Steady State Two-Phase Flow in a Reduced Gravity Environment II
Portland State University Microgravity Team

Title of experiment: Steady State Two-Phase Flow in a Reduced Gravity Environment 2
Topic areas addressed: Fluid dynamics
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Proposal Section I
Technical/Required Format

Flight Week Preference

Choice 1: March 18-27, 2004
Choice 2: March 4-13, 2004
Choice 3: April 1-10, 2004

Mentor Request

A NASA appointed mentor will not be necessary for this experiment.

Synopsis

A greater understanding of low gravity two-phase flow is necessary for the efficient design of next generation spacecraft. In particular, relations achieved with knowledge of two-phase flow are highly useful. After reading about the exposed difficulties with achieving this type of flow by researchers like Colin, Fabre and Dukler, our predecessor group invented a uniquely simple alternative to study two-phase flows that are steady.

Using an inexpensive counter rotating disk design used on board the KC-135, team ‘ALBERT’ achieved a time averaged steady slug velocity within the first parabola. One of their goals was to acquire data useful for determining pressure drops in fluid management systems and in evaluating heat exchanger thermal performance. Their ground tests confirmed Bretherton’s predictions on viscous film deposition in a tube, extending correlations established by Jing Den Chen and G.I. Taylor.

Despite proving the potential of their design for steady state fluid analysis, team ALBERT encountered some problems that limited the accuracy of their findings. Problems with motors, speed controls, and a camera assembly that unfortunately led to slug break up during each parabola. It is the objective of team ALBERT 2 to correct these shortcomings and re-fly the experiment to obtain data useful for future aerospace design.

We believe the changes outlined in the ‘Justification of follow up flight’ section of this relight proposal will demonstrate this technique as an attractive tool to study steady two phase flow in microgravity. Further alterations to the original proposal can be found throughout the remaining sections in highlighted bold text.
Test Objective

The aim of this experiment remains parallel to Team ALBERT's, "to gather reliable experimental data which will be used in comparison with theoretical models of steady two-phase flow in a reduced gravity environment." This will again be achieved by rotating various closed circuit circular loops of differing tube diameters and slug viscosities. As the slug travels a circuit with constant velocity in reduced gravity, a video record of its length will be made. The film deposition rate within each tube will then be calculated and a non-dimensional analysis of the flow will follow.

Test Description

The following test description mirrors that of team ALBERT's, and has been highlighted in bold text to reflect our intended alterations. Refer to the 'Justification of Follow-up Flight', for the complete itemization of our proposed changes.

The unique characteristic of this experiment is that it produces a slug flow that is truly steady and fully developed.

![Diagram of closed circuit loop](image)

Figure 1: Schematic of the closed circuit loop containing a steady slug.

A series of 1g experiments have been developed to compare and predict fluid behavior in a reduced gravity environment (Figure 1). A predetermined volume of 5 centistoke silicone oil is injected into a transparent tube and then sealed. The closed circuit tube has sufficient length so that the radius of the loop is significantly larger than that of the tube ($r_p/r_l << l$). Additionally, the volume of liquid selected coats the tube wall while allowing for a slug of length ($L_s$) to form during a steady rotational velocity. A circular aluminum plate contains narrow thin grooves capable of fitting selected tubes on the face while a perpendicular shaft mounted to the center of the plate is attached to a gear motor. In turn, the motor connects to an autotransformer that enables variable voltage and control of rotational speed. The 1g apparatus consists of a motor and plate mounted to a hinged support. In a reduced gravity environment, this apparatus requires a modified version of the preliminary 1g apparatus as shown in Figure 2 and 3.
Figure 2: Schematic of the apparatus used in a 1g environment.

Figure 3: Schematic of the apparatus to be used in a reduced gravity environment.
By mounting the motor and plate to a larger disk, the liquid in the tube is forced to form a slug using an applied centrifugal force. The rotational speed of the disk is used to simply collect the slug, not to simulate gravity. Once the slug has completely formed, the plate is rotated to start the test. The plate is designed such that after the necessary data is collected, it can be quickly and safely exchanged with another plate that has a different tube diameter, fluid property or both. **Two cameras are positioned over the tube, one located close to the slug equilibrium position, the other further away to view the entire upper disk.** Adjustment of the rotational speed is manually controlled in response to the live video, while motion capture software will be used to analyze the **close up footage** later.

