Capillary-Inertial Colloidal Catapult Powered by Surface Energy

by

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Thesis submitted in partial fulfillment of
the requirements for the degree of
Master of Science in the Department of
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ABSTRACT

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Abstract

To discharge micron-sized particles such as colloidal contaminants and biological spores, an enormous power density is needed to compete against the strong adhesive forces between the small particles and the supporting surface as well as the significant air friction exerted on the particles. These thesis deals with colloidal catapults that achieve such a high power density by extracting surface energy released upon drop coalescence within an extremely short time period, which is governed by the capillary-inertial process converting the released surface energy into the bulk inertia of the merged drop.

In our model system, two symmetric drops coalesce on top of a spherical particle, the resulting capillary-inertial oscillation is perturbed by the solid particle, giving rise to a net momentum eventually propelling the particle to launch from the supporting surface. Liquid drops of nearly identical size are inkjet-printed to initiate the symmetric coalescence on a colloidal particle, and the resulting launching velocity of the particle-drop complex is measured. The measured launching velocity follows a scaling law that accounts for the redistribution of the momentum of the merged drop onto the particle-drop complex, and is therefore proportional to the capillary-inertial velocity characterizing the coalescing drops.
The physical insights from our model system are applicable to other colloidal catapults using capillary-inertial flow to carry payloads. The first system is relevant to self-cleaning of colloidal contaminants, where particles are removed upon exposure to vapor by two condensate drops growing and eventually coalescing on the particle. The second system closely mimics a ballistospore discharge system, in which a spherical condensate drop (the Buller’s drop) coalesces with the adaxial drop on a flattened particle (the wetted fungal spore), and the coalescence releases enough surface energy to propel the particle to launch from the supporting substrate. Compared to the model system with symmetric drop coalescence on a spherical particle, which is also relevant to self-cleaning, the ballistospore-mimicking catapult with asymmetric coalescence on a flattened particle is more effective in generating momentum toward the self-propelled launching.
Dedication

To my best friend, Kuzco. You will forever be in my heart.
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1. Introduction

In order to discharge micron-sized particles, such as colloidal contaminants and fungal spores, a large amount of energy needs to be released in order to combat the adhesive forces of the surface. When two liquid drops merge together on a superhydrophobic surface, enough surface energy is released to propel the droplets upward and off the surface (Boreyko, 2009). This is due to the impingement of the liquid bridge during coalescence upon the surface (Boreyko, 2009, Boreyko, 2010). It is known that the jumping momentum is enough to propel the merged drop off the surface, but the problem that’s faced is whether or not the coalescence of two drops is enough to propel a payload off the surface as well. If so, there must exist a relation between the mass that can be carried away from the surface and the amount of surface energy released. When the surface isn’t superhydrophobic, there is still an impingement and an overall upwards momentum from the two coalescing droplets. Here, it is shown that this upward momentum is sometimes enough to detach a colloidal particle from a surface or a fungal ballistospore from its sterigma.

The process of spore launching from basidiomycete fungi has been studied and viewed, (Webster 1984, Pringle 2005, Noblin 2009) however, attempts to simulate and replicate the launching process remain scarce. For engineering applications, understanding the mechanism and efficiency of such miniscule systems can prove very
beneficial. This paves the way for controlled studies of fungi discharge, critical for areas such as weather cycles and crop diseases. The two mechanisms of particle removal in this work also can be applied to develop self-cleaning surfaces that do not necessarily need to be superhydrophobic.

There are over 30,000 species of fungi that discharge ballistospores (Pringle 2005). Ballistospores are the reproduction mechanism for many fungal species. They are discharged from the sterigma once a spherical drop of water, also known as Buller’s drop, coalesces with another drop on the adaxial side of the ballistospore. (Fig. 1) Naturally, this occurs under condensation during periods of high humidity. The discharge acceleration of ballistospores has been measured to be over 10,000 g’s (Pringle 2005). Once the Buller’s drop reaches a critical radius by means of condensation, it coalesces with the adaxial drop, and the momentum carries the projectile away from the sterigma. The goal of the spore would is to

![Figure 1: Ballistospore components and an image sequence of a launching ballistospore.](image)
discharge with a large enough velocity to exit the velocity boundary layer. Once it exits this velocity boundary layer, it is able to be carried away by wind or rain, and the fungus can reproduce. However, the underlying physical mechanism remains elusive due to its miniscule size.

