Study of Pinch-Off and Reconnection of Liquid-Liquid Flows in Micro- and Macro-Gravity Conditions

Topic Area: Fluid Dynamics

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1. Abstract

Topological transitions that occur in liquid/liquid flows with significant interfacial tension are found in many practical applications. For example, when crude oil is pumped from a well there exists an oil-water mixture. This mixture must in turn be separated before the oil is transported to a pipeline or tanker. However, current separation processes are hard to design without using expensive trial and error techniques. Because of this, numerical models for mixing and separation have been developed at the University of Minnesota. Preliminary experiments under normal gravity conditions were performed to serve as a foundation from which numerical techniques were developed. However, more tests under a variety of gravity conditions need to be performed so that the numerical model can be tested and made more applicable to a wider range of flows. We believe that testing these viscous flows under gradient gravity fields would increase the accuracy of the model and thus leading to less complex and more cost efficient models for separation processes.

2. Synopsis

There are many industrial applications today related to energy production, conversion, and use where topological changes such as pinch-off and reconnection of immiscible fluids are an important factor in efficiency and performance. The goals for these applications vary from efficiently separating emulsions consisting of fine scale droplets to maximizing mass transfer rates (such as in waste processing systems). Since these processes are too complex to be computed based on first principles, models must be developed. Before a model is developed, however, we must have a firm understanding of the dynamics of these systems.
These systems are difficult to characterize experimentally and model theoretically and numerically for several reasons: (1) the number of independent parameters affecting the flow behavior can be large, (2) the transitions usually occur over very short time and space scales relative to those of the local flow, and (3) the classical mathematical description of fluid motion becomes much less reliable at transitions. It is for these reasons that we intend to perform the proposed experiment. Specifically, we will be using index matching and laser sheet flow visualization to examine flow structure and topology. The proposed experiments will allow us to vary gravity to either increase or decrease the importance of buoyancy driven flows. The results of these experiments will then be used to test the numerical models for these transitions. Once the models are perfected designers in various areas such as energy production and conversion, internal combustion engines, and nozzle-spraying technologies to come up with more efficient separation methods can use them.

3. Test Objectives

The overall objectives for our experiments are to obtain quantitative experimental data documenting the dynamics of real transitions that can serve as a benchmark for the computational study. Specifically:

- Experimentally characterize the dynamics of the pinch-off transitions of a fluid jet into a bath of another immiscible fluid.
- Examine the interactions of two immiscible fluids with significant surface tension. i.e. quantify the time it takes for two liquids, a heterogeneous mixture of the two fluids, to separate/coalesce into two distinct fluids.
- Compare experimental results to numerical models for these systems.

4. Test Description

Pinch-off experiment

Since the objective of this experiment is to compare micro- and macro- gravity results of this experiment to those of the results obtained by Dr. Longmire at the University of Minnesota – Twin Cities under normal 1g conditions, we plan to use a similar procedure and apparatus. We plan to use a closed-loop facility with the flow driven by a magnetic-drive pump where the mean velocity will be controlled by a needle valve. Upstream of the test section, the flow will pass through a honeycomb straightener before it is accelerated through a round nozzle with a 1-cm exit diameter. The apparatus will contain a piston-driven forcer (speaker) that can be used to impose a regular sinusoidal perturbation on the nozzle exit velocity where the purpose is to create repeatable pinch-off conditions.

For this experiment, we plan to use a test section filled approximately ¾ full with a solution of glycerin in water. The remainder of the tank will be filled with Dow Corning 200 fluid. These fluids were chosen because their indices of refraction could be matched, a necessary condition for clear flow visualization. The glycerin/water solution will then be pumped through the flow circuit and injected through the nozzle into the Dow fluid.

For flow visualization, dye will be added to the jet fluid. Illumination sheets will then be generated by a laser and a series of lenses and passed through the jet. All images will be captured using a video camera. What we will be looking for in these images are the interface shape in the evolving jet, the evolving interface angles through the pinch-off, and any oscillations in the drops that form. An example of what we will be looking for can be seen in Figure 1.
In addition to the pinch-off experiment where the dynamics of transition interfaces are examined, we wish to look at the reconnection rates. The idea of this experiment is to start out with a heterogeneous mixture of fine, immiscible fluid particles. The fluids used will be water and olive oil since the surface tension values are readily available. The container for these fluids will be a cubical glass box that will be sealed to prevent the existence of air bubbles that could perturb our system.