In both environments, the motor and autotransformer is adjusted to provide a steady rotational speed. The slug diminishes in length as it coats the inner tube while slowly moving one quarter of the circle in the direction of spin. In this position, the slug of liquid is allowed to reach a steady-state condition as the plate continues to rotate. A digital image is collected and analyzed to measure slug length and determine the final volume. This data allows for calculations of film deposition and film thickness while examining two-phase slug flow in both 1g and reduced gravity environments.

A one-dimensional force balance was performed to determine the average steady velocity of the liquid slug as seen in Figure 1 (Young, 308). At steady state (i.e. steady average velocity), a force between acceleration, viscosity, and surface tension yields

\[ F_a - F_\mu - F_\sigma = 0, \]

where \( F_a = \rho \pi r^2 L_s a, F_\mu = 8 \pi V \mu e (L - L_s) + \mu_s L_s, \) and \( F_\sigma = 2 \pi r_1 \sigma (\cos \theta_{adv} - \cos \theta_{rec}), \) with \( \rho \) as liquid density, \( r \) as the inner radius of the tube, \( L_s \) as the length of the liquid slug, \( V \) as the average steady velocity, \( \mu e \) as the gas viscosity, \( L \) as the length of the entire tube, \( \mu \) as the slug viscosity, \( \sigma \) as surface tension, \( \theta_{adv} \) and \( \theta_{rec} \) as the advancing and receding dynamic contact angles, and \( a \) is acceleration. In a 1g environment, \( a \) is defined as the gravitational acceleration, \( g \), where \( \phi \) represents the angle of inclination with respect to gravity. Alternatively, in a reduced gravity regime \( a \) represents centrifugal acceleration, \( R_d \omega_d^2 \), where \( R_d \) is the radius of the larger disk and \( \omega_d \) is the disk rotational velocity.

The fundamental assumption is that the trailing meniscus can be approximated as spherical. This requires that the tube Bond number and Capillary number are small, \( Bo_t = \rho a R_t/\rho << 1, \) and \( Ca = \mu V/\sigma << 1 \) (Incropera, 357). It follows that the tube radius and slug length are such that \( r/L_s << 1, \) and the respective dynamic contact angle effects be \( 1 - \cos \theta_l << 1. \) From this, the force balance of equation (1) may be solved explicitly for the average steady velocity

\[ \nu = \frac{\rho a L_s R_t^2}{8(\mu e (L - L_s) + \mu_s L_s)}. \]  

The film thickness \( \delta \) deposited by the slug of length \( L_s \) is accurately computed from the slug length measurement,
\[ \delta = \sqrt{R_i^2 - \frac{R_i^2 (L_{so} - L_{sf})}{L - L_{sf}}} \]

where \( L_{so} \) is the initial slug length and \( L_{sf} \) is the final slug. The slug is assumed to uniformly coat the inner circumference of the tube for preliminary analysis. This assumption will be investigated further during the course of the project. Dynamic capillary affects and dynamic contact angle will also be included in the complete analysis.

Tilting the plate from a vertical to a horizontal position in a 1g environment decreases the effect of the gravitational force in the direction of flow (Colin, 533), lowers the rotational velocity needed for steady state conditions and allows for insight predicting low gravity conditions.

The 1g test provides experimental data that can be compared to theory and previously published results. The result of 1g testing aids in the proper selection of tube radius, fluid viscosity, and rate of rotation in a reduced gravity environment. For comparison, data collected during preliminary test in preparation of this proposal was plotted against experimental data gathered in Jing-Den Chen’s research on film thickness surrounding a bubble in a capillary (Chen, 347) and F.P. Bretherton predictions on film thickness (see Figure 4).

