and the 2.5:1 models show almost no change (Fig. 5a,b). The snail model shows a very interesting pattern in drag coefficients when plotted along Reynolds number. Although there is a considerable gap between the two different size models, which is not seen as drastically in the other two species, both plots from the 1:1 and 2.5:1 scale models begin to decrease starting at approximately Re = 20,000 and continue to decrease until about Re = 40,000. Because both models begin to decrease at similar points it could mean that the plot of the 2.5:1 scale model is an accurate representation of the drag coefficients experienced by the snail body shape at higher Reynolds numbers (Fig. 5c).

The higher drag forces experienced by these body shapes at higher flow velocities pose serious risks to their real life benthic counterparts. The snail being the most heavily affected by drag forces is at the greatest risk for dislodgment via hydrodynamic forces, which could affect foraging time and efficiency (Etter 1995). Previous literature has shown that snails, however, can combat these threats by either changing their morphology to be more streamline or to seek shelter during times of high wave energy (Denny 2006). The limpet and chiton have been shown to be less likely to be dislodged via drag forces compared to snail. Possible explanations for this are the natural low profiles of the chiton and limpet body shape, which could reduce the size of the turbulent wake and thus the pressure drag force. Limpets have been shown to adapt the shape of their shell based on the wave energy present in the environment they grew in. It is possible that the sample specimen used for the limpet model grew in a high wave action environment and is better suited for coping with larger hydrodynamic forces, which could explain some of the lower drag forces experienced by my models (Fig. 3). Although this low profile streamline shape may reduce drag forces, it may cause the limpet shell to be more susceptible to other drag forces, as it has been shown that limpets are more likely to be dislodged via lift forces than drag forces (Denny 2006).

Body shape and scale play a major role the drag forces experienced by the model organism. Certain body shapes like the limpet appear to obtain lower and lower drag coefficients with increasing flow velocity, while the snail experiences a wide variety. By scaling organisms to larger sizes to achieve higher Reynolds number, insights can be made to the flow forces affecting normally scaled organisms in high flow environments. Similar experiments performed in the future should include: higher flume speeds to test the convergence of drag coefficients across differently scaled models, more scaled models to achieve higher and lower Reynolds numbers to observe change in drag coefficients.

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