We will be using a mixing device to cause fluid separation. Once a heterogeneous mixture has developed, we will start a stopwatch, indicating the start of the experiment. We will then be interested in the rate of fluid separation. Using dimensional analysis we derived the following equation that relates the characteristic time we are going to measure as a function of other known quantities:
Where the significant parameters are:

\( t_B \) = thickness of heterogeneous fluid mixture
\( T_r \) = run time of reconnection experiment
\( T_m \) = total amount of time of mixing
\( \rho_a \) = density of fluid A
\( \mu_a \) = viscosity of fluid A
\( g \) = gravity force
\( \omega_r \) = mixer rotation rate
\( \omega_t \) = mixer translation frequency
\( S_r \) = reconnection rate (dependent variable)

In addition to obtaining the reconnection rate, we will also be examining the "nature" of the coalescence. i.e. What do the interfaces look like under different conditions? The results of this experiment will then be compared with separate tests done at normal gravity.

5. Equipment Description

The main elements of our experimental apparatus are:

**Pinch-Off Experiment:**

- **Laser:** Model ULTRA CFR Nd: YAG Laser System (class IV) with cooling unit, manufactured by Big Sky Laser Technologies, Inc.

- **Plexiglas Box:** The sides of the box will be made of ½" Plexiglas while the top and bottom will be capped with PVC that holds the glass sheets together. The PVC will be sealed with an o-ring and fastening screws. The other seals will be made with GE Silicone II Household Sealant and Glue. The container will hold DOW Silicon Oil and a Water/Glycerin mixture.

- **Nozzle:** The jet nozzle will be made with PVC with a 1-cm exit diameter and a 4-cm inlet diameter.
Forcing Speaker System: This speaker will impart a sinusoidal oscillation on the flow to help form a repeatable pinch-off from the jet. It imposes the oscillation onto the flow by using a piston attachment connected to the speaker. We will be using is a Realistic Radio Shack model #40-1348 operated at a frequency of 10 Hz.

Pump: We will be using a 1/35 HP magnetically driven pump manufactured by the Little Giant Pump Company. This motor will provide us with smooth, consistent performance.

Signal Generator: The signal generator will be used to generate repeatable oscillations in the speaker to create starting points for pinch-off.

Amplifier: The amplifier will be used to amplify the signal generated by the signal generator in order to get noticeable speaker amplitudes.

Figure 2: Pinch-Off Experimental Assembly
Reconnection Experiment:

**Plexiglas Box**: This is a glass box that will be made from ½" thick Plexiglas with a hole cut out of the top. Inserted in this hole will be a shaft with attachments inside the box so that when the mixer is on, a uniform heterogeneous mixture will be created. The box will be filled with fluid A (olive oil) and B (water) (refer to Figure 3).

**Mixer**: The purpose of the mixer is to create a heterogeneous mixture of the two viscous fluids. The idea of the mixer is to have it rotate and oscillate translationally to get a repeatable mixture for each test.

**Stopwatch**: The stopwatch will be used to measure the time for the reconnection rates. This stop watch will be placed in the scope of the video camera and will be reset at the time of liquid mixture.

Figure 3: Reconnection Experiment Apparatus
**Video Cameras:** The digital cameras will be used to capture images of both the pinch-off and reconnection experiments.

**Accelerometers:** The accelerometers will be used to get real-time acceleration values corresponding to any particular moment in the experiment. The values will be recorded by the video cameras. Each accelerometer will have its own power supply and will be hooked up to a voltmeter to obtain the gravity values.

**Frame:** The frame will be a structure made of aluminum angle stock. This structure will support our experiments and any sharp angles will be rounded and padded in accordance with the hazard checklist.

**Entire System:** To get an idea of what the picture looks like, please refer to Figure 4.
6. Structural Load Analysis

Component Weights:

1. Glass box for reconnection experiment along with mixing motor......................20 lbs
2. Experimental assembly for pinch-off experiment including test cell, pump, amplifier, signal generator, and speaker.................................80 lbs
3. Two digital video cameras................................................................................20 lbs
4. Two digital accelerometers...............................................................................5 lbs
5. Power strip with surge protector........................................................................1 lbs
6. Laser, including cooling system.........................................................................150 lbs
7. Fluids. These include approximately 2 gallons Dow Silicone Oil, 4 gallons of a glycerin-water mixture, 1 gallon of water, and 1 gallon of olive oil.............80 lbs
8. Aluminum frame..................................................................................................150 lbs
The test equipment will be mounted to a 64 in x 24 in x 60 in aluminum frame bolted to the aircraft hold down bolt pattern. The aluminum frame will be fabricated from Al angle stock that has ultimate shear strength of 27 ksi. Components will be bolted using 0.5-inch steel bolts using a configuration that will provide 9-g safety factors of 5 or more. The bolts will be tested for failure in shear and in tension. Failure in tension will be due to the 2-g load. The base of the structure will be a 0.375-inch Al plate bolted to the aircraft by 8 bolts.