![Dimensionless Film Thickness vs. Capillary Number](image)

**Figure 4:** \( \delta r \) as a function of \( Ca \), (•) Data for 1 cst silicone oil in our closed circuit loop, (⋆) Comparative data from Jing-Den Chen’s research on film thickness surrounding a bubble in a capillary and F.P. Bretherton’s predictions (–).

This plot displays a direct correlation between the preliminary data collected using our closed circuit loop and both the experimental results of Chen’s data as well as Bretherton’s theoretical prediction. According to the theory and preliminary tests, reduced gravity will enable a far greater tube diameter to be tested while maintaining a tube Bond Number less than 1.0. Reduced gravity will also enable varied viscosities, tube sizes, and flow rotation speeds to be recorded and modeled. This data is not attainable in a 1g environment for larger tube diameters, Bo \( << 1 \) can not be achieved (and the flows stratify). Once the tube Bond number is greater than 1.0, capillary forces no longer dominate the system, and gravity begins to play a complicating
role rapidly draining the thin films and eventually destabilizing the liquid slug. This information will provide insights to an area of science where little data has been successfully collected, particularly in regards to a truly steady slug flow.

**Justification of Follow-Up Flight**

There are no other previous flights dealing specifically with slug flow confined to a continuous loop in a reduced gravity environment other than that performed by our predecessor, team ALBERT. Although promising data and proof of time averaged steady state flow was obtained during the first parabola in the previous experiment, various inherent problems with the apparatus limited the effective range and accuracy of the results.

ALBERT's results showed that the slug and small disk shared an average 2.11 in/s velocity; however, both deviated from this average by as much as 30%. As shown in figure 5 below, unsteadiness in velocities was highest during transition between g-environments. The unsteadiness was caused by irregular rotation rates of the small and large disks as well as by slug break up.

![Graph showing velocity data over time](image)

**Fig 5**: 3rd Parabola Slug Velocity v. Small Disk Average Velocity
The purpose of this re-flight proposal is to correct many of the difficulties encountered with the apparatus during those past flights while maintaining their experimental aim. The list below itemizes these difficulties and our proposed alterations in respective bold and plain text:

- **Unsteady disk rpm and control range, leading to the entrainment of bubbles during 2-g pull up.** Usize the controls and motors for steady disk rpm and motor torque. This will allow for better slug coalescence during 2g and a smooth transition of the slug into equilibrium position during low-g.

- **Limited viewing area and image quality of the video capture** Mount a second camera further away from the small disk to better determine slug coalescence. Increase the rigidity of the camera mountings to limit vibration. Apply a frosted lower surface on the small disk and add backlighting to provide for accurate slug volume and contact angle measurements.

- **Small apparatus size** Increase the overall size to accommodate new camera arrangements and larger disks. The larger disks will increase the testable range of tube diameters and reduce slug distortion caused by the disk-tube radius aspect ratio. Additionally, the size increase will improve in-flight ergonomics.

These alterations to last year’s proposal are highlighted in bold text throughout the remaining sections.
References


Proposal Section II

Experiment Safety Evaluation
(Flight and Ground Operation)

Flight Manifest

The four primary flyers include Brian O’Neel, Jason Mooney, Paul Rofkar, and Jim Cloer. There is not an alternate flyer for this experiment, and a team journalist will be appointed after the proposal has been accepted. None of the proposed flyers have prior flying or ground crew experience with the RGSFOP.

Experiment Description/Background

Team Albert’s unique method of studying two-phase slug flow was designed by using a closed circuit circular loop. The most valuable and unique aspect of this design was the partial achievement of steady state, fully developed slug flow. Despite the problems encountered with the apparatus during their flights, the design proved unique in furthering our understanding of controlling steady state two-phase flow. The flow control was not as simple, reliable, or as accurate as they had anticipated, yet, their limited results were shown to be inspirational. We believe that consistent steady state flows can be achieved with alterations to the same apparatus.

