To the Graduate Council:

I am submitting herewith a thesis written by Nobuhisa Yasuda entitled “Liquid Viscosity Measurement Technique Using Space Microgravity Environment.” I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.

Basil N. Antar, Major Pofessor

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(Original signatures are on file with official student records)

LIQUID VISCOSITY MEASUREMENT TECHNIQUE USING SPACE MICROGRAVITY ENVIRONMENT

A Thesis
Presented for the
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Degree
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Nobuhisa Yasuda
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ABSTRACT

The purpose of this research is to validate a method of determining viscosity of highly viscous liquids with known surface tension in which is not confined by solid wall.

The major part of the work involves comparing and analyzing the data from the Fluid Merging Viscosity Measurement experiments (FMVM), conducted onboard the ISS, with results from numerical analysis codes. In these experiments, two different size or equal size droplets are deployed and allowed to merge under the action of the known surface tension without any external forcing. The drop merging process is performed in the zero gravity environment of space on board the ISS. Simultaneously, computer codes are used to determine the viscosity by producing the matching curves of the experimentally measured contact radius speed with theoretical calculation for the model experimental data.

Using this technique, the value of viscosity was determined with reasonable accuracy for several liquids tested.

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ABBREVIATIONS AND SYMBOLS

b	Surface Tension Vector
BEM	Boundary Element Method
C, Q, S	Second Rank Tensors
c_l	Coordinate of Focal Point of Left Circle
c_r	Coordinate of Focal Point of Right Circle
CD	Contact Diameter
CR	Contact Radius
DTCR	Dimensional Theoretical Contact Radius
DTT	Dimensional Theoretical Time
FEM	Finite Element Method
h_1	Distance between y-axis and Focal Point of Left Circle, c_l
h_2	Distance between y-axis and Focal Point of Right Circle, c_r
ISGG	Initial Surface Geometry Generator
ISS	International Space Station
l	Length
l_s	Length Scale
l^*	Non-dimensional Length
m_1	Parameter which ranges form 0 to n_1
m_2	Parameter which ranges form 0 to n_2
n	Normal Unit Vector
N_f	Number of Frames
n_1	Number of Points on Left Circle
n_2	Number of Points on Right Circle
p	Pressure
p_s	Pressure Scale
R	Radius of Droplet
r	Initial Contact Radius
s_f	Frame Speed
T	Stress Tensor

t	Time
t_s	Time Scale
t^*	Non-dimensional Time
$\mathbf{u}$	Velocity Vector of Fluid
V_s	Velocity Scale
$\mathbf{x}$	Interior Point
$\mathbf{y}$	Free Surface Location
α	Angle from Contact Radius to x-axis on Left Circle
β	Angle from Contact Radius to x-axis on Right Circle
Γ	Region of Fluid
δ_{ij}	Kronecker Delta
μ	Viscosity
v	Kinematic Viscosity
ρ	Fluid Density
σ	Coefficient of Surface Tension
Φ	Interpolation Function
Ω	Interior Area of Fluid Region

CHAPTER 1: INTRODUCTION

Viscosity is a molecular property of all fluids related to the momentum transport between molecules. Another definition of viscosity is the ratio of the shear stress to the velocity gradient. According to Young (2001), viscosity describes the fluidity of a fluid. There are some other properties of fluid such as density and specific weight, and so on. Comparing two liquids, the difference in the viscosity may make these fluids flow in completely different manner. Normally the viscosity of a fluid depends on its temperature. Couette Flow is a good example to understand this property. Consider the conditions with following properties in 2-D geometry (See Figure 1):

1. There is a fluid filled gap between two solid parallel plates. The distance between these two plates is *h*.
2. The plate length is much larger than *h*.
3. The bottom plate is held stationary and the top plate is pulled by a tangential force, *F*/unit area, acting parallel to the other plane.

If a force, *F*, is known, then the speed of the top plate, V, depends on a viscosity μ of the fluid; $V \propto \frac{F}{\mu}$. This formula shows that for a known force the velocity of the upper plate is inversely proportional to the fluid viscosity. In addition U = $u(y)$ is a fluid velocity between the plates, therefore $V = u(h)$.

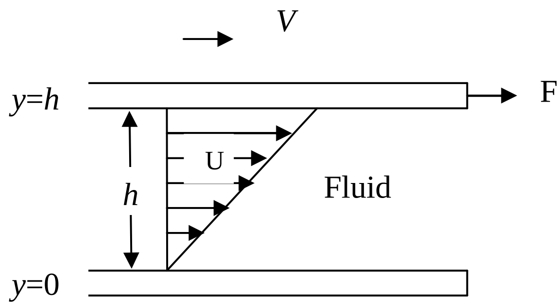


Figure 1: Fluid Between Two Parallel Plates

There exist many different types of viscometers for determining the viscosity of a fluid, ranging from very simple to complex devices. One such viscometer involves counting the seconds for a liquid to drain off a stick, and another is fully automated machines (Brookfield). The dimension of viscosity, in the general sense, is $force \cdot time$ per length squared (FTL^{-2}). In British Gravitational (BG) units, viscosity is usually given in $lb \cdot \sec/ ft^2$ and in the International System (SI) units, it is $N \cdot s / m^2$. However, in this paper it will be described in the metric CGS system (centimeter-gram-second) with units of $g / cm \cdot s$ which is referred to as a poise, P. As an example, the viscosity of water at room temperature is about 0.01 P. In almost all viscometers in common usage, the fluid is always in contact with a solid wall. Figure 2 shows sketches of different viscometers in common usages.

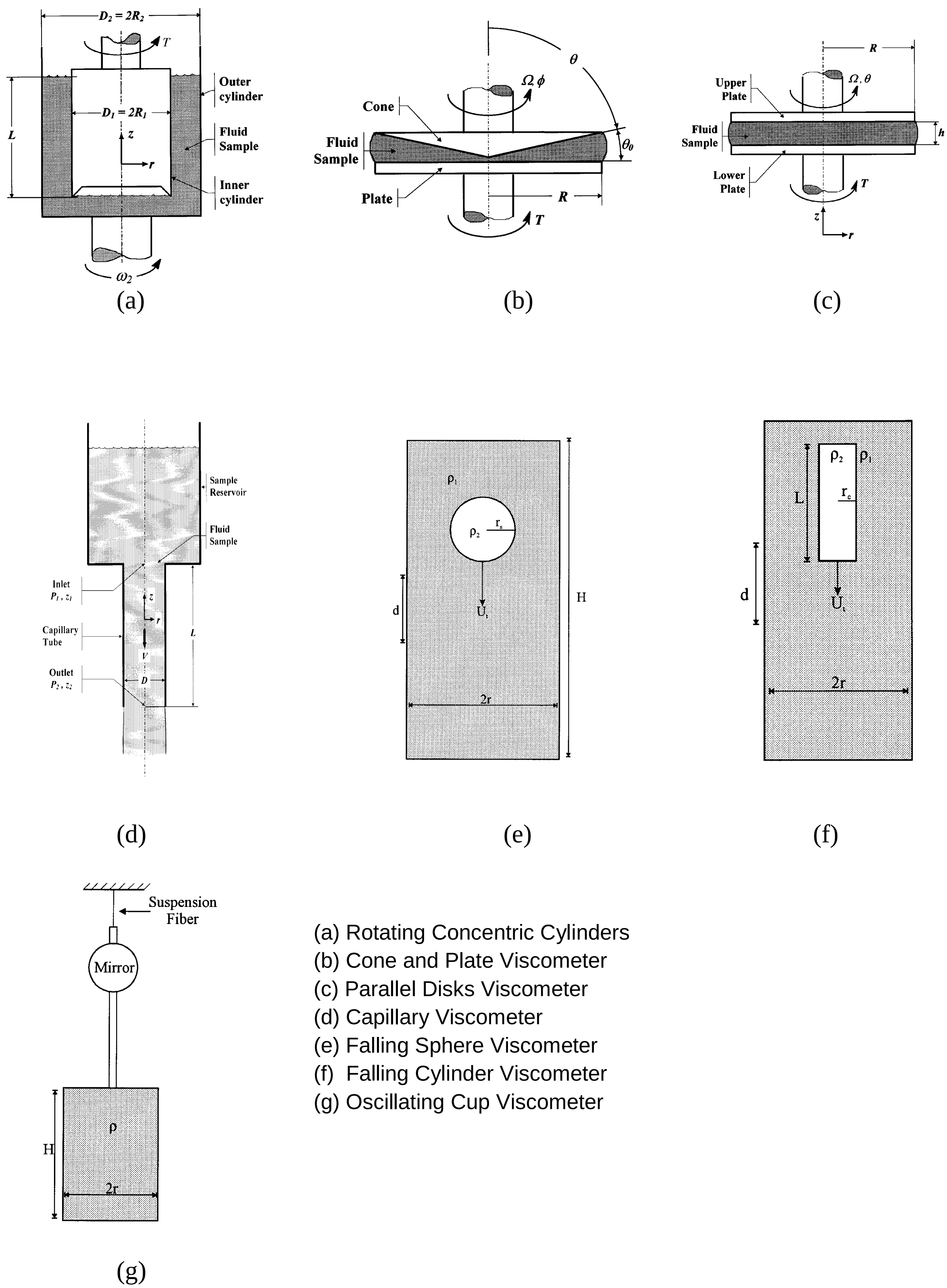
A major problem arises in trying to determine the viscosity of certain fluids when it is impossible to contain the fluid at certain temperatures. For example, a metallic glass melt, such as PdSiCu, can be undercooled to a temperature of 575 degree C or 200 degrees below its melting temperature of 775 degree C (Naka 1978). Glass melts in such a state are said to be undercooled, which means that the melt is at a temperature below the phase transition temperature without the occurrence of the transformation to solid (Callister 2000). At these undercooled temperatures, the liquid melt will crystallize with the introduction of a solid object to act as a nucleation site; anything solid works adequately. Since all of the common viscometer instruments require the liquid to be in contact with a solid boundary, undercooled liquids, such as low temperature glass melts, liquid metals, water, etc., will crystallize and solidify when they touch the surface of a viscometer. When this happens, it is impossible to obtain viscosity values of the undercooled liquid at these temperatures and holes are left in the models depicting the viscosity variations of these melts with temperature which are usually presented graphically.

One common way to estimate the viscosity values of undercooled liquids is to extrapolate from the measured viscosities at higher liquid temperatures. However, these have been known to greatly over or underestimate the true values (Etheridge 1999). Many model equations exist to predict these values, but knowing which one is correct is impossible without having actual experimental data points.

In order to determine the viscosity of these undercooled liquids, Antar's reference designed a low-gravity containerless measurement technique. A terrestrial containerless technique either by acoustic or magnetic levitation will fail because of the sample deformation due to positioning errors, including fluid circulation and gravitational body forces deforming the body shape. Also, these techniques impose extraneous forces on the liquid that cannot be measured easily. The proposed technique for this type of viscosity determination is based on both detailed measurements as well as numerical simulations of the shape relaxation properties of two merging liquid drops of the same liquid. The speed of evolution of the free surface and its geometry during the coalescence of two liquid volumes in a zero gravity environment is directly proportional to the liquid viscosity and its surface tension. It will be shown that by knowing the surface tension of the liquid, the viscosity can be determined by computing the rate of coalescence of the drops.

A test bed with a long duration steady microgravity environment is required for successful experiments of the terrestrial containerless techniques. In this microgravity environment the surface tension plays a dominant role. Furthermore the surface tension is the dominate force on the fluid for this configuration. The followings are some types of test bed for simulating microgravity, with approximate time of weightlessness of: drop tower (10seconds), Parabolic flight aircraft (25 seconds), sounding rocket (1 minute), Space Shuttle (several days), and International Space Station (ISS) (months). In this thesis, ISS experiments will be described.

The viscosity measurement technique developed by Antar involves accurate numerical simulation of the actual drop coalescence as well as performing a microgravity experiment involving the coalescence of pre measured liquid drops. Chapter 2 discusses the drop coalescence experimental set up as performed in the ISS. Chapter 3 describes the derivation of the mathematical model used for the drop coalescence numerical simulation. Chapter 4 describes the details of using the mathematical model to perform the numerical simulation of the drop coalescence process.



(a) Rotating Concentric Cylinders
(b) Cone and Plate Viscometer
(c) Parallel Disks Viscometer
(d) Capillary Viscometer
(e) Falling Sphere Viscometer
(f) Falling Cylinder Viscometer
(g) Oscillating Cup Viscometer

Figure 2: Traditional Common Usage Viscometers

CHAPTER 2: EXPERIMENTAL SETUPS

The experiment aboard the International Space Station (ISS) was performed by Astronaut Mike Ficke in August 2003 and later by Astronaut John Phillips in May 2005 both for the purpose of validating the drop coalescence technique on board the ISS for determining the viscosity of liquids (Antar 2007). The objective of this experiment was to allow two equal size or unequal size liquid droplets to merge under the action of the known surface tension force alone in a low gravity environment. Although there was a problem on a bridging effect in the previously conducted experiment on board the NASA/KC-135 experiment, the setup of the ISS experiment tried to remove this problem. Another advantage of the ISS experiment is the availability of the long period of low gravity environments.

Figure 3 shows a setup of the experiment with a minimum amount of payload being sent up to the ISS. In addition, there was a restriction that only 1 kg could be carried onto the station. Thus any material already on board the ISS such as a background sheet with a known spacing square and the video camera recording the merging process was utilized. The background was attached to a stand that was already onboard the ISS. Several strings, taken from a sewing kid on board the station, were taped vertically in front of the background sheet with a common use digital video camera and a flashlight pointed straight on to the string.

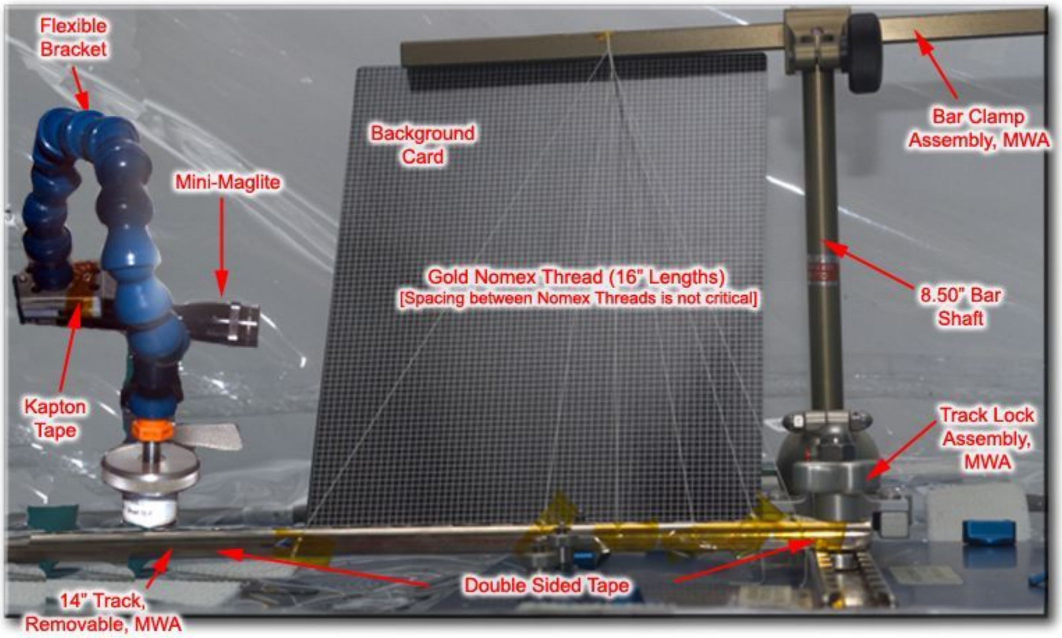


Figure 3: FMVM Setup in the ISS

The experiment was open to the environment and was manually manipulated by the astronaut. The first task of the astronaut was to inject a 1cc drop of liquid onto it. The string was then held on to the test stand. The next string was separated and another 1cc drop of the same liquid was placed on the string. These two strings were brought together manually in a slow manner so the drops would have little to no horizontal velocity as they touched. As soon as the drops were touching the tension on the incoming drop's string was released and coalescence due to surface tension alone took place. Once coalescence of the two spheres took place the two strings were brought together and anchored to the test stand (Figure 4).

The third string was separated next and a 2cc drop, which was the same size as the merged droplet described above, was injected onto it. This 2cc drop was then slowly brought to join with the 2cc drop created by the first merging. As soon as the two drops were made to touch, tension was again let off the incoming string and the surface tension caused the two drops to coalesce. All three strings were then combined and secured to the frame. A 4cc drop, which was the same size as the drop created by the previous step, was then injected onto a fourth string. The two 4cc drops were then merged in the same manner as the previous steps. Finally a 0.5cc drop was injected onto the final string, slowly brought to the 8cc drop created by the previous merging and allowed to coalesce.

