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Capillarity-Driven
Droplet Ejection

by

Andrew Paul Wollman

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Mechanical Engineering

Thesis Committee:
Mark Weislogel, Chair
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Portland State University
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Abstract

Drop Towers provide brief terrestrial access to microgravity environments. When used for capillary fluidics research, a drop tower allows for unique control over an experiment's initial conditions, which enables, enhances, or otherwise improves the study of capillary phenomena at significantly larger length scales than can normally be achieved on the ground. This thesis provides a historical context for the introduction of a new, highly accessible, 2.1s tower design used for capillary research and presents a variety of demonstrative experimental results for purely capillarity-driven flows leading to bubble ingestion, sinking flows, multiphase flows, and droplet ejections. The focus of this thesis is paid to capillarity-driven droplet ejection including historical significance, mathematical models, criteria for ejection and experimental validation. A scale analysis provides a single parameter Su^+ which is used to predict the flow velocity at the base of the nozzle. By simplifying the flow in the nozzle we identify two criteria for auto-ejection, the nozzle must be 'short' and the velocity of the flow must be sufficient to invert the liquid meniscus and overpower surface tension at the nozzle tip such that $We^+ > 12$. Drop tower experiments are conducted and compared to analytical predictions using a regime map. This thesis also includes results from experiments conducted in a stationary ground-based laboratory and aboard the International Space Station which clearly demonstrate droplet ejection in regimes from transient liquid jets to large isolated drops. Droplets generated in a microgravity environment are 10^6 times larger than $1g_0$ counter-parts.

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Nomenclature

Latin Letters

A	cross-sectional area	m^2
A_n	cross-sectional area of nozzle exit	m^2
A_t	cross-sectional area of tube exit	m^2
$\mathbb{C}$	constant	
$\mathbb{D}$	time scale shift constant	
D_n	diameter of the nozzle	m
g	relative gravitational acceleration	m s^{-2}
g_0	acceleration due to Earth's gravity	m s^{-2}
K	imbibition or penetration constant, entrance region loss coefficient	$\text{m}^2 \text{s}^{-1}$
K_n	nozzle loss coefficient	
$\ddot{\ell}$	penetration acceleration	m s^{-2}
$\dot{\ell}$	penetration velocity	m s^{-1}
ℓ	imbibition or penetration length	m
ℓ^*	nondimensional penetration length	
ℓ_{Jurin}	Jurin length	m

L_1	tube submersion aspect ratio	
L_2	tube size aspect ratio	
L	length of tube and nozzle	m
L_0	submerged length	m
L_σ	capillary length	m
L_n	length of nozzle	m
L_s	length scale	m
L_t	length of tube	m
$W_t(t_t)$	nondimensional velocity at tube end	
n	unknown constant	
Q	flow rate	$\text{m}^3 \text{s}^{-1}$
Q_n	flow rate at nozzle exit	$\text{m}^3 \text{s}^{-1}$
Q_t	flow rate at tube exit	$\text{m}^3 \text{s}^{-1}$
R	radius	m
r	radial coordinate of cylindrical system	
R_f	radius of fluting	m
R_n	radius of nozzle exit	m
R_r	reservoir radius	m
R_t	radius of tube	m
R_t	tube radius	m
$s(t)$	surface reorientation time function	
t	time	s
t^*	nondimensional time	
t_μ	viscous time scale	s

t_r	resident time in nozzle	s
t_s	time scale	s
t_t	nondimensional time at tube end	
$\forall$	volume	m ³
V	characteristic velocity	m s ⁻¹
W	velocity scale in z -coordinate direction	
z	axial coordinate of cylindrical system	

Greek Letters

α	nozzle constriction aspect ratio	
ϕ_f	fluting aspect ratio	
μ	dynamic viscosity	kg m ⁻¹ s ⁻¹
ν	kinematic viscosity	m ² s ⁻¹
ρ	density	kg m ⁻³
σ	surface tension	kg s ⁻²
τ_r	reorientation time	s
θ	contact angle	
θ_d	dynamic contact angle	

Subscripts

c	container
d	dynamic

f	fluting
g	gap
n	variable pertaining to the nozzle exit region
s	scale
r	reorientation; reservoir, resident
t	variable pertaining to the tube exit region

Superscripts

$''$	second derivative with respect to time
$\cdot$	first derivative with respect to time
$+$	modified dimensionless quantity
$*$	nondimensional variable

Dimensionless Quantities

Bo	Bond number	$\frac{\rho g R^2}{\sigma}$	$\frac{\text{BUOYANCY}}{\text{SURFACE TENSION}}$
Bo ⁺	modified Bond number	$\frac{\rho g R L_s}{2\sigma}$	$\frac{\text{BUOYANCY}}{\text{SURFACE TENSION}}$
Ca ⁺	modified Capillary number	$\frac{\mu L_s^2}{\sigma R t_s}$	$\frac{\text{VISCOUS}}{\text{SURFACE TENSION}}$
Ca	Capillary number	$\frac{\mu V}{\sigma}$	$\frac{\text{VISCOUS}}{\text{SURFACE TENSION}}$
Re	Reynolds number	$\frac{LV}{\nu}$	$\frac{\text{INERTIA}}{\text{VISCOUS}}$
Su ⁺	modified Suratman Number	$\text{Su} \frac{\mathbb{D} R^2}{8 L_s^2} \cos \theta_d$	$\frac{\text{SURFACE TENSION}}{\text{DISSIPATION}}$

Su	Suratman Number	$\frac{\rho \sigma R}{\mu^2}$	$\frac{\text{SURFACE TENSION}}{\text{DISSIPATION}}$
We ⁺	modified Weber number	$\frac{\text{We}}{\alpha^3(1 + K_n)}$	$\frac{\text{INERTIA}}{\text{SURFACE TENSION}}$
We	Weber number	$\frac{\rho R V^2}{\sigma}$	$\frac{\text{INERTIA}}{\text{SURFACE TENSION}}$

Acronyms

AOI	area of interest
DDT	Dryden Drop Tower
DS	drag shield
DT	drop tower
ER	experiment rig
ESA	European Space Agency
FKA	Russian Federal Space Agency
GRC	Glenn Research Center
INTA	<i>Instituto Nacional de Técnica Aeroespacial</i> (Spain)
ISS	International Space Station
LEO	low Earth orbit
MGLAB	Micro-Gravity Laboratory of Japan
NAS	network area storage

NASA	National Aeronautics and Space Administration
NMLC	National Microgravity Laboratory (China)
PDMS	Polydimethylsiloxane
PF	parabolic flight
PSU	Portland State University
PTFE	Polytetrafluoroethylene
QUT	Queensland University of Technology (Australia)
RRS	release and recovery stage
SR	sounding rocket
ZARM	<i>Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation</i> (Germany)

Chapter 1

The Dryden Drop Tower

1.1 Microgravity

The terms ‘microgravity’, ‘compensated gravity’, and ‘low gravity’ all refer to environments where the impact of acceleration forces are weak. While gravity results from an object’s mass and therefore can never truly be ‘zero’, researchers can employ methods to study microgravity phenomena in gravity’s *apparent* absence through simulation, where the effects of sedimentation, buoyancy, and convection do not mask other more subtle forces.

Scientists and researchers are interested in studying low gravity phenomena as they occur in life science, material science, combustion, fluid science, and fundamental physics in order to gain new insights into their fields of study. For instance, life scientists are studying microgravity’s effect on cell biology [31, 81], bacteria [8], bone longevity [161], and motion sickness in fish [4, 5]. Material scientists study crystal growth [116, 143] and measure material properties more accurately [92] in the apparent absence of gravity. Researchers interested in combustion gain new insights by studying droplet combustion [83] and flame spread [132] in a weightless environment. Fluid mechanicians investigate a myriad of phenomena in a microgravity environment such

as fluid management in space [41,82,109,112,178], two phase flow [149,150,166], evaporation [108], heat transfer [32], boiling [118,142], thermocapillarity [175,182], soluto-capillarity [134], and other capillarity-driven flows [42,140,146].

1.2 Microgravity Simulation

In order to study such subtle phenomena, scientists and researchers simulate microgravity through neutral buoyancy [98], magnetic levitation [12], and freefall [106]. The freefall method is especially effective as it does not introduce additional body forces to counteract the force of gravity. When employing the freefall method, the microgravity environment is called a ‘near weightless’ or ‘freefall’ environment.

Freefall simulates microgravity by allowing the experiment to succumb to Earth’s gravity. Albert Einstein observed [106];

"I was sitting in a chair in the patent office at Bern when all of a sudden a thought occurred to me: ‘If a person falls freely, he will not feel his own weight.’ I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation."

In mathematical terms, an experiment’s actual weight on Earth is described by the equation $W_{\text{Earth}} = m_{\text{exp}} g_0$ where weight of the experiment equals its mass m_{exp} times Earth’s gravitational acceleration g_0 . If the experiment were freely falling, the equation $W_{\text{Earth}} = m_{\text{exp}} (a_{\text{exp}} - g_0)$ would describe the experiment’s apparent weight. In the absence of other forces such as air resistance, no reactionary force imposes on the experiment and it therefore ‘feels’ no effect of gravity.

Four major platforms have been developed to simulate microgravity environments via freefall: low Earth orbit (LEO) [113], sounding rockets [49], parabolic flight [88],

and drop towers [10]. A brief summary of the facilities' function, benefits, and limitations is described below. Figure 1.1 compares each platform's approximate quality and duration of microgravity.

Figure 1.1: Microgravity duration and quality for freefalling microgravity simulation facilities.

1.2.1 Low Earth Orbit

For long duration freefall, experiments are placed in low Earth orbit (LEO). There are two main categories: manned orbiting facilities such as the International Space Station (Pictured in Fig. 1.2), and unmanned satellites such as Foton (ESA) and Spektr (FKA) satellites. Experiments aboard the ISS can last up to months at a time. Experiments can be controlled via telemetry by researchers on Earth or be manually operated by astronauts on board. Experiment cost and development time are two limitations of this platform.

Figure 1.2: A photograph of the ISS in low Earth orbit. (Photo courtesy of NASA.)

1.2.2 Sounding Rockets

Sounding rockets are used to launch (Fig. 1.3) scientific payloads above the Earth's atmosphere where they can fall freely for up to 20 minutes [107]. While the payload does not enter orbit, the rocket provides enough push for the ballistic trajectory of the payload to experience several minutes of freefall. Provided rotational forces do not contaminate the experiment, sounding rockets provide a cost-effective and viable method for microgravity simulation despite often long experiment development lead time. Experiments are controlled via telemetry but on-the-fly adjustments to the experiment are limited to robotic operations.

Figure 1.3: Sounding rocket launch. Although you can see the parabolic arc of the first stage, note that the payload still has three more stages and will continue to rise farther into space where its final freefall will occur above the atmosphere. (Photo courtesy of Kolbjørn Blix Dahle kolbjorn@rocketrange.no)

1.2.3 Parabolic Flight

For lower costs and shorter lead times, experiments can be flown in ballistic trajectories aboard aircraft such as NASA's KC 135 or DC-9 pictured in Fig. 1.4, ESA's A300, or FKA's Ilyushin Il-76. In these facilities researchers accompany their experiment and make adjustments *in situ* if necessary. Simulated microgravity lasts for up to 25 seconds at a time with multiple parabolas a day. The atmospheric environment impacts the *g*-level. 'g-jitter' produced by aircraft vibration and center of gravity offsets also reduce the acceleration environment quality [169].

Figure 1.4: NASA's DC-9 in the downward portion of its ballistic trajectory. (Photo courtesy of NASA.)

1.2.4 Drop towers (DT)

The most accessible facilities for low cost access to low g environments are drop towers. Fig. 1.5 is a photograph of the 2.1 second Dryden Drop Tower at Portland State University. Despite their short durations, drop towers provide researchers with high quality microgravity with well-controlled initial conditions. Drop towers enable experiments to be repeated quickly and cheaply compared to other simulation methods. Because they are ground-based they also enable researchers to modify the experiment relatively quickly.

Figure 1.5: The DDT spans all 6 stories of the Northwest Center for Engineering, Science and Technology at the Maseeh College of Engineering and Computer Science Portland State University.

1.3 Drop Tower History

1.3.1 Historical Towers of Science

Towers have a rich history in scientific discovery. The first recorded instance of a tower being used for scientific inquiry occurred in 1568 when Simon Stevin of Bruges dropped two lead spheres of different mass from the New Church bell tower in Delft disproving Aristotle's theory that objects fall at a rate proportional to their mass [136]. While conventional wisdom holds that Galileo Galilei conducted the experiment off the bell tower of the cathedral in Pisa, Galilei did not arrive in Pisa until 3 years after Stevin conducted and published his results [168]. In 1781 William Watts, a plumber from Bristol England, invented a method for manufacturing shot by dripping molten lead in a tower [75]. During freefall the lead's surface tension forces would pull the lead into a spherical ball before solidifying into a hard, spherical shot ball. This method of production replaced the older, slower, and more expensive method of casting each ball individually. Watts' tower became the precursor to modern microgravity towers.

1.3.2 Microgravity Drop Towers

In 1957 Seichiro Kumagai and Hiroshi Isoda conducted the first drop experiment to study droplet combustion in freefall for 0.5s [83]. In 1959, NASA scientist Robert Siegel designed and built the US's first drop tower [142] and the first tower used to study space applications. Fig. 1.6 portrays Robert Siegel and his drop tower. Siegel conducted experiments on transient capillary rise in straight glass tubes [140] and boiling experiments [142] in an effort to quantify fluid and heat transfer phenomena in the weightless environment of space. Siegel's 'tower' provided less than a second of microgravity

Figure 1.6: Photograph of Robert Siegel and his drop tower. Steel pipe spikes under the experiment platform were used to decelerate the experiment platform as they impacted a bed of sand. Note also the umbilical cord used to power lights and heaters onboard the experiment rig. (Photo courtesy of NASA.)

(0.75s).

With the advent of the space race, microgravity experiments gained popularity as did drop towers. By 1965 there were 19 functioning drop towers in the United States alone [32]. While not as common as in the early 1970's, microgravity research continues to be conducted in drop towers around the world today.

1.4 Contemporary Drop Towers

Today drop towers around the world are used to simulate microgravity for scientific research. Table 1.1 summarizes key parameters of several contemporary towers. The Maseeh College of Engineering and Computer Science at Portland State University introduces the Dryden Drop Tower.

Table 1.1: Summary of contemporary drop towers used for microgravity research

Facility	Drop Height [m]	Microgravity		Peak Decel. [g_0]	Drop Rate [# / day]
		Duration [s]	g -level [g_0]		
DDT	31	2.1	10^{-4}	15	>30
INTA	21	2.1	$10^{-3} - 10^{-5}$	n/a	n/a
MGLAB	150	4.5	10^{-5}	10	6
NASA-GRC	31	2.2	10^{-5}	30	12
NASA-GRC	155	4.18	10^{-6}	65	2
NMLC	116	3.5	10^{-5}	12	4
QUT	24	2	10^{-4}	25	20
ZARM	146	4.74 - 9.3	10^{-6}	50	3

NASA-GRC-United States The Glenn Research Center (GRC), once home of Siegel's first drop tower, now houses two drop towers, a 2.2 second tower (Fig. 1.7(A)) and the 5.18 second 'Zero Gravity Facility' (Fig. 1.7(B)). Experiments in the 2.2 second drop tower fall 30.5m inside a drag shield (DS) achieving microgravity levels better than $10^{-4}g_0$. The experiment package falls into a vented airbag with a peak deceleration of $30g_0$ [88].

Experiments falling in the 155m evacuated chamber (1.3Pa) of the Zero Gravity Facility achieve microgravity levels as low as $10^{-6}g_0$ and land in a cylinder of expanded polystyrene spheres with a peak deceleration of $65g_0$. During the 1970's experiments

requiring 10s low- g time were conducted by shooting up the tower with a catapult system. The catapult system is no longer used at GRC.

(A) the 2.2 second drop tower

(B) the Zero Gravity Facility

Figure 1.7: Schematics of NASA GRC drop towers; (A) shows the 2.2 second drop tower, (B) shows the Zero Gravity Facility.

ZARM-Germany Fig. 1.8 shows a photograph of the world's largest (operational) drop tower at the *Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation* (ZARM), an institute at the University of Bremen, Germany. Here, experiments in a DS fall 146m inside an evacuated (1Pa) drop chamber for 4.7s, achieving a microgravity levels of $10^{-6}g_0$. A catapult system can shoot the experiment up from the ground lengthening the microgravity time to 9.3s. The DS decelerates by landing in a cylinder of expanded polystyrene spheres with a peak deceleration of $50g_0$ [39, 50, 51].

Figure 1.8: Photograph of *Fallturm Bremen*, the drop tower at ZARM (Photo courtesy of Peter Gorges.)

MGLAB-Japan The Micro-Gravity Laboratory's 4.5 second underground drop tower of Toki City, Japan can be seen in the photograph and schematic in Fig. 1.9(A). Experiments placed inside a DS are dropped inside an evacuated tube and experience a microgravity level as low as $10^{-5}g_0$. An array of friction dampers, cushions and bellows decelerate the experiment package with a peak value of $10g_0$ [68].

NMLC-China Fig. 1.9(B) shows a photograph of the 3.5 second drop tower at the National Microgravity Laboratory (China) (NMLC) in Beijing. Experiments are placed in a sealed and evacuated DS to less than 30 Pa which minimizes air drag on the experiment enabling microgravity levels of $10^{-5}g_0$. An electromagnetic release mechanism releases the DS and experiment. After 60 m of freefall a computer controlled mechan-

Figure 1.9: Photograph of MGLAB’s drop tower vacuum chamber bell jar, schematic and DS (Photo curtesy of MGLAB). Photograph of NMLC’s drop tower (Photo curtesy of NMLC).

ical net-like device catches the DS and decelerates the payload over 22 m with a peak deceleration of $12g_0$. [183]

INTA-Spain Fig. 1.10(A) provides a photograph of the *Instituto Nacional de Técnica Aeroespacial's* 2 second drop tower enclosed in an elevator shaft located in Torrejón de Ardoz, Spain. INTA's drop tower features an optional sealed DS where experiments can experience $10^{-6}g_0$. Experiments in the unsealed DS experience $10^{-4}g_0$ [67, 153].

QUT-Australia Fig. 1.10(B) shows Queensland University of Technology's 2.0 second drop tower. Shearing a wire allows the experiment, shrouded by a DS, to freely fall 23.5 meters achieving a g -level lower than $10^{-4} g_0$ similar to NASA's 2.2s tower. The DS and

(A) INTA's drop tower

(B) QUT's drop tower

Figure 1.10: Photograph of the drop tower at INTA (Photo courtesy of INTA). Photograph of QUT's drop tower (Photo courtesy of QUT).

experiment are decelerated by a vented air bag at the base of the drop shaft with a peak deceleration of $25g_0$. Experiments in fluid dynamics, nanomaterials, and combustion are dropped up to 20 times a day. [147].

PSU - Dryden Drop Tower Portland State University's 2.1s Dryden Drop Tower (DDT) stands 31.1 meters above the atrium of the Northwest Center for Engineering, Science and Technology alongside the central staircase as shown in Fig. 1.5. Fig. 1.11 is an annotated schematic of key features and events of the DDT. Its highly public location requires particular safety accommodations and the design includes an open steel truss tower enclosed by a stainless wire mesh with two limited access points, warning lighting, intercom alerts, active video monitoring at each floor, and a unique passive magnetic deceleration system. The experiment, mounted to an experiment rig, falls

freely inside a drag shield guided by two ‘non-contact’ stainless steel cables that run the length of the tower. Two aluminium fins rigidly mounted to the DS pass through two 1.1m long permanent magnets at the lower level of the tower. The relative motion between the fins and parallel magnetic fields generate eddy currents in the fins that resist motion and decelerate the DS before it comes to rest on foam pads. Fig. 1.12 shows an annotated averaged acceleration profile of the drop. A touch-screen computer permits safe, single-operator control of the primarily automated tower functions which allows for a convenient and efficient operation capable of approximately 6 drops per hour.

Since its inaugural drop in 2009, over 1200 drops have been conducted for capillary fluidics research; of which 1000 drops have occurred during the 2011-2012 academic year alone. Chapter 2 presents a review of select investigations.

Figure 1.11: Schematic of DDT features and operation. Noted events: (1) DS and ER release, (2) 2.13s low-g period where $g < 2 \times 10^{-4} g_0$, (3) ER lands in DS, (4) DS enters magnets and achieves peak deceleration $\sim 14g_0$, (5) DS achieves terminal velocity in magnets $\sim 1g_0$, and (6) DS lands on foam padding $\sim 2g_0$. Event labels correlate to Fig. 1.12 labels. Key features include: (a) steel tower, (b) warning lights, (c) guide cables, (d) RRS, (e) access points, (f) DS, (g) ER, (h) camera and (i) intercom speakers at each level (LL-5), (j) control computer, (k) permanent magnets, and (l) foam pads for landing. See Fig. 1.5 for photograph.

Figure 1.12: Average drop tower acceleration history with noted events: (1) DS and ER release, (2) 2.13s low-g period where $g < 2 \times 10^{-4} g_0$, (3) ER lands in DS, (4) DS enters magnets and achieves peak deceleration $\sim 14 g_0$, (5) DS achieves terminal velocity in magnets $\sim 1 g_0$, and (6) DS lands on foam padding $\sim 2 g_0$.