In order to employ a scaling argument, we make use of the capillary-inertial velocity $u_{ci}$:

$$u_{ci} = \sqrt{\frac{\sigma}{\rho_l r_B}}$$  \hspace{1cm} (1.1)

where, $\sigma$ is the surface tension, $\rho_l$ is the density of the liquid, and $r_B$ is the radius of the Buller’s drop. This capillary-inertial velocity will take into account the different sizes of Buller’s drops, which we will visit later.

Consider two similar-sized drops on a flat plate with a contact angle of $90^\circ$. When they coalesce, the contact angle remains the same, but the surface area is reduced by about 21% by performing a mass conservation analysis. This excess surface energy is converted into kinetic energy, promoting the lifting of the particle from the surface. The particle prohibits the coalescence from expanding downward in the vertical direction, and thus, creates a force onto the particle, which is transmitted to the surface.

Although it would be useful to measure actual ballistospore discharges with a high-speed camera, it is out of the scope of this project. Instead, a model system was
introduced in order to measure the effect of the initial jumping velocity from the surface in relation to the payload that the merged droplet is carrying. This system uses large hydrophobic micron-sized spherical particles with two equal-sized “Buller’s” drops resting upon the particle. Once these drops coalesce, the particle detaches from the surface, similar to the ballistospore. We will refer to this system, shown in Figure 2, as the “colloidal catapult” for the remainder of this paper. A second system with geometry close to the ballistospore’s was created in the lab and compared to the colloidal catapult. The mechanism of ballistospore discharge was revealed by modeling a micron-sized system after a ballistospore. In this way, we can view the coalescence of the Buller’s drop and the adaxial drop at high speeds, as well as track the velocity and position of
the entire projectile. Very specific conditions have to be met for the experimental ballistospore to jump from the surface. An example is the superhydrophobic surface used as the substrate and a hydrophilic particle being used. The velocity measurements of the experimental ballistospore were compared to actual ballistospore data. The main focus of this thesis is the colloidal catapult, because the experiments were easily reproducible and had simple geometry. The case of the experimental ballistospore is more difficult to reproduce, however, it has implications about the nature of coalescence of actual ballistospores because of the close geometry to that of a ballistospore.

The reason for two systems is to compare different colloidal catapult mechanisms for velocity, and subsequently, efficiency. Using a numerical simulation detailing the interfacial fluid dynamics, the conversion of capillary pressure into upward momentum was also modeled. The 2-D and 3-D models, which were performed by Fangjie Liu, are discussed later in this work.

In this thesis, we will first discuss the experimental methods employed to create the colloidal catapult and the experimental ballistospore jumping mechanisms. Next, we will analyze the conversion of surface energy to kinetic energy via the launching velocity of each system in conjunction with scaling laws and compare the results of the efficiency of each system. Finally, we will compare the mode shapes of coalescence of
droplets on the colloidal catapult and experimental ballistospore with the interfacial fluid dynamics flow simulations.
2. Methods

The colloidal catapult experiment required two water droplets on top of a spherical particle to coalesce and launch the particle off the surface. The particles used were 150µm radius polystyrene particles (Grinding Media Depot, Product ID: SCHNOR 2040). The particles were placed on silicon surface and a 20µm nozzle diameter inkjet printer from MicroFab Technologies Inc. (Product ID: MJ-AL-01-20-8MX) dispensed pure de-ionized water droplets onto the particle. The contact angle between water and polystyrene is about 87⁰ (Li 2007). Once the first droplet grew to a certain size, the particle and surface were moved horizontally, using an XYZ stage, and another droplet was printed. The printing alternated between drops when printing. This was done for two reasons: It kept the particle from tipping over because of a large shift in the center of mass, and so the droplets would coalesce at relatively the same size. Once the growing droplet came into contact with the adjacent droplet, they coalesced and the drops and particle detached from the surface. The goal of each case was to have as symmetric of coalescence as possible. This means that the drops needed to be roughly the same size and at the same height on the particle. If a particle had coalescing drops on top that had a high variation from each other, the particle would be more susceptible to rotation and the velocity measurements would be accurate, but some of the energy would be converted into rotational energy, which is unwanted for this experiment.
Figure 3: Schematic of colloidal catapult experiment just before coalescence of drops.

