Results of the Fluid Merging Viscosity Measurement International Space Station Experiment

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The purpose of FMVM is to measure the rate of coalescence of two highly viscous liquid drops and correlate the results with the liquid viscosity and surface tension. The experiment takes advantage of the low gravitational free floating conditions in space to permit the unconstrained coalescence of two nearly spherical drops. The merging of the drops is accomplished by deploying them from a syringe and suspending them on Nomex threads followed by the astronaut's manipulation of one of the drops toward a stationary droplet till contact is achieved. Coalescence and merging occurs due to shape relaxation and reduction of surface energy, being resisted by the viscous drag within the liquid. Experiments were conducted onboard the International Space Station in July of 2004 and subsequently in May of 2005. The coalescence was recorded on video and down-linked near real-time. When the coefficient of surface tension for the liquid is known, the increase in contact radius can be used to determine the coefficient of viscosity for that liquid. The viscosity is determined by fitting the experimental speed to theoretically calculated contact radius speed for the same experimental parameters. Recent fluid dynamical numerical simulations of the coalescence process will be presented. The results are important for a better understanding of the coalescence process. The experiment is also relevant to liquid phase sintering, free form in-situ fabrication, and as a potential new method for measuring the viscosity of viscous glass formers at low shear rates.

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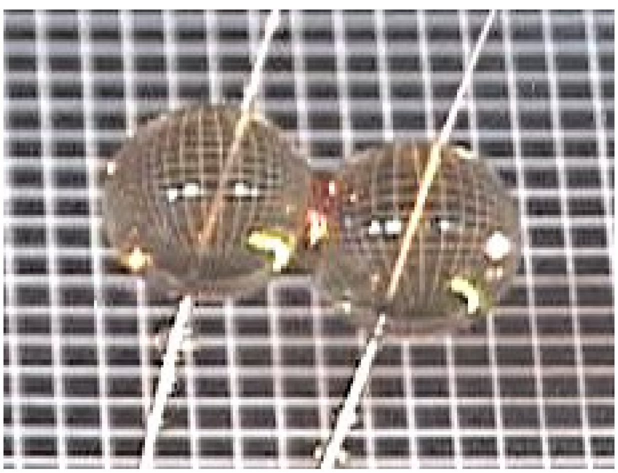
This Picture shows astronaut Mike Fincke deploying one of the liquid drops onto the Nomex thread.



Two 1 ml liquid drops of honey in the process of coalescing to a single spherical drop.

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I. Introduction

In response to the call for low upmass experiments, on of the authors (EE) the PI of the NRA "Mechanisms for the Crystallization of ZBLAN" proposed the "Fluid Merging Viscosity Measurement" (FMVM) experiment for the International Space Station (ISS). FMVM was a natural follow on experiment for examining the measurement of viscosity of highly viscous liquids using two drop coalescence. The main purpose of the experiment is to advance a totally new and different method for viscosity measurement. Currently the measurement of viscosity is limited for liquids that are susceptible to crystallization. A method for determining the viscosity of highly viscous substances that are susceptible to crystallization over the most important viscosity range for crystallization behavior does not exist. A method suitable to containerless processing to avoid container walls to heterogeneous nucleation is indicated. The process should use relatively small samples for quickly getting the material to temperature and to quickly measure the viscosity. Even though FMVM uses strings to maintain control of the liquid spheres, it is anticipated that one of the containerless processing methods could be utilized in low gravity for completely containerless property measurement. FMVM was only meant to validate the principle.

The relaxation of liquid to a sphere is one potential method for determining the viscosity of very viscous liquids. During the coalescence of two spheres of liquids to one sphere, the fluid flow is driven by the reduction of surface energy but limited by the resistance to fluid flow by the liquid viscosity. The FMVM experiment was supported by prior coalescence experiments on the low gravity KC-135 parabolic aircraft. Low gravity exploratory experiments were performed with glycerin on KC-135 aircraft for short (10 sec) experiment times.

The time constant of the experiment is proportional to the viscosity. Frenkel[2] was the first to propose an analytical model for the coalescence of two spheres where the coalescence time constant is proportional to the liquid viscosity and coalescence time and inversely proportional to surface tension. But, due to the limitations of his analytical solution, Frankel was able to model only the initial phases of the coalescence process of two spherical drops. Later work by Hopper[3,4] produced analytical solutions for the coalescence rate of two infinitely long cylindrical drops accurate throughout the whole coalescence process.