A video tape of this sequence of the coalescence process was then downloaded from the ISS to NASA, placed on DVD and delivered to UTSI in digital format.

The experiment was planned for determining the viscosity of several liquids including Glycerin, Silicone Oil, Honey, and Corn Syrup. The properties of these liquids and their designation code are given in Table 1. Small quantities of these liquids had to be upmassed to the ISS before performing the equipment. The different liquids were placed in different syringes.

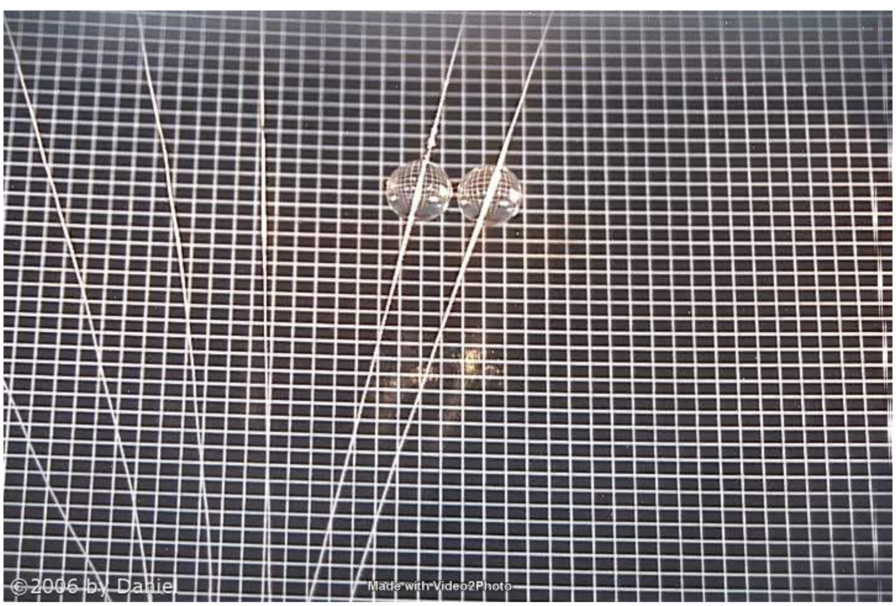


Figure 4: The Setup for the coalescence

Table 1: List of liquid properties used in the FMVM tests on the ISS Experiments

Liquid	**Designated Code**	**Density (*g/cc*)**	**Surface Tension (Erg/cm^2)**	**Viscosity (Pa·*cm*)**
Glycerin	A1	1.17	63	1,490
Silicone Oil	B1	0.97	21.5	12,500
Silicone Oil	B2	0.97	21.5	100,000
Honey	D1	1.45	90	12,500
Honey (thick)	D2	1.47	88	42,000
Corn Syrup	E1	1.41	83	2,200
Corn Syrup (thick)	E2	1.41	90	15,000

CHAPTER 3: MATHEMATICAL MODEL

An analytical formulation of the problem of liquid droplet coalescence can best be investigated through solutions to the equations of motion of an incompressible fluid. In this chapter, the analytical derivations by Antar are followed (2003).

We begin by looking at the equations of conservation of mass and momentum for an incompressible fluid:

$$\nabla \cdot \mathbf{u} = 0 \qquad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = \frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} \qquad (2)$$

where $\mathbf{u} = (u_1, u_2, u_3)$, is the fluid velocity vector field, p is the pressure field inside the liquid mass, ρ is the fluid density, and $\nu = \mu / \rho$ is the liquid kinematic viscosity. Because we are interested in the merging of the liquid drops under the influence of surface tension or capillary forces alone, the inertia terms can be neglected since the fluid motion is relatively slow which is a reasonable assumption for the coalescence problem. By neglecting the inertia terms the momentum equation becomes

$$\frac{\partial \mathbf{u}}{\partial t} + \mu \nabla^2 \mathbf{u} - \nabla p = 0 \qquad (3)$$

where μ is the liquid dynamics viscosity. Inertia terms are also eliminated in non-accelerating fluid motion such as Stokes Flow. Equation (1) and (3) are linear partial differential equations describing the viscous fluid motion for creeping flows which constitute the flows taking place in the coalescence of two liquid masses such as two liquid drops. Since the equations are linear, there exist closed form analytical solutions for this system in terms of the Stokeslets, depending on the initial and boundary conditions.

The problem of coalescence of materials is also basically concerned with the merging of two liquid masses. In this experiment, we are interested in the free surface evolution as the masses merge. This makes the problem essentially a capillary one. Thus any solution to equations (1) and (3) must be consistent with the free surface boundary condition given by the following expression, representing the balance of the surface forces:

$$\mathbf{T}\cdot\mathbf{u} = -\sigma\left(\frac{1}{R_1}+\frac{1}{R_2}\right)\mathbf{n} = \mathbf{b} \qquad (4)$$

where $\mathbf{n}$ is the unit vector normal to the free surface pointing away from the liquids, σ is the coefficient of surface tension, R_1 and R_2 are the principal radii of curvature of the free surface, $\mathbf{b}$ is a surface tension vector, and $\mathbf{T}$ is the stress tensor which is given in Cartesian coordinates by its components:

$$T_{ij} = -p\delta_{ij} + 2\mu\varepsilon_{ij}\,,\ \varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \qquad (5)$$

The solution to equations (1), (3), and (4) exists and is unique due to the linearity of the equations. However, analytical solution can only be obtained for very simple geometries of the free surface; otherwise if the free surface is complex then the solution to this problem must be obtained through numerical approximation. The problem of the calescence of two liquid drops involves changing of the shape of the two liquid drops with time until they completely merge into a single drop. Thus the simulation of the drop coalescence experiment will involve a very complex change of the free surface geometry as a function time.

In order to accurately simulate the drop coalescence experiment the solution to problem (1), (3), and (4) must be obtained numerically in this case. For the numerical simulation of the coalescence problem to be totally accurate then the numerical solution of the merging process must be obtained for two merging liquid spheres. Such simulation will require a three-dimensional solution. Thus, in order to create a representative mathematical model of the actual experiment, we need a three-dimensional model. However, to demonstrate the solution method adopted here in a clear manner and without the added geometrical complication of the spherical coordinate system, the solution method would be given first for a geometrically simpler two-dimensional model which represents the merging of two infinitely long liquid cylinders.

TWO-DIMENSIONAL GEOMETRY

For the two-dimensional case of cylindrical drops, the set of governing equations and boundary conditions shown before for the liquid coalescence problem reduces to the following linear boundary value problem for the velocity field with derivative boundary conditions, in a coordinate system as follows:

$$\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} = 0 \tag{6}$$

$$\mu\left(\frac{\partial^2 u_1}{\partial x_1^2} + \frac{\partial^2 u_1}{\partial x_2^2}\right) - \frac{\partial p}{\partial x_1} = 0 \tag{7}$$

$$\mu\left(\frac{\partial^2 u_2}{\partial x_1^2}+\frac{\partial^2 u_2}{\partial x_2^2}\right)-\frac{\partial p}{\partial x_2}=0 \tag{8}$$

$$p-2\mu\left(\frac{\partial u_1}{\partial x_2}+\frac{\partial u_2}{\partial x_1}\right)=p_0-\sigma\kappa \tag{9}$$

where κ is the curvature of the free surface given by 1/R for the two-dimensional case, and p_0 is the pressure of the air surrounding the liquid. Equations (6)-(9) were assumed to be for steady state conditions; which mean the time dependence is neglected.

The region of fluid in this formulation is defined by Γ and the interior area denoted by Ω. There exists a unique solution to the system (6)-(9) in terms of the velocity field **u**$\{u_1, u_2\}$, given in the following integral form (Antar 2003).

$$c_{ij}\, u_j(x_i)+\int_\Gamma q_{ij}(x_i, y_i)u_j\, d\Gamma_y=\int_\Gamma s_{ij}(x_i, y_i)b_j\, d\Gamma_y \tag{10}$$

where in the above y_i is the position vector of the free surface Γ while x_i is any point in the interior of the liquid mass Ω (i=1,2) and (j=1,2) are the coordinate directions and:

$$c_{ij}\{=\delta_{ij}, x\in\Omega; =\delta_{ij}/2, x\in\Gamma; =0, x\in\Omega\}$$

$$q_{ij}=\frac{r_i r_j}{\pi R^4} r_k y_k$$

$$s_{ij}=\frac{1}{4\pi}\left[\frac{r_i r_j}{R^2}-\delta_{ij}\log R\right]$$

where $r_i = x_i - y_i$, $R=\sqrt{r_1^2+r_2^2}=|x-y|$, δ_{ij} is the Kronecker delta, and Ω’ is the complementary region given by $\Omega\cup\Gamma$. The solution given by equation (10) is in a non dimensional form in which the velocity, pressure and time scales respectively have been used as follows:

$$V_s=\sigma/\mu,\ p_s=\sigma/L,\ t_s=L\mu/\sigma \tag{11}$$

where L is any appropriate length scale, and for the geometry being considered in here could present the radius of one of the cylinders.

Equation (10) can be written as the following vector symbolic notation:

$$C\,\mathbf{u}(\mathbf{x})+\int_{\Gamma}Q(\mathbf{x},\mathbf{y})\mathbf{u}\,d\Gamma_y=\int_{\Gamma}S(\mathbf{x},\mathbf{y})\mathbf{b}\,d\Gamma_y \tag{12}$$

where *C*, *Q*, and *S* are the second rank tensors whose elements are c_{ij}, q_{ij} and s_{ij}, respectively. In order to ensure a unique solution to this problem equation (12) must be solved together with the added constraint that the liquid mass must be conserved at the free surface using the following mathematical representation:

$$\int_{\Gamma}\mathbf{u}\,d\Gamma=0 \tag{13}$$

Equation (12) and (13) form the basic mathematical model for describing the coalescence process in a two-dimensional Cartesian system. Note that in this form the original differential equation system has been transformed to a system of bounded integral equation in which the free surface is represented by the integration bounds. Such integral formulation for the problem lends itself to a solution through an integral method such as a Finite Element Method (FEM) or the Boundary Element Method (BEM). The BEM is basically a part of FEM in which only the solution on the boundary of the domain, Γ, is sought while in the FEM the solution is throughout the full domain, Ω of the problem (Becker 1992).

Equation (12) and (13) were solved using the BEM, a method that is ideally suitable for solving the boundary value problem for the free surface. Also with the BEM the free surface velocity of drop **u** is the unknown but eliminates the need to compute the full velocity field within the interior of the drop. In addition, the BEM method performs the surface integrations given in equation (12) and (13) by subdividing the surface into segments. This is accomplished by allowing the surface boundary Γ to be discretized into a sequence of boundary curve elements Γ_i in which the velocity and surface tension force vectors are written in terms of their values at a sequence of N nodal points in the following manner. After dividing the boundary Γ into N elements, Γ_1……, we define velocity and surface force tensions u and b which apply at a typical element "j" in the following manner:

$$\mathbf{u} = \Phi u^i$$

$$\mathbf{b} = \Phi b^i$$

where u^i and b^i are the nodal element velocity and surface tension, respectively. The interpolation function Φ is a 2 x 2M matrix of shape functions which are the standard finite element-type functions given by

$$\mathbf{\Phi}=\begin{bmatrix} \phi_1 & 0 & \phi_2 & 0 & \cdots & \phi_M & 0 \\ 0 & \phi_1 & 0 & \phi_2 & \cdots & 0 & \phi_M \end{bmatrix} = \begin{bmatrix} \Phi_1 & \Phi_M & \cdots & \Phi_M \end{bmatrix}$$

After substituting the shape functions into equation (12) and discretizing the boundary Γ we get the following expansion for any arbitrary nodal point, *i*:

$$C^i u^i + \sum_{j=1}^{N}\left(\int_{\Gamma_i}\left(Q - Q^r\right)\Phi \, d\Gamma_\eta\right)u^j = \sum_{j=1}^{N}\left(\int_{\Gamma_i}\left(S - S^r\right)\Phi \, d\Gamma_\eta\right)b^j \tag{14}$$

Equation (14) can be written as a matrix equation in the following form by exchanging the summation and integration operators:

$$C^i u^i + \sum_{j=1}^{N}\left(F^{ij} - G_r^j\right)u^j = \sum_{j=1}^{N}\left(H^{ij} - I_r^j\right)b^j \tag{15}$$

where $F^{ij} = \int_{\Gamma_i} Q\,\Gamma\, d\Gamma_\eta$; $G_r^j = \int_{\Gamma_i} Q^r\,\Phi\, d\Gamma_\eta$

$$H^{ij} = \int_{\Gamma_i} S\,\Gamma\, d\Gamma_\eta \;;\; I_r^j = \int_{\Gamma_i} S^r\,\Phi\, d\Gamma_\eta$$

Equation (15) represents N algebraic equations for N Variables u, representing the velocity of the nodal points of the free surface curve, Γ. The solution of the system (15) yields the velocity nodal point. From knowledge of the velocity of every nodal point the shape evolution of the free surface curve can be determined as a function of time by integrating the following equation at each time step, t:

$$\frac{dx}{dt} = \mathbf{u}(x) \tag{16}$$

Equation (15) gives us the time dependent shape of the free surface as the liquid drops merge. In the above solution method we begin with the initial geometry at time, t_0. This initial geometry is used to determine the velocity of the boundary after the first time step. From that velocity then the position x of the boundary can be determined by integrating the following:

$$x_b = \int \mathbf{u} dt$$

The new boundary is then used as initial conditions in the second time step and so on. This is called the time marching technique.

THREE-DIMENSIONAL GEOMETRY

In anticipation of the use of the numerical results in conjunction with experimental measurements, the coalescence of two-dimensional circular cylinder is not exactly similar to the experimental data which were performed with two spherical drops. Thus, the analysis described above for rectangular Cartesian coordinate system is modified in the manner described below to enable the simulation of the coalescence process of two spherical drops. This can be easily accomplished by introducing the following transformation from the Cartesian coordinate system (x_1, x_2, x_3) used in the analysis for the two-dimensional case outlined above, to a cylindrical coordinate system (r, θ, z) needed for the spherical geometry

$$x_i=(x_1, x_2, x_3)^T=(r\cos\theta, r\sin\theta, z)^T \tag{17}$$

The cylindrical coordinates are functions of all three Cartesian coordinates. Then the temsoral function in (10) namely c_{ij}, q_{ij} and u_{ij} must all be written for i, j =1, 2, 3 in the following manner:

$$c_{ij}\left\{= \delta_{ij}, x \in \Omega;\ = \frac{\delta_{ij}}{2}, x \in \Gamma;\ = 0, x \in \Omega\right\} \tag{18}$$

$$q_{ij}(x_i, y_i) = \frac{3(x_i, y_i)(x_j, y_j)(x_k, y_k)n_k}{4\pi|\mathbf{x}-\mathbf{y}|^5} \tag{19}$$

$$s_{ij}(x_i, y_i) = \frac{1}{8\pi}\left[\frac{\delta_{ij}}{|\mathbf{x}-\mathbf{y}|} + \frac{(x_i - y_i)(x_j - y_j)}{|\mathbf{x}-\mathbf{y}|^3}\right] \tag{20}$$

where again the position vector **y** represents the free surface location while **x** represents an interior point.

After successive substitutions of the cylindrical coordinate in equation (10) and upon integration along the θ-direction, equation (10) takes the following form for cylindrical coordinates:

$$c_{\alpha\beta}\, u^c_\beta + \int_\Gamma q^c_{\alpha\beta}\, u^c_\beta\, d\Gamma = \int_\Gamma s^c_{\alpha\beta}\, b^c_\beta\, d\Gamma \tag{21}$$

where the superscript c stands for cylindrical coordinates, and α and β are either 1 or 2 and hence $u^c = (u^c_1, u^c_2)^T = (u_r, u_z)^T$. The coefficients $q^c_{\alpha\beta}$ and $s^c_{\alpha\beta}$ can be written in terms of complete elliptic integrals of the first and second kind (van de Vorst 1995).

It can be seen from examining the governing equation (3) and the boundary condition (4) that the evolution of the free surface shape, as the two liquid volumes merge, is dependent upon the only two parameters that appear in these equations; μ and σ, the liquid viscosity and the surface tension coefficient, respectively. Also due to the uniqueness of the solution of equation (3), the evolution of the free surface curve shape is also a unique function of the two parameters μ and σ, i.e.

$$\mathbf{x} = \mathbf{x}(t; \mathbf{x}_0, \mu, \sigma), \ \mathbf{x}_0 = \mathbf{x}(t = 0)$$

In other words, the free surface shape evolution will be different for different values of either μ or σ. Thus, the objective of this analysis is to determine the viscosity of the liquid from the experimentally indentified unique shape evolution of two merging liquid volumes of the same fluid under the action of surface tension alone. This is accomplished by comparing the experimentally measured merging geometry and velocity of the free surface with the numerical approximation obtained from equation (21) together with the oppropriate values for both the viscosity and the surface tension.