The jumping process was captured with a high-speed camera (Phantom V10) with a long distance K2 microscope attached. The frame rate for these videos was 10,000 and 20,000 frames per second with an exposure time of 24.5µs. The frequency of droplets exiting the inkjet nozzle ranged from 60 to 700 Hz. This was controlled by a function generator (Agilent 33220A 20MHz). The function generator was connected to a high-voltage amplifier (AA lab systems Model # A-301 HS HV Amplifier), which, in turn, was connected to the inkjet printer. The waveform used was a square waveform with a rise and fall time of 5µs. This was recommended by the inkjet printer manufacturer and optimized in the lab. The jumping particle videos were analyzed using ImageJ software.
3. Results

3.1 Launching Process

A representative case of spherical colloidal catapult jumping is shown in Figure 4. The mode shapes of coalescence of the droplets are shown. Once they began to coalesce, the high surface tension of water (72mN/m) quickly pulled them together and a force transmitted to the particle. This force transmitted to the surface, and drove the particle to jump from the surface.

Figure 4: Image sequence showing coalescing and jumping process of colloidal catapult.

In this image sequence, the polystyrene particle is roughly 350 µm in radius. The jumping process is similar in shape for all sizes of particles in the colloidal catapult experiments in this thesis. The coalescence is almost symmetric. A symmetric coalescence will prompt the particle to jump mostly straight up with little rotation. This is desirable in order to more easily compare the particles’ energy conversion and not take into account rotation. Also, if the velocity is high in the x-direction, the velocity is
difficult to analyze because that means there must exist a frictional force between the substrate and the particle due to the single contact point on the sphere. The symmetry of coalescence has to do with a few factors: the variation in droplet sizes, the positioning of the particles on the particle, and the surface wettability on the particle. The projectile decelerates in the air due to the drag and gravity forces. Once the particle departs from the surface, the coalesced droplet is still oscillating. This oscillation continues until the viscous dissipation completely eradicates it.

3.2 Velocity Measurements

Figure 5 shows a distance versus time graph showing the in-plane distance of the entire projectile for the jumping process of the particle. The distance was measured using ImageJ using a threshold brightness level. The software tracked the movement of the figure and a velocity was extracted. The oscillation of the coalescing droplets is somewhat apparent because of the oscillation of the early data points in the measurement. The drops are oscillating in and out of the plane, and the camera is only able to capture one direction of the oscillation. The initial velocity is extracted from each case by accounting for gravity and averaging the slope of distance versus time using a trendline. The drag of the projectile is negligible in these cases. This is because the
Stoke’s drag acting on the projectile is roughly an order of magnitude smaller than the gravity force acting on the particle.

Figure 5: Velocity measurement of a typical colloidal catapult projectile.

Figure 5 shows a representative velocity measurement of the jumping distance of polystyrene particles on a silicon surface. The total y distance is taken as modified y distance without the effect of gravity. The modified y distance is calculated as follows:

$$y_{mod} = y_{dist} + \frac{1}{2} gt^2$$

This equation accounts for the loss in vertical distance due to gravity. The reason for this is so that we have a linear trend that we can get a slope for, which translates to the initial velocity of the projectile. The reason we don’t take into account the x and z dimension velocity is because only one camera is being used to capture the experiment,
and because the origin of the force creating movement in either direction is likely due to a friction force, which is unknown. As noted before, we don’t take into account the drag on the projectile. You can notice the oscillation of the merged droplet in the early stages of launching, but after about 0.5 milli-seconds, the oscillation is terminated due to viscous dissipation.

In order to conserve momentum, the argument exists between the droplets and the entire projectile, not accounting for losses:

\[
V = \frac{(m_{d1} + m_{d2})V_d}{m_{d1} + m_{d2} + m_p}
\]  \hspace{1cm} (3.2)

where: \( V \) = initial velocity of projectile
\( m_{d1} \) = mass of the first drop
\( m_{d2} \) = mass of the second drop
\( m_p \) = mass of the particle
\( V_d \) = velocity of the droplets

If we divide this equation by \( u_{ci} \) then we will effectively non-dimensionalize the equation and have:

\[
\frac{V}{u_{ci}} = \frac{(m_{d1} + m_{d2})V_d}{(m_{d1} + m_{d2} + m_p)u_{ci}}
\]  \hspace{1cm} (3.3)

To simplify, we use the dimensionless variables:

\[
V^* = \frac{V}{u_{ci}} \quad \text{and} \quad m^* = \frac{(m_{d1} + m_{d2})}{(m_{d1} + m_{d2} + m_p)}
\]  \hspace{1cm} (3.4)
If \( \frac{V_d}{u_{ci}} \) remains constant for the system, we get:

\[
V^* \propto m^*
\]  (3.5)

Figure 6: Dimensionless plot of colloidal catapult experiments on a silicon substrate.