The FMVM method is also interesting because it can be tested by computational fluid mechanics. Using the Boundary Element Method (BEM), Antar et al[5,6] were able develop an accurate numerical solution for the coalescence of both two infinitely long cylindrical drops as well as two spherical drops. In fact the BEM is capable of accurately modeling the coalescence process for any two liquid masses of arbitrary initial shapes. It was shown that the rate of coalescence can be characterized by the rate of neck diameter growth. A comparison of the 2 dimensional cylinder model with the 3-D sphere model showed slightly different neck diameter growth rates. Coalescing spheres grow slower than cylinders. The KC-135 experimental data fit the 3-D spherical coalescence model up to a normalized neck diameter of 0.5. Since the experiment constrained the drops keeping them from forming a sphere, the final shape was a cylindrical liquid bridge and above the 0.5 normalized neck diameter, the data fit the 2-D cylindrical model. The objective of FMVM was to examine the coalescence of 2 viscous drops beyond the limitations of the KC-135 experiments. The ISS provided the opportunity for much longer experiments, much larger samples, more viscous liquids, and unconstrained fluid motion in the weightless coll. Fluid Merging Viscosity Measurement ISS Experiment

The experimental design parameters are quite simple. Using supplies on the ISS, setup an apparatus to attach 2 strings on which liquid drops were deployed to maintain control. The experiment required the measurement of the initial diameters of the 2 drops and use an on-board digital camcorder to record the coalescence of the drops. Subsequent analysis of the recorded tape provided measurements of the time dependent change in the neck diameter with coalescence time. Several low toxicity viscous fluids spanning 2 orders of magnitude viscosity range were selected. The manifested fluids were contained in syringes that were also used to deploy the liquids onto the strings. The liquids included honey, corn syrup, glycerin, and two different silicone oil viscosity standards. The surface tension of the flight liquids was determined both by the pendant drop methods and the drop-weight and the viscosity was measured with a Brookfield rotating spindle viscometer calibrated with viscosity standards.

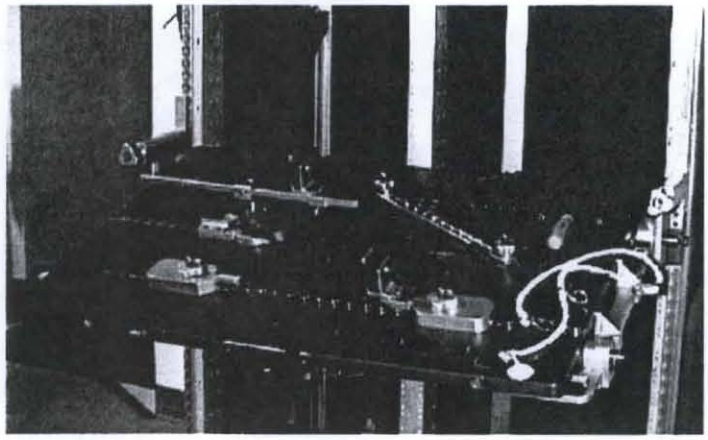

Figure XX. The MWA utility kit used to set up the FMVM

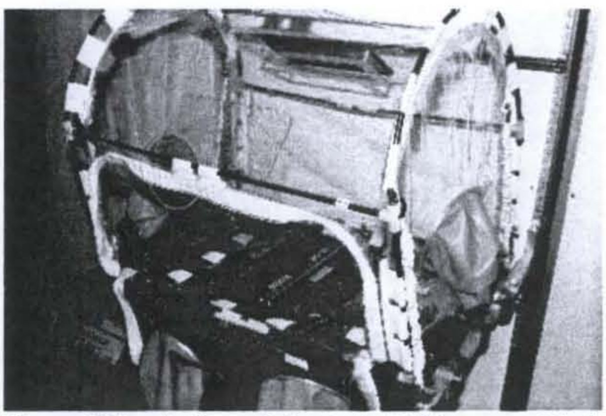

Figure XX. A Ground Support Multipurpose Work Apparatus (MWA) that was used on the International Space Station for containment of the experiment.