CHAPTER 4: COMPUTER MODEL

In order to get the analytical and numerical solutions to the coalescence of the two drops, equation (10) and (21) were coded into a computer program (Antar 2003). Since we are only interested in surface deformation of two drops, a Boundary Element Method (BEM) was applied to describe the system. There are three programs of this model: [1] the initial surface geometry generator, [2] a double symmetry coalescence program, and [3] a single symmetry coalescence program. These three programming codes were originally written by Antar (UTSI) and edited by his students.

The correct integration of equation (1) and (3) subject to the boundary conditions (4) will give the velocity of the free surface surrounding the fluid in equation as well as its positions. In our problem, the fluid will be contained within the two coalescing drops. As the drops coalesce they will merge into a single drop as shown in Figure 9 and Figure 10. It can be seen that as the two drops merge into a single drop the contact radius will change from zero at the time of the drops just touching each other to the value of the final resulting drop. Thus contact radius can be considered to represent an adequate measure of the extent of the merging process (Figure 8). In all of the discussion that follows we will use the contact radius (or diameter) to represent the extent of the drop merging process.

The initial surface geometry generator is used just for creating initial points of the surface of droplets in order to implement the evolution by coalescence. Figure 6 and Figure 7 show examples of an initial surface geometry. In addition, the ratio of these two droplets was set up 1 to1 in Figure 6, and 3 to 1 in Figure 7.

The symmetry coalescence programs show the process of the evolution of the free surface during coalescence. All physical properties were written in non-dimensional form to be able to use this program for all materials as in equation (11):

$$t^* = \frac{t}{t_s} \Rightarrow t = t^* \cdot t_s$$

$$l^* = \frac{l}{l_s} = \frac{l}{L} \Rightarrow l = l^* \cdot L$$

where t^* is the non-dimensional time, t is the actual time, t_s is the time scale, l^* is the non-dimensional length, l is the actual length, and l_s is the length scale. The time scale is defined as $t_s = L\dfrac{\mu}{\sigma}$, where μ is the dynamic viscosity in units of $\dfrac{dyne \cdot s}{cm^2}$ and σ is the surface tension in units of $\dfrac{dyne \cdot s}{cm}$. The program gives the solution in time step increments of $0.01\,t^*$. The plot can also be displayed at selected time so that the surface geometry progression can be shown visually clearly.

INITIAL SURFACE GEOMETRY GENERATOR

The purpose of the Initial Surface Geometry Generator (ISGG) is to define the initial conditions geometry representing the two drops as they initially come into contact with each other. This initial geometry is represented by data points along the boundary surface s of two circles in contact. The user of the ISGG software must specify the number of data points desired along the circumference of each circle, N_1 and N_2, the radius of each circle, R_1 and R_2, and the initial contact radius (Figure 6 and Figure 7). After this process, the computer program measures the angles from the contact radius to the x-axis on both circles. In this case, these are α for the left circle and β for the right one (see Figure 5). Then it proportionally divides number of data points, $n = n_1 + n_2$ between two circles, where n_1 and n_2 are numbers of points in the left circle and the right circle, respectively.

The focus of the left circle, c_l, on the x-axis is placed a distance h_1 away from the origin, *0*; therefore the coordinate of the focal point of the left circle is $c_l(-h_1, 0)$, and h_1 is calculated as $\sqrt{R_1^{\,2} - r^2}$, where R_1 is the radius of the left circle and *r* is the initial contact radius between the two circles. The first point (x_1, x_2) is at $x_1 = -(h_1 + R_1)$, $x_2 = 0$, and the following points are located at $x_1 = -[h_1 + R_1 \cos(m_1 \cdot \delta_\alpha)]$, $x_2 = [R_1 \sin(m_1 \cdot \delta_\alpha)]$, where m_1 is a parameter which ranges from 0 to n_1. The last point must be at $x_1 = 0$, $x_2 = r$. The program then starts plotting the right circle. The coordinate of the focal point of the right circle, c_r is $c_r(h_2, 0)$, where $h_2 = \sqrt{R_1^{\,2} - r^2}$. The value of the points on the surface of the right circle can be written as $x_1 = -[h_2 + R_2 \cos((n_2 - m_2) \cdot \delta_\beta)]$, $x_2 = [R_2 \sin((n_2 - m_2) \cdot \delta_\beta)]$, where m_2 is a parameter which goes from 0 to n_2. The last point must be at $x_1 = h_2 + R_2$, $x_2 = 0$.

The program outputs these data points into a text file. Importing these data by using Excel or similar software, a graph of these points can be created to visualize and to make sure of a proper boundary. When these points are correct, the desired portions of the circles are input into a coalescence program.

Moreover, the volume change due to the merging process is not considered by the generator. The program just set up two circles of finite radii without coalescence.

Importantly note in the numerical simulation of the merging drops, a small but finite initial contact radius must be specified representing a very short time after the two drops touch. Ideally, this initial contact radius at the time $t^* = 0$ is of zero length when the two drops just touch each other. However, the numerical approximation to the coalescence problem will become singular whenever this contact radius is taken to be zero. Thus in order to avoid this singularity the initial contact radius must have a small but finite value. In addition, the smallest contact radius can be seen if $l^*\left(t^* = 0\right) \approx 0.1$. Also it should be noted that this slight error in the initial conditions will have almost no effect on the development of the coalescence process after some finite time has elapsed.

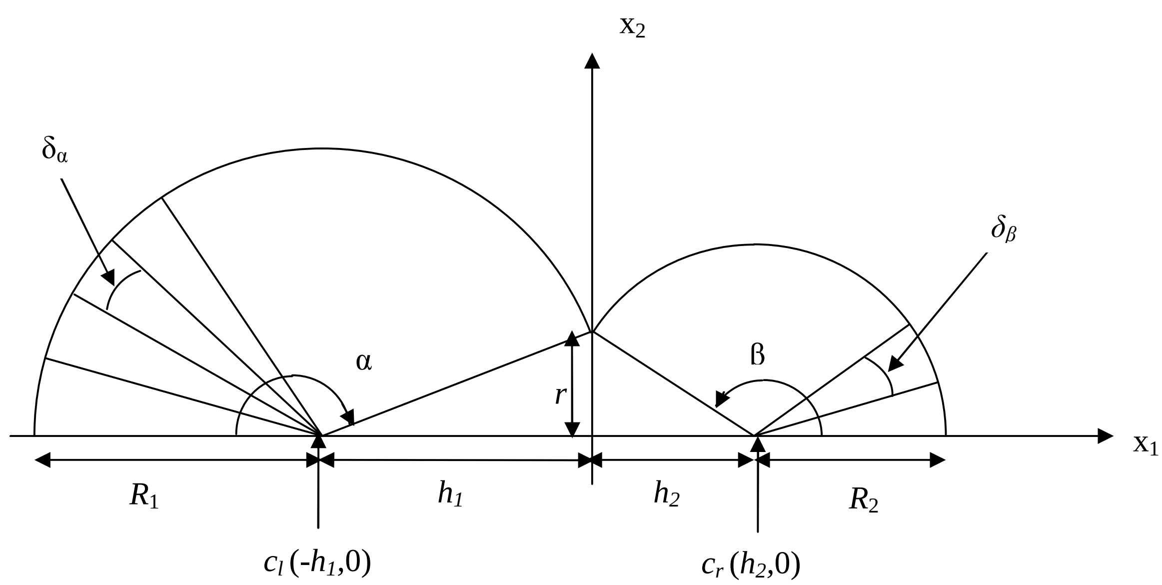


Figure 5: Initial Value Circles

EVOLUTION OF A MERGED DROPLET FROM TWO EQUAL DIAMETER DROPLETS

A double symmetry coalescence program is used for equal sized droplets, in which the surface geometry in all four quadrants was a symmetrical mirror image. Therefore the right semicircle of the initial surface geometry only needs to be entered, and then the program decides the rest of the geometry. Furthermore, only positive x and y value in the first quadrant are needed to be entered into the program. All the initial (x, y) values were entered from the abscissa to the ordinate.

A user also needs to specify a number of time steps. The computer codes predict the merging of two cylinders and output updated values of the free surface at each time step. All values of the points on the free surface can be obtained, however, the value of contact radius at each time step is only required to calculate and determine the viscosity with the known surface tension. Hence a separate output file which contains the contact radius at each time step was set up. For equal sized circles, the point of contact radius is always located at $x_1 = 0$.

Viscosity is calculated by comparing the contact radius length versus time between the theoretical data the computer code predicted to the experimental data.

EVOLUTION OF A MERGED DROPLET FROM TWO INITIALLY DIFFERENT DIAMETER DROPLETS

A single symmetry coalescence program is used for unequal sized droplets. Positive x_2 values of the points on the free surface are required to be entered into the program codes and then the computer creates the negative x_2 side of the graph.

In this case, there is an issue to determine the contact radius. The x_1 value of the contact region moves towards the smaller droplet's side (the right droplet's side) so it is hard to gain x_2 values, which are the values of the contact radius at each time step. To resolve this problem, we calculated the distance between the origin and each point on the free surface of either drop. The point which has the shortest distance to the origin is the contact radius.

The other issue is that after some time steps, the contact radius cannot be recognized, and its measurement becomes ambiguous. However we still can use the contact radius but we will not be able to gain the complete set of data.

Another way to create a continuous curve over the entire coalescence process is to measure the total distance between the two farthest points on the abscissa. These axial points are both at $x_2 = 0$. Similarly to a double symmetry coalescence program, a separate output file which contains two x_1 values at each $x_2 = 0$ at each time step was set up; then the axial width can be calculated. In order to determine the viscosity we follow the same procedure as in the case of the double symmetry coalescence program.

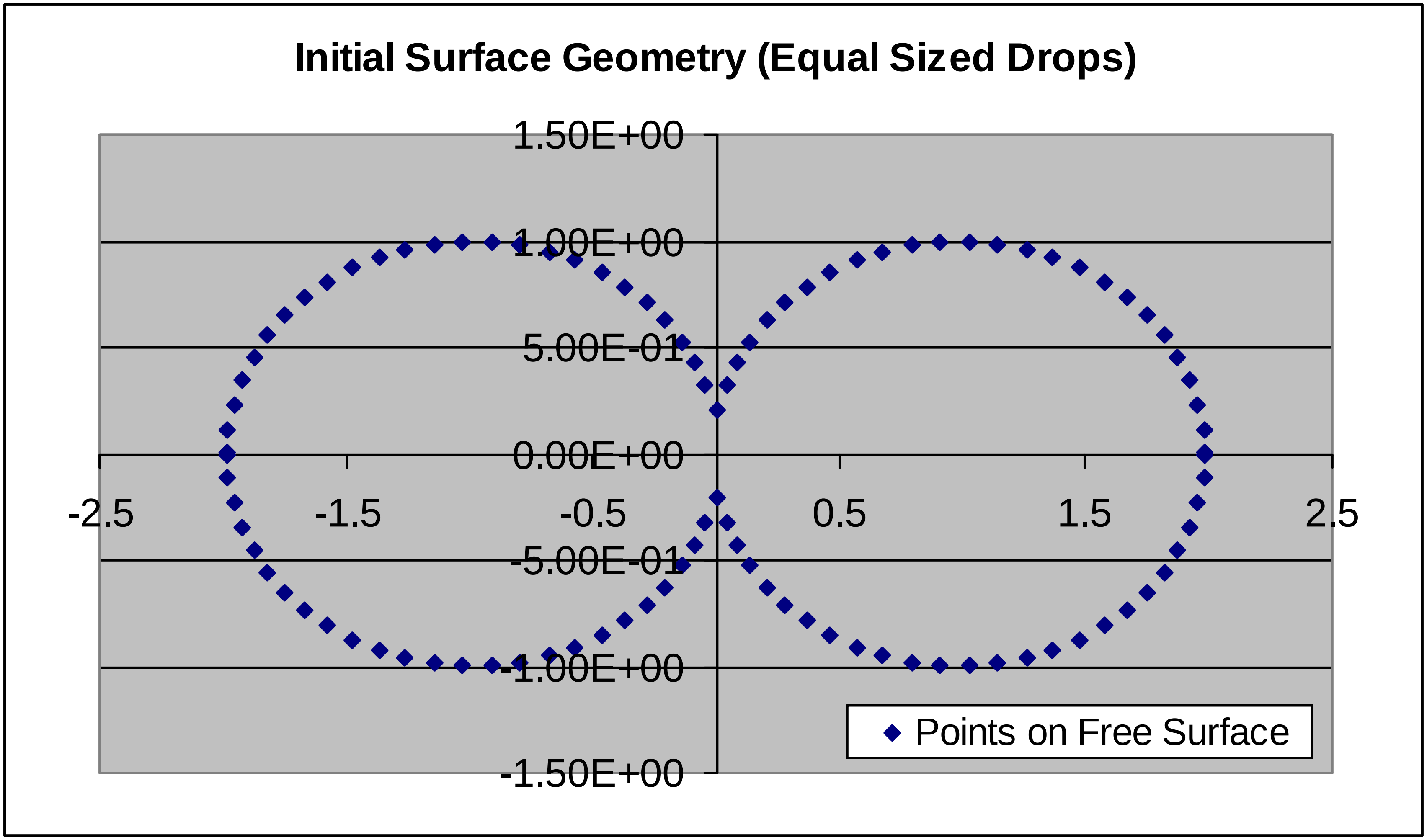


Figure 6: Initial Values (Equal Sized Drops)

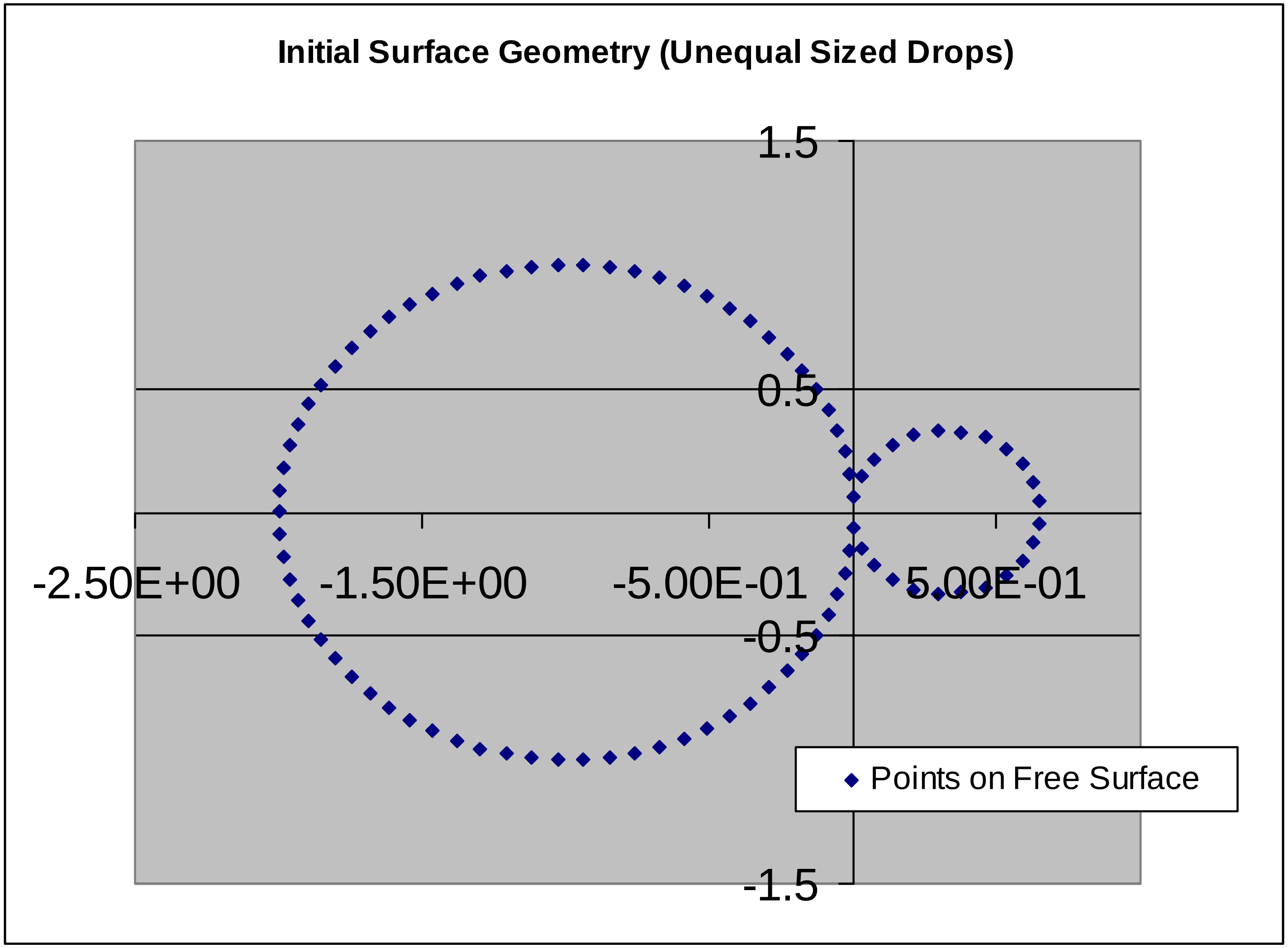


Figure 7: Initial Value (Unequal Sixed Drops)