The overall scaling argument of the colloidal catapult experiments using 150µm radius polystyrene particles and a silicon substrate is shown in Figure 6. The relation between \( V^* \) and \( m^* \) are indeed proportional. The model is not perfect, however. In actual experiments, the trendline wouldn’t cross through the origin. This is because small droplets that coalesce don’t produce enough force to lift the particle off the
surface. The actual cutoff regime would lie on the positive x-axis somewhere around 0.05 for this experiment. However, the trendline is forced through the origin to show the proportionality between $V^*$ and $m^*$, which is still close to the data points, as seen by the $R^2$ value. These dimensionless variables are used to show how efficient the system is in converting surface energy to translational momentum. The linear scaling argument follows a consistent upward trend. The higher the slope, the larger the velocity the same $m^*$ has.

Another thing to note in this graph is the consistency of the data. The $R^2$ value of the linear trend is 0.92, which indicates a close match with the data. It will be shown later in the condensation experiments that it is very difficult to achieve a consistent measurement for the colloidal catapult. The reason we believe this is so consistent is the size of the experiment as well as the relatively well-controlled setup. The inkjet printer ensures the drops are placed directly on the particle, and not on the substrate. Also, the silicon surface is anatomically smooth, enabling a consistent contact area with the particle as well as a low van-der-waals force.
3.3 Comparison to Model

A two-dimensional interfacial flow simulation was done to verify the mode shapes of the coalescing droplet. The contact angle used in the simulation was 90°, which is close to the value for water on polystyrene.

Figure 7: 3-D colloidal catapult experiment compared to a 2-D interfacial flow dynamics simulation.

Figure 7 shows the profile of the coalescence of two water droplets on a polystyrene particle. The non-dimensional time $t^*$ that was used to compare the experiment to the model is:
\[ t^* = \frac{t}{\sqrt{\frac{\rho_l r_B^3}{\sigma}}} \]  

(3.6)

Where: 
- \( t \) = time
- \( \rho_l \) = density of the liquid
- \( r_B \) = radius of the droplet
- \( \sigma \) = surface tension of the liquid

A quantitative comparison between the two would hold no significance because of the two versus three-dimensional setups. For the two dimensional simulation, mass is conserved in two dimensions, therefore the droplets oscillate at a different frequency and mode shape due to the drop’s inability to extend into the third dimension. In the experimental case, the mass is conserved in all 3 dimensions. The third dimension we are unable to view, and this is the reason for the discrepancy between simulation and experiment. Another possible reason for discrepancy is the pinning of the triple contact line. In the simulation, the contact line remains pinned. However, in the experiment, it may be possible for the contact line to move slightly. The profile of the coalescence, however, closely matches in both cases.
4. Applications

There are a few applications of such a colloidal catapult system. The first application is in self-cleaning. In nature, many surfaces are known to clean themselves in the presence of condensation, such as insect wings and lotus leaves. Here, we show how the colloidal catapult is a mechanism for self-cleaning. Shown in the appendix is another related self-cleaning mechanism using aggregated particles. The second application covered is related to the discharge of fungal ballistospores, in which two drops coalesce to launch the spore from the sterigma.

4.1 Self-Cleaning

On a superhydrophobic surface, particles can be easily cleaned from the surface by jumping drops, lifting drops, or aggregating particles (Wisdom 2012). Though this colloidal catapult system has not been confirmed to work on a superhydrophobic surface, it is trivial to substitute the underlying silicon surface for a superhydrophobic surface and perform the same experiment. During periods of high humidity, superhydrophobic surfaces, such as a lotus leaf, accumulate water. Once large enough droplets coalesce, they may jump off the superhydrophobic surface, or just roll off due to gravity. These moving drops carry colloidal contaminants with it, providing a self-
cleaning mechanism (Barthlott 1997). However, it is a little more difficult to self-clean if the surface is not superhydrophobic.