Chapter 2

New Investigations in Capillary Fluidics Using a Drop Tower

2.1 Introduction

Drop towers are designed to study large length scale capillary phenomena that are common to fluid systems aboard spacecraft where body forces such as gravity are nearly absent. A typical experiment consists of a fluid filled chamber mounted to an experiment rig which is then dropped by any number of methods while the transient response of the fluid is photographed by high-speed cameras. For example, Fig. 2.1 schematically depicts a pedagogical test to study sudden capillary rise in families of cylindrical tubes. The tubes are partially submerged in a wetting fluid that fills a reservoir to its brim. Upon release of the experiment into freefall, the capillary forces are no longer resisted by gravity and transient passive capillarity-driven flows ensue. Digitized values for the rise height of the bulk meniscus, such as those shown in Fig. 2.2(A) and (B), quickly and clearly identify the transitions from inertial to viscous regimes for such flows [94, 119, 146, 164]. Such studies provide novice researchers with ample introduction to length scale effects $\gtrsim 10\text{mm}$ in common low-g capillary flows compared to Earth-bound experiments $\lesssim 1\text{mm}$.

This chapter presents a selection of spontaneous capillary flows that build on the

Figure 2.1: (A) Free body diagram of experiment (B) schematic of (a) experiment rig (ER) for spontaneous capillary rise drop tower tests. Families of (e) tubes are partially inserted into a (d) bath of wetting liquid that just fills the fluid reservoir. The flow is backlit by a (f) diffuse LED screen and filmed at maximum working distance by a (b) high speed video camera. (c) A splash guard protects the camera from liquid splashes upon deceleration. (C) Dynamic rise heights of the menisci in (a) 2.9, (b) 3.8, (c) 7.1, and (d) 10.8mm ID circular tubes are shown after 2s of flow where 0.65cS PDMS rises a maximum length of 143mm in (b) 3.8mm ID tube. The arrow highlights the optimal tube used to achieve maximum flow length within the freefall time. (D) Dynamic rise heights of the menisci in (a) 2.9, (b) 3.8, (c) 7.1, and (d) 10.8mm ID circular tubes are shown after 2s of flow where 5cS PDMS rises a maximum length of 67mm in (d) 10.8mm ID tube. The arrow highlights the optimal tube used to achieve maximum flow length within the freefall time.

passive nature of the ‘sudden capillarity rise’ common to drop towers. The near-step reduction of local acceleration serves as a simplified initial condition for the analysis of such flows. Furthermore, the reduced-g environment of freefall permits larger milli-to-macro-scale test cell geometries that may be designed and fabricated quickly and cheaply when compared to equivalent micro-fabricated devices, surfaces, and test cells.

Figure 2.2: Sample of reduced data from tests performed in Fig. 2.1b, where the capillary rise in circular tubes height $l(t)$ is plotted against t and $t^{1/2}$ for 0.65cS (solid symbols) and 5cS PDMS (open symbols). Predicting the flow that travels the farthest in the 2.1s drop time available is an optimization problem between capillary, inertial, and viscous forces as functions of tube dimensions.

2.2 A Selection of Capillary Fluidics Experiments

By reducing the complexity, costs, and test turnaround time, the barriers for creative investigations using a drop tower are significantly reduced. This is particularly noticeable in capillary fluidics research where the behavior of liquids due to wetting and container geometry are often surprising if not counterintuitive. The ease of access also promotes more of a trial and error mentality, which, due to the difficulty and expense of achieving the weightless state, is traditionally lacking in the aerospace community. The routine exposure to even the short duration phenomena common to the drop tower builds familiarity and intuition that serves the designers of fluid systems for spacecraft well with carryover to microfluidics application in the terrestrial environment.

Particular challenges in capillary fluidics concern the statics, dynamics, and stability of free surface flows that are intricately tied to wetting and geometry [165]. This

chapter demonstrates a selection of potentially illuminating phenomena studied using a drop tower. While any one of the following examples could be the topic for an individual thesis, this work merely introduces each phenomena and briefly describes initial results. Chapter 3 details one phenomena, capillarity-driven droplet ejection, in greater detail.

2.2.1 Auto-Ingestion

Experiments demonstrate how capillarity-driven flow in a conduit can create sufficient inertial to imbibe bubbles or breach gaps. The DDT has enabled our research group to provide conclusive evidence for these phenomena.

Perhaps surprisingly, we observe drop tower tests employing partially open conduits to passively ingest air bubbles. Fig. 2.3 shows an example of capillary rise in a singly-fluted tube (akin to a ‘cross’ fitting). The tube ID is 6.6mm with an elongated through-hole diameter of 5.6mm and length 11mm. During the drop the capillary flow carries the liquid past the holes. The reduced pressure in the tube causes the interfaces that form across the holes to curve inward. These occluding interfaces reduce the local cross flow area which necessitates that the local velocity increase to maintain the flow rate. According to Bernoulli, the increased local velocity leads to further decreases in pressure that eventually lead to a temporary destabilization of the interface resulting in a gas bubble ingestion.

For further experiments and theory for ingestions in forced flows in a variety of partially open conduits see [93, 131]. However, the present ingestion occurs for a passive

Figure 2.3: Capillary rise of 0.65cS PDMS in a singly-fluted tube resulting in auto-ingestion. The tube ID is 6.6mm and the through-slot radius and length are 2.8mm and 11mm respectively. Images presented at 6.7Hz.

capillary flow. Auto-ingestion is governed by local Weber number

$$We_f \equiv \frac{\rho V^2 R_f}{4\sigma} \text{fcn}(\phi_f) \gg 1, \quad (2.1)$$

where $\phi_f \equiv R_f / R_t$ with R_f being the fluting hole radius, V is flow velocity, and ρ and σ are the fluid's density and surface tension respectively. Auto-ingestion is increasingly likely when the fluting hole ID is of comparable order to the tube ID, $\phi_f \sim \mathcal{O}(1)$.

2.2.2 Capillary Flow Across Gaps

A drop tower experiment of a capillary flow along a segmented tube is shown in Fig. 2.4 as a further example of auto-ingestion. Two lengths of 6.6mm ID tube are separated by a 1.6mm gap. Due to sufficient inertia, the 0.65cS PDMS liquid jumps the gap, forms a dynamic liquid bridge, and continues to rise due to capillary forces. Again, the capillary under-pressure in the liquid draws the liquid bridge interface inward increasing local velocities and leading to flow instabilities and ingestion. As the liquid column

extends, viscous forces reduce the rise rate (i.e., flow rate) to the point that further ingestion is no longer possible.

Such ‘gap flows’ also reveal one manner in which the inertia of larger length scale capillary systems are capable of establishing a capillary connection across physically disconnected conduits or passageways. An ingestion criterion for this geometry is

$$\text{We}_f \equiv \frac{\rho V^2 L_g}{4\sigma} \text{fcn}(\phi_g) \gg 1 \quad (2.2)$$

where $\phi_g \equiv 1 - L_g/2R_t$ and here L_g is the gap length. Again, bubble ingestion is increasingly likely for $g \sim \mathcal{O}(R_t)$.

2.2.3 Macro-Surfactant Phenomena Including ‘Sinking’ in Microgravity

At a liquid surface, the definition of the word ‘float’ is largely a $1g_0$ concept deriving from the buoyancy force. When the acceleration of gravity is negligible, solids ‘float’ or ‘sink’ solely based on their geometry and wettability. In this context, ‘float’ means that a body remains at the surface (surface active) and ‘sink’ means that a body is drawn completely into one of the fluid phases.

For example, Fig. 2.5A shows a drop tower test that is performed with a 19mm diameter styrofoam sphere floating in a 33mm ID circular cylinder filled nearly to its brim with perfectly wetting 0.65cS PDMS ($\theta = 0^\circ$). Release of the experiment results in a spontaneous injection of the sphere into the liquid. The experiment is repeated in Fig. 2.5B only water is used possessing a wetting angle of approximately $\approx 115^\circ$ on the now teflon coated sphere. In this case the sphere prefers to remain on the liquid surface in the reduced gravity state. Thus, from Fig. 2.5, macro-scale particle injections

Figure 2.4: Capillary rise of 0.65cS PDMS in a 6.6mm ID tube. The tube is segmented, but the flow readily bridges the 1.6mm gap. The subsequent continued rise results in an auto-ingestion at the gap.

and capture, are readily demonstrated using a drop tower.

Further studies in self-assembly at surfaces or in macro-surfactant phenomena may be conducted using the drop tower approach exploiting the unique effects of gravity being ‘switched off’. For example, the rate of ‘sinking’ in low-g is readily observed in the simple drop tower experiments shown in Fig. 2.6. For these tests an empty, sealed plastic syringe bobs vertically in a circular cylindrical container partially filled with 0.65cS PDMS. The lateral motion of the syringe is restricted by a low friction slider

that allows only vertical motion. When released into freefall, buoyancy forces are eliminated and the under-pressure created in the annular gap between the container wall and the syringe results in the syringe being drawn (or pushed) into the liquid at a predictable rate.

Two drop tests are shown in Fig. 2.6 where only the contact angle is varied on the syringe by applying a coating of 3M's FC-724 surface modifier. The contact angle in Fig. 2.6A is 0° while that of Fig. 2.6B is $59 \pm 2^\circ$. The sink rate may be determined in at least two limits: the narrow annular gap limit where quasi-steady Hagen-Poiseuille flow results and the large gap limit which obeys a time-dependent boundary layer solution. Contrary to sinking or floating in a gravitational environment, the density difference between the solid and liquid only determines the rate of sinking, not whether the solid sinks.

2.3 Macroscale Capillary Fluidics Test Cell Manufacturing

So far it has been demonstrated that a variety of interesting and applicable fluid phenomena may be studied anew in the unique low-g environment of a drop tower. The length scales over which capillary forces are significant are greatly expanded such that complex test cells are large enough to be fabricated quickly and cheaply. For example, a manufacturing technique for test cells was developed herein to explore passive capillary flows in a variety of channel geometries.

The method derives from 2-D planar microfabrication but at the macroscale; basically test cells constructed of sheet lay-ups, a sample test cell assembly of which is depicted in Fig. 2.7. Details of test cell manufacturing are provided in Appendix E.1. The various layers are drawn in a CAD software. Typically, the center layers have a

A

B

Figure 2.5: Freefall behavior of ‘floating spheres’ (a model of macro-surfactants) in a 33mm diameter right circular cylinder filled to the brim with a test liquid: 30Hz image sequence of (A) a 19mm diameter polystyrene sphere in perfectly wetting 0.65cS PDMS ($\theta = 0^\circ$), (B) the same sphere in slightly non-wetting water ($\theta \approx 115^\circ$). Following the drop, the spheres are either injected or captured on the surface, respectively. The sphere of (B) remains ‘surface active.’

capillary channel cut out with a laser cutter. Double-sided tape is often applied to the acrylic sheets prior to the cutting and the layers are aligned and sealed together in a press or vice. The custom channels take the form of cartridges that are then inserted into a similarly designed support structure that partially submerges the base of the cartridge in a pinned liquid reservoir prior to the drop. The test cell of Fig. 2.7 is designed to explore passive two-phase flow phenomena using a drop tower.

Figure 2.6: Image sequence at 30Hz of 16.2mm diameter cylindrical bob (syringe) placed in a 33mm ID cylindrical reservoir partially filled with 5cS PDMS. (A) uncoated perfect wetting bob, (B) FC724-coated bob with contact angle of $\theta = 60^\circ$. The sink rate is a strong function of the wetting conditions.

Figure 2.7: (A) exploded isometric view of a typical test cell showing the layers used in construction; (a) clear acrylic channel covers with (d) air exit holes, (b) double sided tape, and (c) colored acrylic sheet with (e) channel cutout. (B) Schematic of (a) experiment rig (ER) for spontaneous capillary rise drop tower tests. (e) Test cell (cartridge) supported in pinned (d) reservoir. The flow is backlit by a (f) diffuse LED screen and filmed at maximum working distance by a (b) high speed video camera. (c) A splash guard protects the camera from liquid splashes upon deceleration.

2.3.1 Bubble-Slug Flow Generators

Figure 2.8A provides an image of the Fig. 2.7B cartridge partially submerged in a reservoir of test liquid. During the drop, capillary rise occurs in both the left and right channels labeled L and R, respectively. Upon entering microgravity, the liquid in the right channel quickly rises past the channel intersection, as depicted in Fig. 2.8A position 1 to position 2. Simultaneously, liquid rises in the left channel displacing a column of air ahead of the interface. The air pocket in the left channel is effectively pumped

Figure 2.8: (A) Bubble-slug generator with 4mm square channels: (L)eft and (R)ight channels indicated serve as gas and liquid pumps, respectively. Right channel outlined by dashed line is area of interest that is repeated in (B). (B) Photograph of test cell with history of right channel flow at 10Hz. The $t^{1/2}$ behavior is readily observed in both rise height and bubble size. The leading liquid slugs are observed to thin and rupture as they advance. Test fluid is 0.65cS PDMS.

into the liquid column of the right channel. In this case the viscous flow in the right channel pinches off air bubbles at a rate $\sim t^{1/2}$. A regular bubble-slug flow results that is passively generated, of large-length scale, and is highly repeatable. Such flows may be studied directly or may be employed as diagnostic flows to study other downstream phenomena in low-g—for example, drain and rupture of large-length scale advancing liquid slugs as observed in Fig. 2.8B.

In a similar manner, a variety of flow regimes are achieved by varying the geometry of the channels and channels' intersections. Further examples are shown in Figs. 2.9-

2.11 where the ratio of channel diameters is varied, as in Fig. 2.9, or the intersection style is varied, as in Fig. 2.10. A myriad of variations are imaginable as have been investigated in terrestrial microfluidics flows [33].

The gas and liquid flow rates can be easily controlled by adjusting the geometry of the channels. Since large channels produce significantly inertial capillary flows the flow rates are often constant $\sim t$ for a large portion of the drop test. In Fig. 2.11 a narrow right channel converts the capillary rise to a pure corner flow [166] which is over-driven downstream by the gas flow from the left channel. As the driven liquid builds, the Kelvin-Helmholtz instability results in the formation of slugs which are then driven further along the tube by the capillary forces. In such a manner the transition from annular to slug flows may be studied at large length scales using a drop tower. Quantitative research efforts are continuing along these lines.

2.4 Summary

The capillary fluidics experiments qualitatively presented herein demonstrate new directions for drop tower research. The DDT provides control over fluid initial conditions that allow gravity to be effectively ‘switched off.’ Large-length scale capillary phenomena occur with practical capillary lengths up to approximately 10cm. The particular capillarity fluidics examples reported herein may each be studied on their own right. However, each phenomena may also be used as a means to study other low-g phenomena. A variety of low-g behaviors from coalescence to rebounds to gas entrainment and splashing are observed depending on the properties and dimensions of the system. Such phenomena may be inherently interesting, but they are also particularly practical, especially for the study of large-length scale capillary phenomena common

Figure 2.9: (A) Bubble-slug generator with 4 x 2mm left channel and 4mm square right channel: (L)eft and (R)ight channels indicated serve as gas and liquid pumps, respectively. Right channel outlined by dashed line is area of interest that is repeated in (B). (B) Photograph of test cell with history of right channel flow at 10Hz. Test fluid is 0.65cS PDMS.

aboard spacecraft. Concerning multiphase flows, the bubble-slug generators of §2.3.1 establish passive two-phase flows that can in turn be used to further develop passive separation methods. Temperature, concentration, or wetting gradients can be introduced downstream to quantify additional effects that have applications in space as well as on Earth. In this way, the drop tower adds unique capabilities for the continued study of capillary fluidic phenomena. Another of these phenomena under investigation is capillarity-driven droplet ejection, which is addressed in depth in Chapter 3.

Figure 2.10: (A) Bubble-slug generator with 4mm square channels with a nozzle at intersection: (L)left and (R)ight channels indicated serve as gas and liquid pumps, respectively. Right channel outlined by dashed line is area of interest that is repeated in (B). (B) Photograph of test cell with history of right channel flow at 10Hz. The $t^{1/2}$ behavior is readily observed in both rise height and bubble size. The leading liquid slugs are observed to thin and rupture as they advance. Air bubbles are smaller and appear more regularly than in other cells. Test fluid is 0.65cS PDMS.

Figure 2.11: (A) Bubble-slug generator with 4mm square left channel and 4 x 2mm right channel: (L)eft and (R)ight channels indicated serve as gas and liquid pumps, respectively. Right channel outlined by dashed line is area of interest that is repeated in (B). (B) Photograph of test cell with history of right channel flow at 10Hz where corner flows are driven to form an annular flow that transitions to a capillarity-driven slug flow due to the Kelvin-Helmholtz instability. (0.65cS PDMS)

Chapter 3

Capillarity-Driven Droplet Ejection

3.1 Introduction

In 1956 a team of NASA scientists considered the problems of fluids management in the weightless environment of space. NASA scientist Robert Siegel designed, built, and conducted experiments with the first drop tower specifically designed for fluids research. One of the first fluid experiments conducted in a weightless environment of a falling platform were those of capillary rise in glass tubes partially submerged in a water reservoir [140]. Siegel knew that surface tension forces would pump the fluid along the tubes but was interested in how the fluid would behave once it reached the end of the tube. He wondered if the fluid would reach the top of the tube and either stop, continue to wet the sides of the tube, or expel itself from the end of the tube [141]. After conducting drop tower experiments, Siegel witnessed the liquid rise in the tube, pin at the tube's lip, and bulge out of the tube only to be drawn back into it again. Siegel concluded that in a zero gravity environment, liquid could never expel itself from a tube, but would instead oscillate at the tube end until it came to rest there. Fifty years later, I repeat Siegel's inaugural experiments using the DDT facility at Portland State University. The results can be seen in Fig. 3.1. Nobel Laureate P.G. de Gennes supported

Figure 3.1: Spontaneous capillary rise of 0.65cS PDMS at 0.2s intervals in a 60mm long, 9.9mm ID circular tube. The liquid rises to the tube end and pins, but cannot achieve enough momentum to auto-eject from the tube.

Siegel's findings using a pressure argument. He concluded [36];

It should by now be obvious that capillarity will never be able to generate a jet (or a spring, contrary to what da Vinci believed). In order for a liquid to come gushing out of a tube, it would have to be in a state of overpressure, which would produce an inverted meniscus. But such a scenario would be incompatible with a rising liquid (which, as we know, implies an underpressure to balance the hydrostatic pressure). If one were to dip a tube of height h smaller than H in a liquid bath, the entire tube would fill with liquid and the meniscus would adopt whatever curvature offsets the hydrostatic pressure difference - pgh with the bath.

However, by altering the tube exit geometry, ample inertia may be developed in a nozzle to overcome surface tension enabling ejections of single drops as shown in Fig. 3.2, to transient jets as shown in Fig. 3.3. Single droplet auto-ejections in the approximate range 0.08ml to 2ml are readily achieved in a drop tower. A $4.7\mu\text{l}$ droplet shown in Fig. 3.2 and a $370\mu\text{l}$ droplet shown in Fig. 3.4 demonstrate the variety of

Figure 3.2: Spontaneous capillary rise of 5.0cS PDMS in a 60.6mm long, 6mm ID circular tube (images at 10Hz). The tube nozzle exit 1.2mm ID. Sufficient inertia develops in the nozzle to overcome surface tension and auto-eject a single 4.7μl drop.

droplet sizes that can be auto-ejected.

Experiment setup and procedure details appear in section 3.7. At the suggestion of M. Weislogel, this ‘auto-ejection’ was first demonstrated by high school science teacher C. Murray and students [16] at NASA GRC’s 2.2s drop tower as part of the NASA DIME program [61].

There is no physical reason this phenomena can not occur under $1g_0$ conditions. Details of successful terrestrial $1g_0$ ejections and the experimental setup and procedure are provided in §3.7. A sample image of terrestrial $1g_0$ capillarity-driven droplet ejection is shown in Fig. 3.5A.

As part of this effort, capillarity-driven droplet ejection has also been demonstrated aboard the International Space Station. M. Weislogel was allowed email access to

Figure 3.3: Spontaneous capillary rise of 0.65cS PDMS in a 73.5mm long, 9.2mm ID circular tube (images at 10Hz). The 3.88mm tube nozzle exit ID produces a transient jet which eventually breaks up into $6 \approx 0.02\text{ml}$ drops.

Figure 3.4: Spontaneous capillary rise of 0.65cS PDMS in a 60.5mm long, 9.6mm ID circular tube (images at 10Hz). The 5.0mm tube nozzle exit ID ejects a single $370\mu\text{l}$ drop.

Figure 3.5: Select frames of auto-ejection following capillary rise in tubes demonstrated in A) $1g_0$ test using 0.65 cS PDMS and B) aboard ISS using water.

United States Astronaut Don Pettit aboard the International Space Station (ISS) and posed the idea to make a tube with a nozzle from equipment aboard the ISS and perform auto-ejection demonstrations. Pettit agreed to participate and conducted a series of ejection experiments in his ‘free’ time. Details of the experiment are provided in §3.7. A sample image of auto-ejection conducted aboard the ISS appears in Fig. 3.5B.