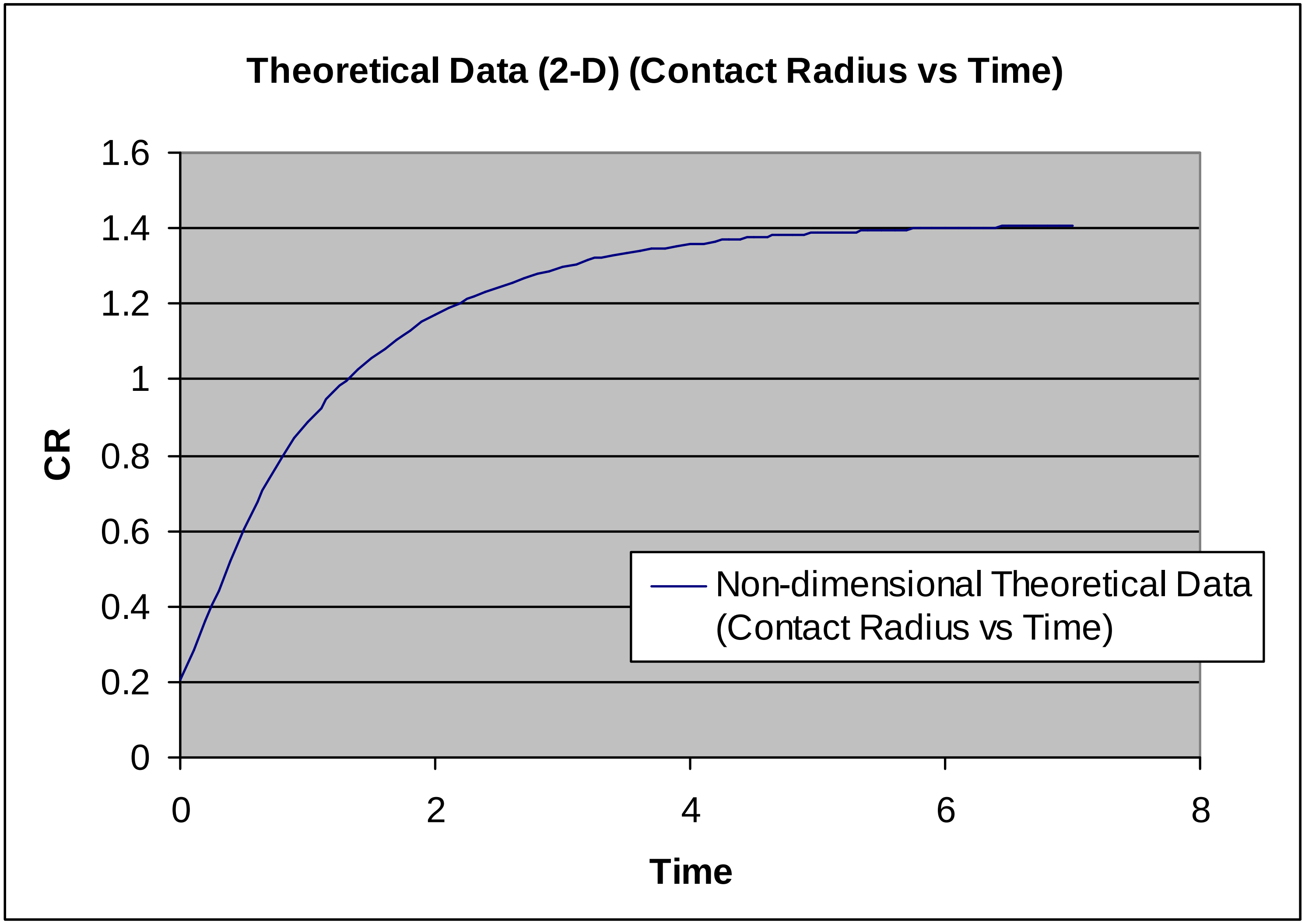


Figure 8: Theoretical Data (2-D) (The ratio of two droplets is 1:1) created by the computer program codes

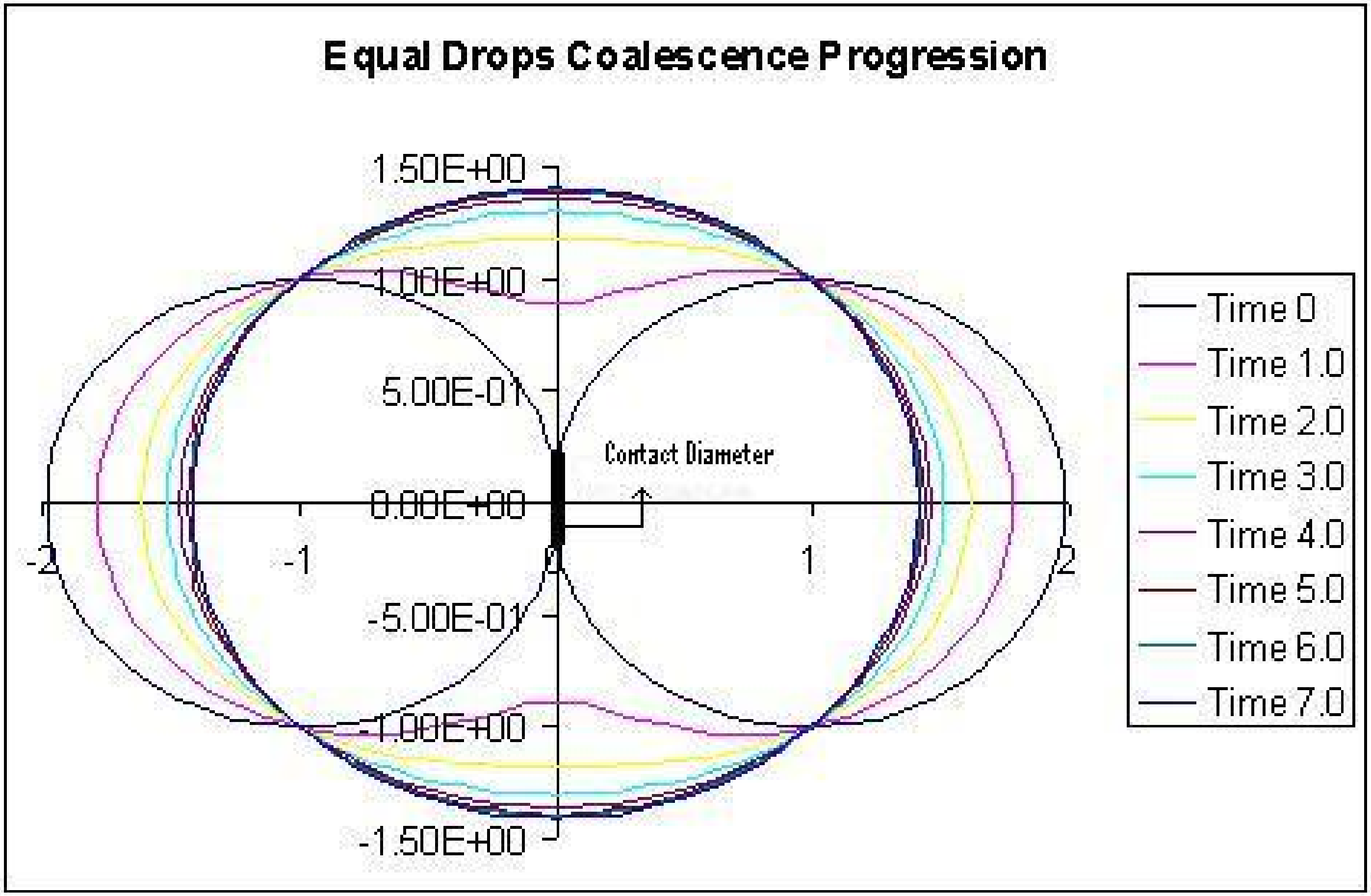


Figure 9: Equal Cylinder Progression until $t^* = 7.0$

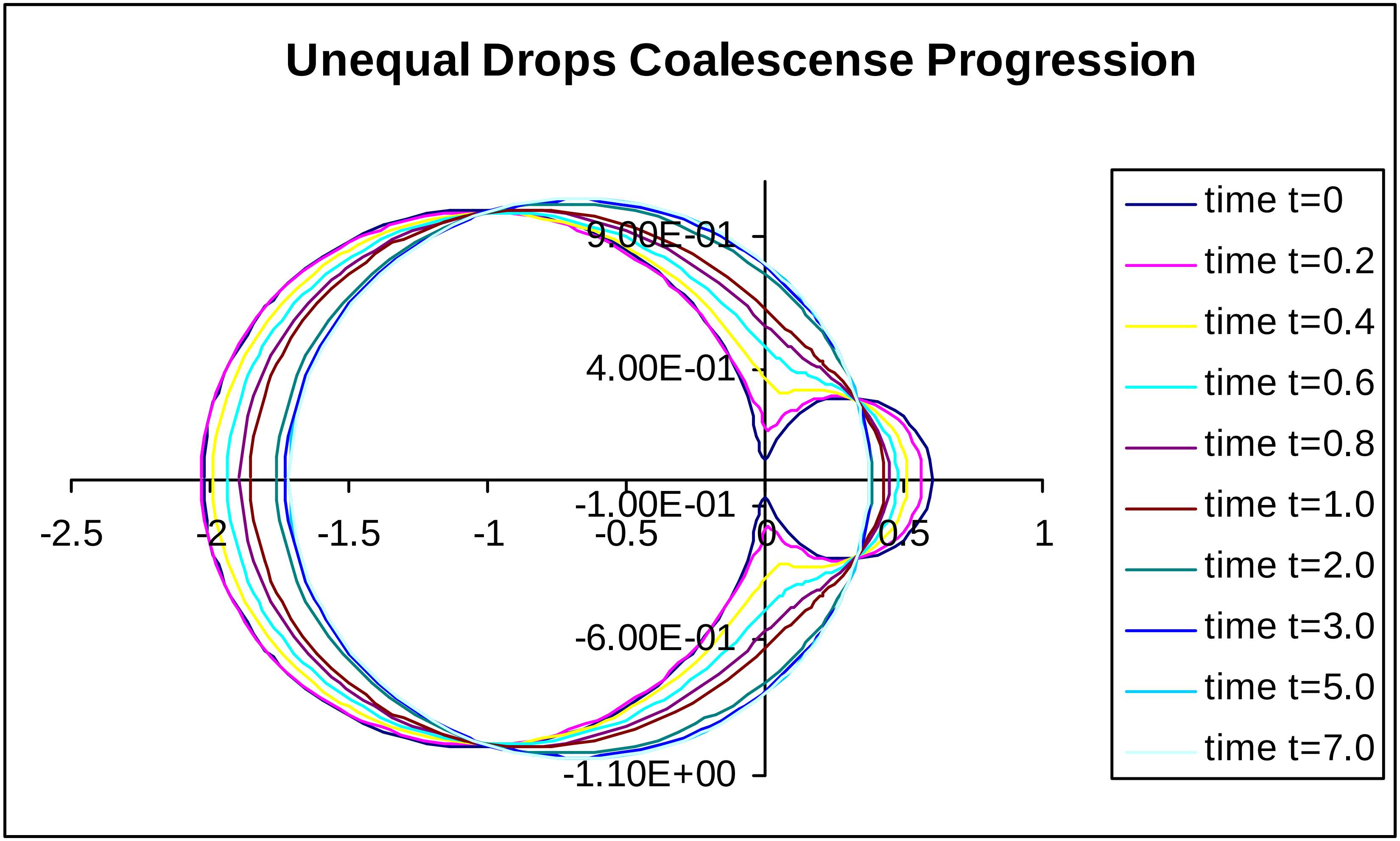


Figure 10: Unequal Drops Coalescence Progression until $t^{*} = 7.0$

CHAPTER 5: RESULTS AND DISCUSSION

The experiments are performed aboard the ISS with various liquids, however, in this thesis, only one liquid was analyzed. The main data source was taken through video during the experiments using the on board digital video camera available for use by the astronauts. In addition, the video camera used by the ISS flight engineers was not a dedicated camera for FMVM experiment and as such was not a high speed video camera. The camera used had a nominal speed of 30 frames /second, which is normally available on commercial video cameras. The FMVM experiment videos available for analysis in this study were in VHS format that was later digitized and recorded on DVD's. Although the original FMVM data that were recorded during the ISS experiments were digital, these digital data sets were not available for analysis.

The data analyzed in this chapter were transmitted to the ground in one of three modes. The first mode involved actual VHS recording of the live transmission to the control room at NASA/MSFC. The second mode involves delated downloading of all videos recorded by the video camera on board the ISS to NASA/JSC. These videos were then recorded on VHS tapes by the audiovisual office at NASA/JSC and then distributed to the various PI's involved in these days activities including the FMVM experiments. The last mode involved direct VHS copies of the actual videos retrieved from the ISS a long time later. The actual FMVM experiment digital data recordings were retrieved by STS-114 which landed on August 5, 2005. However, this data set was never released to us for analysis yet. Consequently all of the data analyzed in this section are in the first two formats discussed above.

The data video from the ISS experiment was developed on DVD in a VOB format as discussed above, which is a multiplex of video and audio data. Before any analysis could be performed, this video needed to be separated into individual single frames. To accomplish this, the files were converted to an AVI (Audio Video Interleave) format, the most common file format for strong audio/video data on the PC, to allow for an AVI splitter to break the video into its individual frames. The AVI converter also gave information about the video. The ISS video's resolution was 740x480.

The following is the list of software required for analyzing the video data:

- ü Microsoft Excel
- ü Spotlight (either 8 or 16)
- ü Video2Photo (Free software. http://www.pixelchain.com/)
- ü ImToo MPEG Converter (Free software. http://www.imtoo.com/mpeg-encoder.html)
- ü VTK 5.0 (Free software. http://www.vtk.org/)

Once the video had been broken into its individual frames, a NASA program called Spotlight was used to take length measurements of the images. Spotlight was written to analyze sequences of images generated in fluid physics experiments (Klimek 2004). It is specifically designed to track points over a sequence of frames. By specifying areas of interest (AOIs), a user can manipulate a frame in order to more accurately find certain points. These points are either tracked manually by clicking on them with the mouse, or automatically by varying contrast or another distinguishing marker.

To ensure that accurate data points were established, manual AOI tracking was used. This required the user to click on a point to be measured and then the program centered AOI on that point. Two AOIs were used in data analysis. this program only gives distances in terms of pixels.

The data was taken from a Spotlight text file and then entered into Microsoft Excel. The next step was to convert the number of pixels into a meaningful measure of length and in order to do this, a calibration was performed. The FMVM experiment had a background with grid spacing behind the merging drops. Spotlight was used to measure the length of these squares. A column in the Excel data sheet was then included to convert the number of pixels in data into centimeters by dividing the data by the unit of pixels/cm calibration number.

The lengths then needed to be plotted versus time to produce any truly meaningful data. From Spotlight we tracked certain points in every frame that was created from the video files. From the film speed of the camera the time between each frame in the video was calculated. Dividing each frame by the frame speed gave the approximate time of that data point: $\frac{N_f}{s_f} = \sec$, where N_f is number of frames and s_f is the frame speed. A frame speed is defined as $s_f = \frac{N_f}{t}$, where t is time in seconds. The contact radius raw data in engineering units, of cm versus seconds, were shown in Figure 20, Figure 22, Figure 24, and Figure 26, for the experiment based on merging equal drops of ISS. Note that the first data point recorded had a contact radius of 0.15 *cm*. It is impossible to observe the $r = 0$ data from the video.

Since the viscosity is buried in the time scale, we dimensionalized the computer model and matched it with the data curve to find the correct scales and viscosity. The length was the first thing to be changed, implemented by multiplying our length scale to the l^* value. This is very simple because we set the radius of the length circle to 1 l^*. The length scale then was the radius of the large drop before coalescence, measured earlier by Spotlight. A column in Excel was set up to multiply all the non dimensional lengths by this scale.

The next issue was to transform the non-dimensional time t^* into a time t in seconds. However, since the time, t_s is defined by the viscosity that we are trying to determine: $t_s = \frac{l_s \cdot \mu}{\sigma}$, we cannot simply calculate this value. To determine the time scale we implemented a guess and check technique. With the two curves plotted together, the physical data is held constant, the length scale is already determined and we varied the time scale. A cell was set up in Excel which allowed the time scale to vary until the two curves matched up.