In the following experiment, silanized glass particles (Cospheric, Product Ids: P2043SL-S2-2.5 and P2075SL-2.5) were placed on a hydrophobic surface (contact angle \( 90^\circ < \theta < 180^\circ \)) of Teflon. When the glass was treated with an octadecyltrichlorosilane surface chemistry, the contact angle jumped to about 102°. The particles that were used for this experiment had a radius of anywhere from 20µm to 40µm. The experimental setup is shown in Figure 8. As water is heated up in the superhydrophilic copper wick surface, it evaporates and condenses on the cooler Teflon surface. With particles located on the Teflon surface, the water will routinely condense on top of the hydrophobic particles as well. The condensation period would usually last only a few seconds before the particles jump from the surface. Three or more droplets would routinely coalesce on top of the particle, however I only analyzed cases that only had two droplets. Also, sometimes the drops coalesced with droplets on the surface, which introduced a capillary force between the particle and the surface, and therefore, the particle can no longer jump due to coalescing drops.
Figure 8: Experimental setup of colloidal catapult experiment using condensation as the source for coalescing drops.

The jumping process of the colloidal catapult under condensation was captured, as shown in Figure 9.

Figure 9: Image sequence showing colloidal catapult under condensation.

The image sequence was taken at 15,037 frames per second. Each frame is 66µs apart. The particle and droplet seem to rotate when jumping upon coalescence. This is likely due to the asymmetry of the coalescence. There are other smaller drops located on the particle that may offset the center of mass of the particle. For a smaller colloidal catapult system, the coalescence and profile follow the same scaling laws, however they coalesce
at a faster velocity due to the miniscule size. The colloidal catapult experiments under condensation were analyzed, and the results are shown in Figure 10.

![Figure 10: Dimensionless plot of colloidal catapult experiment under condensation on Teflon](image)

Figure 10 shows the same V* and m* for particles with a 20µm and 35µm radius. There is a very large scattering of data in this plot. This is likely due to the inconsistency in the attachment force of particle to teflon. The teflon is not anatomically smooth, like the silicon wafer. In addition, the condensate can nucleate between the teflon surface and the particle, which would introduce a capillary force that could greatly alter the attachment depending on the size of liquid bridge between the particle and surface.
There is also a larger likelihood that there may have been three or more coalescing droplets in these cases. However, this is not known because the camera is only pointed at one face of the coalescing droplets. The two coalescing drops are not always the same exact size due to the uncontrollability of condensation on the particle. This leads to a higher chance of asymmetry and possibility of rotation instead of translation of the particle. The translation of the projectile was the only thing measured in these experiments.

This colloidal catapult mechanism is possible on superhydrophobic surfaces found in nature, however not a likely occurrence due to the prevalence of jumping drops that are more likely to disrupt the process. On a hydrophobic surface in nature it is more likely to happen due to the lack of jumping drops. On a hydrophilic surface, however, a thin film of liquid will most likely spread on the surface when undergoing condensation. This thin film will attach to the particle and prohibit the contaminant from jumping due to the large force of capillary action.

4.2 Ballistospore Launching

Another experiment was performed in the lab mimicking the launching process of a ballistospore. This was done using large particles and an inkjet printer. For the ballistospore reproduction experiment, two drops coalesced on a hemispherical particle
to achieve launching. Similar to the ballistospore one drop rested on the adaxial side of
the hemispherical particle. This drop coalesced with another drop growing on the
superhydrophobic surface. This growing drop is akin to the Buller’s drop on a
ballistospore. The liquid drops were inkjet-printed onto the particle and
superhydrophobic copper surface created in the lab. The hemispherical particles used
were polystyrene, with an average radius of 150 µm (Grinding Media Depot). These
particles were cut into hemispheres by use of a thin razorblade. The particles were
placed in an oxygen plasma asher (Emitech K-1050X) for 2 minutes at 100W to render
them hydrophilic. The particles were placed on a superhydrophobic copper surface and
then were rotated to partially stand up, similar to the orientation of a ballistospore. The
setup schematic can be seen in Figure 11.