This chapter details capillarity-driven droplet ejection by providing some historical context and by presenting a force balance model to predict the velocity of the flow in a tube, which I developed over the course of the research. A nondimensional equation governed by a single parameter Su^+ models capillary rise. Using scaling arguments, one of many simplified dimensional models of capillary rise is presented and compared to other models. I provide criteria for capillarity-driven droplet ejection along with details for the drop tower, terrestrial, and ISS experiments, as well as for the data collection, reduction, and analysis. Regime maps and discussion conclude the chapter.

3.2 Conditions Necessary for Auto-Ejection

Figure 3.6 illustrates the nomenclature utilized in this section. Flow in the nozzle is complicated by developing boundary layers, significant viscous normal stresses leading to large dynamic contact angles, and capillary wave dynamics [1, 13, 99, 111, 127, 130, 156, 157, 181]. All such complexities are ignored and the flow in the nozzle is modeled as inviscid. Such a simplification is appropriate if the nozzle is ‘short’ enough. Here, a nozzle is considered short when the flow through it does not fully develop. The resident time of liquid in the nozzle is

$$t_r \sim \frac{\forall_n}{Q_t} = \frac{\pi L_n R_{avg}^2}{A_t W_t}, \quad (3.1)$$

where $\forall$ is the volume of the nozzle, Q_t is the flow rate entering the the nozzle, R_{avg} is the average radius of the nozzle, A_t is the cross-sectional area of the nozzle base, and W_t is the velocity of the flow entering the nozzle. The viscous time scale is

$$t_\mu = \frac{R_{avg}^2}{\nu}, \quad (3.2)$$

where ν is the viscosity of the fluid. Thus $t_r/t_\mu \ll 1$ must be satisfied for viscous flows entering the nozzle to turn inertial and inertial flows entering the nozzle to stay inertial. Dividing 3.1 by 3.2 yields a short nozzle condition

$$\frac{t_r}{t_\mu} = \frac{L_n \nu}{W_t R_t^2} \ll 1. \quad (3.3)$$

Figure 3.7: Schematic illustrating the conditions necessary for droplet ejection. (A1) Flow entering the nozzle must (B3) leave inertial, (C) inertia must be able to invert the meniscus from (3) to (4), and (D) remaining inertial forces must overpower surface tension forces sufficient to exceed the (E) Rayleigh breakup length, where (F) a drop is pinched off.

must be rewritten in terms of W_{t1} . To do this, a loss coefficient K_n is ascribed to the nozzle to account for the resistance generated. Applying an energy balance over the nozzle yields

$$W_{t2} = \frac{W_{t1}}{(1 + K_n)^{1/2}}. \quad (3.5)$$

Applying continuity, the flow rate at each end of the nozzle must balance such that

$$Q_n = Q_{t2},$$

where Q_n and Q_{t2} are flow rates at the nozzle end and tube end, respectively. The flow rates are rewritten in terms of their respective cross-sectional areas

$$A_n W_{n3} = A_t W_{t2},$$

where A_n and A_t are the nozzle and tube exit cross-sectional areas, respectively, and W_n and W_{t2} are the respective nozzle and tube exit velocities. The fluid velocity at the nozzle exit is solved in terms of the velocity at the tube end

$$W_{n3} = \frac{A_t W_{t2}}{A_n}.$$

Rewriting the areas in terms of radii yields,

$$W_{n3} = \frac{R_t^2 W_{t2}}{R_n^2}, \quad (3.6)$$

where R_n and R_t are the nozzle exit and tube radii, respectively. Introducing $\alpha = R_n / R_t$ and rewriting 3.6 yields

$$W_{n3} = \frac{W_{t2}}{\alpha^2}. \quad (3.7)$$

Plugging 3.5 into 3.7 yields

$$W_{n3} = \frac{W_{t1}}{\alpha^2 (1 + K_n)^{1/2}}. \quad (3.8)$$

Figure 3.7C depicts the dynamic inversion of the meniscus. The velocity of the meniscus at position 3 is inverted to position 4. The decrease of velocity of the meniscus due to the inversion of the curvature of the meniscus in terms of dynamic pressure is expressed by

$$\frac{\rho W_{n3}^2}{2} - \frac{\rho W_{n4}^2}{2} = \frac{4\sigma}{R_n}, \quad (3.9)$$

where the dynamic pressure at position 3 is $\rho W_{n3}^2 / 2$ and the dynamic pressure at posi-

tion 4 is $\rho W_{n4}^2/2$. Rewriting 3.9 in terms of the velocity at position 4 yields

$$W_{n4}^2 = W_{n3}^2 - \frac{8\sigma}{\rho R_n}. \quad (3.10)$$

Plugging 3.8 into 3.10 yields

$$W_{n4} = \left(\frac{W_t^2}{\alpha^4 (1 + K_n)} - \frac{8\sigma}{\rho R_n} \right)^{1/2}. \quad (3.11)$$

After the inversion of the meniscus, the flow must have sufficient inertia to overpower the surface tension that resists the flow to extend past the Rayleigh breakup length πD_n , where D_n is the diameter of the nozzle. Comparisons of the two dominant forces can be made by balancing inertial and surface tension terms at the end of the nozzle;

$$\frac{\rho W_{n4}^2}{2R_n} \sim \frac{2\sigma}{R_n^2}. \quad (3.12)$$

Rearranging 3.12 the terms to one side of the equation produces the condition necessary for ejection

$$\frac{\rho R_n W_{n4}^2}{4\sigma} \gtrsim 1. \quad (3.13)$$

Plugging 3.11 into 3.13 yields

$$\frac{\rho R_n}{4\sigma} \left(\frac{W_{t1}^2}{\alpha^4 (1 + K_n)} - \frac{8\sigma}{\rho R_n} \right) \gtrsim 1.$$

Pulling out $W_{t1}^2/\alpha^4 (1 + K_n)$ reveals that

$$\frac{\rho R_n W_{t1}^2}{4\sigma \alpha^4 (1 + K_n)} \left(1 - \frac{8\sigma \alpha^4}{\rho R_n W_{t1}^2} \right) \gtrsim 1,$$

which can be written in terms of the Weber number $We = \rho R W_{t1}^2 / \sigma$,

$$\frac{We_t}{4\alpha^3(1+K_n)} \left(1 - \frac{8\alpha^3(1+K_n)}{We_t} \right) \gtrsim 1. \quad (3.14)$$

By introducing a modified Weber number We^+ such that $We^+ = We/\alpha^3(1+K_n)$, Eq. 3.14 reduces to

$$\frac{We^+}{4} \left(1 - \frac{8}{We^+} \right) \gtrsim 1,$$

which simplifies to

$$We^+ \gtrsim 12. \quad (3.15)$$

Therefore if a short nozzle of length $L_n \ll W_t R_t^2 / \nu$ is placed atop a tube and the flow at the tube end satisfies $We^+ \gtrsim 12$, then the inverted meniscus will likely extend farther than the Rayleigh breakup length, as seen in Fig. 3.7D, pinch off at least one drop, and auto-eject as shown in Fig. 3.7E-F. With the conditions for auto-ejection defined in terms of velocity of flow entering the nozzle W_{t1} , experimental measurements and force balance models are used to predict W_{t1} and therefore capillarity-driven droplet ejection. A review of historical models used to predict W_{t1} is provided in the following section.

3.3 Governing Equation for Capillary Rise

Placing one end of a small tube vertically into a liquid bath, as depicted in Fig. 3.8, one observes spontaneous liquid rise in the tube to a length where the capillary pressure driving force balances gravitational forces. As the liquid wets the inner surface of the tube, a meniscus curvature develops rapidly to generate a pressure difference across

the interface. The underpressure created is the driving force pumping the liquid along the tube. The final rise height is referred to as the ‘Jurin length’ $\ell_{\text{Jurin}} = 2\sigma \cos\theta / \rho g_0 R$, where σ is the surface tension, θ is the contact angle, ρ is the density difference across the interface, and g_0 is the acceleration due to gravity ($\sim 9.81\text{m/s}^2$) [36].

Figure 3.8: Schematic of capillary rise showing Jurin’s length

The transient response of the fluid is complicated by capillary surface formation, the moving contact line problem [78], dynamic contact angles [117, 130, 139, 177], fountain effects [160], and entrance/exit region boundary layers for both liquid and gas [135, 144]. Only numerical simulations are sufficient to solve the complete flow behavior and even those are challenged by the somewhat incomplete boundary conditions at the interface. However, for this work a simple 1-D capillary rise force balance is sufficient to calculate the average flow velocity along a circular cylinder.

Imbibition of a fluid into a porous media has been studied since the early 1700’s. While Leonardo da Vinci recorded qualitative observations and conjecture on the subject well before 1700 [36], it is Robert Boyle and Francis Hauksbee who first recorded

quantitative observations on the subject of what is now referred to as ‘capillary rise’ [19, 64, 65]. The physician James Jurin also made careful measurements of capillary rise [76, 77]. Boyle’s, Hauksbee’s and Jurin’s contributions focused on equilibrium phenomena.

In 1908, two soil scientists from the Bureau of Soils of the United States Department of Agriculture, Bell and Cameron, studied the transient response of liquid water movement through a packed bed of soil, paper and small circular tubes and derived the formula

$$\ell^n = K t, \quad (3.16)$$

where ℓ is the fluid’s position, n and K are unknown constants, and t is time [11]. By assuming Poiseuille flow, Bell and Cameron determine that the movement of liquid through a capillary is described by the equation $\ell^2 = K t$, where $n = 2$ from the previous equation.

The imbibition constant K remained a tabulated empirical constant until 1918 and 1921, respectively, when German scientist Lucas [94] and English scientist Washburn [164] independently determined that the imbibition constant is dependent on material and geometric properties of the fluid and tube where $K = \sigma R \cos \theta / 2\mu$, where R is the tube radius and σ , θ , and μ are material properties surface tension, contact angle, and dynamic viscosity, respectively. The differential equation governing the position of the interface, as derived by Lucas and Washburn is

$$\ell \ddot{\ell} + \dot{\ell}^2 + \frac{8\nu}{R^2} \ell \dot{\ell} = \frac{2\sigma \cos \theta}{\rho R}, \quad (3.17)$$

subject to $\ell(0) = 0$ and $\dot{\ell}(0) = 0$, solved at long times where $\ell \dot{\ell} \sim 0$ and $\dot{\ell}^2 \sim 0$ with

$\ell(0) = 0$ yields

$$\ell^2 = \frac{\sigma R \cos \theta t}{2\mu}. \quad (3.18)$$

In 1922, Rideal [128] also contributed to the now famous Lucas-Washburn equation, but the model is accurate only as $t \rightarrow \infty$. Since Lucas and Washburn, many scientists have attempted to improve predictions.

In 1923, Bosanquet [18] added terms back into the force balance that Lucas, Washburn, and Rideal had neglected. Bosanquet solved the original force balance yielding

$$\ell^2 = \frac{\sigma \cos \theta R}{2\mu} \left[t - \frac{\rho R^2}{8\mu} \left(1 - \exp \left[-\frac{8\mu}{\rho R^2} t \right] \right) \right].$$

In 1944, Pickett [115] added gravity to the model obtaining

$$\ell \ddot{\ell} + \dot{\ell}^2 + \frac{8\nu}{R^2} \ell \dot{\ell} + g_o \ell = \frac{2\sigma \cos \theta}{\rho R},$$

where kinematic viscosity $\nu = \mu/\rho$. Pickett solved the model for small values of time t yielding

$$\ell^2 = \frac{\rho^2 R^4}{32\mu^2} \left(\frac{2\sigma}{\rho R} - g_o \ell_{\text{Jurin}} \right) \left(\frac{8\mu}{\rho R^2} t - 1 + \exp \left[\frac{8\mu t}{\rho R^2} \right] \right).$$

In 1946, Brittin [22] added tube end effects to obtain

$$\ell \ddot{\ell} + \frac{5}{4} \dot{\ell}^2 + \frac{8\nu}{R^2} \ell \dot{\ell} + g_o \ell = \frac{2\sigma \cos \theta}{\rho R}.$$

In 1961, Siegel [140] modeled capillary rise for capillary rise in fractional gravitational fields. In 1971, Szekely et al. [151] adjusted the model to accommodate the entrance

region of the tube:

$$\left(\ell + \frac{7}{6}R\right)\ddot{\ell} + \frac{5}{4}\dot{\ell}^2 + \frac{8\nu}{R^2}\ell\dot{\ell} + g_o\ell = \frac{2\sigma\cos\theta}{\rho R}.$$

In 1976, Levine et al. [90] further adjusted the parameters associated with the entrance region:

$$\left(\ell + \frac{37}{36}R\right)\ddot{\ell} + \frac{7}{6}\dot{\ell}^2 + \frac{8\nu}{R^2}\left(\ell + \frac{R}{4}\dot{\ell}\right) + g_o\ell = \frac{2\sigma\cos\theta}{\rho R}.$$

In 2003, Stange et al. [146] established a contemporary model equation for micro-gravity capillary rise in a straight, circular, cylindrical tube

$$(\ell + L_0 + \mathbb{C}_1 R)\ddot{\ell} + \left(\frac{1+K}{2}\right)\dot{\ell}^2 + \frac{8\nu}{R^2}\left(\ell + L_0 + \frac{R}{4}\right)\dot{\ell} = \frac{\sigma}{\rho}\left(\frac{2s\cos\theta_d}{R} - \frac{1}{R_c}\right), \quad (3.19)$$

where L_0 is the submerged depth of the tube of radius R , K is the loss coefficient for the entrance region of the tube, s is the time shift function to account for the reorientation of the meniscus upon a step reduction of gravity, θ_d is the dynamic contact angle, R_c is the radius of curvature of the reservoir, $\mathbb{C}_1 = 73/60$, and ν , σ , and ρ represent kinematic viscosity, surface tension, and density difference across the interface, respectively.

While the Lucas-Washburn equation continues to be studied and additional models for capillary rise continue to emerge [25, 54–56, 145, 176], Eq. 3.19 is the latest model for capillary rise in a circular tube in microgravity. It is the most accurate model to date and is employed herein as a starting place for simplified analysis.

Figure 3.9: Three different tube inlet configurations from key capillary rise experiments; (A) Siegel, (B) Stange et al. (C) this study. Tube inlet configurations contribute to different entrance regions' pressure losses. Geometry and configuration of the inlet determines the degree of pressure loss.

3.4 Review of Governing Equation Terms

This section reviews the empirical correlation expressions to determine the significance of each term in Eq. 3.19. Figure 3.9 illustrates three different experimental tube inlet configurations used in three different studies. Each entrance region has a specific loss coefficient associated with it. In Eq. 3.19, the empirical relation K accounts for pressure loss in the entrance region of the tube. Each tube geometry is different and will require a different value of K . The loss coefficient associated with configuration Fig. 3.9C is half that of configuration 3.9B [14, 104, 105]. Stange et al.'s experiments employ the configuration of Fig. 3.9B while experiments conducted for this study have the tubes mounted using the configuration of Fig. 3.9B.

To account for the pressure loss associated with the entrance length, Stange et al. used a relation developed by Sparrow et al. [144] where K is expressed as an infinite

series

$$K = \frac{4}{3} + \sum_{i=1}^{\infty} \frac{8}{\alpha_i^2} \exp[-4\alpha_i^2 \text{Re}_z \text{Re}_d^2 - 3] \exp[-4\alpha_i^2 \text{Re}_z \text{Re}_d^2],$$

where the Reynolds number $\text{Re}_z = z\dot{\ell}/\nu$ is based on the flow length z . For ‘long’ tubes where the flow length is greater than the entrance region $K = 4/3$ [146]. Since $K = 4/3$ accounts for the loss in Fig. 3.9B, and Fig. 3.9C has half the loss as Fig. 3.9B, this study uses a value of $K = 2/3$ because the configuration of the tube mount is that depicted in Fig. 3.9C and the parameter associated with the pressure loss due to the tube’s entrance region is expressed by $\mathbb{C}_2 \equiv (1 + K)/2 = 5/6$.

The time shift function $s(t)$ appearing in Eq. 3.19 is empirically determined to allow for the reorientation of the interface from its $1g_0$ to its microgravity configuration. This reorientation must occur before significant bulk capillarity rise ensues. It is expressed by Stange et al. as

$$s(t) = 1 - \exp[-\mathbb{C}_3 t/\tau_r], \quad (3.20)$$

with $\mathbb{C}_3 = 11.138$ and where the reorientation time is

$$\tau_r = \left(\frac{\rho R^3}{\sigma} \right)^{1/2}.$$

Stange et al. employ a correlation by Jiang et al. [74] for calculating the dynamic contact angle

$$\cos \theta_d = 1 - 2 \tanh(4.96 \text{Ca}^{0.702}), \quad (3.21)$$

where the Capillary number is $\text{Ca} = \mu\dot{\ell}/\sigma$. The radius of curvature of the reservoir R_c can influence the speed at which the interface rises. Stange et al.’s approximation for R_c is specific to their experimental set up and duration [146]. The experimental set up

Figure 3.10: Cylindrical reservoir of radius R_r and height H over-filled with fluid an additional capillary height L_σ . As fluid is drawn up the tube the volume of liquid in the reservoir is depleted. Liquid remains pinned to the lip of the reservoir until $R_c = R_r$. In a microgravity environment the liquid interface takes the shape of a spherical cap.

and duration for the present study differ from Stange et al.'s experiment, and uses a different value of R_c . Prior to each drop experiment, the reservoir is over-filled with the liquid pinned to the top lip of the reservoir as seen in Fig. 3.10. Liquid drawn into the tube draws liquid from the over-filled portion of the reservoir. Only after the over-filled volume has depleted does the rising fluid in the tube begin to draw liquid out of the reservoir, leading to flow resisting reservoir curvature. A correlation of liquid height in the tube to liquid volume change in the reservoir is

$$R_c(\ell) = \frac{R_r^4 - R_r^2 \tilde{V}^{2/3} + \tilde{V}^{4/3}}{2(\tilde{V} - R_r^2 \tilde{V}^{1/3})}, \quad (3.22)$$

where $\tilde{V}(\ell) = -R_r^2 L_\sigma + 6R_t^2 \ell + \left(4R_r^6 + (R_r^2 L_\sigma - 6R_t^2 \ell)^2\right)^{1/2}$, $L_\sigma = (\sigma/\rho g)^{1/2}$ is the capillary

length, R_r and R_t are the reservoir and tube radii, respectively, all of which are known values with ℓ being the only variable. Appendix A.1 contains a detailed derivation of Eq. 3.22.

3.5 Scaling and Nondimensionalization of the Governing Equation

The model equation 3.19 was nondimensionalized to identify key parameters that govern the flow. Stange et al. nondimensionalized Eq. 3.19 using the characteristic viscous time $t_s = R^2/\nu$, and velocity $V_s = (2\sigma/\rho R)^{1/2}$. In this work, I use a different scaling in hopes of identifying a single salient parameter governing the flow in significantly reducing the parametric space and in turn simplifying data presentation. Choosing $\ell \sim L_s$, $t \sim t_s$, $\ell^* = \ell/L_s$, and $t^* = t/t_s$ Eq. 3.19 is converted to

$$\begin{aligned} \frac{L_s^2}{t_s^2} \left(\ell^* + \frac{L_0}{L_s} + \mathbb{C}_1 \frac{R}{L_s} \right) \ddot{\ell}^* + \mathbb{C}_2 \frac{L_s^2}{t_s^2} \dot{\ell}^{*2} + \frac{8\nu L_s}{R^2 t_s} \left(\ell^* + \frac{L_0}{L_s} + \frac{R}{4} \right) \dot{\ell}^* \\ = \frac{\sigma}{\rho R} \left(2s^* \cos^* \theta_d - \frac{R}{R_c^*} \right), \end{aligned} \quad (3.23)$$

where the dependent and independent variables have been nondimensionalized and $K = \mathbb{C}_2 = 5/4$, $s^* = 1 - \exp[-\mathbb{C}_3 t_s t^*/\tau_r]$, with $\mathbb{C}_3 = 4.6/0.413 = 11.138$,

$$\cos^* \theta_d = 1 - 2 \tanh \left(\left(\frac{\mathbb{C}_4 \mu L_s}{\sigma t_s} \dot{\ell}^* \right)^{0.702} \right), \quad (3.24)$$

with $\mathbb{C}_4 = 9.2458$, and R_c is given by Eq. 3.22.