CONVERTING VIDEO

The first thing to do for this project is obtaining the video file. This file was received as a computer file or a DVD. If this video file is anything other than AVI the ImToo program had to be used in order to convert the file. The free version of this program will only allow 5 minutes of translation.

ImToo MPEG Converter was opened, and then under the File menu tab Add was clicked on to search for the video file (Figure 11). The interior box in the program gave useful information about the video file, including size of the file, which was useful for error calculation, and frame rate, which was needed for the Excel calculations. Near the bottom of the screen there were two lines “Profile” and “Destination.” The profile line allowed us to determine the type of file which we ended up with and AVI needed to be selected. The Destination line or Browse allowed us to choose where the new file is placed. When everything was ready, the button labeled “Encode” was pressed to start the translation process. Because of using the free version, a pop-up box came up asking for one’s name and user registration but this time it is ignored by pressing the “Later” button. A warning popped up, “ok” was clicked, and the process started. A status bar in the main window showed us the progress of the video translation. A new file was found in the destination folder with the same name previously assigned to the file, only difference was that it was an AVI file.

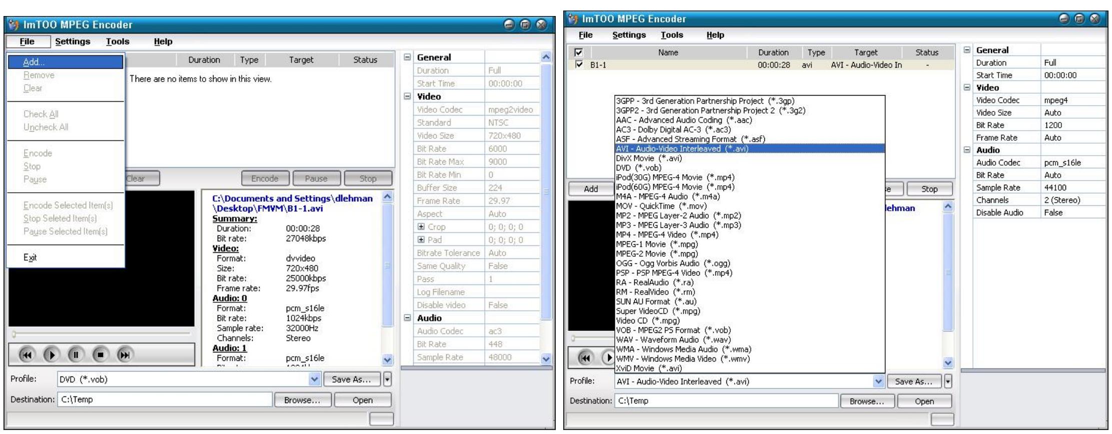


Figure 11: ImToo

SPLITTING FRAMES

Video2Photo has a very useful interface to split frames. The main window goes over how the process works. To start splitting frames, "Next >" needed to be clicked. The next page was the Select page and it gave three options: Video Camera, Video File, or Streaming Video. In this project, the middle option, called "Offline Video Files" had to be chosen.

Clicking on the file icon at the end of the "File Name" line, this allowed us to search for and select the video file created in the previous section. After selecting the desired offline video file, "Next" at the bottom of the screen was pressed. This brought up the Seek page and started immediately playing the video selection. Underneath the video there was a slide bar which represented the amount of time played. Under that there were two sets of buttons, the left set and the right set appeared to be common VCR style buttons for Play, Pause and Stop. The square stop button was selected, and then using the slide bar the moment before the two drops start to merge was found. It was important that the process was started before the drops merged so one could start measuring from the very first merging frame.

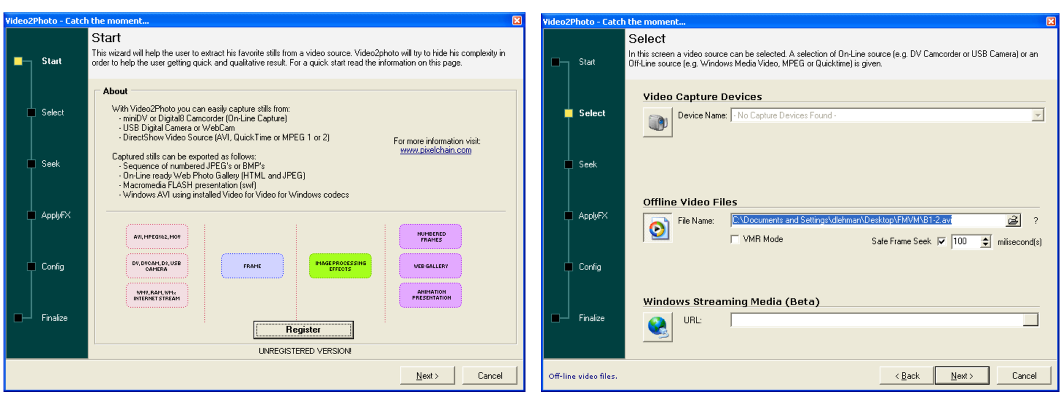


Figure 12: Video2Photo

At this point the very left button of the left set, which was the “Selection In” button, was pressed and the start of the selection was marked to be used. The “play” button was hit and we watched until the merging was completed, at which time the second button from the left, which was the Selection Out button, had to be pressed and the end of the selection was marked. After pressing the Selection Out button a blue bar became visible in the slide bar above. At this point the third button of the set, which added the selection to the selection list, was pressed. In the white space to the right of the window the selection appeared in the form of “Range_000###_000###.” Clicking “Next” took us the next step. The “Apply FX” page was shown. So at the bottom of the page clicking “Next”, we moved on to the “Config” page. First, we left the Export as “Numbered Frames.” Under File Settings, BMP or JPG does not affect the number of pixels and since there were on the order of 500 frames created, the jpg option with 65% compression was used. The Root name was arbitrary decided so that what file these pictures were from could be found. Clicking “Next” took us the next step as usual.

On the “Finalize” page there were two video windows. Under the video windows there was an “Output Folder” destination line, and we pressed the folder icon at the end of the line to search for an appropriate destination for the photo files. When everything was ready the render button under the right video window was pressed, then we watched the video frame by frame as it converts the selection into photos. Once the process was completed a window popped up and showed thumbnails of the created files. The window was closed and then finish was pressed end.

MEASURING THE DROPS

The Spotlight program was used for this step (Figure 14). Once the main spotlight window opened up, "go to File" and "down to Open" was chosen. This brought up a search box; navigated to the file where we saved the split video photos. Clicking on the very first photo file brought up an image of the two drops before they touch.

The zoom button was used to get a closer look of the droplets, the cursor was run over the image, and it was noticed that several numbers on the bottom of the screen moving; they were in the style of (###, ###) rgb:(##,##,##). The set of numbers on the left gave information of the pixel position from the top left corner. The first number was the x-direction, and the second number was the y-direction. The second set of numbers was the color in a RGB format, these numbers was ignored.

At this point we determined how many pixels were in a known length. It would be very helpful if the video had a ruler in it (Figure 13). We did this along several parts of the ruler, as there could be an angle between the plane of the ruler and the camera, which would distort the pixel to length ratio.

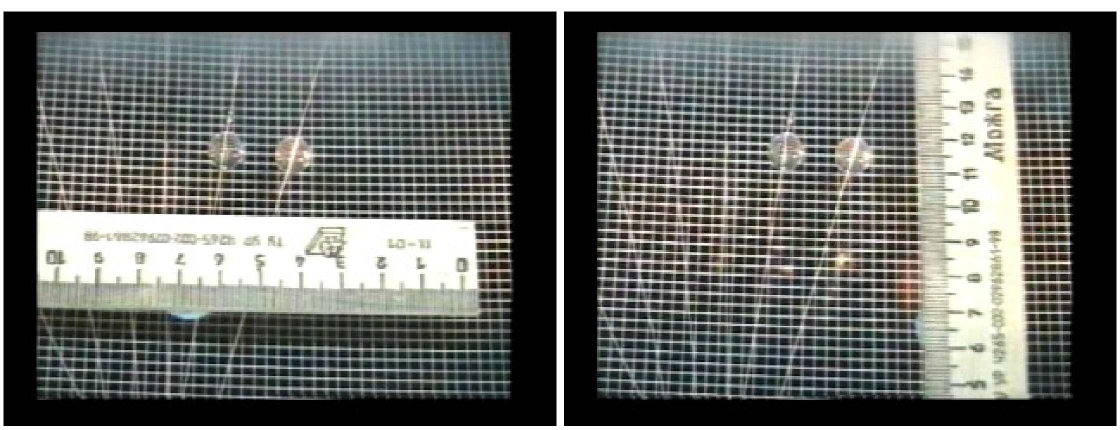


Figure 13: A Ruler in the Video

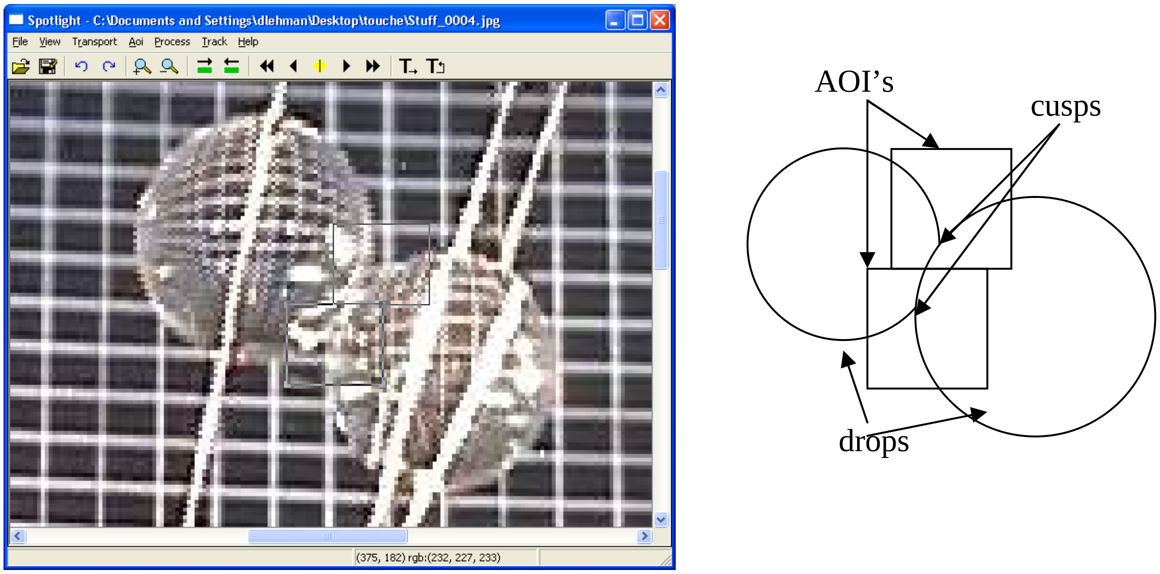


Figure 14: Spotlight (NASA Program)

To determine the size of the drops, the cursor was placed at the very top of the smaller drop. Then again the cursor was placed over the opposite side of the drop, trying to make one of the numbers match up, the left (x-direction) number matched. The numbers that differ, subtracting them gave us the diameter. For example, if the top of the drop was at (285, 95) and the bottom at (285, 160) the drop is 165 pixels in diameter. The same process was done for the large drop. To continue the example, if the large drop is 330 pixels, then the ratio between the two drops is 1:2. This ratio was required to know to create the theoretical dataset.

The size of the large drop played a role in the equation to determine the viscosity. Later a theoretical dataset was created, and the radius of the large drop was set to 1. That number was dimensionless. The reason why the radius of the large drop was set it to 1 is that calculating the length scale was simply finding the radius of the large drop, which was what we did in the previous paragraph. In the example the large drop has 330 pixels in the diameter, which will give 165 pixels for the radius of the large drop. If the image has 30 pixels/*cm* then the radius of the large drop is 5.5 *cm*. Thus in the example, the length scale, $l_s = 5.5$ *cm*.

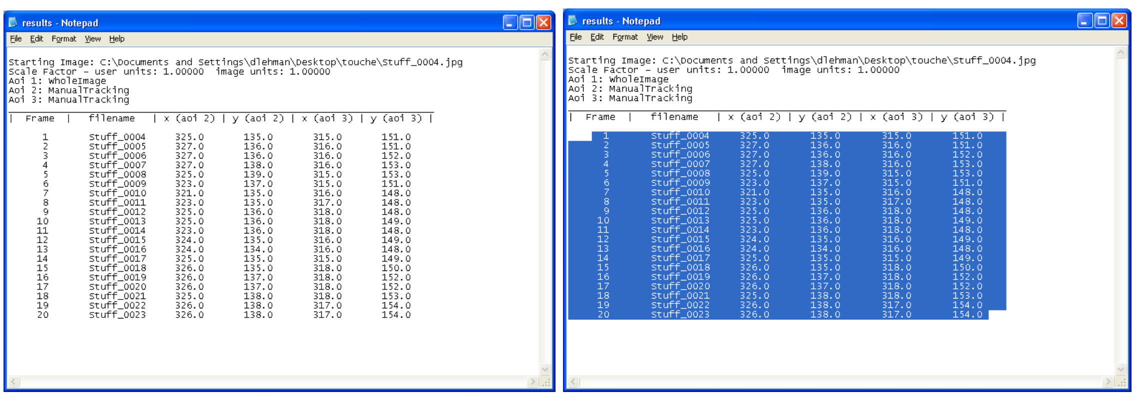
The next part was measuring the contact radius growth with time. We needed to advance to the photo that shows the very first contact of the two drops. Although if there was a lot of jitter before the drops started to merge (usually occurs due to trying to delicately move the drops in zero gravity) advance until the jittering calmed down and the drops were about to start merging. The advancement of the frames could be done by clicking on the "Step Forward" button, which looked like a single right facing arrow. ▶

Tracking blocks were placed around the areas of interest (AOI). We went-up to the AOI menu button AOI à New à Manual Tracking. This process was done twice to have two square outlines on top of the picture. Then the size of the boxes were adjusted so they were not too large on the screen, but still covered the cusp of the contract radius. One box was placed over each cusp.

To start the measuring of the contact radius the "Step Back" button was clicked once, the single backwards facing arrow. Then the "Track Continuous" button, the upper case T with the arrow that looped back to it, was clicked. When clicking the track continuous button, the image advanced one frame, which was why we stepped back a frame to start.

It was noticed that one of our AOI boxes was highlighted, and the other looked plain (usually it was the top box that is highlighted). Inside this box the cusp of the contact radius was shown, the cusp was just clicked. That AOI centered itself on where we clicked, the highlight then changed to the second AOI. Clicking the cusp in the second box centered the box, advanced the frame to the next image, and changed the highlighting to the first AOI.

We continued the clicking on the cusps of each successive frame until we got to the very end of the merging, usually around 500 frames, thus 1000 clicks. When they were done, the stop button that replaced the track continuous button was clicked. During each click, the program recorded the x and y position and stored it in a results file. To obtain this data we went to the Track menu and went down to “Results file.” A dialog box was popped up, and we clicked the view button and this opened a text file with a bunch of numbers (Figure 15). The large data block, which included the frame number, filename and the x and y position of the two AOIs was highlighted. This data was copied and pasted into an Excel file, and saved. The template that Daniel Lehman made was used for it.



results - Notepad

Starting Image: C:\Documents and Settings\dlehman\Desktop\touche\Stuff_0004.jpg
Scale Factor - user units: 1.00000 image units: 1.00000
Aoi 1: WholeImage
Aoi 2: ManualTracking
Aoi 3: ManualTracking

Frame	filename	x (aoi 2)	y (aoi 2)	x (aoi 3)	y (aoi 3)
1	Stuff_0004	325.0	135.0	315.0	151.0
2	Stuff_0005	327.0	136.0	316.0	151.0
3	Stuff_0006	327.0	136.0	316.0	152.0
4	Stuff_0007	327.0	138.0	316.0	153.0
5	Stuff_0008	325.0	139.0	315.0	153.0
6	Stuff_0009	323.0	137.0	315.0	151.0
7	Stuff_0010	321.0	135.0	316.0	148.0
8	Stuff_0011	323.0	135.0	317.0	148.0
9	Stuff_0012	325.0	136.0	318.0	148.0
10	Stuff_0013	325.0	136.0	318.0	149.0
11	Stuff_0014	323.0	136.0	318.0	148.0
12	Stuff_0015	324.0	135.0	316.0	149.0
13	Stuff_0016	324.0	134.0	316.0	148.0
14	Stuff_0017	325.0	135.0	315.0	149.0
15	Stuff_0018	326.0	135.0	318.0	150.0
16	Stuff_0019	326.0	137.0	318.0	152.0
17	Stuff_0020	326.0	137.0	318.0	152.0
18	Stuff_0021	325.0	138.0	318.0	153.0
19	Stuff_0022	326.0	138.0	317.0	154.0
20	Stuff_0023	326.0	138.0	317.0	154.0

Figure 15: Data in NotePad

CREATING THEORETICAL DATASET

Next a computer model for the size ratios found in the experiment was created. The computer generated curves are plotted in non-dimensional length(l^*) versus non-dimensional time(t^*).