The hold down bolt safety factor at 2-g loading is calculated using the NASA supplied figure of 5000 pounds per bolt:

Shear stress due to a 9-g forward crash loading is calculated using the equation:

\[ \tau = \frac{P}{bd} \]

This shear stress gives a sufficient safety factor for the bolts with respect to the ultimate shear stress of the steel, which is 58 ksi.

The bearing stress for the foundation plate beam accounts for the tearing of the bolts through the plate, and is calculated using the equation:

\[ \sigma = \frac{P}{bt} \]

Where \( P = \text{load per bolt} \); \( t = \text{thickness of the plate} \); \( d = \text{diameter of the bolt} \).

This bearing stress gives a sufficient safety factor for the plate with respect to the ultimate shear stress of Al, which is 27 ksi.
7. Electrical Load Analysis

1. Pump
2. Amplifier
3. Signal Generator
4. Power Strip w/surge protector
5. Laser
6. Liquid Mixer

One 110-volt AC, 60 Hz power outlet will be required for the surge protector to power the laser, pump, amplifier, mixer, and function generator. Batteries will be used in the video equipment and the accelerometers.

8. Pressure Vessel Certification

The test cells for both experiments are sealed containers at atmospheric pressure. These containers will be tested at the University of Minnesota prior to transportation to Ellington Field. No further certification will be needed.

9. In Flight Test Procedures

The in flight test procedures will be made as automated and simple as possible so that the experiments can be run easily under the constantly changing gravity environment. The step by step process once we are in the air and able to move about the cabin is:

1. Supply power to the signal generator, amplifier, pump, and laser. This will begin the closed loop circulation of fluids in the pinch-off experiment that will run continuously during the flight. Also supply power to the mixing device for the reconnection experiment.

2. Turn on digital video cameras and focus them on the images of the pinch-off and reconnection experiments. These will also be run continuously during the flight.

3. Once zero gravity is reached, open laser shutter, turn on mixer and start the stopwatch that is attached to the box of the reconnection experiment. Leave the mixer turned for a specific amount of time as shown in Table 1.

4. Repeat step 3 for other parabolas.

5. After all of the parabolas are completed, turn off the power to the instruments and make sure secure for landing.

<table>
<thead>
<tr>
<th>Parabola</th>
<th>Time to Leave Mixer On</th>
<th>Parabola Position</th>
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Day 1

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Day 2

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<td>20-40</td>
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Table 1: Test Matrix for Reconnection Experiment

10. Parabola Requirements

The proposed experiments will try to make use of all of the parabolas executed during the flight. In addition to performing our experiments under the micro-gravity portion of the parabolas, we will also be interested in performing tests under the macro-gravity portions of the flight. The reason we will be running the experiments during the micro- and macro-gravity portions of the flight is because the main purpose of our experiment is to find how pinch-off and reconnection between two viscous fluids vary with gravity.

11. Test Support Requirements

Ground Support: N/A

In-Flight Support: Six 110-volt AC power outlets will be required to power the laser, pump, amplifier, mixer, and function generator. Batteries are being planned to use in the video equipment.

12. Data Acquisition System
The main components of our data acquisition system are two digital video cameras. In addition to these we will be supplying our own accelerometer to record gravity levels during the flight.

13. **Test Operating Limits or Restrictions**

None.

14. **Proposed Manifest for Each Flight**

**Equipment List:**

1. Glass box for reconnection experiment along with mixing motor
2. Experimental assembly for pinch-off experiment including test cell, pump, amplifier, signal generator, and speaker
3. Two digital video cameras
4. Two digital accelerometers
5. Protective screen for laser
6. Power strip with surge protector
7. Laser
8. Experimental stand
9. Fluids. These include approximately 2 gallons Dow Silicone Oil, 4 gallons of a glycerin-water mixture, 1 gallon of water, and 1 gallon of olive oil.

15. **Photographic Requirements**

Two digital video cameras will be used during the experiment to capture the pinch-off and reconnection of the fluids. These cameras will give us frame by frame pictures of the experiment that we can use to determine the velocity and vorticity fields present in the flows.