The driving force term of Eq. 3.23 is chosen to be $\mathcal{O}(1)$ in the nondimensional equation. Dividing 3.23 by the capillary pressure term enables the evaluation of the relative order of magnitude of the remaining terms. The gravity term is added to the equation

for completeness. Dropping asterisks(*) for clarity, 3.23 becomes

$$\begin{aligned} \frac{\rho R L_s^2}{2\sigma t_s^2} \left(\left(\ell + \frac{L_0}{L_s} + \mathbb{C}_1 \frac{R}{L_s} \right) \ddot{\ell} + \mathbb{C}_2 \dot{\ell}^2 \right) + \frac{4\mu L_s^2}{\sigma R t_s} \left(\ell + \frac{L_0}{L_s} + \frac{R}{4L_s} \right) \dot{\ell} + \frac{\rho g R L_s}{2\sigma} \ell \\ = 1 - 2 \tanh \left(\left(\frac{\mathbb{C}_4 \mu}{\sigma} \frac{L_s}{t_s} \dot{\ell} \right)^{0.702} \right) \left(1 - \exp \left[\frac{-\mathbb{C}_3 t_s t}{\tau_r} \right] \right) - \frac{R}{2R_c}. \end{aligned} \quad (3.25)$$

By introducing dimensionless quantities such as modified Bond number $\text{Bo}^+ = \frac{\rho g R L_s}{2\sigma}$, Capillary number $\text{Ca} = \frac{\mu L_s}{\sigma t_s}$, modified Capillary number $\text{Ca}^+ = \frac{\mu L_s^2}{\sigma R t_s}$, modified Weber number $\text{We}^+ = \frac{\rho R L_s^2}{\sigma t_s^2}$, and geometric parameters $L_1 = \frac{L_0}{L_t}$ and $L_2 = \frac{R}{L_t}$, Eq. 3.25 is rewritten as

$$\begin{aligned} \frac{\text{We}^+}{2} \left((\ell + L_1 + \mathbb{C}_1 L_2) \ddot{\ell} + \mathbb{C}_2 \dot{\ell}^2 \right) + 4\text{Ca}^+ \left(\ell + L_1 + \frac{L_2}{4} \right) \dot{\ell} + \text{Bo}^+ \ell \\ = 1 - 2 \tanh \left((\mathbb{C}_4 \text{Ca} \dot{\ell})^{0.702} \right) \left(1 - \exp \left[-\frac{\mathbb{C}_3}{\text{We}^{+1/2}} t \right] \right) - \frac{R}{2R_c}. \end{aligned} \quad (3.26)$$

Equation 3.26 is a second order nonlinear differential equation with seven parameters. For experiments conducted herein the ranges for expected empirical values of the parameters in Eq. 3.25 are listed in table 3.1, where small terms are identifiable that may be successfully neglected at $\mathcal{O}(1)$. Because $\mathbb{C}_3 \text{We}^{+1/2} \gg 1$, the meniscus re-orientation time is short compared to the total time of the flow. Thus the driving force is ‘turned on’ quickly and $s(t)$ rapidly approaches unity. For small enough velocities, $\cos \theta_d \approx \cos \theta \approx \text{constant}$. Assuming $L_0/L_t \ll 1$, $\mathbb{C}_1 R/L_t \ll 1$, $R/4L_t \ll 1$, $\text{Bo}^+ \ll 1$, $s(t) \approx 1$, Eq. 3.26 reduces to the general form of the Lucas-Washburn Eq. 3.17,

$$\frac{\rho R L_s^2}{2\sigma t_s^2} (\ell \ddot{\ell} + \mathbb{C}_2 \dot{\ell}^2) + \frac{4\mu L_s^2}{\sigma R t_s} \ell \dot{\ell} = \cos \theta_d. \quad (3.27)$$

Table 3.1: Experimental range of parameters

Term	Range
L_1	$0.05 \leq L_0/L_t \leq 0.11$
$C_1 L_2$	$0.26 \leq C_1 R/L_t \leq 0.53$
$L_2/4$	$0.01 \leq R/4L_s \leq 0.05$
Bo^+	$0.003 \leq \text{Bo}^+ \leq 0.02$
$R/2R_c$	$R/2R_c \ll 10^{-3}$
$\mathbb{C}_4 \text{Ca}$	$0.016 \leq \mathbb{C}_4 \text{Ca} \leq 0.119$
$\mathbb{C}_3/\text{We}^{+1/2}$	$8.97 \leq \mathbb{C}_3/\text{We}^{+1/2} \leq 20.2$
Ca	$1.8 \times 10^{-3} \leq \text{Ca} \leq 12.8 \times 10^{-3}$
Ca^+	$0.008 \leq \text{Ca}^+ \leq 0.181$
Su^+	$1.15 \leq \text{Su}^+ \leq 2.85 \times 10^3$
We^+	$0.303 \leq \text{We}^+ \leq 1.54$

3.5.1 Time scale t_s

The scale equation balance of 3.27 is

$$\frac{\rho R L_s^2}{2\sigma t_s^2}, \frac{4\mu L_s^2}{\sigma R t_s}, \cos\theta_d \sim 0. \quad (3.28)$$

Scaling methods similar to those demonstrated in [167] are exploited to solve for time scale t_s to find

$$t_s = \frac{\mathbb{D}\rho R^2}{4\mu((1 + \text{Su}^+)^{1/2} - 1)} \equiv \frac{\mathbb{D}\rho R^2}{4\mu \text{F}_{\text{Su}^+}}, \quad (3.29)$$

where $\text{Su}^+ = \text{Su} \frac{\mathbb{D}R^2}{8L_s^2} \cos \theta_d$ is a modified Suratman number and $\text{Su} = \rho \sigma R / \mu^2$ is the Suratman number, where again θ_d is treated as constant. Evaluating 3.29 at the limit $\text{Su}^+ \ll 1$ gives $t_s = 4\mathbb{D} \frac{\mu}{\sigma} \frac{L_s^2}{R \cos \theta_d}$ and at the limit $\text{Su}^+ \gg 1$ gives $t_s = \mathbb{D} \left(\frac{\rho R L_s^2}{2\sigma \cos \theta_d} \right)^{1/2}$. $\mathbb{D}$ is an $\mathcal{O}(1)$ constant that allows some flexibility to improve the quantitative nature of the qualitative scaling approach.

3.5.2 Nondimensionalized simplified governing equation

Plugging 3.29 into 3.27 yields

$$\frac{\left((1 + \text{Su}^+)^{1/2} - 1\right)^2}{\text{Su}^+} (\ell \ddot{\ell} + \mathbb{C}_2 \dot{\ell}^2) + \frac{2\left((1 + \text{Su}^+)^{1/2} - 1\right)}{\text{Su}^+} \ell \dot{\ell} = 1, \quad (3.30)$$

The nondimensional governing equation is a second order nonlinear ordinary differential equation subject to boundary conditions $\ell(0) = 0$ and $\dot{\ell}(0) = 0$ with one parameter Su^+ . For capillarity-driven flow the characteristic velocity is $V \sim \sigma / \mu$ which reduces both Weber and Reynolds numbers to the Suratman number, the details of which are provided in appendix A.3. As desired, evaluating 3.30 at the limit $\text{Su}^+ \gg 1$, Eq. 3.30 simplifies to $\ell \ddot{\ell} + \mathbb{C}_2 \dot{\ell}^2 = 1$, Bernoulli's equation, and for $\text{Su}^+ \ll 1$, Eq. 3.30 simplifies to $\ell \dot{\ell} = 1$, the Lucas/Washburn equation in the viscous limit.

3.6 Analysis

Equation 3.30 is selected as the simplified model for 1-D capillary rise in a tube. Equation 3.30 is scaled such that the length scale L_s is the length of the tube L_t . The variable ℓ becomes the fractional position of the length of the tube where $\ell = 0$ is the free surface reservoir height and $\ell = 1$ is the end of the tube. t_t is the time it takes for the fluid to

reach the end of the tube where $\ell = 1$. W_t is the velocity of the flow and $W_t(t_t)$ is the average dimensionless velocity of the flow at the end of the tube. Equation 3.30 is solved numerically using Mathematica 7 for various values of Su^+ . A plot of nondimensional position as a function of nondimensional time is shown in Fig. 3.11. Equation 3.30 is

Figure 3.11: Nondimensional rise for various Suratman numbers. The top of the tube is $\ell = 1$. For all values of Su^+ $\ell \sim \mathcal{O}(1)$ at $t \sim \mathcal{O}(1)$ and $\ell \approx 1$ as $Su^+ \rightarrow \infty$.

solved numerically for ℓ , $\dot{\ell}$, and t from which these variables are evaluated at the tube end for various Su^+ . Figure 3.12 shows the desired result that t_t and $W_t(t_t)$ are fairly independent of Su^+ for $Su^+ \gg 1$ as each quantity asymptotically approaches 1.118 and 0.8944, respectively. The $\mathcal{O}(1)$ results suggest that by choosing $\mathbb{D} = 1.118$, $W_t = t_t = 1$ for $Su^+ \gg 1$. The fact that $\mathbb{D} \approx 1$ argues favorably for the Su^+ scaling. Figure 3.13 verifies that solving Eq. 3.30 for t_t and $W_t(t_t)$ collapses to 1 as $Su^+ \rightarrow \infty$.

Figure 3.12: Values of t_t and W_t as a function of Su^+ from Eq. 3.30 with $\mathbb{D} = 1$. Both converge to a constant $\mathcal{O}(1)$ value. The experimental range $1.1 < Su^+ < 2.9 \times 10^3$ is noted.

Figure 3.13: Values of t_t and W_t as a function of Su^+ from Eq. 3.30 with $\mathbb{D} = 1.118$. For $Su^+ \rightarrow \infty$, $W_t \rightarrow 1$. The experimental range $1.1 < Su^+ < 2.9 \times 10^3$ is noted.

3.6.1 The complete nondimensional model

Plugging Eq. 3.29 into Eq. 3.25 and selecting $L_s = L_t$, and parameters L_1 , L_2 , and F_{Su^+} , the complete nondimensionalized force balance is written,

$$\begin{aligned} \frac{F_{Su^+}^2}{\mathbb{D}^2 Su^+} ((\ell + L_1 + \mathbb{C}_1 L_2) \ddot{\ell} + \mathbb{C}_2 \dot{\ell}^2) + \frac{2F_{Su^+}}{\mathbb{D} Su^+} \left(\ell + L_1 + \frac{L_2}{4} \right) \dot{\ell} + Bo^+ \ell = \\ 1 - 2 \tanh \left(\left(\frac{\mathbb{C}_4 F_{Su^+} L_2}{2 \mathbb{D} Su^+} \dot{\ell} \right)^{0.702} \right) \left(1 - \exp \left[-\frac{\mathbb{C}_3 \mathbb{D}}{F_{Su^+} L_2} \left(\frac{Su^+}{2} \right)^{1/2} t \right] \right) - \frac{R}{2R_c}. \end{aligned} \quad (3.31)$$

There are four parameters in this equation: Su^+ , Bo^+ , and geometric parameters L_1 and L_2 . For convenience Table 3.2 summarizes the constants in Eq. 3.31. The numerical solution of Eq. 3.31 and 3.30 for velocity at the tube end show favorable agreement.

Table 3.2: Constants in nondimensionalized force balance Eq. 3.31

Constant	Value
$\mathbb{C}_1$	73/60
$\mathbb{C}_2$	5/6
$\mathbb{C}_3$	11.138
$\mathbb{C}_4$	9.246
$\mathbb{D}$	1.118

3.6.2 Alternative dimensional scaled equation for capillary rise

Because the nondimensional equations suggest that the dimensionless length of the tube, the time it takes the flow to get to the end of the tube, and the velocity of the flow at the end of the tube are approximately equal to 1, further manipulation of the scales yields convenient dimensional design tools for determining critical geometry for tubes used in auto-ejection experiments. Appendix A.2 contains additional derivation

details. Since

$$\frac{t}{t_s} = \frac{4\mu F_{\text{Su}^+}}{\mathbb{D}\rho R^2} = 1, \quad (3.32)$$

solving for L_s yields

$$L_s = \left(\frac{2R\sigma \cos\theta_d}{\mathbb{D}\rho R^2 + 8\mu t} \right)^{1/2} t, \quad (3.33)$$

and

$$W_s = \frac{L_s}{t_s} = \frac{4L_s\mu F_{\text{Su}^+}}{\mathbb{D}\rho R^2}. \quad (3.34)$$

By substituting ℓ for the arbitrary length scale L_s , Eq. 3.33 becomes

$$\ell = \left(\frac{2R\sigma \cos\theta_d}{\mathbb{D}\rho R^2 + 8\mu t} \right)^{1/2} t, \quad (3.35)$$

when at small times $\ell \sim (2R\sigma \cos\theta_d/\mathbb{D}\rho R)^{1/2} t$, the linearly time-dependant convective inertial flow and at long times $\ell \sim (R\sigma \cos\theta_d/2\mu)^{1/2} t^{1/2}$, the diffusive viscous regime of Lucas-Washburn. Equation 3.35 can be used to quickly determine the length of the tube needed for ejection to occur at time t for a prescribed fluid and tube radius. Equations 3.35, 3.4, 3.34, and 3.15 provide useful design guides for capillarity-driven droplet ejection experiments and applications.

3.7 Experiments

Using the DDT, I conducted experiments with the help of two undergraduate assistances, to verify the scaling results. Additional experiments are conducted in a terrestrial lab and aboard the ISS.

3.7.1 Drop tower experiments

The drop tower tests follow the procedures described in appendix F. A user guide for the drop tower has also been developed by the author and is available upon request. Simax Glass tubes were employed (Northwest Technical Glass) with nozzles formed by heating the tube, pulling it in the axial direction, and grinding the tip smoothly. Cameras image the ensuing capillary rise at 60Hz or 400Hz depending on the camera used. Table 3.3 summarizes the cameras used during the experiments. Table 3.4 lists the tubes used for the drop tower experiments. Table 3.5 lists the fluids used.

Table 3.3: Cameras used to record experiments and demonstrations.

Manufacturer	Camera Model	Sensor	Frame Rate (fps)	Image Resolution	Where Used
Panasonic	HDC-TM700	CMOS	59.94	1080 x 1920	drop tower
Panasonic	HDC-TM900	CMOS	59.94	1080 x 1920	drop tower
Nikon	J1	CMOS	400	640 x 240	drop tower
Canon	XH G1	CCD	30	720 x 480	ISS
Phantom	v4.3	CMOS	1200	800 x 600	lab bench
Phantom	v4.3	CMOS	1942	640 x 480	lab bench

Figure 3.14 shows an annotated schematic and photograph of the experiment rig. Over 200 experiments are conducted. Strict procedures are followed to minimize fluid contamination and the number of external uncontrolled variables. The glass tubes are washed with warm soapy water and rinsed with methanol at the beginning of each day. The tubes are air dried. After dried, the tubes' exterior walls are coated with 3M's Polytetrafluoroethylene (PTFE) barrier coating FC-724 to minimize the liquid rise outside the tube and reduce the curvature of the liquid in the reservoir. The FC-724 cures for 20 minutes before the tubes are placed in their respective tube mounts. Fig. 3.15 provides a photograph of the tube mounting. The mounting scheme selected helps

Table 3.4: Glass tubes used in drop tower experiments. (dimensions in mm)

ID	Total Length L	Tube Length L_t	Nozzle Length L_n	Tube Diam. D_t	Nozzle Diam. D_n	Tube Radius R_t	Nozzle Radius R_n	Tube OD	Tube Label
23	60.47	47.74	12.73	5.91	1.26	2.955	0.63	9.04	*NOZZLE 9X1.25
24	60.36	49.88	10.48	5.97	2.51	2.985	1.255	9.06	*NOZZLE 9X2.5
25	60.48	46.67	13.81	5.93	3.75	2.965	1.875	9.02	*NOZZLE 9X3.75
26	60.53	47.8	12.73	9.48	2.51	4.74	1.255	13.96	*NOZZLE 14X2.5
27	60.49	47.17	13.32	9.53	5.03	4.765	2.515	13.96	*NOZZLE 14X5.0
28	60.61	49.42	11.19	9.51	7.53	4.755	3.765	13.96	*NOZZLE 14X7.5
29	114.12	107.9	6.22	9.64	2.57	4.82	1.285	13.96	*NOZZLE 14X2.5B
30	114.13	108.69	5.44	9.61	4.94	4.805	2.47	13.96	*NOZZLE 14X5.0B
31	114.23	108.61	5.62	9.51	7.41	4.755	3.705	13.96	*NOZZLE 14X7.5B
32	120.31	109.08	11.23	15.4	3.74	7.7	1.87	18.93	*NOZZLE 19X3.75
33	120.21	108.4	11.81	15.45	7.53	7.725	3.765	18.93	*NOZZLE 19X7.5
34	120.5	108.79	11.71	15.43	11.19	7.715	5.595	18.93	*NOZZLE 19X11.2
35	60.64	48.98	11.66	20.29	10	10.145	5	23.92	*NOZZLE 24X5.0
36	60.42	47.54	12.88	20.27	5.06	10.135	2.53	23.92	*NOZZLE 24X10
37	60.65	50.3	10.35	20.23	14.96	10.115	7.48	23.92	*NOZZLE 24X15

Table 3.5: Dow Corning PDMS test fluids used in drop tower experiments.

$\nu \pm 2\%$ (cS)	$\rho \pm 5$ (kg m ⁻³)	$\sigma \pm 5\%$ (kg s ⁻²)	μ (kg m ⁻¹ s ⁻¹)
0.65	760	0.0159	0.000494
1.0	816	0.0174	0.000816
2.0	872	0.0187	0.001744
5.0	913	0.0197	0.004565
10.0	935	0.0201	0.00935
20.0	949	0.0206	0.01898

Figure 3.14: Drop tower experiment setup: (A) Schematic and (B) photograph. At one end of the (1) ER main body a (2) camera is mounted and supported by a (3) mount. At the opposite end sits the (4) light panel and (5) splash shield. Inside the splash shield sits the (6) fluid reservoir and (7) light shield. The (8) glass tubes are mounted in a (9) tube mount and placed in the reservoir. An (10) onboard battery powers the light panel and (11) weights are adjusted to assure a level ER.

to minimize L_1 and maximize R_c (see §3.4). The number of tubes tested per drop are determined by the tube's outer diameter. If the tubes are too close liquid rises between them and potentially interferes with the overall capillary rise rates [13,20]. A light shield for each tube reduces peripheral reflection and improves image quality significantly. Careful attention is paid to the list of common errors described in Appendix E.7 ensuring quality images. Experiments are not randomized but are ordered to minimize

Figure 3.15: Tube #36 in tube mount.

transition time between test fluids. The flow chart in Fig. 3.16 provides a best practice work flow to minimize the number of experiments conducted, each of which is repeated at least three times.

Figure 3.16: Experimental procedure flowchart.

3.7.2 $1g_0$ Experiments

As a proof of concept, terrestrial experiments are conducted in the Surface Tension Lab at Portland State University. Capillary rise in tube arrays hand drilled into acrylic blocks can be seen in Fig. 3.17. The necessary hardware for these $1g_0$ experiments

Figure 3.17: $1g_0$ capillarity-driven droplet ejection. Images taken by high speed camera at 1942fps.

include a high speed camera, parallel light source, fluid reservoir, precision lab jack, vibration isolation table, and tubes with nozzles machined into acrylic blocks. Figure 3.18 shows an annotated schematic and photograph of the experiment setup. The high speed camera sits opposite a parallel light source. The remaining experimental equipment sits between the two on top of the vibration isolation table. The machined acrylic block is mounted above the lab jack and the fluid reservoir. The reservoir is filled to

(A)

(B)

Figure 3.18: $1g_0$ experiment setup: (A) Schematic and (B) photograph. The experiment is set up on an (4) isolation table. Using a (1) high speed camera opposite a (5) parallel light source. Between the camera and light source the (6) acrylic block is mounted. Below the block the (2) reservoir sits on top of a (3) precision lab jack.

the brim with test fluid 0.65 cS PDMS and placed on the lab jack. The jack is slowly raised toward the block containing the capillary holes. Eventually the liquid from the reservoir makes contact with the block whereupon the fluid wicks along the base of the block and rises up the machined capillary holes. The liquid accelerates at the nozzles and ejects. The high speed camera is triggered via computer and the footage is cropped to include only the ejection. The acrylic block is emptied, air dried with an air hose, remounted, and tests repeated. Fig. 3.17 displays the $1g_0$ capillarity-driven droplet ejection.

3.7.3 ISS experiments

United States Astronaut Don Pettit was emailed a request to demonstrate capillarity-driven droplet ejection aboard the ISS. He complied with astonishing results. Figure 3.19 depicts capillarity-driven droplet ejection of water aboard the ISS.

Figure 3.19: Capillarity driven droplet ejection aboard the ISS. Images taken at 30 Hz.

The tube was hand made by Pettit using the procedure outlined in appendix E.2 [114]. Additional equipment includes a piece of paper, a camera, a wire loop, and water. Figure 3.20 shows an annotated schematic and photograph of the experiment setup. Pettit's describes his methods [114]:

I made a 110mm tube from my 3M color laser printer sheets (you have some of these, I gave you some a few years ago) 25mm diameter and necked it down to 10mm using an orange peel splice. It was held together with kapton tape (on the outside). These are the same sheets that our 0g cup is made from (I have made six more and will video a crew toast).

When the open end was place in a 50mm diameter sphere of water, it shot a single 10mm sphere. I have good video and will work on making it small enough to e-mail. I will downlink the HD when I get the chance. I took a few quick stills, lo-res images attached.

This is exciting stuff. You should be here.

Figure 3.20: Space experiment aboard the ISS setup. (A) Schematic and (B) photograph of the experiment setup. The (1) camera is mounted orthogonal to (2) a white piece of paper. The (3) spherical reservoir is held in place by (4) the wire loop. The (5) tube is manipulated by Pettit in all experiments.