This ratio was then entered into the initial surface geometry generator to obtain the initial geometry that was placed into the coalescence computer program. This provided the non-dimensional equivalent for the drops we were analyzing. The contact radii versus time were then graphed using Excel and presented in Figure 19. Then the scales were needed to be change into engineering units.

Once the value of t_s was found, it was plugged into the equation $\mu = \frac{t_s \cdot \sigma}{l_s}$ to obtain the viscosity.

DETERMINING VISCOSITY

This section was performed in Excel. A template created by Antar's Lab which should be quite easy to utilize was used (Figure 18). Light blue cells are the ones that needed to be filled in; comments are in them to help. Opening both the template file and the file of the two sets of data from above (File A), and in file A, we highlighted the data that pasted from Spotlight, and then went to the "Data" menu, and pulled down to "Text to columns…" A convert text to columns wizard popped-up and gave us choices on how to convert. Clicking the "Delimited" button, and then at the bottom clicking "Next.", we went to the next. The window looked like as follow, then click "Finish." We highlighted the data of the newly formed columns and copied (Figure 16).

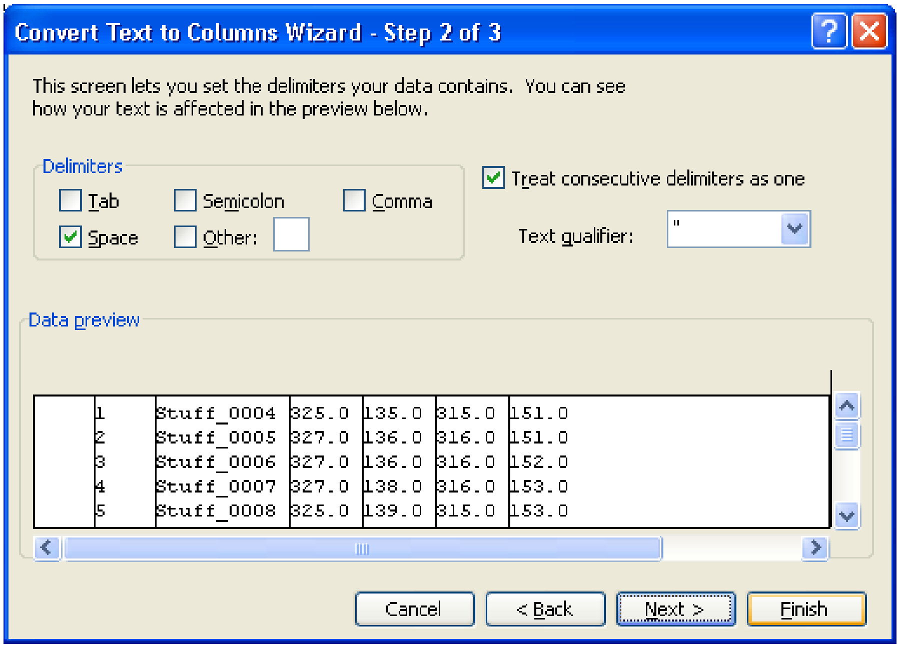


Figure 16: Microsoft Excel (Convert Text to Columns)

We Switched to the template file (Spotlight page). We clicked on cell A3, a pop-up message appeared telling us to paste the copied cells there (Figure 17).

Now before accidentally saving over the template and lose it, we must have chosen File à Save As… and renamed the excel file. We found the film speed and typed that film speed into cell J3. We found the pixel length from Spotlight and type into cell J6. Because the template can not guess how many frames we have there is an estimated length of columns G & H. What to do was to match up the columns. If our G & H are longer than the newly pasted cells, highlight the extra and delete. If it is shorter, click on the very last G cell, right now it's set as G132, and double click the lower right corner of the cell. That should extend the column to the bottom of the newly added cells. We did the same for the H column.

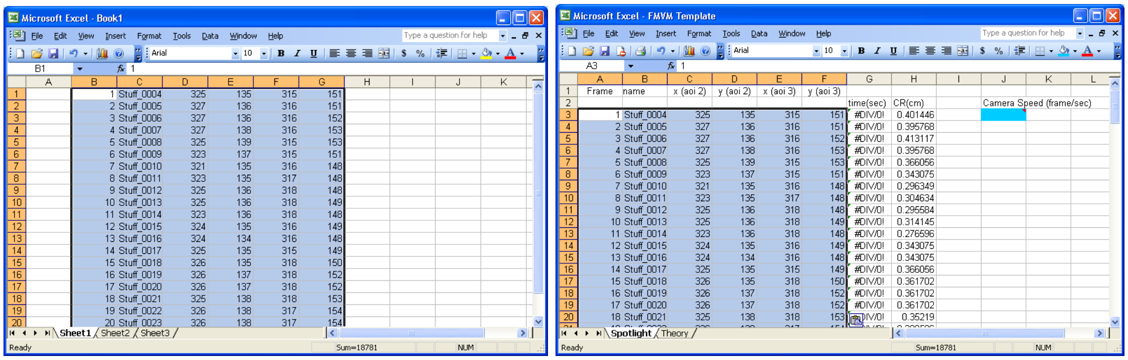
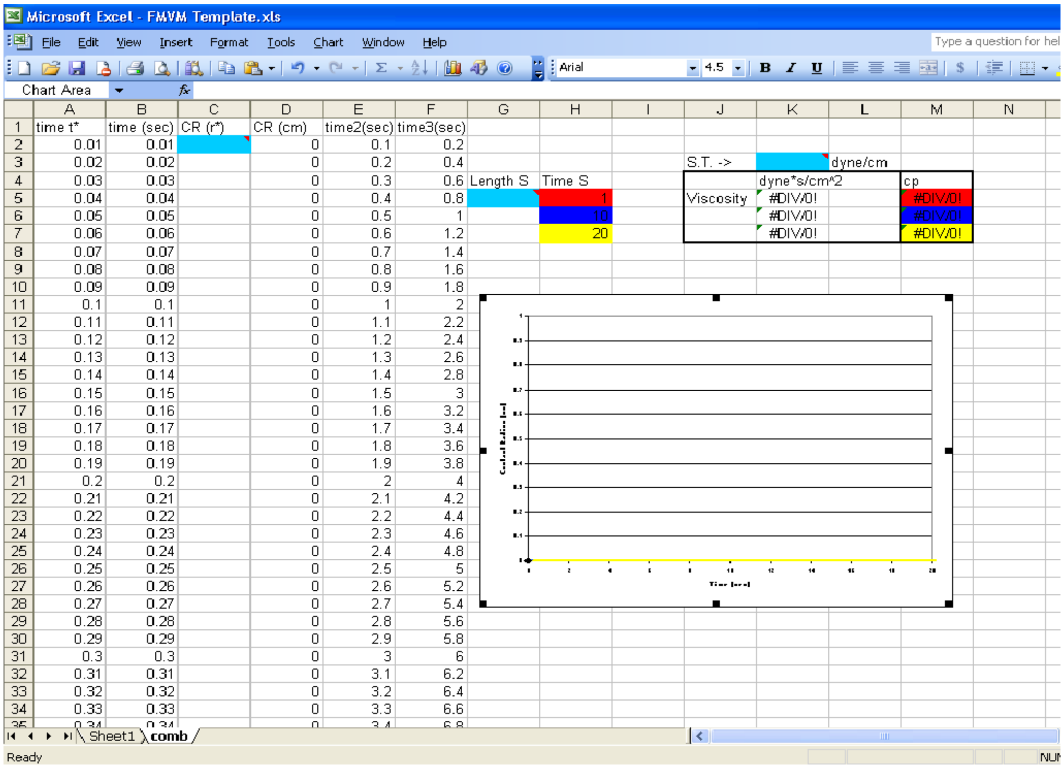


Figure 17: Microsoft Excel

We went back to file A to find the data that we pasted from the program, performed the text to column operation on this data the same way we did it for the Spotlight data, copied the second column (y-position of the contact radius), switched back to the template and then to the Theory page, clicked on C2, and pasted the column there.

We could find the length scale, and type this number into G5 on the theory page of the template. This popped up 3 lines onto the graph below; they won't match up with the data yet. We had already the surface tension of the liquid, so we typed this into the cell K3.

To finish up everything we needed to find the appropriate time scale. The three time scales listed already were color coded. We adjusted a time scale (red will probably be easiest) until the line covers the data nicely. If all of the data points were too crowded on the left side, we shortened the x axis maximum. When we had a line that appears to approximate the data nicely, looked at the corresponding viscosity in M(5-7) which ever was the line that we used. (M5 if we matched the red line). This value is the viscosity in centipoise.



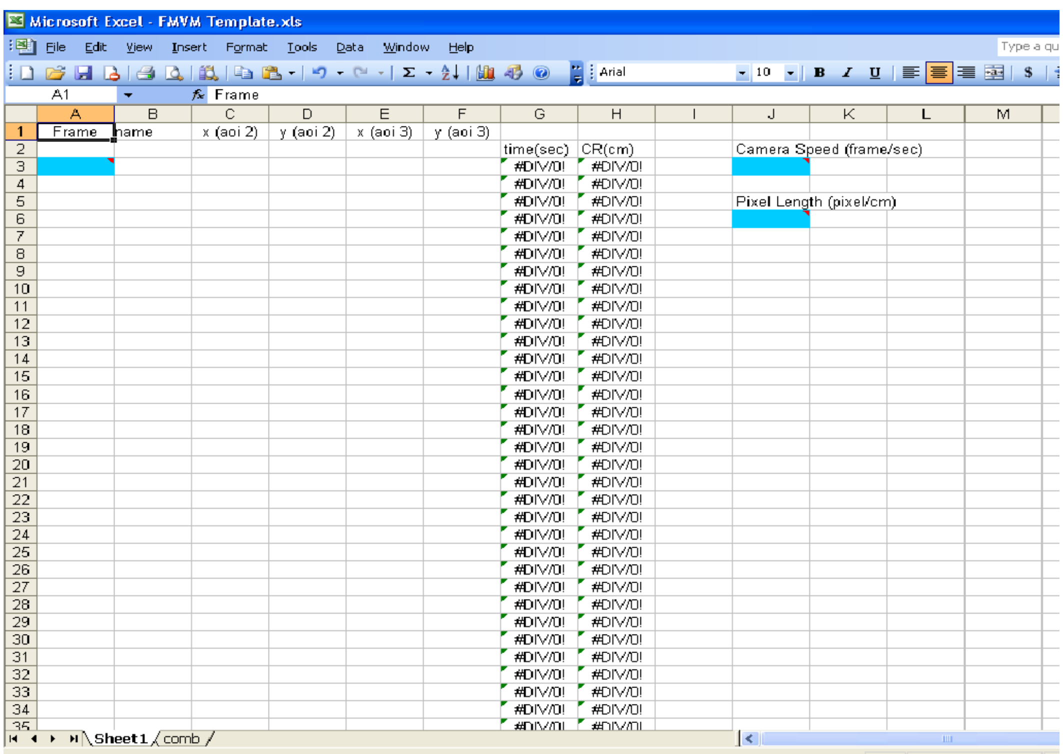


Figure 18: Template

DATA ANALYSIS AND DISCUSSION

The data B1-1, B1-2, B1-3, and B1-4 were analyzed as follows. All four are data of experiments with two equal sized drops but each data has different size. Therefore only one non-dimensional theoretical data was used for analysis of all four experimental data (Figure 18). The droplet size used for the experiment of B1-1, B1-2, B1-3, and B1-4 are 1cc, 2cc, 4cc, and 8cc, respectively. Figure 20, Figure 22, Figure 24, and Figure 26 show experimental plots of the contact radius with time due to coalescence of two drops of B1-1, B1-2, B1-3, and B1-4, respectively.

B1-1

Figure 21 shows the comparison between measured contact radius and one calculated for three value of viscosity. The experimental data plots are between the curves of the viscosity value 12500 cp and 13900cp. The curve of the viscosity value of 12500 cp fits the experimental data the most and this value exactly matches the value of the viscosity we expected for this liquid (Table 1).

B1-2

Similarly, regarding Figure 23, the row data plots seem to match one of the theoretical curves. The value of viscosity looks between 22000cp and 25000cp. However, these values are much higher than the value in Table 1. The reasons are considered as follow:

(1) Camera Angle: The droplets used for the experiment in the video were not at the center of the picture; they were seen above the pictures. Therefore the correct radii were not able to be measured.

(2) Shake: During the experiment, these two droplets were shaking too much and this prevented us from measuring their contact radius correctly.

B1-3

Figure 25 shows the experimental data plots does not match the theoretical curves in the first few seconds but after 5 seconds the plots are between the curves of the viscosity value 12500 cp and 15500 cp. During the experiment, drops moved up and down too much the first 5 seconds, were stable between 5 and 7seconds, and shake again after 7 seconds. Hence the data of B1-3 are reliable between t = 5 and 7. Therefore we can conclude the value of viscosity is between 12500 and 13900cp from this experiment. This data gives 11.2% error.

B1-4

Figure 27 shows raw data plots are between the theoretical curves of the viscosity value 11875cp and 13125cp; the experimental data fits within 5% of the expected value 12500cp. The droplets size in the experiments was big enough to measure the length easily and correctly, and drops had no shake during experiment. Also the objects for the measurements are around the center of the video picture so that the camera angle did not affect them too much.

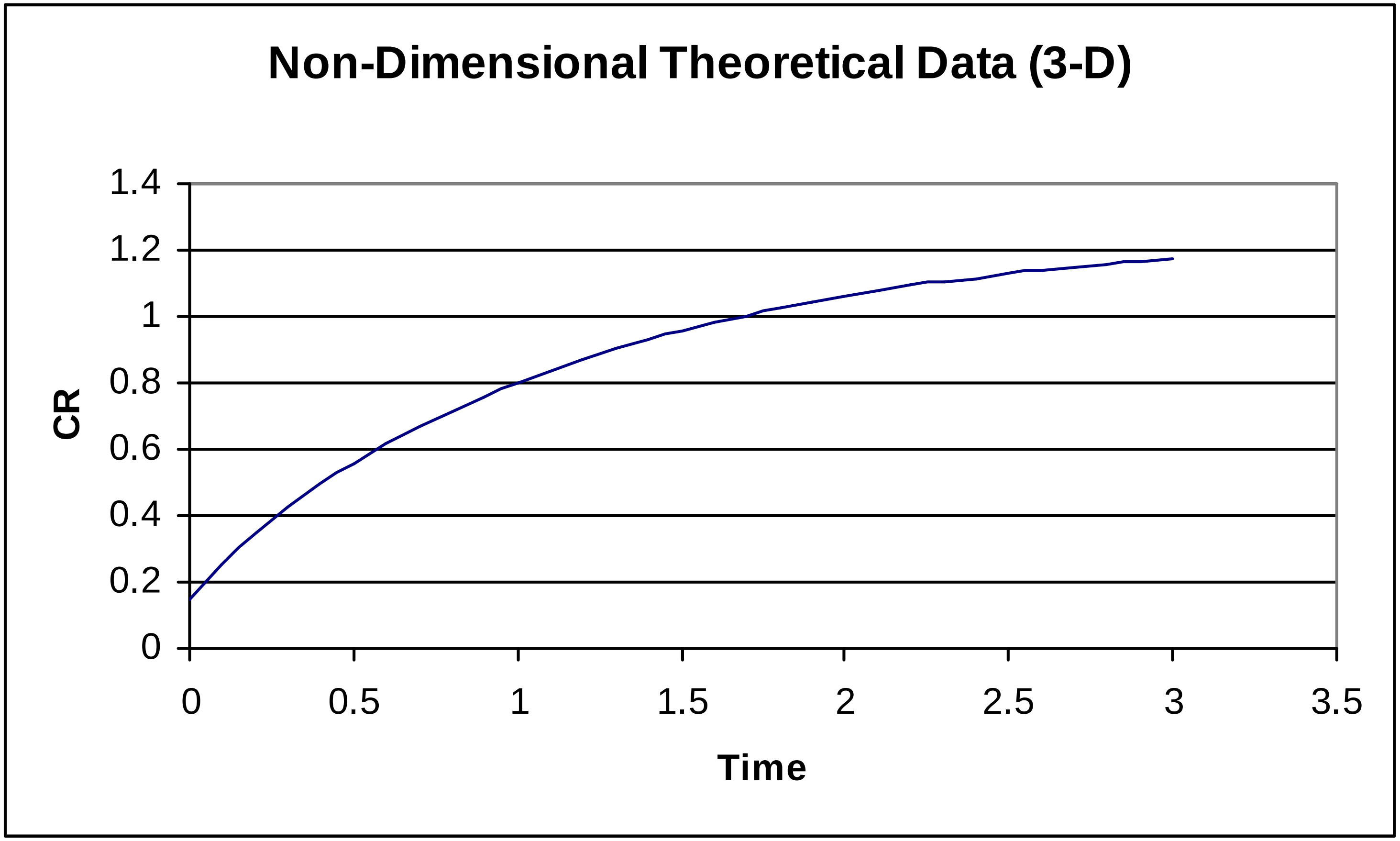


Figure 19: Non-dimensional Theoretical Data (3-D) (The ratio of two droplets is 1:1)