The aim of this experiment is exactly the same as before... to gather reliable experimental data that will be used in comparison with theoretical models of steady two-phase flow in a reduced gravity environment. This will again be achieved by rotating a closed circuit circular loop containing a liquid slug. The slug length will be recorded for various viscosities and tube diameters. From this slug length measurement, a film deposition rate will be calculated and the characteristics of the flow will be documented. This test is to be done in a reduced gravity environment to examine the augmentation of the film thickness and slug size.1 The apparatus is modeled in Figure 6 on the following page.
Figure 6: Cutaway model of the reduced gravity testing apparatus (covers removed).

By mounting the step motor and plate to a second rotating disk, the slug of fluid will be forced to the outer radius so that the slug will contain all of the fluid in the tube. Once the slug has completely formed, the outer plate can be counter rotated to start the test. The plate will be designed so that after the necessary data is collected, it can be quickly and safely exchanged with another plate that has a different tube diameter, fluid property or both. A camera will be positioned over the tube so that the video captured can be analyzed later using motion capture software.

Equipment Description

The simple experiment is fully self-contained and will operate solely on board the KC-135. No ground components are necessary for this experiment. Several disks with a single clear polymer tube of varying diameters containing different viscosities of silicone oil will be prepared prior to shipment of the equipment. The disks will be interchangeable on a single step motor and designed for a quick and safe connect/disconnect, which will occur only during the turns of the KC-135. One of the flyers will operate a dimmer switch that controls the speed of the step
motor, while the other flyer exchanges the disks when necessary and monitors the computer’s control and data storage performance.

**Structural Design**

The materials used for the experiment will include several 1/4” thick, 14” diameter translucent Plexiglass disks with grooves machined for the Tygon tubing to be nested. Each plate will be covered with the same size sheet of clear Plexiglass to provide double containment of the silicone oil. The lower step motor will be mounted onto a board that will be attached to a metal frame that can be bolted to the aircraft floor. All components will be enclosed in a Plexiglas container. All edges/corners will be rounded to NASA specifications. The complete design (i.e. structural components, mounting techniques, etc...) will be included in the formal TEDP submitted after the proposal has been accepted.

**Electrical System**

A standard 110V power supply will be needed to drive the step motors. The step motors will be manually controlled by an off-the-shelf light dimmer. During the disc exchange, all power will be cut to the apparatus by one switch at the power strip mounted to the experiment.

**Laser System**

There are no lasers used on this experiment.

**Crew Assistance Requirements**

Notification of entering and exiting reduced gravity will be helpful in preparing each test.

**Institutional Review Board**

An institutional review board is not applicable to this experiment.

**Hazard Analysis**

- Moving Parts: The rotation rates are less than 20 rpm, however to prevent any unforeseen mishaps, all moving parts of the experiment will be contained in a clear Plexiglas cover mounted on the base frame.
- Fluid Leaks: The Plexiglass plates containing the tubing with less than 10 ml of silicone oil will each be protected by sheets of Plexiglas, providing double containment of the oil. Still, as a contingency to fluid leaks, a box of Kemwipes will also be available for cleanup. The disks will be cataloged and stored in a box with a locking top.
- Electrical Shock: The motors will be plugged into a surge protector with a main power shut-off switch that will be easily identified and accessed on the experiment.
- Sharp Edges: All the edges and corners will be rounded to NASA specifications.
Tool Requirements

No tools are required during the flight or onboard the aircraft. Standard tools for securing the experiment on the ground are all that is needed.

Ground Support Requirements

Ground support is not needed for the success of this experiment.

Hazardous Materials

There are no hazardous materials contained in the experiment. Material Safety Data Sheets (MSDS) are attached for the silicone oils used.

Procedures

- Ground Operations: Assemble the apparatus after shipping and ensure all safety specifications are met.
- Pre-Flight: Secure the rig to the aircraft floor and check power supply. The first disk will be mounted and ready for operation while the other disks will be contained in a secure box.
- In-Flight: During the reduced gravity phase, flyer one will be adjusting rotational speed of the outer disk while flyer two records experimental conditions. During a turn around, flyer one will switch off apparatus power while flyer two prepares the next test disk when it is necessary. After power is turned off and rotations have completely halted, the Plexiglass cover will be opened for test plate exchange. The cover will be re-sealed, the first disk replaced in the locked box, and the system power restored. This procedure is expected to be repeated every seven to ten parabolas and estimated to take less than thirty seconds.
- Post-Flight: Update team members on successes and failures of flight.