3.7.4 Data collection, organization, reduction, and error analysis

Details of data collection and organization can be found in appendix F. The video camera images are uniquely named and archived on the DDT lab's network storage drive. Additional experimental details are tabulated on a spreadsheet (see Appendix B). Data entered for each experiment includes test fluid, tube ID number, tube position in frame, tube submerged depth L_0 , number of ejected drops, tube tilt, scale factor of the image, image size, frame rate of the camera used, location of the reservoir interface, tube and nozzle end, and the amount the image shifts during release. Additional data was gathered for select experiments such as ejected drop diameter. The complete experimental result spreadsheet can be seen in Appendix B.2.

Appendix C documents the detailed procedure and guidelines for data reduction. The video images are converted into a series of PNG still images. The image sequences of the rising meniscus for each tube for each drop was tracked and digitized using

NASA's Spotlight image analysis software [79]. The position of the meniscus center-line in each tube is tracked and converted to a digital coordinate. A MATLAB code (Appendix D) reads the Spotlight data file and calculates velocity using the central difference method. The MATLAB code accounts for skew between camera and tube. Errors due to distortion of the camera optics were measured and found to be at most 3%, but where usually much less and $\leq 1.5\%$ are typical.

3.8 Results

Data analysis establishes repeatability, control, and predictability of droplet auto-ejection.

3.8.1 Repeatability

An identical setup was used for 10 consecutive drops to gauge repeatability. Tube #36 (see table 3.4) at $L_0 = 5\text{mm}$ with 0.65cS PDMS is used for the repeatability analysis. Figure 3.21 and 3.22 show the position and velocity plot from the Spotlight data for the 10 tests. The ejected drop volumes from each experiment are measured and found to be $V_{\text{drop}} = 2.11 \pm 0.14\text{ml}$. Figure 3.23 shows all 10 drops side by side at $t = 1.95\text{s}$.

3.8.2 Control

Capillarity-driven ejected drops from tube #36 (see table 3.4) are analyzed to determine the controllability of the ejection. The nozzle size of each tube is the primary parameter controlling droplet size. Viscosity of the test fluid and the submerged length of the tube also play a roll. The tube is placed at different submerged lengths L_0 for every test fluid. The size of the ejected drop(s) are measured and averaged. Figure 3.24 is

Figure 3.21: Position of the meniscus centerline as a function of time for 10 consecutive drops or tube #36 partially submerged $L_0 = 5\text{mm}$ in 0.65sC PDMS. The meniscus appears to slow down when the contact line reaches the nozzle before speeding up. As only the lowest point of the meniscus is tracked, this behavior is expected.

a plot of drop diameter compared with submerged length. For a single test fluid, the drop volume increases as the submerged depth increases. In other words the drop volume increases with decreased liquid velocity. (Unless otherwise stated, the legend in table 3.6 translates symbols used in plots found in this chapter.)

I also examine the effects of test fluid viscosity on ejected drop volume. Figure 3.25 shows a plot of ejected drop volume and test liquid viscosity. As the viscosity of the fluid increases the drop size increases. Again, drop volume increases with decreased liquid velocity.

Figure 3.22: Velocity of the meniscus centerline as a function of time for 10 consecutive drops or tube #36 partially submerged $L_0 = 5\text{mm}$ in 0.65sC PDMS. Before the contact line reaches the nozzle, the velocity levels out at a constant value $\sim 49\text{mm s}^{-1}$.

Figure 3.23: 10 consecutive drops or tube #36 partially submerged $L_0 = 5\text{mm}$ in 0.65sC PDMS. Images shown at 1.95s after ER release.

Table 3.6: Plot legend for §3.8

Symbol	Meaning
○	No droplets ejected
●	1 droplet ejected
●	2 droplets ejected
●	3 or more droplets ejected
●	$\nu = 0.065\text{cS}$
◆	$\nu = 1\text{cS}$
■	$\nu = 2\text{cS}$
★	$\nu = 5\text{cS}$
◀	$\nu = 10\text{cS}$
▶	$\nu = 20\text{cS}$

Figure 3.24: Ejected drop volume with tube #36 submerged in 1cS PDMS at various depths L_0 . Drop volume increases with L_0 .

Figure 3.25: Ejected drop volume with tube #36 submerged 5mm in various viscosity PDMS fluids. Drop volume increases with ν .

3.8.3 Prediction

The predicted velocity is calculated using Eq. 3.35. Figure 3.26 shows analytical and experimental values of velocity on a scatter plot with the predicted values along the abscissa and the experimental values along the ordinate. A fairly linear relation between the experimental and analytical values for W_t is observed. Any deviation from a linear correlation between the experimental and the analytical predictions for the velocity are understood as shortcomings in the analysis. The percent difference between

Figure 3.26: Experimental vs analytical values of velocity.

the measured and predicted values for equation 3.4 are calculated using

$$\% \text{difference} = \frac{|\text{measured} - \text{predicted}|}{\text{measured}} \times 100. \quad (3.36)$$

Figure 3.27 shows the percent difference between experimental and analytical values for velocity. For fluids $\nu \leq 5\text{cS}$ the predicted behavior for condition 1 is $< 28\%$ different then the measured value with a standard deviation of 7.4. For higher viscosity fluids the error increases to $\leq 312\%$ with a standard deviation of 85.

Equation 3.4 and 3.13 are calculated for each experiment using the measured velocity at the tube end W_{exp} for the experimental condition and the analytically predicted

Figure 3.27: Discrepancy between experimental and analytical values of W_t vs fluid viscosity ν . See Table 3.6 for symbol interpretation.

scale velocity W_{tana} .

Figure 3.28 shows analytical and experimental values for equation 3.4 on a scatter plot with the predicted values along the abscissa and the experimental values along the ordinate on a log-log scale. A fairly linear relation between the experimental and analytical values for the short nozzle is observed. Any deviation from a linear correlation between the experimental and the analytical predictions for the short nozzle condition are understood as shortcomings in the prediction of velocity.

Figure 3.29 shows a plot of experimental vs. analytical values for Eq. 3.13 on a log-log scale. A linear relation between the experimental and analytical values for We^+

Figure 3.28: Regime map for auto-ejection under condition 1. Note the linear behavior of the plot suggesting accurate prediction from single parameter model. See Table 3.6 for symbol interpretation.

appears with a few major exceptions. In Eq. 3.13 the velocity is squared. The larger errors seen in Fig. 3.29 result from the error in velocity prediction also being squared. Figure 3.30 is an image sequence for capillary rise of two different fluids of different viscosities. The differences in contact angle and distortion of the interface in the nozzle are readily apparent. Not depicted in the image is the delay in rise of the 20cS fluid due to the longer reorientation time. Since the flow is slower through the nozzle for the 20cS PDMS, the nozzle is not as short as it is for the 0.65cS PDMS. The differences in contact angle, interface distortion, and velocity of the interface in the nozzle all attribute to

Figure 3.29: Regime map for auto-ejection under We^+ . Note the linear behavior of the plot suggesting accurate prediction from single parameter model for low viscosity fluids. See Table 3.6 for symbol interpretation.

the shortcomings of the simplified model used to predict the flow. Figure 3.31 presents Su^+ vs We^+ as a regime map for auto-ejection.

Using a simplified force balance model and deriving conditions for capillarity-driven droplet ejection, I have demonstrated possibility, repeatability, controllability, and predictability of capillarity-driven droplet ejection. Auto-ejection is clearly a viable method for drop-on-demand delivery system for microgravity droplet experiments.

Figure 3.30: Capillary rise of (A) 0.65cS PDMS and (B) 20cS PDMS in tube #35 at $L_0 = 5\text{mm}$. The dynamic contact angles between each experiment are drastically different. The higher viscosity fluid deforms less in the nozzle and the resulting capillary wave is damped out faster than for the less viscous fluid.

Figure 3.31: Su^+ vs We^+ regime map for droplet auto-ejection. For values of $We^+ \geq 12$ capillarity-driven droplet ejection is expected. See Table 3.6 for symbol interpretation.

3.9 Discussion

The conditions required for droplet auto-ejection are approximated using a scale analysis on a governing force balance equation and compared to experimental results. Discrepancies between theoretical and experimental velocities are due to these simplifications. The two major terms neglected in the scaled equation are the dynamic contact angle $\cos\theta_d$ and the entrance region loss coefficient $\mathbb{C}_1 L_2$. Both show an

$\mathcal{O}(1)$ presence but are neglected such that a regime map might be constructed with a single parameter Su^+ . Future work might consider improvements for $\cos\theta_d$ such as $1 - 2\tanh\theta_d \sim 1 - 2\theta_d + \mathcal{O}(\theta_d^3)$. The term $C_1 L_2$ could also be added back to the scaled equation but such complications compromise the desire for a wieldy closed form design tool for drop ejection. Future work should also consider developing a design tool that correlates drop volume to Su^+ . Equations 3.33, 3.4, and 3.15 provide sufficient accuracy for predicting capillarity-driven droplet ejection. If greater accuracy is desired, Eq. 3.31 should be used to predict velocity of flow in the tube W_t or the full flow problem should be solved with a suitable CFD approach.

3.10 Conclusion

Contrary to the conventional wisdom of the past 50 years, capillarity-driven droplet ejection is possible, predictable, repeatable, and a viable method for drop on demand delivery requirements that abound in microgravity research. Capillarity-driven droplet ejection is an alternative to current drop on demand technologies such as photo-acoustic [152], electro-generator (wire in nozzle) [3, 48], acoustic [23, 48, 100], syringe pump [24], pneumatic [28, 48], collapsing bubble [34, 35, 137, 155, 184], piezo-electric [40, 85], vibration [60, 71–73, 87, 154], MEMS [37, 57], liquid-liquid impacts [17, 52, 89, 103, 125, 126, 163, 174, 180], solid-liquid impact [6], and liquid-solid impact: [9, 126, 129, 133]. The technique described herein can be used as a means to study drop formation [2, 21, 26, 27, 37, 43, 46, 138], drip to jet transition [30, 148], jet breakup [15, 44, 45, 47, 58, 59, 66, 86, 91, 95, 101, 120–124, 138, 158, 159, 162], and droplet combustion [7, 29, 38, 53, 62, 63, 69, 70, 80, 83, 84, 96, 97, 102, 110, 179]. Drop impact, splash, rebound, satellites, adhesion and coalescence are ripe fields that could benefit

Figure 3.32: Tube #35 at $L_0 = 5\text{mm}$ in 2cS PDMS passively generates a liquid jet. The jet impacts a FC724 coated surface normal to the stream. Final frames detail the tail end of the jet impacting the surface and creating disturbances in the generated ‘pool’ which results in subsequent satellite drop ejection.

from this new approach. Figure 3.32 illustrates normal passive jet impingement on a coated surface normal to the jet stream. Numerical simulation will prove to increase prediction precision, but our purpose here is to demonstrate and quickly predict the phenomena. This approach provides design tools for future experiments. Work is continuing to develop passive droplet ejectors to study droplets in microgravity. An entry to the APS Gallery of Fluid Motion is being prepared for the 2012 meeting as well as an accompanying presentation [172]. Dissemination of this work also occurs in poster presentations [171], and pending presentations (COSPAR 2012) [170]. An overview article for journal publication is nearing completion for submission [173].

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Appendix A

Analytical details

A.1 Derivation of R_c

Figure 1.1: Cylindrical reservoir of radius R_r and height H

A cylindrical reservoir shown in figure 1.1 of radius R_r and height H filled to the brim such that the liquid pins to the top rim and is brimming. Surface tension forces hold the overfilled portion of the fluid to the top to a height $L_\sigma = (\sigma/\rho g)^{1/2}$

A capillary tube is placed vertically into the reservoir. As liquid rises in the capillary liquid is drawn out of the reservoir. In a microgravity environment, the surface of the liquid in the reservoir produces constant curvature. The volume $\mathcal{V}_{\text{cap}}$ is estimated as

$$\mathcal{V}_{\text{cap}} \approx \mathcal{V}_{\text{liquid in tube}} - \mathcal{V}_{\text{overflow}} \quad (1.1)$$

The volume of the spherical cap of height h is

$$\forall_{\text{cap}} = \frac{\pi h}{6} (3R_r^2 + h^2). \quad (1.2)$$

The volume of liquid in the cylindrical capillary of radius R_t at a height l is

$$\forall_{\text{liquid in tube}} = \pi R_t^2 l. \quad (1.3)$$

The volume of liquid in the overfilled section of the reservoir is

$$\forall_{\text{liquid in tube}} = \pi R_r^2 L_\sigma. \quad (1.4)$$

Plugging 1.2, 1.3, and 1.4 into 1.1 and solving for h , it yields 3 roots, only one of which is real:

$$h = -\frac{2R_r^2 + 2^{1/3}\tilde{\forall}^{2/3}}{2^{2/3}\tilde{\forall}^{1/3}}, \quad (1.5)$$

where $\tilde{\forall}(\ell) = -R_r^2 L_\sigma + 6R_t^2 \ell + \left(4R_r^6 + (R_c^2 L_\sigma - 6R_t^2 \ell)^2\right)^{1/2}$. The radius of the spherical cap can be written in terms of h and R_r

$$R_{\text{cap}} = \frac{R_r^2 + h^2}{2h}. \quad (1.6)$$

Substitute Eq. 1.5 into 1.6 yields

$$R_c(\ell) = \frac{R_r^4 - R_r^2 \tilde{\forall}^{2/3} + \tilde{\forall}^{4/3}}{2(-R_r^2 \tilde{\forall}^{1/3} + \tilde{\forall})}, \quad (1.7)$$

such that $R_c \gg R_t$ for all tests performed.

A.2 Derivation of approximate capillary rise model

Beginning with

$$\frac{t}{t_s} = \frac{4\mu \left((1 + \text{Su}^+)^{1/2} - 1 \right) t}{\rho R^2} \approx 1, \quad (1.8)$$

substituting Su^+ solving for L yields

$$\frac{\rho R^2}{4\mu \left((1 + \text{Su}^+)^{1/2} - 1 \right)} = t. \quad (1.9)$$

$$\text{Su}^+ = \left(1 + \frac{\rho R^2}{4\mu t} \right)^2 - 1 \quad (1.10)$$

Recalling that $\text{Su}^+ = \frac{\rho \sigma R}{\mu^2} \frac{R^2}{8L_s^2} \cos \theta_d$,

$$\frac{\rho \sigma R}{\mu^2} \frac{R^2}{8L_s^2} \cos \theta_d = \left(1 + \frac{\rho R^2}{4\mu t} \right)^2 - 1, \quad (1.11)$$

which reduces to

$$L_s = \left(\frac{\rho R^3 \sigma \cos \theta_d}{8\mu^2} \frac{1}{\left(1 + \frac{\rho R^2}{4\mu t} \right)^2 - 1} \right)^{1/2}, \quad (1.12)$$

$$L_s = \left(\frac{2\sigma \cos \theta_d R t^2}{R^2 \rho + 8\mu t} \right)^{1/2}, \quad (1.13)$$

where $\cos \theta_d$ is assumed to approach unity thus,

$$L_s = \left(\frac{2\sigma R t^2}{R^2 \rho + 8\mu t} \right)^{1/2}. \quad (1.14)$$

A.3 Dimensionless quantities manipulation

For viscous capillarity-driven flow the Capillary number

$$\text{Ca} \sim \frac{\mu V}{\sigma} \sim 1,$$

and the capillarity velocity scales $V \sim \frac{\sigma}{\mu}$. Plugging this velocity into the Weber number

$$\text{We} \sim \frac{\rho R V^2}{\sigma},$$

yields

$$\text{We} \sim \frac{\rho R}{\sigma} \frac{\sigma^2}{\mu^2},$$

which reduces to

$$\text{We} \sim \frac{\rho \sigma R}{\mu^2} \equiv \text{Su}.$$

Plugging the capillarity velocity into the Reynolds number

$$\text{Re} \sim \frac{\rho R V}{\mu},$$

yields

$$\text{Re} \sim \frac{\rho R}{\mu} \frac{\sigma}{\mu},$$

which reduces to

$$\text{Re} \sim \frac{\rho \sigma R}{\mu^2} \equiv \text{Su}.$$

Thus for viscous capillarity-driven flow $\text{Re} \sim \text{We} \sim \text{Su}$.

Appendix B

Experimental details

B.1 Drop tower experiment matrix

B.2 Drop tower result matrix

Table B.1: Experiment matrix. ‘x’ indicates experiment was conducted.

Liquid Used		0.65cS PDMS												1cS PDMS						2cS PDMS												
		L_{00}			L_{01}			L_{02}			L_{03}			L_{00}			L_{01}			L_{02}			L_{00}			L_{01}			L_{02}			
Submerged Length	Drop Number	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
*NOZZLE 9X1.25	x	x	x	x										x	x	x							x	x	x							
*NOZZLE 9X2.5	x	x	x											x	x	x							x	x	x							
*NOZZLE 9X3.75	x	x	x																													
*NOZZLE 14X2.5	x	x	x											x	x	x																
*NOZZLE 14X5.0	x	x	x											x	x	x																
*NOZZLE 14X7.5	x	x	x											x	x	x																
*NOZZLE 14X2.5B	x	x	x											x	x	x																
*NOZZLE 14X5.0B	x	x	x											x	x	x																
*NOZZLE 14X7.5B	x	x	x											x	x	x																
*NOZZLE 19X3.75	x	x	x											x	x	x																
*NOZZLE 19X7.5	x	x	x											x	x	x																
*NOZZLE 19X11.2	x	x	x											x	x	x																
*NOZZLE 24X5.0	x	x	x											x	x	x																
*NOZZLE 24X10	x	x	x											x	x	x																
*NOZZLE 24X15	x	x	x											x	x	x																

Liquid Used		5cS PDMS									10cS PDMS									20cS PDMS												
		L_{00}			L_{01}			L_{02}			L_{03}			L_{00}			L_{01}			L_{02}			L_{00}			L_{01}			L_{02}			
Submerged Length	Drop Number	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
*NOZZLE 9X1.25	x	x	x	x										x	x	x																
*NOZZLE 9X2.5	x	x	x											x	x	x																
*NOZZLE 9X3.75	x	x	x																													
*NOZZLE 14X2.5	x	x	x																													
*NOZZLE 14X5.0	x	x	x																													
*NOZZLE 14X7.5	x	x	x																													
*NOZZLE 14X2.5B	x	x	x																													
*NOZZLE 14X5.0B	x	x	x																													
*NOZZLE 14X7.5B	x	x	x																													
*NOZZLE 19X3.75	x	x	x																													
*NOZZLE 19X7.5	x	x	x																													
*NOZZLE 19X11.2	x	x	x																													
*NOZZLE 24X5.0	x	x	x																													
*NOZZLE 24X10	x	x	x																													
*NOZZLE 24X15	x	x	x																													