B1-1

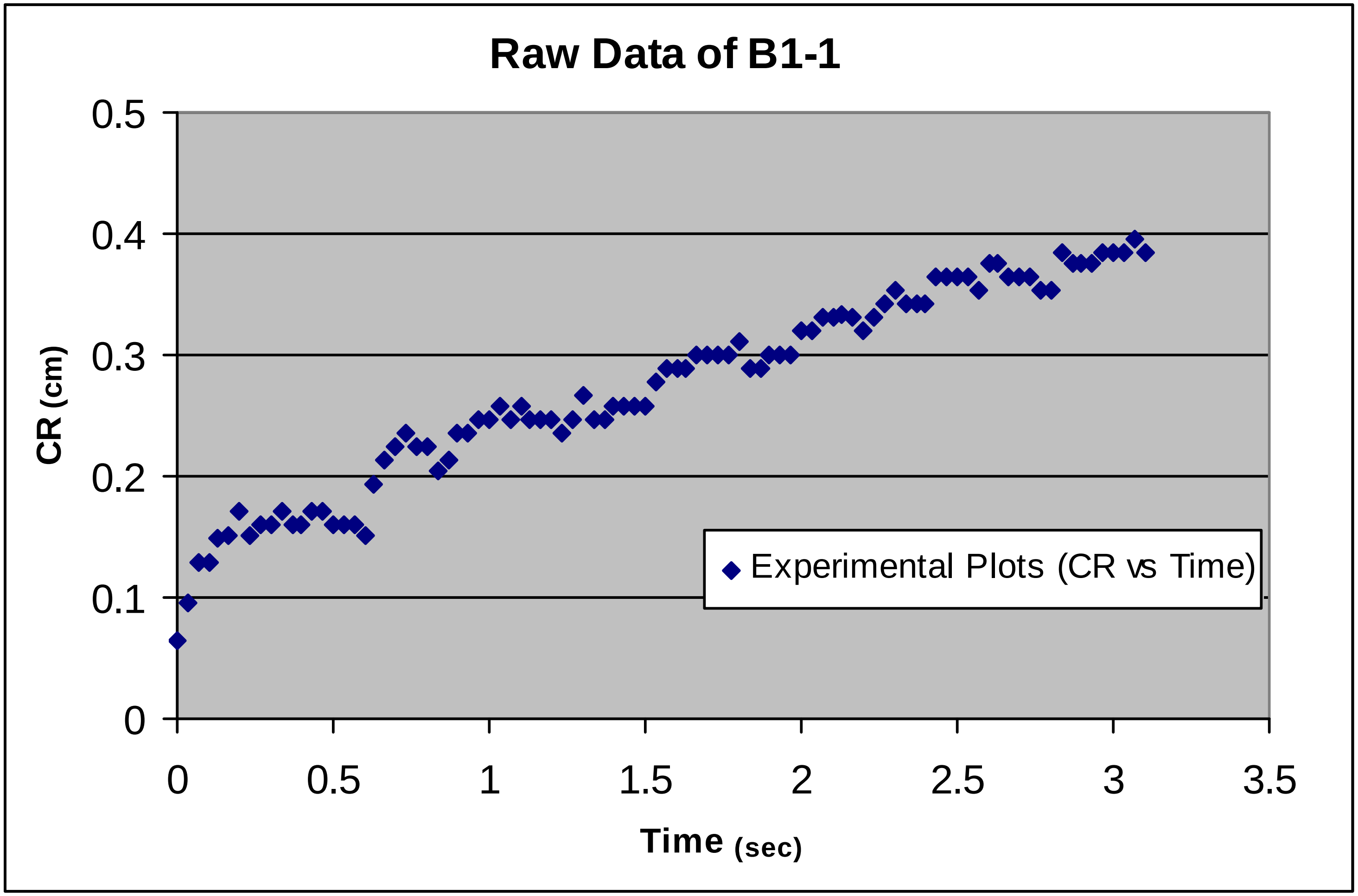


Figure 20: B1-1 Experimental Data of B1-1 (Contact Radius vs. Time)

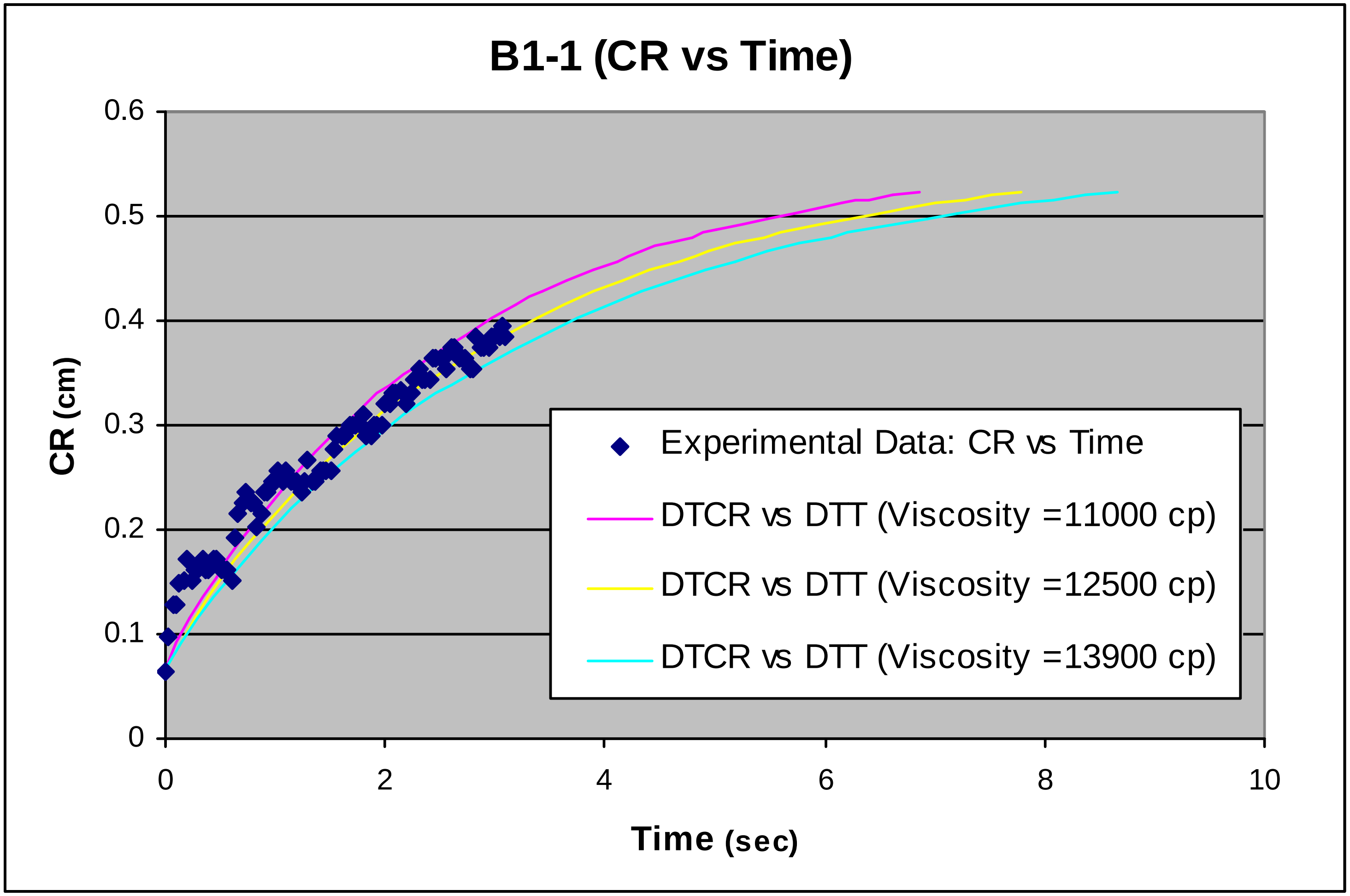


Figure 21: B1-1 Experimental data and Theoretical data (Contact Radius vs. Time)

B1-2

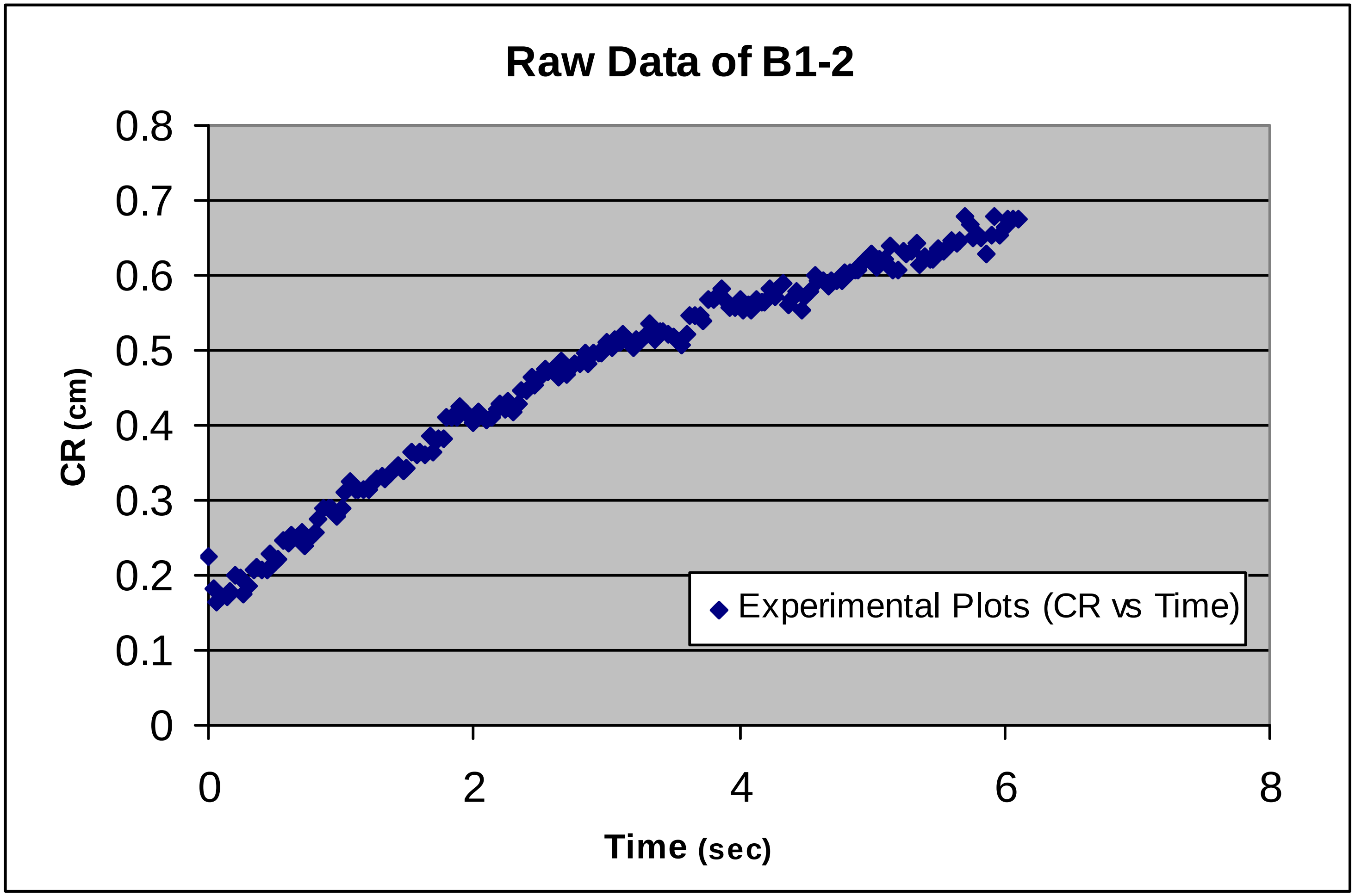


Figure 22: Experimental Data of B1-2 (Contact Radius vs. Time)

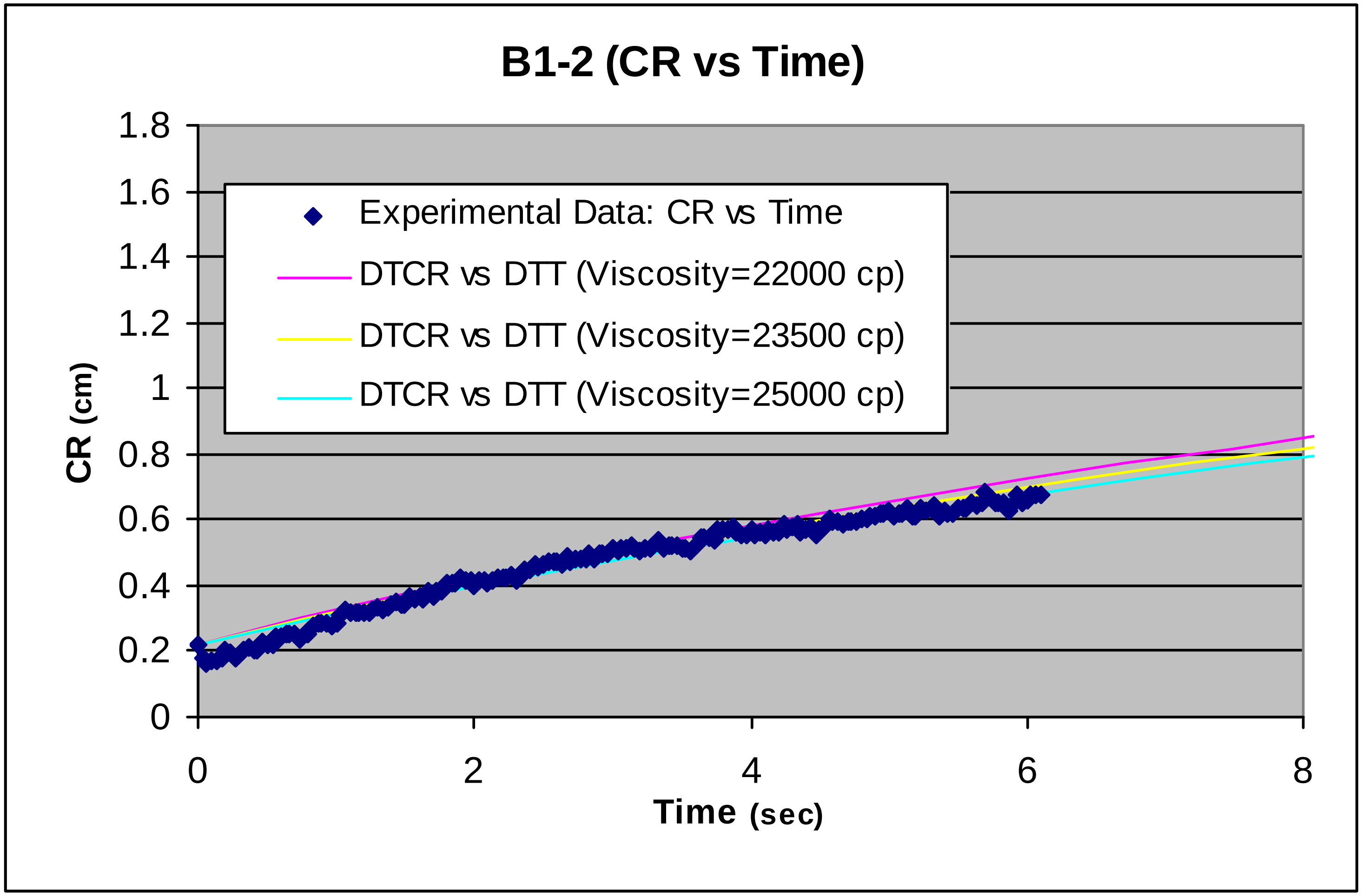


Figure 23: B1-2Experimental data and Theoretical data (Contact Radius vs. Time)