![Figure 11: Experimental setup of ballistospore replication.](image)
Copper was placed in an oxidation solution to create nano-roughness, and subsequently silanized using a fluorinated silane to make the substrate superhydrophobic. The liquid used was a 30%(v) solution of ethanol in water. This was used because if pure water was used, the inkjet printer dispensed the drops at a high enough velocity where they would bounce off the superhydrophobic surface. The surface tension reduced to 36 mN/m, from 72mN/m of pure water. The adaxial drop was then printed onto the flat surface of the particle. Shortly after, the substrate was moved horizontally, using an XYZ stage to print the Buller’s drop. Once the drop grew to a critical size, it coalesced with the adaxial drop, promoting the jumping of the particle from the surface. The frame rate was 10,000 frames per second with an exposure time of 7µs.

An image sequence of the jumping process is shown in Figure 12. As the Buller’s drop grows to a critical size, the drop coalesces with the adaxial drop, and the upward momentum propels the projectile off the surface. Because of the miniscule size of the ballistospore (10µm), the process is not able to be replicated using an inkjet printer. The smallest nozzle available to use is a 10µm diameter nozzle, which would impinge the particle at a high velocity, causing the particle to become encapsulate by it. This size is the most controllable that is available in our lab.
Figure 12: Image sequence showing coalescence of Buller’s drop to adaxial drop and the jumping action in the experimental ballistospore.

Figure 13 shows the scaling relation between $V^*$ and $m^*$ for the three experimental ballistospore data points and two actual ballistospore species measured in Noblin, 2009. In the case of the ballistospore, $m^*$ is the mass of the Buller’s drop divided by the entire mass of the projectile. This is because the Buller’s drop is the “active” drop. This means that the Buller’s drop is actively coalescing into the adaxial drop, instead of an equal contribution, like that of the colloidal catapult. The adaxial drop can be thought of as part of the wettable spore. Figure 13 shows a close relation between the experimental ballistospore and actual ballistospore data. The trend line has a slope of 1. This is very interesting because it suggests that the velocity of the projectile directly correlates with the size of Buller’s drop in relation to the spore size. Of course, the ballistospore can’t be modeled exactly due to the existence of the sterigma, which is what keeps it in place before the coalescence of drops.
Figure 13: Dimensionless plot comparing the experimental ballistospore to actual ballistospore data.
Figure 14: A) 3-D simulation performed coalescing a spherical drop with a drop on a flat surface. B) Velocity field of coalescence. The large arrow shows 1 unit of capillary-inertial velocity at $t^*=0$. (Both courtesy of Fangjie Liu)

Figure 14 shows a 3-D simulation of a ballistospore’s geometry, with the spore standing up. It was simulated as a spherical drop coalescing with a drop on a flat, hydrophilic surface. Over the course of the coalescence, you can see the upward momentum of the coalesced drops. This is enough to detach the spore from the
sterigma. The velocity field in B was shown to verify the upward capillary-inertial velocity at different non-dimensional times. At $t^* = 4.04$, the largest capillary-inertial force is produced, propelling the droplet upward at the largest momentum.

More experiments can be done to determine if in fact, this geometry is the most effective at producing a higher velocity based on the size of the drop and spore.
5. Conclusion

The two systems studied have many similarities, including the ability to jump from non-superhydrophobic surfaces. The entire plot showing the results from both experiments is shown in Figure 15.

![Figure 15: Dimensionless plot of colloidal catapult data on silicon, ballistospore data, and experimental ballistospore data (Noblin et al, 2009).]

When plotted on the same graph, it is easily discernable which system is more efficient at removing particles from the surface. The geometry of the ballistospore allows for a higher transfer of momentum from a spherical drop to a flat drop, when the
orientation is directed upward. In the case of the colloidal catapult, the momentum still translates upward, but two coalescing drops also translate momentum in the horizontal direction perpendicular to the direction of drop coalescence. The capillary-inertial velocity of the coalescence in this direction is dissipated by viscous effects. If the colloidal catapult condensation data were to be added to this plot, the scattering would envelop the colloidal catapult data already on the graph. Thus, the colloidal catapult system is represented by just the inkjet printed data in Figure 15.