On-orbit resources such as the MWA Utility Kit (Figure XX), were utilized for the experimental setup. A configuration was tested on the ground during preparation for operations on the ISS. Figure XX is the final setup used. The experiment was contained inside the MWA (Figure XX). The temperatures of the drops were measured with the on-board Scopemeter and temperature probe. The rate of shape change was recorded with a color video camera. Data was captured on lab camcorder and some transmitted real time to ground. Hi-8mm video tape was returned from ISS and was used for detailed post flight analysis. The experimental procedures were developed and test at JSC in order to provide detailed descriptions of how the experimental assembly was set up. Crew procedures were also written to lead the astronaut through the experimental scenario.

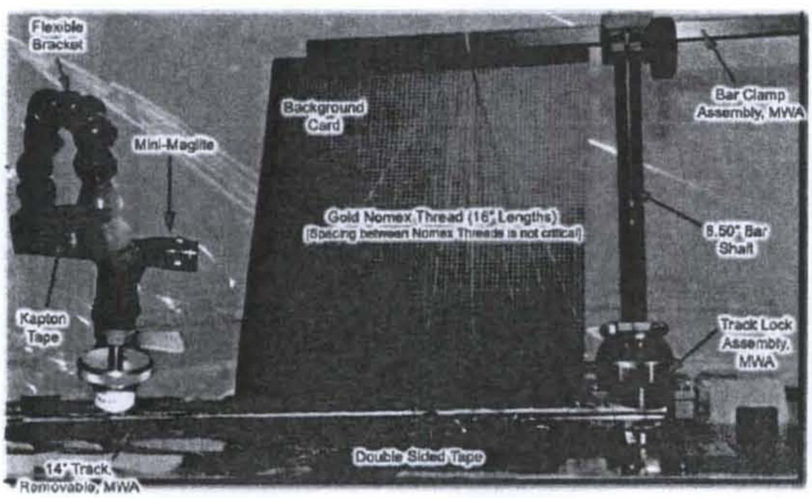

Figure X. The test setup for FMVM experiments.

The on-orbit supplies (Figure XX) were configured to hold the background grid card, and provide support for the Nomex strings that held the drops. A Fluke 190 Scopemeter with temperature probe was used to measure the temperature of the liquid drops. A mini-Maglite provided illumination of the liquid drops, see Figure XX.

Mike Fincke performed the first set of experiment operations including those with the silicone oil viscosity standard liquids.

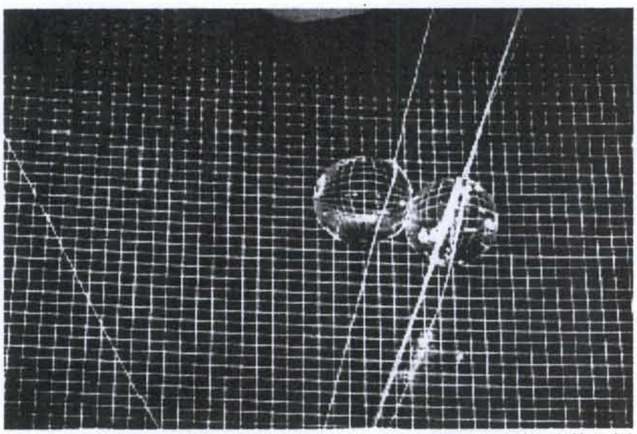

Figure 11. Two 4 ml silicone oil viscosity standard liquid drops in the process of coalescing.

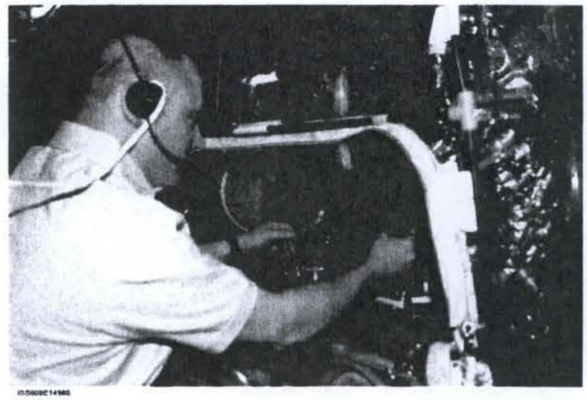

Figure 3. Astronaut Mike Fincke deploying liquid drops onto a Nomex thread inside the MWA.

He converted a number of coalescence video clips from the digital video tape to AVI files that were down linked to the PI.

V. Modeling with COMSOL

COMSOL Multiphysics is finite element analysis software tool that permits modeling of a large number of physical and chemical phenomena. Different types of physics (thermal, fluid flow, physical forces, etc.) can be integrated into the FEA solution to solve complicated interrelated phenomena. The "Level Set Two-Phase Flow" application in COMSOL made it relatively easy to set up to model the fluid flow in coalescing spherical droplets.