B1-3

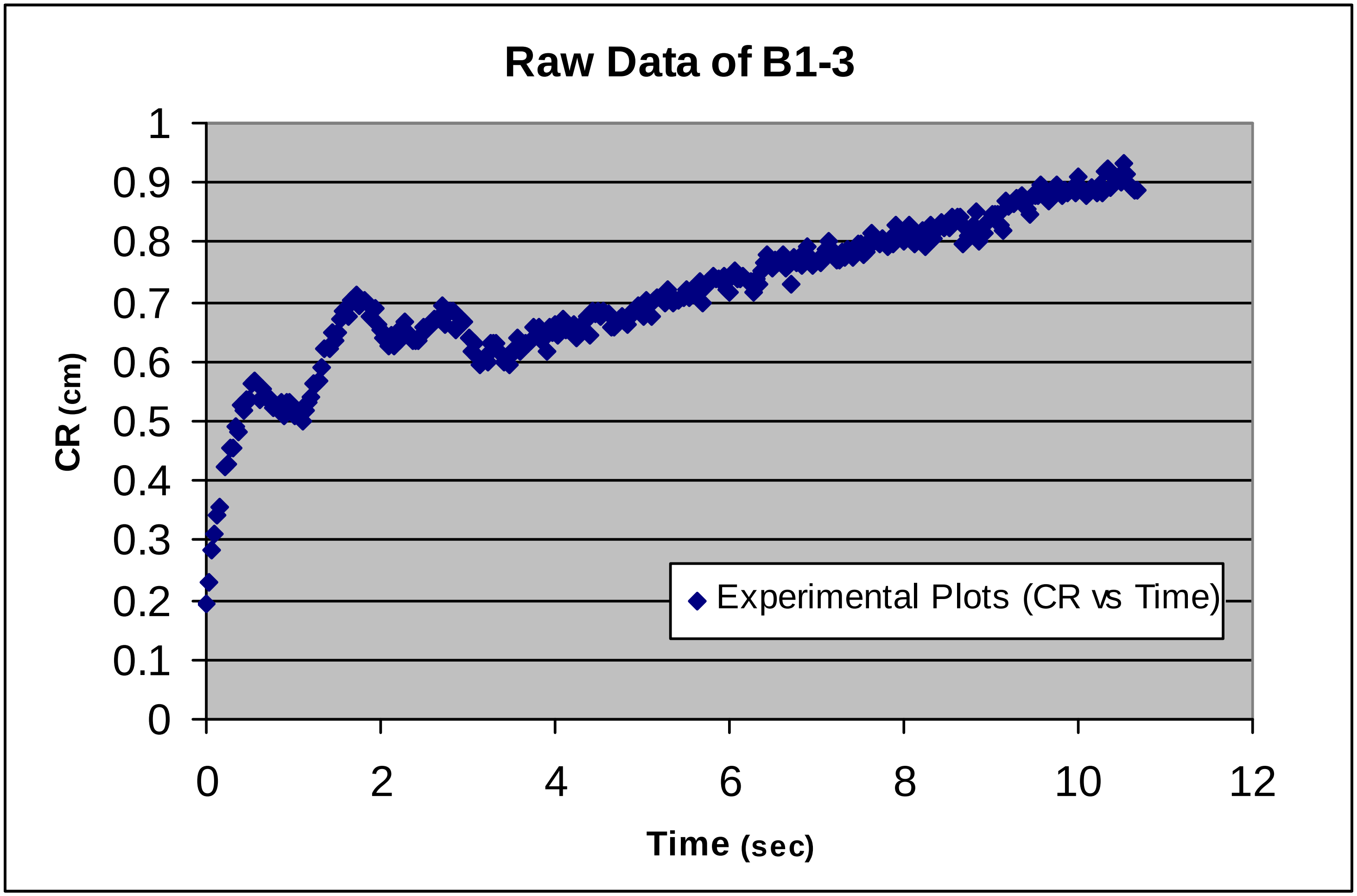


Figure 24: Experimental Data of B1-3 (Contact Radius vs. Time)

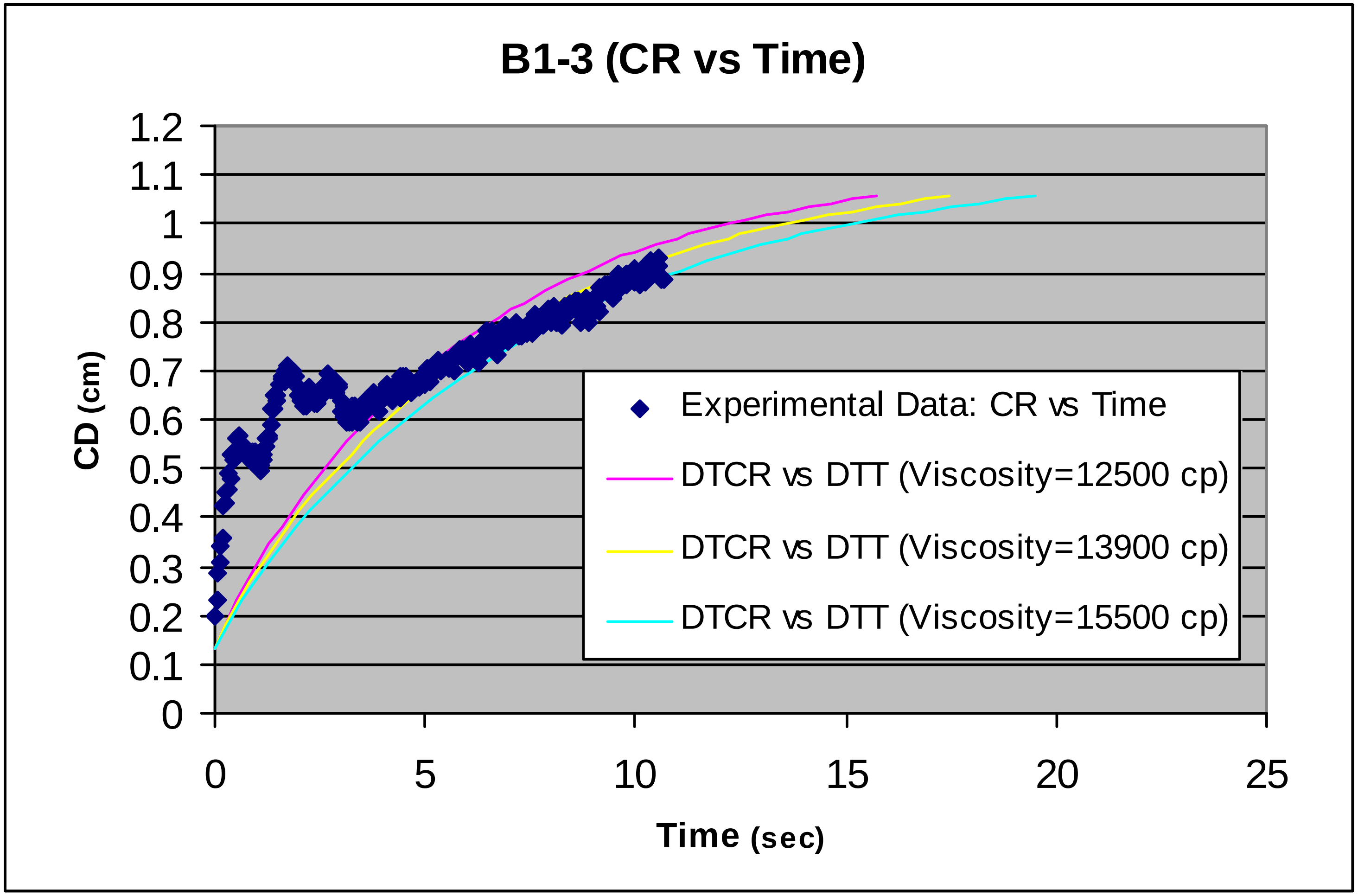


Figure 25: B1-3 Experimental data and Theoretical data (Contact Radius vs. Time)

B1-4

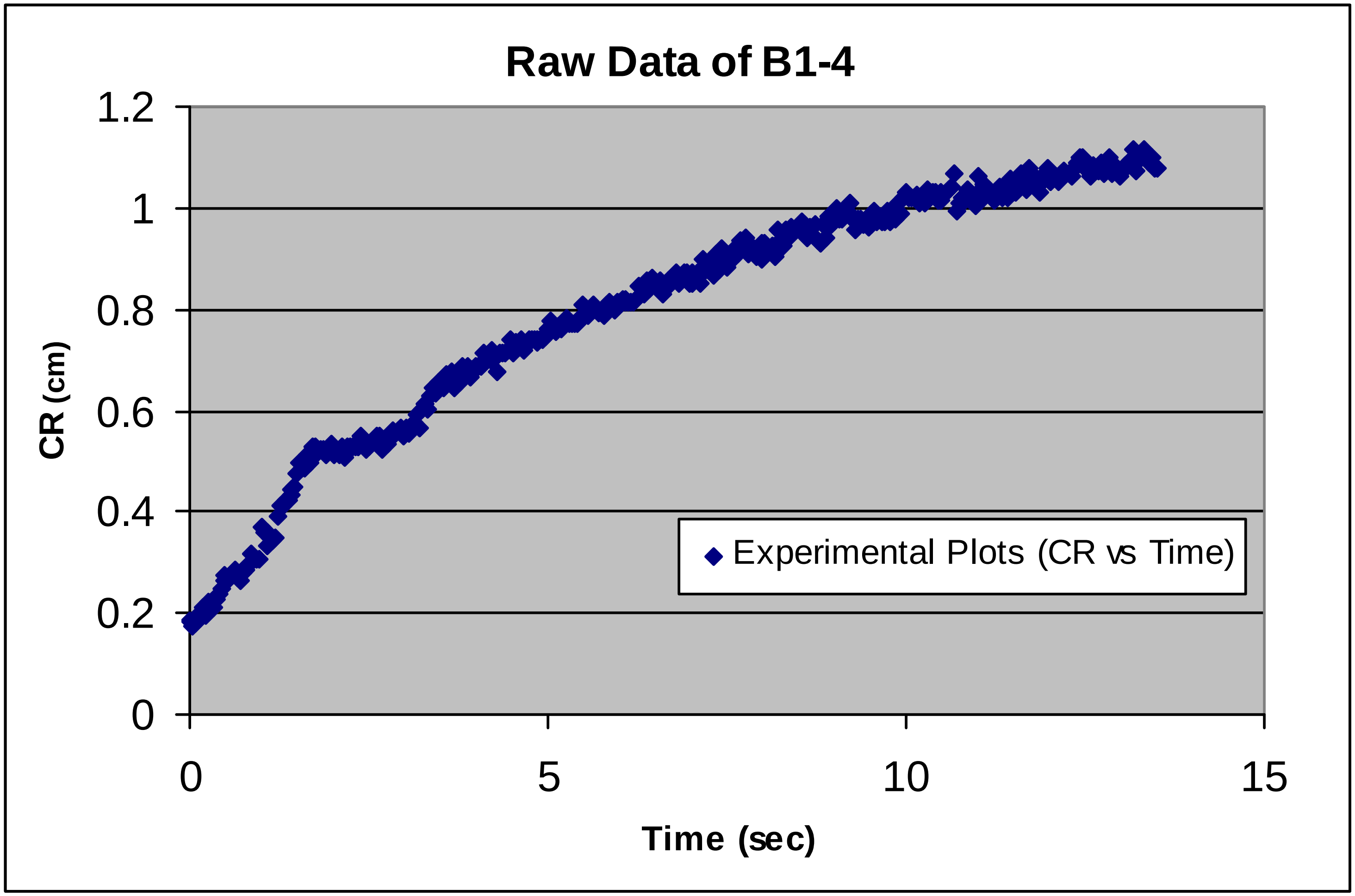


Figure 26: Experimental Data of B1-4 (Contact Radius vs. Time)

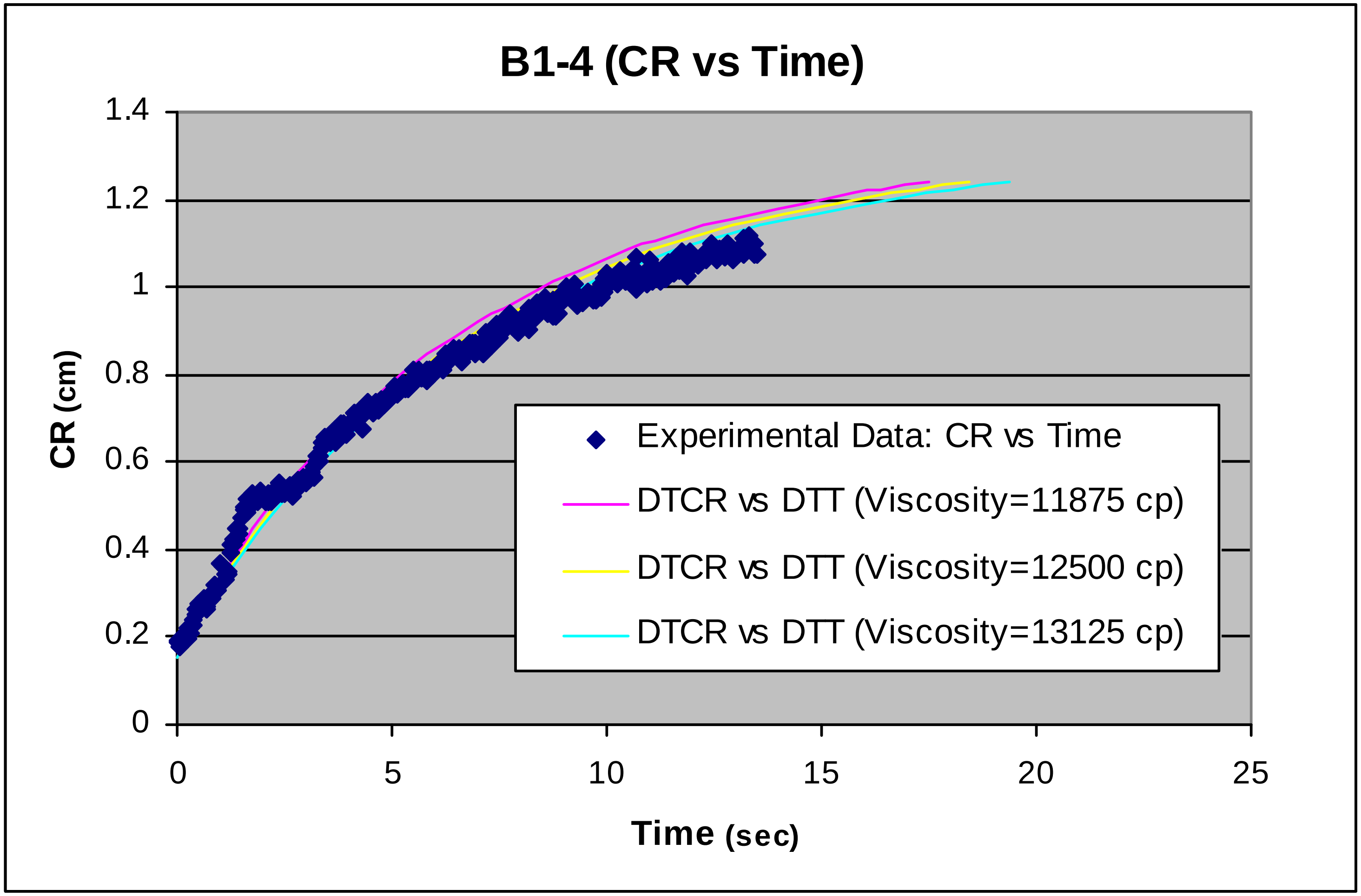


Figure 27: B1-4 Experimental data and Theoretical data (Contact Radius vs. Time)

CHAPTER 6: CONCLUSIIONS, RECOMMENDATIONS AND FUTURE WORK

Using Silicone oil, the droplet merging experiment with four different initial diameters was conducted in a microgravity environment for the purpose of determining the viscosity of a liquid with known surface tension. Based on the results of Chapter 5, it is seen that the data from experiments B1-1 and B1-4 could yield accurate estimate of the viscosity of Silicone oil. However, the data from B1-2 and B1-3 experiments did not yield the desired value of the viscosity of Silicone oil. The calculated value of the viscosity depended on the conditions of the experiments. For future work to continue this study, the droplet merging tests must be performed in a highly controlled environment.

It is clear that the tests that gave the value of the viscosity to within 5% error were performed in stable conditions and had droplet sizes big enough to perform accurate measurement of the contact radius. Also the objects to be measured were at the center of the video picture frame, so that there was least distortion due to camera angle. Thus, these experiments proved that measuring the contact radius progression with time during the coalescence of two drops was very successful in order to determine the value of the viscosity. Therefore, this method with liquids where the viscosity is unknown leads to the determination of an accurate value for the viscosity of liquids with known surface tension. In order to obtain more accurate values of the viscosity a three dimensional model needs to be developed and applied.

The ultimate goal of this study is to develop a method to obtain values of the viscosity for undercooled liquid glass. In order to validate this method for viscosity measurement, tests with liquids having similar viscosity as that of undercooled glass, such as glass transition materials with viscosity ranges from 101 to 106 Poise need to be conducted.

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VITA

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