Showing and quantifying the mechanism of colloidal catapult jumping has been helpful in understanding how jumping droplets can use their surface tension to carry a payload. This is a new mechanism of self-cleaning not previously shown. The measurements of the non-dimensional jumping velocity versus mass ratio help us to quantify the efficiency of the colloidal catapult. Different geometries exist, such as the ballistospore, that have taken advantage of a range of wettabilities to optimize its jumping velocity. There may exist a different geometry that may also take advantage of surface tension to be even more efficient at removing particles or contaminants from a surface.

It has been shown that two coalescing drops can not only jump from surfaces, but carry a payload with them. This paves the way for in-depth studies on other similar systems. The colloidal catapult’s launching mechanism isn’t as efficient at converting
surface energy to kinetic energy as the ballistospore. Every geometry and wettability will likely have a different scaling curve associated with it. Jumping has been viewed on colloidal catapults with a larger and smaller contact angle. The next logical step would be to measure the optimum contact angle for particle jumping. In self-cleaning systems, the contaminant is usually not a sphere, and the experiments in this thesis were used to model such a system. The colloidal catapult system and other self-cleaning mechanisms are not very controllable due to many factors including geometry, contact points with the surface, contact angle, and aggregation. Ballistospores are more easily modeled and reproduced than self-cleaning systems due to the homogeneity of spores. Measuring and interpreting colloidal systems such as these will help to make transparent the mechanism for self-cleaning on different surfaces as well as provide a better understanding of similar biological processes.
Appendix

In many self-cleaning surfaces, particles are not always standing alone. Many times there are multiple colloidal contaminants next to each other. These particles will aggregate in the presence of a liquid-vapor interface. The self-cleaning function of superhydrophobic surfaces is conventionally attributed to the removal of contaminating particles by impacting or rolling water droplets, implying the action of external forces such as gravity. In this appendix, a new self-cleaning mechanism is shown whereby the contaminated surface was exposed to condensing water vapor, and the contaminants were autonomously removed by the self-propelled jumping motion of the resulting liquid condensate, which partially covered or fully enclosed the contaminating particles. The jumping-condensate mechanism was shown to spontaneously clean both superhydrophobic and hydrophobic surfaces.

On superhydrophobic surfaces, there are three reported mechanisms by which particles are removed autonomously on the micro-scale: floating, lifting, and aggregation (Wisdom 2012). To study the mechanism of aggregation, 100µm-diameter silver-coated glass particles were placed in a row on superhydrophobic and hydrophobic surfaces. For simplicity and reproducibility of experiments, a spherical particle was used on a flat plate. Also, the particles were placed in only one direction to directly view the jumping mechanism. In order to remove these particles from the
surface by methods other than wind or vibration, which is common in natural self-cleaning surfaces, condensing water vapor was introduced. The aggregating mechanism discussed in this appendix happens when particles with a drop of liquid coalesce with an adjacent particle’s drop on top. The coalescence process was viewed with a high-speed camera (Phantom V.10) with a microscopic lens attached.

The experimental setup is the same as Figure 8, except there were multiple silver-coated glass particles lined up on a superhydrophobic surface using a razorblade. Figure 16 shows a jumping process of 3 particles.

![Image of particles coalescing](image)

**Figure 16:** Coalescence of two droplets on the two right particles triggered by a jumping drop shown only in the first frame.

When a drop jumps and lands between the two drops on top of the two particles on the right, the two drops coalesce and the particles aggregate. Due to the asymmetry of the particles and the coalescence, the particle on the right is lifted and spins the entire aggregation of particles into the air. The particles remain aggregated throughout the jumping motion due to the liquid bridge between each of them holding them together.
Figure 17: Coalescence of drops on silver-coated glass particles on Teflon.

Figure 17 shows a more symmetric coalescence with three particles jumping upon coalescence of the drops on top. The Teflon surface has a contact angle of about $110^\circ$ with water (Veeramasuneni 1997)(Chen 1999). This is not large enough for jumping drops to exist. This coalescence was due to the growing drops on top, and not due to any jumping drops. The drops grew as a result of condensation on the particle. When one of the two drops coalesced, the drops enlarged horizontally to coalesce the third droplet immediately. This caused the jumping motion to be almost symmetric. The two outer particles left the surface, allowing for the jumping force to be transmitted through the middle particle. As the surface area got smaller, the kinetic energy grew and propelled the particles from the surface. This jumping mechanism was also seen for two particles.
Bibliography