Table B.2: Results Matrix for experiments conducted with 0.65cS PDMS

Drop Name	Experiment Parameters				Measured	Image	height	width	Frame Rate	FSStart	Frame 1		Drop jitter
	Fluid	Tube	TubePos	Lnot							TubeEnd	NozzleEnd	
Drop_00922_DropEjection_PDMS_065_SubmergedLength_5mm_dry_3	1	25	1	5	179.89	87	1080	1920	59.94	1040	620	510	0
Drop_00922_DropEjection_PDMS_065_SubmergedLength_5mm_dry_3	1	24	2	5	179.42	87	1080	1920	59.94	1042	617	512	0
Drop_00922_DropEjection_PDMS_065_SubmergedLength_5mm_dry_3	1	23	3	5	178.31	87	1080	1920	59.94	1046	642	518	0
Drop_00923_DropEjection_PDMS_065_SubmergedLength_5mm_wet_3	1	25	1	5	179.69	76	1080	1920	59.94	1067	697	606	0
Drop_00923_DropEjection_PDMS_065_SubmergedLength_5mm_wet_3	1	24	2	5	179.23	76	1080	1920	59.94	1070	695	609	0
Drop_00923_DropEjection_PDMS_065_SubmergedLength_5mm_wet_3	1	23	3	5	176.76	75.06	1080	1920	59.94	1072	731	615	0
Drop_00924_DropEjection_PDMS_065_SubmergedLength_5mm_wet_3	1	25	1	5	178.91	71.01	1080	1920	59.94	1113	782	685	0
Drop_00924_DropEjection_PDMS_065_SubmergedLength_5mm_wet_3	1	24	2	5	178.60	71.01	1080	1920	59.94	1116	775	690	0
Drop_00924_DropEjection_PDMS_065_SubmergedLength_5mm_wet_3	1	23	3	5	176.77	71	1080	1920	59.94	1121	796	699	0
Drop_00925_DropEjection_PDMS_065_SubmergedLength_5mm_dry_2	1	27	1	5	180.35	157	1080	1920	59.94	1244	763	603	12
Drop_00925_DropEjection_PDMS_065_SubmergedLength_5mm_dry_2	1	26	2	5	180.00	157	1080	1920	59.94	1244	761	607	12
Drop_00926_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	27	1	5	180.00	150	1080	1920	59.94	1219	771	616	12
Drop_00926_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	26	2	5	179.34	150	1080	1920	59.94	1223	762	620	12
Drop_00927_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	27	1	5	179.51	151	1080	1920	59.94	1236	784	628	0
Drop_00927_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	26	2	5	179.05	151	1080	1920	59.94	1240	780	630	0
Drop_00928_DropEjection_PDMS_065_SubmergedLength_5mm_dry_2	1	28	1	5	179.27	106	1080	1920	59.94	1153	815	729	12
Drop_00928_DropEjection_PDMS_065_SubmergedLength_5mm_dry_2	1	29	2	5	179.77	106	1080	1920	59.94	1155	391	338	12
Drop_00929_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	28	1	5	179.32	103	1080	1920	59.94	1140	823	737	14
Drop_00929_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	29	2	5	179.37	103	1080	1920	59.94	1142	409	357	14
Drop_00930_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	28	1	5	178.87	102	1080	1920	59.94	1142	826	739	0
Drop_00930_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	29	2	5	179.02	102	1080	1920	59.94	1148	406	356	0
Drop_00931_DropEjection_PDMS_065_SubmergedLength_5mm_dry_2	1	31	1	5	179.53	103	1080	1920	59.94	1143	393	353	0
Drop_00931_DropEjection_PDMS_065_SubmergedLength_5mm_dry_2	1	30	2	5	180.00	103	1080	1920	59.94	1145	399	351	0
Drop_00932_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	31	1	5	179.40	104	1080	1920	59.94	1144	370	330	0
Drop_00932_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	30	2	5	180.33	104	1080	1920	59.94	1146	371	325	0
Drop_00933_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	31	1	5	180.63	107	1080	1920	59.94	1146	357	317	0
Drop_00933_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	30	2	5	180.36	107	1080	1920	59.94	1147	369	320	0
Drop_00934_DropEjection_PDMS_065_SubmergedLength_5mm_dry_2	1	33	1	5	179.58	142	1080	1920	59.94	1137	401	316	0
Drop_00934_DropEjection_PDMS_065_SubmergedLength_5mm_dry_2	1	32	2	5	180.26	140	1080	1920	59.94	1140	766	668	0
Drop_00935_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	33	1	5	179.71	141	1080	1920	59.94	1138	385	295	0
Drop_00935_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	32	2	5	179.37	141	1080	1920	59.94	1143	750	655	0
Drop_00936_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	33	1	5	179.13	137	1080	1920	59.94	1129	400	318	0
Drop_00936_DropEjection_PDMS_065_SubmergedLength_5mm_wet_2	1	32	2	5	179.42	137	1080	1920	59.94	1131	761	664	0
Drop_00941_DropEjection_PDMS_065_SubmergedLength_5mm_dry_1	1	34	1	5	179.66	159	1080	1920	59.94	1323	456	369	9
Drop_00942_DropEjection_PDMS_065_SubmergedLength_5mm_wet_1	1	34	1	5	179.47	167.07	1080	1920	59.94	1338	448	337	0
Drop_00943_DropEjection_PDMS_065_SubmergedLength_5mm_wet_1	1	34	1	5	178.97	165	1080	1920	59.94	1344	443	333	0
Drop_00944_DropEjection_PDMS_065_SubmergedLength_5mm_dry_1	1	35	1	5	179.37	296	1080	1920	59.94	1499	981	808	0
Drop_00945_DropEjection_PDMS_065_SubmergedLength_5mm_wet_1	1	35	1	5	178.26	296	1080	1920	59.94	1520	993	825	0
Drop_00946_DropEjection_PDMS_065_SubmergedLength_5mm_wet_1	1	35	1	5	180.34	297	1080	1920	59.94	1524	1020	836	20
Drop_00947_DropEjection_PDMS_065_SubmergedLength_5mm_dry_1	1	36	1	5	180.45	263	1080	1920	59.94	1524	872	712	13
Drop_00948_DropEjection_PDMS_065_SubmergedLength_5mm_wet_1	1	36	1	5	180.10	264	1080	1920	59.94	1331	865	718	0
Drop_00949_DropEjection_PDMS_065_SubmergedLength_5mm_wet_1	1	36	1	5	180.77	263	1080	1920	59.94	1340	874	724	13
Drop_00950_DropEjection_PDMS_065_SubmergedLength_5mm_dry_1	1	37	1	5	179.51	250	1080	1920	59.94	1326	855	732	0
Drop_00951_DropEjection_PDMS_065_SubmergedLength_5mm_wet_1	1	37	1	5	179.84	282	1080	1920	59.94	1373	848	711	0

Table B.3: Results Matrix for experiments conducted with 1cS PDMS.

Drop Name	Experiment Parameters			Results	Measured	Image	height	width	Frame Rate	FSStart	Frame 1		Drop litter
	Fluid	Tube	TubePos	Inot	DropNum	tilt					TubeEnd	NozzleEnd	
Drop_00953_DropEjection_PDMS_1_SubmergedLength_5mm_dry_2	2	24	1	5	2	180.38	108	1920	59.94	1378	857	728	13
Drop_00953_DropEjection_PDMS_1_SubmergedLength_5mm_dry_2	2	23	2	5	5	180.85	107	1920	59.94	1378	880	726	13
Drop_00954_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	24	1	5	2	179.90	109	1920	59.94	1392	871	737	12
Drop_00954_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	23	2	5	5	180.10	108	1920	59.94	1393	886	736	12
Drop_00955_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	24	1	5	2	179.91	109	1920	59.94	1401	875	745	14
Drop_00955_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	23	2	5	5	180.66	109	1920	59.94	1403	896	741	14
Drop_00956_DropEjection_PDMS_1_SubmergedLength_5mm_dry_2	2	27	1	5	1	179.59	164	1920	59.94	1396	918	743	12
Drop_00956_DropEjection_PDMS_1_SubmergedLength_5mm_dry_2	2	26	2	5	5	180.61	163	1920	59.94	1398	906	744	12
Drop_00957_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	27	1	5	1	179.76	165	1920	59.94	1408	925	753	15
Drop_00957_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	26	2	5	5	180.65	163	1920	59.94	1406	917	751	15
Drop_00958_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	27	1	5	1	180.00	162	1920	59.94	1422	936	762	-13
Drop_00958_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	26	2	5	5	180.45	166	1920	59.94	1426	931	766	-16
Drop_00959_DropEjection_PDMS_1_SubmergedLength_5mm_dry_2	2	30	1	5	2	180.00	118	1920	59.94	1290	423	373	0
Drop_00959_DropEjection_PDMS_1_SubmergedLength_5mm_dry_2	2	29	2	5	5	180.33	118	1920	59.94	1290	427	369	0
Drop_00960_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	30	1	5	2	180.20	118	1920	59.94	1294	430	383	0
Drop_00960_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	29	2	5	5	180.07	118	1920	59.94	1294	434	380	0
Drop_00961_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	30	1	5	3	180.00	118	1920	59.94	1295	431	383	0
Drop_00961_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	29	2	5	5	180.20	118	1920	59.94	1295	436	381	0
Drop_00962_DropEjection_PDMS_1_SubmergedLength_5mm_dry_2	2	33	1	5	0	180.13	136	1920	59.94	1293	448	346	0
Drop_00962_DropEjection_PDMS_1_SubmergedLength_5mm_dry_2	2	32	2	5	5	180.76	156	1920	59.94	1296	686	755	0
Drop_00963_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	33	1	5	0	180.30	162	1920	59.94	1300	438	351	12
Drop_00963_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	32	2	5	5	180.74	161	1920	59.94	1302	862	747	13
Drop_00964_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	33	1	5	0	180.12	165	1920	59.94	1310	417	306	0
Drop_00964_DropEjection_PDMS_1_SubmergedLength_5mm_wet_2	2	32	2	5	5	180.19	165	1920	59.94	1312	853	735	0
Drop_00965_DropEjection_PDMS_1_SubmergedLength_5mm_dry_1	2	35	1	5	5	179.91	304	1920	59.94	1475	966	772	14
Drop_00965_DropEjection_PDMS_1_SubmergedLength_5mm_wet_1	2	35	1	5	5	180.00	306	1920	59.94	1473	964	770	14
Drop_00967_DropEjection_PDMS_1_SubmergedLength_5mm_wet_1	2	35	1	5	5	180.00	273	1920	59.94	1427	967	795	15
Drop_00968_DropEjection_PDMS_1_SubmergedLength_5mm_dry_1	2	36	1	5	2	180.20	290	1920	59.94	1464	942	775	14
Drop_00969_DropEjection_PDMS_1_SubmergedLength_5mm_wet_1	2	36	1	5	2	179.90	290	1920	59.94	1469	949	778	14
Drop_00970_DropEjection_PDMS_1_SubmergedLength_5mm_wet_1	2	36	1	5	2	179.43	290	1920	59.94	1440	930	763	0

Table B.4: Results Matrix for experiments conducted with 2cS PDMS.

Drop Name	Fluid	Experiment Parameters			Results	Measured	Image	height	width	Frame Rate	FSStart	Frame 1		Drop Jitter
		Tube	TubePos	Lnot		tilt	SF					TubeEnd	NozzleEnd	
Drop_00973_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	24	1	5	2	179.70	112	1080	1920	59.94	1444	933	792	13
Drop_00973_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	23	2	5	5	179.60	112	1080	1920	59.94	1446	953	787	13
Drop_00974_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	24	1	5	2	180.44	114	1080	1920	59.94	1467	948	808	14
Drop_00974_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	23	2	5	5	180.27	114	1080	1920	59.94	1466	964	800	14
Drop_00975_DropEjection_PDMS_2_SubmergedLength_5mm_dry_2	3	24	1	5	1	180.44	113	1080	1920	59.94	1461	940	808	0
Drop_00975_DropEjection_PDMS_2_SubmergedLength_5mm_dry_2	3	23	2	5	4	180.22	113	1080	1920	59.94	1460	960	799	0
Drop_00976_DropEjection_PDMS_2_SubmergedLength_5mm_dry_2	3	27	1	5	0	179.74	169	1080	1920	59.94	1460	969	794	12
Drop_00976_DropEjection_PDMS_2_SubmergedLength_5mm_dry_2	3	26	2	5	4	180.11	169	1080	1920	59.94	1461	958	791	12
Drop_00977_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	27	1	5	0	179.69	170	1080	1920	59.94	1465	967	791	0
Drop_00977_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	26	2	5	4	180.10	170	1080	1920	59.94	1466	959	790	0
Drop_00978_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	27	1	5	0	179.79	170	1080	1920	59.94	1471	973	795	0
Drop_00978_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	26	2	5	4	180.53	170	1080	1920	59.94	1471	966	792	0
Drop_00979_DropEjection_PDMS_2_SubmergedLength_5mm_dry_2	3	30	1	5	0	179.87	119	1080	1920	59.94	1322	452	400	13
Drop_00979_DropEjection_PDMS_2_SubmergedLength_5mm_dry_2	3	29	2	5	1	180.54	119	1080	1920	59.94	1323	460	399	13
Drop_00980_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	30	1	5	1	179.94	118	1080	1920	59.94	1323	452	399	0
Drop_00980_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	29	2	5	5	180.46	118	1080	1920	59.94	1322	459	394	0
Drop_00981_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	30	1	5	1	179.75	118	1080	1920	59.94	1322	456	408	0
Drop_00981_DropEjection_PDMS_2_SubmergedLength_5mm_wet_2	3	29	2	5	5	180.37	118	1080	1920	59.94	1320	464	402	0
Drop_00982_DropEjection_PDMS_2_SubmergedLength_5mm_dry_1	3	32	1	5	5	180.22	169	1080	1920	59.94	1338	886	767	14
Drop_00983_DropEjection_PDMS_2_SubmergedLength_5mm_wet_1	3	32	1	5	5	180.10	169	1080	1920	59.94	1343	889	768	-7
Drop_00984_DropEjection_PDMS_2_SubmergedLength_5mm_wet_1	3	32	1	5	5	180.13	169	1080	1920	59.94	1339	891	767	13
Drop_00985_DropEjection_PDMS_2_SubmergedLength_5mm_dry_1	3	35	1	5	5	180.18	299	1080	1920	59.94	1487	986	796	15
Drop_00986_DropEjection_PDMS_2_SubmergedLength_5mm_wet_1	3	35	1	5	5	180.00	296	1080	1920	59.94	1484	969	797	14
Drop_00988_DropEjection_PDMS_2_SubmergedLength_5mm_wet_1	3	35	1	5	5	180.18	301	1080	1920	59.94	1488	980	793	0
Drop_00989_DropEjection_PDMS_2_SubmergedLength_5mm_dry_1	3	36	1	5	1	179.67	292	1080	1920	59.94	1451	941	775	15
Drop_00990_DropEjection_PDMS_2_SubmergedLength_5mm_wet_1	3	36	1	5	1	180.00	298	1080	1920	59.94	1469	952	774	15
Drop_00991_DropEjection_PDMS_2_SubmergedLength_5mm_wet_1	3	36	1	5	1	180.00	298	1080	1920	59.94	1481	958	782	0

Table B.5: Results Matrix for experiments conducted with 5-20cS PDMS.

Drop Name	Fluid	Experiment Parameters	Results	Measured	Image	width	Frame Rate	Frame 1 TubeEnd	NozzleEnd	Drop Jitter				
Drop_00997_DropEjection_PDMS_5_SubmergedLength_5mm_dry_2	4	24	1	5	0	180.31	109	1080	1920	59.94	1459	967	832	13
Drop_00997_DropEjection_PDMS_5_SubmergedLength_5mm_dry_2	4	23	2	5	0	180.34	109	1080	1920	59.94	1461	982	825	13
Drop_00998_DropEjection_PDMS_5_SubmergedLength_5mm_wet_2	4	24	1	5	0	180.54	112	1080	1920	59.94	1465	967	831	0
Drop_00998_DropEjection_PDMS_5_SubmergedLength_5mm_wet_2	4	23	2	5	1	180.86	112	1080	1920	59.94	1465	978	824	0
Drop_00999_DropEjection_PDMS_5_SubmergedLength_5mm_wet_2	4	24	1	5	0	180.23	110	1080	1920	59.94	1460	964	831	14
Drop_00999_DropEjection_PDMS_5_SubmergedLength_5mm_wet_2	4	23	2	5	1	180.18	109	1080	1920	59.94	1459	985	828	14
Drop_01000_DropEjection_PDMS_5_SubmergedLength_5mm_dry_1	4	26	1	5	1	179.38	174	1080	1920	59.94	1483	968	805	1
Drop_01001_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	26	1	5	2	179.56	175	1080	1920	59.94	1480	964	798	0
Drop_01002_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	26	1	5	2	179.39	174	1080	1920	59.94	1475	966	795	0
Drop_01006_DropEjection_PDMS_5_SubmergedLength_5mm_dry_1	4	32	1	5	3	180.97	166	1080	1920	59.94	1348	902	784	1
Drop_01007_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	32	1	5	3	180.67	167	1080	1920	59.94	1345	895	787	14
Drop_01008_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	32	1	5	3	180.34	167	1080	1920	59.94	1342	896	783	14
Drop_01009_DropEjection_PDMS_5_SubmergedLength_5mm_dry_1	4	35	1	5	3	179.83	288	1080	1920	59.94	1492	989	823	0
Drop_01010_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	35	1	5	2	180.58	290	1080	1920	59.94	1496	1010	833	0
Drop_01011_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	35	1	5	2	179.63	302	1080	1920	59.94	1519	998	822	1
Drop_01012_DropEjection_PDMS_5_SubmergedLength_5mm_dry_1	4	36	1	5	0	180.18	290	1080	1920	59.94	1498	982	822	1
Drop_01013_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.64	290	1080	1920	59.94	1506	984	826	15
Drop_01014_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.64	293	1080	1920	59.94	1514	988	830	15
Drop_01020_DropEjection_PDMS_10_SubmergedLength_5mm_dry_1	5	23	1	5	0	180.00	99	1080	1920	59.94	1362	943	807	0
Drop_01021_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	23	1	5	0	180.00	113	1080	1920	59.94	1426	990	825	0
Drop_01022_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	23	1	5	0	179.66	113	1080	1920	59.94	1445	1013	850	14
Drop_01023_DropEjection_PDMS_10_SubmergedLength_5mm_dry_1	5	26	1	5	0	180.18	146	1080	1920	59.94	1371	949	803	14
Drop_01024_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	26	1	5	0	180.15	164	1080	1920	59.94	1411	941	774	15
Drop_01025_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	26	1	5	0	180.00	163	1080	1920	59.94	1420	944	782	15
Drop_01026_DropEjection_PDMS_10_SubmergedLength_5mm_dry_1	5	32	1	5	1	179.85	212	1080	1920	59.94	1428	868	713	15
Drop_01027_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	32	1	5	2	180.42	224	1080	1920	59.94	1442	851	689	15
Drop_01028_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	32	1	5	2	180.33	227	1080	1920	59.94	1447	857	691	15
Drop_01029_DropEjection_PDMS_10_SubmergedLength_5mm_dry_1	5	35	1	5	2	180.21	305	1080	1920	59.94	1482	975	787	14
Drop_01030_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	35	1	5	3	180.19	298	1080	1920	59.94	1230	730	551	16
Drop_01031_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	35	1	5	3	180.25	299	1080	1920	59.94	1250	751	571	1
Drop_01032_DropEjection_PDMS_10_SubmergedLength_5mm_dry_1	5	36	1	5	0	180.17	304	1080	1920	59.94	1271	753	583	14
Drop_01033_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	36	1	5	0	180.17	306	1080	1920	59.94	1274	762	582	15
Drop_01034_DropEjection_PDMS_10_SubmergedLength_5mm_wet_1	5	36	1	5	0	180.33	305	1080	1920	59.94	1282	763	586	15
Drop_01044_DropEjection_PDMS_20_SubmergedLength_5mm_dry_1	6	35	1	5	0	180.18	298	1080	1920	59.94	1326	846	658	15
Drop_01045_DropEjection_PDMS_20_SubmergedLength_5mm_wet_1	6	35	1	5	0	180.54	280	1080	1920	59.94	1307	866	699	15
Drop_01046_DropEjection_PDMS_20_SubmergedLength_5mm_wet_1	6	35	1	5	0	180.19	280	1080	1920	59.94	1297	861	690	0
Drop_01077_DropEjection_PDMS_5_SubmergedLength_5mm_dry_1	4	36	1	5	0	179.79	273	1080	1920	59.94	1170	706	552	13
Drop_01078_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.10	264	1080	1920	59.94	1167	709	565	0
Drop_01079_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.69	275	1080	1920	59.94	1211	750	590	15
Drop_01080_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.39	285	1080	1920	59.94	1267	793	625	14
Drop_01081_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.55	288	1080	1920	59.94	1266	783	625	15
Drop_01083_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.62	267	1080	1920	59.94	1179	713	563	17
Drop_01084_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.53	272	1080	1920	59.94	1254	783	634	18
Drop_01087_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	179.74	275	1080	1920	59.94	1208	723	581	1
Drop_01088_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.77	275	1080	1920	59.94	1241	770	617	18
Drop_01089_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.71	298	1080	1920	59.94	1315	801	640	18
Drop_01090_DropEjection_PDMS_5_SubmergedLength_5mm_wet_1	4	36	1	5	1	180.80	295	1080	1920	59.94	1327	811	652	1

Table B.6: Results Matrix for experiments conducted with 0.65cS PDMS and different L_0 .