The level set method was used to track the interface that is represented by a contour of the globally defined level set function, ϕ. The "Rising Bubble Modeled with the Level Set Method" located in the COMSOL menu was used to learn how to use the level set method and the initial conditions were used as a starting point for the calculations with our coalescence model. For the level set method, COMSOL Multiphysics uses a smooth step function across the interface between 2 fluids (air and liquid droplets in our case). The actual interface is defined as $\phi = 0.5$, air occupying the domain where $0 < \phi < 0.5$ and the liquid occupying $0.5 < \phi < 1$. During the calculation the level set function is continuously reinitialized so that it keeps the correct shape across the interface. The method models the actual fluid interface by the isolines of the level set function, $\phi = 0.5$.

The axi-symmetric model was geometrically set up with given droplet diameters with the drops in contact. The model was populated with materials properties and other constants and the initial boundary settings were defined for the various domains. Next the mesh was initialized and refined. The method requires the initial calculation of the initial level set function. This and the selection of suitable relative and absolute tolerances required considerable testing. General guidelines are included in the COMSOL Chemical Engineering User's Guide and insight was gained from the previous work of Zimmerman on coalescence. The initial solution time was entered and the initial value calculation performed and saved. The analysis was then changed to transient, the time stepping parameters entered, and the coalescence solved. The software includes extensive postprocessing and visualization capabilities that we have not fully implemented at this time.

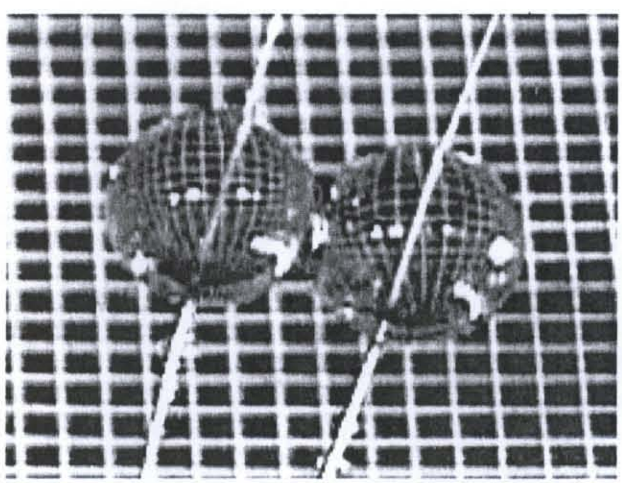

Figure. Two approximately 1 cm liquid drops of honey.

Once we got the model running without errors. The material constants were modified for parametric analysis. For different initial sphere diameters, the geometry had to be modified, which required returning to the initial geometric setup. Experimental scenarios similar to ISS experiments can be calculated by the different values of viscosity, surface tension, and liquid density. Due to the difficulty with changes in the geometric setup, all calculations were limited to 1 cm diameter spheres. A number of calculations were performed with differences in viscosity and surface tension. The results in general validate the original premise by Frenkel[2] that the characteristic coalescence time constant is proportional to the liquid viscosity and the initial sphere diameter but inversely proportional to the surface tension.

Initial evaluation of this simple concept indicates that by calculating the time constant for different viscosity liquids and experimental data with standard liquids, it will be possible to determine the viscosity from an unknown liquid's measured time constant. Initially we are considering the time for the joining liquid neck of two coalescing spheres to reach 0.5 of the initial droplet diameter as the experimental time constant.

Certain difficulties were encountered using the given level set model. Correspondence with COMSOL indicated that these errors were corrected in the soon to be released version 3.5. For that reason no more calculations were performed as of the writing of this paper.

Conclusions

FMVM successfully examined the unconstrained fluid flow behavior of 2 coalescing drops in low gravity on the International Space Station with a number of different viscous liquids. The square root time coalescence dependence liquid sintering was observed in preliminary analysis of the ISS data. A new method for determining the viscosity of highly undercooled liquids is being developed with parametric analysis of the data, the slope of the square root dependence, and the Frenkel time constant.

The coalescence experiment has come full circle. It started 10 years ago with low gravity KC-135 experiments and evolved into the ISS FMVM experiment. As the analysis of the ISS data nears completion, low gravity student DC9 aircraft experiments are continuing the experimental side of the science. This data will also be compared with COMSOL numerical experiments.

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