16. **Hazard Analysis**

**A. Hazard Source Checklist**

NA Flammable/combustible material, fluid (liquid, vapor, or gas)

NA Toxic/noxious/corrosive/hot/cold material, fluid (liquid, vapor, or gas)

NA High pressure system (static or dynamic)
NA Evacuated container

NA Frangible Material

NA Stress corrosion susceptible material

NA Inadequate structural design (e.g. low safety factor)

? High intensity light sources (including laser)

NA Ionizing/electromagnetic radiation

NA Rotating device

NA Extendible/deployable/articulating experiment element (collision)

NA Stowage restraint failure

NA Stored energy device (e.g. mechanical spring under compression)

NA Vacuum vent failure (i.e. Loss of pressure atmosphere)

NA Heat transfer (habitable area over-temperature)

NA Over-temperature explosive rupture (including electrical battery)

NA High/low touch temperature

NA Hardware cooling/heating loss (i.e. loss of thermal control)

NA Pyrotechnic/explosive device

NA Propulsion system (pressurized gas or liquid/solid propellant)

NA High acoustic noise level

NA Toxic off-gassing material

NA Mercury/mercury compound

NA Other JSC 11123, Section 3.8 hazardous material

NA Organic/microbiological (pathogenic) contamination source

j  Sharp corner/edge/protrusion/protuberance

NA Flammable/combustible material, fluid ignition source (i.e. short circuit; under-sized wiring/fuse/circuit
breaker)

→ High Voltage (electrical shock)

NA High static electrical discharge producer

NA Software error

NA Carcinogenic material

B. Hazard Evaluations

Cause Number 1

Hazard Category: High intensity light source.

Hazard Description: Exposure to direct and reflected beams.

Hazard Cause: Laser system.

Hazard Control: Keep the laser covered when not in use, use of protective eyewear, establishment of a controlled access area for laser operation.

Cause Number 2

Hazard Category: Sharp corner/edge/protrusion/protuberance.

Hazard Description: Users could be cut from glass box joints.

Hazard Cause: Our glass boxes have sharp edges.

Hazard Control: Glass boxes will be sufficiently padded to prevent injury.

Cause Number 3

Hazard Category: High voltage (electrical shock).

Hazard Description: The laser's electrical circuit operates at a lethal voltage.

Hazard Cause: Danger of shock injury due to high voltage.
Hazard Control: A surge protector has been included.

NOTE: The laser will be donated by BIG SKY LASER TECHNOLOGIES, INC. The laser, Model Ultra Nd: YAG Laser System, is a Class IV laser.

17. Outreach Plan

Outreach Goals:

The main goal of this program is to transfer the knowledge and experience gained to all types of audiences, ranging through high school students, the general public, the scientific community, and the industrial community. Because we seek to reach the widest audience possible, a Web site is an important part of our outreach. Through this we can make a range of information available to the community, including:

- Team members, advisors and journalist
- Overview of the experiment
- Detailed description of the experiment
- Experiment updates
- Experiment results
- Final Report
- Press Coverage
  - James Dawson, Minneapolis Star Tribune
- Notices of upcoming events: lecture demonstrations in local high schools and at the University of Minnesota
- Contact information for NASA Reduced Gravity Student Flight Opportunities program, for students interested in future flights

The web page can be found at: www.aem.umn.edu/proj-prog/sfo/micro_flows

Outreach Audiences:

Foremost, one of our main and most important audiences is high school students and college freshmen, because they are at the time when career choice is a very important matter. Our goal here is to promote science by presenting the project in lecture demonstrations made at local high schools and at introductory science related courses at the University of Minnesota. This will help to encourage participation in math and science courses and related research activities. Also, more descriptive lecture demonstrations will be made at introductory fluid mechanics courses also at the University of Minnesota.
Second, the scientific and industrial communities are also part of our audience. The proposed experiments will have significant potential to develop more accurate, physically based engineering level models for transitions at liquid/liquid interfaces, as well as improve the understanding of the numerical models for mixing and reaction rates in many industrial flows related to energy production, conversion and use. After analysis of the experimental data, it will be made available through the web page for the use of both of these communities.

In addition, we would also like to encourage the general public to become interested in science and its applications. A temporary exhibit at the Science Museum of Minnesota, and the web page, which can potentially be used by thousands of people, would each be effective means of increasing popular awareness of science applications. Finally, publicity within the University of Minnesota and the local media will provide an ample forum for public outreach.

Furthermore, since this is the first time a group from the University of Minnesota has participated in this program, this project has potential to reach people who may not have the most current image of the types of projects NASA's funding is going to. We believe that not only would this increase interest in other departments of the University, but it would also create ample interest in the space program in the Twin Cities area.

22. Resources