Drop Name	Experiment Parameters			Results		Measured tilt	Image SF	height	width	Frame		Frame l TubeEnd	NozzleEnd	Drop jitter
	Fluid	Tube	TubePos	Lnot	DropNum					Rate	FSStart			
Drop_00952_DropEjection_PDMS_065_SubmergedLength_5mm_wet_L	1	37	1	5	0	179.32	282	1080	1920	59.94	1390	862	724	15
Drop_01110_DropEjection_PDMS_065_SubmergedLength_5mm_dry_6	1	38	1	5	0	180.00	52	1080	1920	59.94	1552	1278	1246	17
Drop_01110_DropEjection_PDMS_065_SubmergedLength_5mm_dry_6	1	39	2	5	0	180.00	52	1080	1920	59.94	1554	1277	1251	17
Drop_01110_DropEjection_PDMS_065_SubmergedLength_5mm_dry_6	1	40	3	5	3	179.25	52	1080	1920	59.94	1555	1292	1257	17
Drop_01110_DropEjection_PDMS_065_SubmergedLength_5mm_dry_6	1	41	4	5	2	179.46	52	1080	1920	59.94	1554	1298	1257	17
Drop_01110_DropEjection_PDMS_065_SubmergedLength_5mm_dry_6	1	42	5	5	5	180.00	52	1080	1920	59.94	1557	1298	1253	17
Drop_01110_DropEjection_PDMS_065_SubmergedLength_5mm_dry_6	1	43	6	5	5	179.51	52	1080	1920	59.94	1559	1316	1254	17
Drop_01111_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	38	1	5	0	179.02	48	1080	1920	59.94	1548	1295	1268	15
Drop_01111_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	39	2	5	0	180.40	48	1080	1920	59.94	1549	1293	1270	15
Drop_01111_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	40	3	5	2	180.20	48	1080	1920	59.94	1549	1316	1281	15
Drop_01111_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	41	4	5	2	180.20	48	1080	1920	59.94	1550	1310	1275	15
Drop_01111_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	42	5	5	5	179.21	48	1080	1920	59.94	1550	1313	1270	15
Drop_01111_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	43	6	5	5	179.60	48	1080	1920	59.94	1550	1328	1270	15
Drop_01112_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	38	1	5	0	179.33	50	1080	1920	59.94	1604	1336	1305	6
Drop_01112_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	39	2	5	0	180.00	50	1080	1920	59.94	1604	1334	1307	6
Drop_01112_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	40	3	5	2	180.22	50	1080	1920	59.94	1605	1343	1306	6
Drop_01112_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	41	4	5	2	180.00	50	1080	1920	59.94	1606	1354	1313	6
Drop_01112_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	42	5	5	5	179.57	50	1080	1920	59.94	1606	1352	1307	6
Drop_01112_DropEjection_PDMS_065_SubmergedLength_5mm_wet_6	1	43	6	5	5	179.55	50	1080	1920	59.94	1607	1371	1307	6
Drop_01113_DropEjection_PDMS_065_SubmergedLength_5mm_dry_3	1	44	1	5	1	179.42	117	1080	1920	59.94	1603	1336	1302	0
Drop_01113_DropEjection_PDMS_065_SubmergedLength_5mm_dry_3	1	45	2	5	4	179.77	117	1080	1920	59.94	1606	1342	1303	0
Drop_01113_DropEjection_PDMS_065_SubmergedLength_5mm_dry_3	1	46	3	5	5	180.23	117	1080	1920	59.94	1607	1358	1299	0
Drop_01114_DropEjection_PDMS_065_SubmergedLength_5mm_wet_3	1	44	1	5	1	179.78	119	1080	1920	59.94	1621	1354	1322	17
Drop_01114_DropEjection_PDMS_065_SubmergedLength_5mm_wet_3	1	45	2	5	3	179.77	119	1080	1920	59.94	1623	1359	1321	17
Drop_01114_DropEjection_PDMS_065_SubmergedLength_5mm_wet_3	1	46	3	5	5	179.55	119	1080	1920	59.94	1625	1394	1330	17

Appendix C

Data Reduction Details

C.1 Overview

Data reduction is a critical part of the experimental process and this section is written as a ‘how to’ manual for future investigations. Below are details on how reduction of data is conducted for the drop tower experiments described in section 3.7.

C.2 Video Conversion

The Drop videos are uploaded to the network area storage (NAS) by following the procedure in appendix E5. Video conversion is done by following the procedure in appendix E6.

C.3 Experimental Result Matrix

The experiment matrix (appendix B.1) records what experiments are conducted. The experimental result matrix is a spreadsheet that lists results and critical experimental parameters used in the data analysis stage. The experimental result matrix is located on the NAS at Z:\Projects\test\ExpMatrix.xlsx. As data are reduced, the fields in this matrix are filled in. The experiment result matrix can be seen in B.2. The column headings are described in detail in the following subsections.

C.3.1 Drop Name

The Drop Name column has the name of the drop, not the name of the experiment. Since one drop can consist of multiple experiments, it is important not to confuse the two.

C.3.2 Fluid

The Fluid column is where the fluid used in the experiment is recorded. The ID number representing the fluid is selected from the table in table C.1.

Table C.1: Fluid Names and ID numbers

Fluid	
Name	ID num
0.65 cS PDMS	1
1 cS PDMS	2
2 cS PDMS	3
5 cS PDMS	4
10 cS PDMS	5
20 cS PDMS	6

C.3.3 Tube

The Tube column is where the Tube ID number is recorded. Table 3.4 lists the tube name and IDs. The tube name is taken from the Droplog, matched with its ID number and recorded in the matrix.

C.3.4 TubePos

The TubePos column is where the tube position ID number is recorded. The figure to the right shows a schematic of how to interpret tube position. The Tube at the lowest location in the frame is 1 and increases as they appear farther up in the figure.

C.3.5 Lnot

The Droplog has a record of the submerged length of the tube. The Lnot column is where the submerged length (L_0) is recorded. There are four possible values for Lnot; 5 mm, 10.73mm, 23.2mm, and 35.6mm. The figure to the right illustrates submerged length.

C.3.6 Results

The Results column is where the number of ejected drops is recorded.

C.3.7 Image Tilt

The Image Tilt column is where the tilt of the image due to camera rotation is recorded. This data is taken using Spotlight. Details on how to use Spotlight to obtain this data are in section C.4.1. The figure to the right illustrates image tilt.

C.3.8 Image SF

The Image SF column is where the image's scale factor for each image is recorded. This data is gathered using Spotlight. Details on how to use Spotlight to obtain this data are in section C.4.2.

C.3.9 Height

This column is where the pixel resolution for the height of the images is recorded. Since the images are always transformed to 1920 x 1080 image, the value in this column is always 1080.

C.3.10 Width

This column is where the pixel resolution for the width of the images is recorded. Since the images are always transformed to 1920 x 1080 image, the value in this column is always 1920.

C.3.11 Frame Rate

The Frame Rate column is where the frame rate of the camera (and image sequence) is recorded. For most of the experiments, 59.94 should be entered into this column but the camera used does impact the entry.

C.3.12 FSStart

The FSStart column is where the free surface starting pixel position for each tube is recorded. This data is taken using Spotlight. Details on how to use Spotlight to obtain this data are in section C.4.3. The figure to the right illustrates the location of FSStart for a single tube.

C.3.13 TubeEnd

The TubeEnd column is where the end of the tube's pixel position is recorded. This data is taken using Spotlight. Details on how to use Spotlight to obtain this data are in section C.4.4. The Figure to the right illustrates the location of the end of a single tube.

C.3.14 NozzleEnd

The NozzleEnd column is where the end of the nozzle's pixel position is recorded. This data is taken using Spotlight. Details on how to use Spotlight to obtain this data are in section C.4.5. The figure to the right illustrates the location of the nozzle end for a single tube.

C.3.15 Drop Jitter

The Drop Jitter is where the image jitter due to the drop is recorded. This data is taken using Spotlight. Details on how to use Spotlight to obtain this data are in section C.4.6. The figure to the right is an illustration of drop jitter.

C.3.16 Drop Frames

These cells have a grey background and a bold orange font. Excel will calculate these values based on the information in the FSStart, TubeEnd, NozzleEnd, and Drop Jitter columns to the left under Frame 1 heading. Therefore do not enter any information in these columns.

C.4 Spotlight

After the videos have been converted to a PNG sequence, Spotlight is used to reduce the data. The preferred order of events is as follows: (Details of each step can be found in the indicated subsections.)

1. In Spotlight, the first PNG of the drop's converted video is opened. (...Frame 0000)
2. The image tilt is measured with the angle tool area of interest (AOI) and the value is recorded. (for details see section C.4.1)
3. The image scale factor is measured and recorded. (for details see section C.4.2)

4. The location of the free surface starting location, the TubeEnd, and the NozzleEnd for each tube in the image are measured and recorded. (for details see sections C.4.3, C.4.4, and C.4.5)
5. The Drop Jitter for each drop is measured and recorded. (for details see section C.4.6)
6. The meniscus for each tube in drop image sequence is tracked and digitized. (for details see section C.4.8)

C.4.1 Image Tilt

1. From the menu: Aoi→New→angle tool

2. The angle tool Aoi appears in the upper left corner of the window.

- 3.
- Place the large cross on a stiff straight horizontal object toward the right side of the image.
 - Place the small box on the same stiff straight horizontal object toward the left side of the image.
 - The Angle Tool Aoi information appears in the lower left hand corner of the window. Record the number next to 'angle:' in the appropriate column of the experiment results matrix.

4. Delete the angle tool Aoi.

C.4.2 Scale Factor

1. From the menu: Aoi→New→line profile

2. The line profile Aoi appears in the upper left corner of the window.

3. The line profile: Luminance plot window pops up. In this window, the length of the line is displayed in pixels. This is the important figure.

4. Place one end of the line on the top side of the outer diameter(OD) of the tube and place the other end of the line on the bottom side of the tube OD. In the appropriate excel column, enter the length of the line in pixels.

5. Remember to use the zoom command to get a better idea of where the end of the line actually is.

C.4.3 FSStart

1. Align the Line Profile Aoi along the reservoir lip to get the angle correct. Then place the Line Profile Aoi along the edge where the tube center plane meets the free surface of the reservoir.

2. Place the tip of the mouse pointer at the intersection of the tube center line and the Line Profile Aoi. The pixel that is below the mouse pointer tip has location and color. This information is displayed in the lower right hand corner of the window. The format of the information is (X-location in pixels, Y-location in pixels) rgb: (red percentage, blue percentage, green percentage) Record the X-location of the pixel in the appropriate column of the experiments result matrix.

C.4.4 TubeEnd

1. Align the Line Profile Aoi along the reservoir lip to get the angle correct. Then place the Line Profile Aoi across the tube connecting the two points where the straight tube section ends.

2. Place the tip of the mouse pointer at the intersection of the tube center line and the Line Profile Aoi. The pixel that is below the mouse pointer tip has location and color. This information is displayed in the lower right corner of the window. The format of the information is (X-location in pixels, Y-location in pixels) rgb: (red percentage, blue percentage, green percentage). Record the X-location of the pixel in the appropriate column of the experiments result matrix.

(1037, 508) rgb:(0.675, 0.675, 0.612)

C.4.5 NozzleEnd

1. Align the Line Profile Aoi along the reservoir lip to get the angle correct. Then place the Line Profile Aoi across the nozzle exit hole.

2. Place the tip of the mouse pointer at the intersection of the tube center line and the Line Profile Aoi. The pixel that is below the mouse pointer tip has location and color. This information is displayed in the lower right corner of the window. The format of the information is (X-location in pixels, Y-location in pixels) rgb: (red percentage, blue percentage, green percentage). Record the X-location of the pixel in the appropriate column of the experiments result matrix.

(1037, 508) rgb:(0.675, 0.675, 0.612)

C.4.6 DropJitter

1. Place one end of the Line Profile Aoi on a fixed, easy to recognize point in the frame.
2. Advance the image sequence by pressing the Fast Forward icon.

3. ...Frame 0001 then the video needs to be converted correctly.) Eventually the image stabilizes and becomes clear again. Stop the 'movie' after the image stabilizes.
4. Place the opposite end of the Line Profile Aoi on the same fixed point as before.

5. The Line Profile Aoi length is the amount the camera shifts during a drop. The value of the Line Profile Aoi length should be recorded in the appropriate column of the experiment results matrix.
6. Delete the Line Profile Aoi.

C.4.7 Set Tracking Results File

1. From the menu: Tracking→Results File ...

2. The window for selecting the results file pops up.

3. Click on 'Select' and navigate to the Raw data folder for the drop. This folder is located on the NAS. A general path is below. Make sure the drop name of the images match the drop name for the data file.
Z:\Experiments\Data\<drop name> \Raw\

4. In the file name field enter the name of the data file. It should follow the general formula: <drop name>_<tube position>.

5. Click Save to return to the results file window. Press OK.

C.4.8 Tracking Menisci

1. From the menu: Aoi→New→manual tracking

2. The manual tracking Aoi appears in the upper left corner of the window.

3. Adjust size and starting position of the Aoi by clicking and dragging the corners of the box.

4. Set up the Aoi:
From the menu: Aoi→Process sequence...

5. The Image Processing Sequence window will pop up. Click on the Add button.

6. The Add Ip Operation window will pop up. Click Contrast stretch button.

7. The Contrast - linear stretch processes has been added to the Image Processing Sequence. Add another Contrast Ip Process. Select the second Contrast Ip Process and Click the Edit button.

8. The Contrast Stretching Selection window will pop up. Select Contrast Enhance. Click OK.

9. Click on the Add button again and click on the Filtering button. Repeat 7 more times.

10. Select the first filter and click on the Edit button. The Filter Type Selection window will pop up. Select minimize noise filter and click OK.

Go through all the filters and select the values you see in the image to the right. The list should read:

Contrast - linear stretch

Contrast - contrast enhance

Filter - minimize noise

Filter - minimize noise

11. Filter - despeckle

Filter - despeckle

Filter - despeckle

Filter - despeckle

Filter - despeckle

Filter - sharpen

Filter - sharpen

Filter - despeckle

12. The Manual Tracking Aoi is now set up. Tracking the meniscus can now begin. Start tracking at a frame where the meniscus is not obscured by the free surface. Fast forward the image sequence until the meniscus can be tracked without any trouble. Once you find the first frame where the meniscus is in clear view, go one frame back. When you press Track continuously, Spotlight will advance the image sequence one frame forward before you can start tracking.

13. Press the Track Continuously button.

14. Use the mouse pointer to track and click on the lowest point of the meniscus as it travels along the tube. Do this until the first frame past the time the liquid passes through the nozzle.

At the completion of the above instructions, all information on the current tube has been gathered and recorded. If there are more tubes in the same drop, continue on with those. Be careful to match the tube position and tube information with the correct tube. If there are no more tubes left to record in the image sequence go onto the next sequence.

Appendix D

Data analysis MATLAB code

```

1 % Fluid Properties for PDMS
2 %
3 % Matrix Layout
4 % Row 1 = 0.65cS PDMS
5 % Row 2 = 1cS PDMS
6 % Row 3 = 2cS PDMS
7 % Row 4 = 5cS PDMS
8 % Row 5 = 10cS PDMS
9 % Row 6 = 20cS PDMS
10 %
11 % Matrix Structure
12 %
13 % | nu [mm^2/s] | rho [kg/mm^3] | sigma [kg/s^] | mu [kg/(mm*s)] | theta |
14 %
15 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
16 FluidProp = [[0.65,760E-9,0.0159,494E-9,0];...
17             [1,816E-9,0.0174,816E-9,0];...
18             [2,872E-9,0.0187,1744E-9,0];...
19             [5,913E-9,0.0197,4565E-9,0];...
20             [10,935E-9,0.0201,935E-9,0];...
21             [20,949E-9,0.0206,1898E-9,0]...
22             ];
23 % Set index values for variables
24 NUindex = 1;
25 RHOindex = 2;
26 SIGMAindex = 3;
27 MUindex = 4;
28 THETAindex = 5;

```

Listing D.1: Importing fluid properties

```

1 % Tube Properties of tubes used in experiments
2 %
3 % Matrix Layout
4 % Row n = tube ID
5 %
6 % Matrix Structure (all units are mm)
7 %
8 % | L | L_t | L_n | D_t | D_n | R_t | R_n | OD |
9 %
10 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
11 %
12 % Import data from data file
13     [~,~,raw] = xlsread('Z:\Projects\test\MasterSpreadsheet.xlsx',...
14         'TubeID','C4:J40');
15 % Make it a matrix
16     TubeProp = cell2mat(raw(1:end,:));
17 % Set index values for variables
18     Lindex = 1;
19     Ltindex = 2;
20     Lnindex = 3;
21     Dtindex = 4;
22     Dnindex = 5;
23     Rtindex = 6;
24     Rnindex = 7;
25     ODindex = 8;

```

Listing D.2: Importing tube properties


```

1 % Experiment Properties
2 %
3 % Matrix Layout
4 % Row n = Experiment
5 %
6 %
7 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
8 %
9 % Import data from data files
10 [ExpPropNum,ExpPropTxt,ExpProp] = ...
11     xlsread('Z:\Projects\test\ExpMatrix.xlsx','Exp');
12 % Determine the number of data files that need to be imported.
13 xHeaderLines = 2;
14 LineCount = size(ExpPropTxt);
15 DataFileCount = LineCount(1)-xHeaderLines;
16 % Set index values for variables when using text
17 txtDropNameindex = 1;
18 txtFluidNameindex = 2;
19 txtTubeNameindex = 3;
20 txtTubePosindex = 4;
21 txtLnotindex = 5;
22 txtEjectedNumindex = 6;
23 txtSFinindex = 8;
24 txtImageHeightindex = 9;
25 txtImageWidthindex = 10;
26 txtFrameRateindex = 11;
27 txtImageTiltindex = 16;
28 txtFSStartindex = 17;
29 txtTubeEndindex = 18;
30 txtNozzleEndindex = 19;
31 % Set index values for variables when using numbers only
32 DropNameindex = txtFluidNameindex-1;
33 FluidNameindex = txtFluidNameindex-1;
34 TubeNameindex = txtTubeNameindex-1;
35 TubePosindex = txtTubePosindex-1;
36 Lnotindex = txtLnotindex-1;
37 EjectedNumindex = txtEjectedNumindex-1;
38 SFinindex = txtSFinindex-1;
39 ImageHeightindex = txtImageHeightindex-1;
40 ImageWidthindex = txtImageWidthindex-1;
41 FrameRateindex = txtFrameRateindex-1;
42 ImageTiltindex = txtImageTiltindex-1;
43 FSStartindex = txtFSStartindex-1;
44 TubeEndindex = txtTubeEndindex-1;
45 NozzleEndindex = txtNozzleEndindex-1;

```

Listing D.3: Importing experiment results

```

1 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
2 %
3 % Find Data File Names and import data files
4 %
5 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
6 %
7 % Initialize variables
8 DropName = cell(DataFileCount,1);
9 DataFileName = cell(DataFileCount,1);
10 %
11 for i=1:LineCount-xHeaderLines
12     % Make a matrix with the name of the names of all the drops from
13     % the ExpProp matrix; skip the xHeaderLines
14     DropName{i,1} = ExpPropTxt(i+xHeaderLines,txtDropNameindex);
15     % Use the name of the drop to make a matrix of the name of the data
16     % files associated with the drop. The naming structure should be
17     % <Drop information>_<Total number of experiments>_<ExpNum>.txt
18     DataFileName{i,1} = strcat(char(DropName{i}),...
19     '_ ',num2str(ExpProp{i+xHeaderLines,txtTubePosindex}));
20 end
21 % Define working folders names to be used later.
22 NetworkFolder = 'Z:\';
23 ExperimentFolder = 'Experiments\';
24 DataFileFolder = 'Data\';
25 ProjectFolder = 'Z:\Projects';
26 ProjectName = '\test';
27 DataPath = [ProjectFolder,ProjectName,'\RawData'];
28 % Define file type we are looking for. data files are .txt files in
29 % windows
30 FileType = '.TXT';
31 % Search for data files
32 % Initialize variables
33 SearchPath = cell(DataFileCount,1);
34 SearchCMD = cell(DataFileCount,1);
35 TXTFiles = cell(DataFileCount,1);
36 DataFilesPerDrop = cell(DataFileCount,1);
37 FileIndex = cell(DataFileCount,1);
38 for i=1:DataFileCount
39     % Define search path that is unique to each drop. ie look in each drop
40     % data folder. Define a path
41     SearchPath{i,1} = strcat(NetworkFolder,ExperimentFolder,...
42     DataFileFolder,DropName{i},'\Raw\');
43     % Define the search comand.
44     SearchCMD{i,1} = strcat(SearchPath{i},'*',FileType);
45     % a matrix that contains all the txt files found
46     TXTFiles{i,1} = dir(char(SearchCMD{i}));
47     % Count data files per drop that are in each folder.

```

```

49         %[DataFilesPerDrop{i,1},~] = size(TXTFiles{i});
        DataFilesPerDrop{i} = size(TXTFiles{i},2);
        % Make an index for each file found in the drop folder based on its
51         % tube location that is pulled from the Exp matrix
        FileIndex{i,1} = cell2mat(ExpProp(i+xHeaderLines,txtTubePosindex));
53     end
    % Convert to matrices
55     DataFilesPerDrop = cell2mat(DataFilesPerDrop);
    FileIndex = cell2mat(FileIndex);

```

Listing D.4: Searching for data files

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
2 %
% Import data from each data file
4 %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
6 %
% Initialize variables
8 FileNames = cell(DataFileCount,1);
FullFileName = cell(DataFileCount,1);
10 s = cell(DataFileCount,1);
RawData = cell(DataFileCount,1);
12 %
for i = 1:DataFileCount
14     % Make sure there is a file to work with. If so then do the work. if
    % not then just leave it blank. It will get filled in later.
16     if DataFilesPerDrop(i) > 0
    % Make a matrix and fill it with the names of the found data files.
18         FileNames{i,1} = TXTFiles{i}(FileIndex(i,1)).name;
    else
20         FileNames{i,1} = ' ';
    end
22     % Make a matrix and fill it with the file path and name of the data
    % files.
24     FullFileName{i,1} = strcat(char(SearchPath{i}),FileNames(i,1));
    % Import data file if there is data to import otherwise make up some
    % data so we dont get an error
26     if DataFilesPerDrop(i) > 0
28         s{i,1} = importdata(char(FullFileName{i}),...
            ' ',HeaderLines);
30     else
        s{i,1} = struct('data',zeros(1,2)); % made up data.
32     end
    % Take the data and place it in the RawData matirix
34     RawData{i,1} = s{i,1}.data;
end

```

Listing D.5: Importing experimental data

```

1 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
2 %
3 % Clean up data from each data file
4 %
5 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
6 %
7 % copy the raw data to a new matrix that can be manipulated
8     CleanDataTemp = RawData;
9 %
10 for i=1:DataFileCount
11     % Count the number of data points for every file
12     [DataPointsPerFile,~] = size(RawData{i});
13     % Count the number of variables for every data file
14     [~,VariablesPerDataSet] = size(RawData{i});
15     % If the last 'y' value is equal to the penultimate 'y' value then
16     % delete the last data point. This last data point is an artifact from
17     % Spotlight manual tracking.
18     if isequal(CleanDataTemp{i}(DataPointsPerFile,2),...
19         CleanDataTemp{i}(DataPointsPerFile-1,2));
20         CleanDataTemp{i}(DataPointsPerFile,:) = [];
21     end
22 end
23 %Delete any negative values. These are used to indicate bad readings.
24 for i=1:DataFileCount
25     NegNumExists = find(CleanDataTemp{i}(:,2)>ExpPropNum(i,FSStartindex));
26     CleanDataTemp{i}(NegNumExists,:) = [];
27 end
28 % transfer data to a clean file
29 CleanData = CleanDataTemp;
30 % clear the temp data
31 clear CleanDataTemp;

```

Listing D.6: Cleaning up the data

```

1 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
2 %
3 % Transform data from each data file
4 %
5 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
6 %
7 % Initialize variables
8     ScaleFactor = cell(DataFileCount,1);
9     FSStart = cell(DataFileCount,1);
10    FreeSurface = cell(DataFileCount,1);
11    time = cell(DataFileCount,1);
12    height = cell(DataFileCount,1);
13 %
14 for i=1:DataFileCount
15     % Make sure there is a file to work with. If so then do the work. if
16     % not then just leave it blank. It will get filled in later.
17     if DataFilesPerDrop(i,1) > 0
18         % SF is pixials to mm
19         ScaleFactor{i,1} = ExpPropNum(i,SFindex) ./ ...
20             TubeProp(ExpPropNum(i,TubeNameindex),ODindex); %%%%%%%%%%
21         % Free Surface Start
22         FSStart{i} = ExpPropNum(i,FSStartindex);
23         FreeSurface{i,1} = abs((FSStart{i})-FrameXMax);
24         % Transform data
25         % Convert frame number to time in seconds
26         time{i} = ((CleanData{i}(:,1))./ExpPropNum(i,FrameRateindex));
27         % Convert 'y' pixial to distance in mm from the starting
28         % free surface (units go from px to mm)
29         % Adjust for image tilt.
30         height{i} = ((abs(CleanData{i}(:,2))-FrameXMax) - ...
31             (FreeSurface{i}))./ cell2mat(ScaleFactor(i))./ ...
32             sind(ExpPropNum(i,ImageTiltindex));
33     else
34         % SF is pixials to mm
35         ScaleFactor{i,1} = [];
36         % Free Surface Start
37         FSStart{i,1} = [];
38         FreeSurface{i,1} = [];
39         % Transform data
40         % Convert frame number to time
41         time{i} = [];
42         % Convert px to mm
43         height{i} = [];
44     end
45 end

```

Listing D.7: Transforming the data into proper coordinate system


```

    TE = ExpPropNum(: , TubeEndindex) ;
    NE = ExpPropNum(: , NozzleEndindex) ;
49 % Transform coordinates
    FreeSurface = cell2mat(FreeSurface) ;
    ScaleFactor = cell2mat(ScaleFactor) ;
51 TubeEnd = ((abs(TE-FrameXMax))-FreeSurface) ./ ScaleFactor ;
53 NozzleEnd = ((abs(NE-FrameXMax))-FreeSurface) ./ ScaleFactor) ;
55 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
57 % Material Properties
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    NU = FluidProp(FLUID, NUindex) ;
    RHO = FluidProp(FLUID, RHOindex) ;
59 SIGMA = FluidProp(FLUID, SIGMAindex) ;
    MU = FluidProp(FLUID, MUindex) ;
61 THETA = FluidProp(FLUID, THETAindex) ;

```

Listing D.8: Calculate Properties

Appendix E

Manufacturing Details

E.1 Drop tower test cells

This section details the manufacturing process of the test cells.

E.1.1 General Design Considerations

When laying out the drawing of the CAD model make sure to use the proper template. If the template is not available adjust the drawing settings as follows:

1. Set line width to as thin as possible
2. Line color informs the laser what to do. Set line color per desired function.
 - (a) black means raster
 - (b) blue means engrave
 - (c) red means cut

Each test cell has at least three layers. The front and back layers are the simplest to make as they only need to be cut out of acrylic. The middle section(s) require extra steps and will be handled separately. When laying out the test cell in a drawing, group pieces cut from the same material together. This will speed up the process. Select clear acrylic for the front and back layers of the test cell. For best image results, select opaque black material for the middle layers. Place blue etching lines on the middle section(s) to aid in tape location.

Before going to the laser, make sure the test cell is fully defined and the drawings are ready to print with appropriate settings.

E.1.2 Equipment

Ensure essential equipment is gathered before starting. The Figure below shows the equipment necessary for manufacturing the test cell. Each item can be found in the test cell manufacturing box available in the lab.

Hand held supplies include:

1.
 - (a) lint free tissues (Kimwipes)
 - (b) double-sided tape (3M 444 2inchs wide)
 - (c) scissors
 - (d) assembly jig
 - (e) surface ground steel bars
 - (f) cleaning solvent (Methanol)

2.
 - A (a) laser cutter, (b) control computer, (c) air assist system, and (d) air filter system are available through the PSU MME department.

E.1.3 Cutting Parts out with the laser

After the test cell has been designed, and the drawing is ready to print to the laser, the test cell is ready to be cut.

1. Place acrylic sheet in the laser cutter on the honeycomb material support. Ensure sufficient acrylic sheet material is available and that the material is placed tightly in the origin of the laser cutter.

BE CAREFUL NOT TO BEND, BANG, MANGLE OR IN ANY OTHER FASHION DESTROY OR DEFACE THE HONEYCOMB.

2. Open CAD drawing and print to the laser. Open the laser GUI to operate the laser cutter. Turn on the laser and ensure correct settings have been set for material type and thickness. Position the parts using the 'relocate' view.

3. When ready, press the green play button in the upper righthand corner of the GUI and the laser will start cutting the part.

4. After the part has been cut out, open the laser cutter door and take out the parts and remaining material

5. Now that the end pieces have been cut out and removed from the laser cutter, it is time for to cut the middle section(s). The middle section(s) are a bit more tricky to make. First place your middle layer material into the laser cutter, making sure that it is placed correctly against the origin.

6. Open up the drawing for the middle section and print to the laser cutter. Open the laser GUI and ensure correct settings have been set for material type and thickness. Position the parts using the 'relocate' view.

DO NOT PRESS PLAY. THE LASER CUTTER'S ORDER OF OPERATION IS AS FOLLOWS. FIRST, IT COMPLETES THE RASTER LAYER, ANY LINES THAT ARE BLACK. SECOND, THE LASER ENGRAVES ANY LINES THAT ARE BLUE. FINALLY, THE LASER CUTTER CUTS OUT ALL RED LINES. WE USE THE ORDER OF OPERATIONS TO OUR ADVANTAGE HERE. WHEN 'PLAY' IS PRESSED THE LASER WILL ENGRAVE THE LOCATION MARKERS FOR THE TAPE ON THE ACRYLIC BEFORE IT CUTS OUT THE MIDDLE SECTION(S). BE READY TO PUSH THE 'PAUSE' BUTTON ON THE LASER CUTTER IMMEDIATELY AFTER THE ENGRAVING PROCESS HAS COMPLETED, BUT BEFORE THE CUTTING PROCESS BEGINS.

7. When ready, press the green play button in the upper righthand corner of the GUI and the laser will start engraving the part.

8. Immediately after the engraving process has completed, but before the cutting process begins, push 'pause'

9. Open the laser cutter door and take out the engraved acrylic. Pay attention to the position of the engraved acrylic, you will have to put it in the cutter in the exact same placement in step 13.

10. Wipe down the acrylic with the Methanol and a lint-free tissue

11. Very carefully lay tape across the cleaned surface inside the engraved markings. Ensure no air gets trapped under the tape. Use the jig to smooth out any trouble spots. Use scissors to cut the tape as to ensure straight cuts normal to the tape's side edges.

12. Flip the acrylic over. The laser can only engrave one side at a time so the back does not have any markings. However, the back needs to have tape applied on the opposite side, directly above the tape on the other side. Carefully apply tape to the back side of the acrylic sheet (I recommend measuring first). Again be careful not to get air trapped under the tape. Also be careful to cover the entire length of the channel but not too long as the tape is really expensive. Measure twice, cut once.

13. After both sides of the middle section(s) have tape applied, put the acrylic sheet back onto the honeycomb in the laser cutter in the exact location and orientation it was in before you took it out.

14. Press the pause button on the laser cutter and the laser cutter will continue the job from the end of the engraving phase and move into the cutting phase.

15. When cutting has finished, take the parts and extra material out of the laser cutter. Dispose of extra material in recycling bin. If nothing else needs to be cut, turn off the laser cutter using the GUI and turn off the air assist system.

E.1.4 Building Test cell

1. Place the assembly jig on a flat surface such as a lab bench.

2. Clean the assembly jig with cleaning solvent and lint-free tissue. Place the test cell's back panel on the jig. Clean the top surface with cleaning solvent and lint-free tissue.

3. Remove the tape backing from the side of the middle section that mates up with the back panel.

4. Turn the middle section over, line up the pin holes and place the middle section on the jig.

5. Press down evenly, and firmly on the middle section, sliding it over the alignment pins.

6. Repeat steps 3 through 5 for all remaining middle section(s).

7. Clean the test cell's front panel with cleaning solvent and tissue.

8. Remove the tape backing from the middle section that mates up with the front panel.

9. Align the front panel over the alignment pins and place on jig.

10. Press down evenly, and firmly on the front panel, sliding it over the alignment pins.

11. Remove the test cell from the assembly jig.

12. Place the test cell on the surface ground (shiny) side of one of the steel bars.

BE CAREFUL NOT TO SCRATCH OR DING OR DEFACE THE SURFACE GROUND SIDE OF THE STEEL BARS. IF YOU SCRATCH THE FACE OF THE BAR IT WILL SCRATCH THE FACE OF YOUR TEST CELL.

13. Place the other steel bar down on top of the test cell with the surface ground (shiny) side facing the test cell.

14. Being careful not to let them slip over each other, pick up the sandwiched test cell and the steel bars and place them in a press or vise. Clamp down on the steel bars and test cell to get as much air out as possible.

15. Take the sandwiched test cell and the steel bars out of the vise. The test cell is now finished and ready to be mounted in a reservoir and dropped.

E.2 Astro Tube

This section details the manufacturing process of the tubes with nozzles constructed aboard the ISS by astronaut Don Pettit [114].

Tubes are constructed from clear 3M transparencies. They are cut and rolled into a tube and taped together with Kapton Tape. The nozzle end of the tube is cut into 'orange peel slices,' folded over into a nozzle and taped together with Kapton Tape. A pattern for future tube manufacturing was developed by the author and can be found in Fig. 5.1

Figure 5.1: Pattern to be printed on a transparency and cut for tube manufacturing aboard the ISS. This pattern is for a 25 mm ID tube with a 10 mm nozzle diameter. The pattern is scaled 1:1.

Appendix F

Lab Handbook

F.1 DDT Lab NAS file structure

The DDT Lab has its files on the NAS. The file location for the NAS is:
\\ddtvideos.mme.pdx.edu\ddt There are 11 folders on that drive; each with a specific purpose. These folders are:

1. AccelerometerData (See section F.1.1 for details.)
2. AdobePremiereProjects (See section F.1.2 for details.)
3. DDT_Data (See section F.1.3 for details.)
4. DDT_Misc (See section F.1.4 for details.)
5. Documentation (See section F.1.5 for details.)
6. DropLog (See section F.1.6 for details.)
7. Experiments (See section F.1.7 for details.)
8. ForPublication (See section F.1.8 for details.)
9. Matlab (See section F.1.9 for details.)
10. Outreach (See section F.1.10 for details.)
11. zzz_CameraDump (See section F.1.11 for details.)

The purpose of each folder will be described below.

F.1.1 AccelerometerData

This folder is for Accelerometer Data. In this folder there should be a folder for each drop. Each folder for each drop should be labeled to match the accelerometer data column in the drop log (i.e. "Drop_00032"). In each drop folder there should be three folders: Plots, Raw, and Work. Each of these folders has their own use and function. The Raw folder is where raw data from the data logger should be stored. If another software package is used to work on the data, (i.e. Excel or Matlab), then the imported raw data can be saved in the Work folder. Any final plots that are worthy of publication, either in a report, thesis, paper, or poster presentation, should be saved in the Plots folder.

F.1.2 AdobePremiereProjects

This folder is for saving Adobe Premier projects. This folder is for movie editing projects for the lab.

F.1.3 DDT_Data

The DDT_Data folder is for saving important data regarding DDT. Some examples are the hanging mass of the DS and old tasks lists.

F.1.4 DDT_Misc

This is a catch-all folder for DDT-related files. Already present in the folder are files, DDT installation pictures, the DDT control computer backup and various images and videos of the drop tower.

F.1.5 Documentation

This folder is where all critical documentation resides. These could be data sheets for drop tower components (i.e. accelerometer, and data logger), Fluid data sheets, and experimental documentations. There are also Solidworks documents of the tower and various components. The DDT user guide and critical lab handbook documentation is also in this folder. If you have a question, this folder would be an excellent first place to look for the information. Also, as you complete or conduct projects for the drop tower, place all documentation in this folder.

F.1.6 DropLog

The only file in this folder is the excel spread sheet of the drop log. No other files should be saved in this folder and the drop log is not to be moved from this folder.

F.1.7 Experiments

This folder is where all the data from the experiments live. In this folder there are additional folders. These additional folders are Data, Misc, MTS, OLD, PNG, and ToBe-Converted. Each of these folders have their own purpose that is not to be deviated from.

Data

The data folder is where data for the experiments reside. Each drop has its own folder. In each drop folder there should be three folders, Plots, Raw, and Work. Each of these folders has their own use and function. The Raw folder is where raw data from the data logger should be stored. If another software package is used to work on the data, (i.e. Excel or Matlab), then the imported raw data can be saved in the Work folder. Any final plots that are worthy of publication, either in a report, thesis, paper, or poster presentation, should be saved in the Plots folder.

Misc

The Misc folder is where related videos and files go. They need to be named correctly and exist in this folder only if they do not fit in any other folders.

MTS

This folder has all the appropriately named move files reside. None of these should be deleted or renamed. The DataLog.xlsx is the original namer and should not be deviated from.

OLD

This is where all the old videos reside. This is what existed before the current system was set up. This folder is not to be added to and will eventually be deleted. As experiments continue to be worked on the data from this folder should be moved to the appropriate Data folder.

PNG

This folder has a folder for each drop. In each of those folders is the converted video into a sequence of images.

ToBeConverted

This folder is to be used for mass video naming. Drew used it to rename 730 videos. It serves no other function.

F.1.8 ForPublication

This folder is for work related to a specific publication. Any files that exist here should be copied from the main Experiments folder. All files in this folder should be copied from somewhere and not be the only copies.

F.1.9 Matlab

All Matlab scripts that have to do with workflow in any way should reside in this folder. Any documentation of any Matlab functions should also reside in this folder. Any peripheral files should be related to Matlab scripts in some way (i.e. renaming keys, etc).

F.1.10 Outreach

This folder has all documents related to any outreach the DDT lab is conducting. In this folder there should be other folders with the name and date of the outreach event. Again, this folder should not have any original data. All data, videos, pictures etc should be copied from its original source into this folder.

F.1.11 Zzz_CameraDump

This is a third back-up. This folder has a copy of the original camera shots and video footage from the camera. It is unlikely this will ever be needed but it should be left alone in case we need to go back to the original video.

F.2 The Work Flow

F.2.1 During Drop Campaign

1. Follow Procedures in User Guide for drop campaign
2. **Make sure critical camera settings are set correctly!** (see section F.3 for details)
3. Log each drop in the drop log booklet
4. After RRS retrieves DS, crop Camera footage and delete pre- and post-drop footage (see section F.4 for details)

5. DO NOT DELETE DROP FOOTAGE NO MATTER HOW BAD IT LOOKS
6. Review footage of drop and make any adjustments necessary
7. Reset experiment and continue drop campaign

F.2.2 After Drop Campaign

1. Put DDT away per User Guide
2. Clean up lab workspace
3. Upload videos to the WorkingFolder on the Blue Hurricane (See Section F.5)
4. Transcribe Drop log booklet to Droplog.xlsx
5. Rename video files in WorkingFolder with name output from Droplog.xlsx
6. Run Matlab script MakePNGAndDataFolders.m from the WorkingFolder. This will do the following:
 - (a) Identify the MTS video files in the WorkingFolder
 - (b) For every video, make a PNG folder, name it after the video, place it on the NAS in the correct folder
 - (c) For every video, make a Data folder with subfolders, name it after the video, place in on the NAS in the correct folder
 - (d) Move the MTS video file to the NAS in the correct folder
7. Convert Videos (see section F.6)

F.2.3 During Data analysis

1. Data should be stored in the folder:
`\\ddtvideos.mme.pdx.edu\ddt\Experiments\Data\<Drop>`
2. Raw data from spot light should be stored in the *Raw* folder
3. Data analysis should be stored in the *Working* folder
4. Any images of plots should be stored in the *Plots* folder

F.3 Camera Settings

The camera has critical settings that need to be configured before it can be used in a drop. The following settings are appropriate for the Panasonic HDC-TM700 camera.

1. Make sure you are in Manual mode
2. Make sure O.I.S. is off
3. Focus: Manual
4. White Balance ('WB'): Cloudy Day
5. Shutter Speed ('SHTR'): 1/2000
6. Iris: <Automatic ~ 18*dB* >
7. Flash: Off
8. RedEye: Off
9. Self-Timer: Off
10. Soft skin mode: Off
11. Tele Macro: Off
12. Gridlines: Off

F.4 How To Crop Videos

1. Take camera out of DS off the ER mount
2. Switch to playback mode
3. Press Menu
4. Press Edit scene
5. Select Divide
6. Press Set
7. Press OK
8. Select video

9. Find Drop
10. Press scissors icon when you hear gate latches open
11. Select Yes, divide more scenes
12. Allow video to play for 4 seconds
13. Divide scene again by pressing scissors
14. Select No, do divide more scenes
15. Select Return
16. Delete pre- and post- drop videos
 - (a) Press Menu
 - (b) Press Edit Scene
 - (c) Select Delete
 - (d) Press Select
 - (e) Press OK
 - (f) Select bookend videos
 - (g) Press delete
 - (h) Select Yes
 - (i) Press Return
17. Review Video
18. Make sure you switch the camera back to video record mode
19. Place back into DS on ER

F.5 How to Upload Videos

1. Plug camera into Blue Hurricane
2. Open the camera memory in file explorer
3. Select the videos to be uploaded
4. Copy and Paste into WorkingFolder on BlueHurricane

F.6 How To Convert Videos

1. Open Adobe Media Encoder
2. From the Queue Tab, Click '+' to open movie file to add to queue
3. Navigate to movie of interest on the NAS
4. Select 'Open'. This will place file in queue.
5. The queue tab has 5 columns: Source Name, Format, Preset, Output File, and Status
6. From the Format pull down menu select 'PNG'
7. From the Preset pull down menu select 'DDT_Preset'
8. click on the yellow under lined 'PNG'. This will bring up the Export Settings Window.
9. Under Export Settings verify the Export Settings are correct (DDT_Lab Preset should be selected):
 - (a) Format: PNG
 - (b) Preset: DDT_Preset
 - (c) Comments: none
 - (d) Export Video is checked
10. Double click on the Output Name
11. Change the folder to which the images will be saved by using the Windows' Explorer interface. Select the PNG folder that is has the name of the drop. The PNG folder was generated by the Matlab code and resides on the NAS.
12. To the end of the file name add "_Frame 0" (that is: <underscore> Frame <space> <the number zero>)
13. On the right hand side of the pop up window verify additional settings are correct
 - (a) Under the Filters Tab: Gaussian Blur is Unchecked
 - (b) Under the Video Tab:

- i. Width = 1920
 - ii. Height = 1080
 - iii. Aspect ratio is unlinked
 - iv. Export As Sequence is checked
 - v. Frame Rate = 59.94
 - vi. Aspect = Square Pixels (1.0)
 - vii. Render at Maximum Depth is checked
 - viii. Include Alpha Channel is checked
 - (c) Make sure that Use Maximum Render Quality is checked
 - (d) Use Previews is Unchecked
 - (e) Use Frame Blending is Unchecked
14. Use the controls on the bottom left of the pop up window to crop the video down to display only the drop (Use yellow slider to get close and use arrow keys once you get close because this cannot be approximate)
- (a) Go to one frame before the release disturbance can be seen
 - (b) Click Set In Point triangle
 - (c) Go to the frame where the first impact disturbance can be seen
 - (d) Click Set Out Point triangle
15. When done, click 'Okay'. This will return you to the Queue.
16. Repeat until finished adding all drops
17. Press the play button in the upper right corner of the Queue tab to start conversion process.

F.7 Common Mistakes

Steps in preventing common errors:

1. Make sure the camera is tight on the ER mount
2. Make sure the camera is level with experiment
3. Make sure the initial conditions are set correctly (is the reservoir filled?)
4. Make sure the camera is focused
5. Make sure the zoom is correct
6. Make sure you have good battery life
7. Make sure the front shield is clean
8. Make sure you document the experiment completely