Proposal Section III

Outreach Plan

The ALBERT group had initiated several outreach plans which are being passed along to their successors, team ALBERT 2, for which we will continue to stimulate interest in the “Steady Two-Phase Flow” project as well as the NASA reduced gravity student flight program. In collaboration with team ALBERT, ALBERT 2 will also strive to engage other engineering students here at Portland State University as well as other groups in the community. Team ALBERT’s participation in this program has successfully excited other students interested in science and technology. So far, this plan has generated an immense interest in fluid mechanic studies as well as continued education here at Portland State University.
The outreach plan remains the same as before by extending to a variety of audiences, yet with the added powerful evidence of the ALBERT group’s rewards in striving to explore new fields of study. The following is a review of the outreach plan written by team ALBERT, but with added positive amendments and events.

Currently, we have arranged several presentations concerning this experiment towards college students. In addition to team ALBERT’s goals, each presentation we make to this audience will convey the importance of the research, demonstrate the need for clear critical thinking skills and the process for learning to work in a professional research environment. With a video presentation of the ALBERT group’s adventure and hard work, we have made plans to highlight aspects of the project with added CAD model animation suitable for explaining what we are trying to accomplish.

Regional student chapter president of the American Society of Mechanical Engineers (ASME), Jamie Kelso, has agreed to us giving one of these presentations. Additionally, student journalist Ryan Hume from Portland State University’s school newspaper the Vanguard has committed to write an ongoing article about the progression of the project. We anticipate this will encourage future participation of students from all different departments at Portland State University in this type of program.

Our outreach plans are not limited to college students who are interested in science. We are also trying to expose the community in Portland, including a variety of education levels, about the reduced gravity flight opportunities program. We intend to continue the display of images from the NASA reduced gravity experience and interactive exhibit at the Oregon Museum of Science and Industry (OMSI) in Portland, Oregon. OMSI currently has a display of ALBERT’s efforts in their physical science wing that we intend to update and maintain, complimented with added video demonstrations. The museum offers tours and interactive classes for all age groups with similar objectives to our group. Three outreach opportunities have been again presented along with a newly added interactive concept for young science enthusiast:

- Participating in multiple one-hour presentations with OMSI at a K-12 school.
- Organizing a presentation at OMSI for an audience of 5-200 people ranging in education levels from kindergarteners to college students.
- Arranging a presentation with the planetarium department at OMSI.
- A simple low-g experiment has been proposed through Blair Baldwin, Lead Teacher Educator at OMSI. We intend to interact with the Blazer kid’s clubs closely associated with learning about science and technology in the Portland area. Their small experiment shall be self contained, affixed within our apparatus and adhere to the same safety requirements.

Our team will be submitting the final paper for potential publication and presentation during the American Institute of Aeronautics and Astronautics (AIAA) conference at the Reno meeting in January 2005. Our demonstrably reliable and valuable scientific data from experimentation will provide continuing research opportunities with two-phase flow in a reduced gravity environment. Submission to the AIAA conference will occur after the final report has been completed.

The progress of Team ALBERT 2 can be accessed at www.me.pdx.edu/~microgravity. This website will provide current reports with ongoing experimental analysis and outreach opportunities.
Proposal Section IV

Administrative Requirements

Institutional Letter of Endorsement

See attached letter.

Statement of Supervising Faculty

See attached letter.

Budget Planning

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Table 1: Budget is for 4 team members

Possible sources of funding include:

Oregon’s Institution State Space Grant

Private sponsorship

Institutional Review Board

An Institutional Review Board will not be required for this experiment.

Human Research Test Subject

No research will be done on humans during this experiment.
Institutional Animal Care and use Committee

No research will be done on animals during this experiment.

Parental Consent Form

All participating team members are over 18 and require no parental consent.

Appendix/Student I.D. Information

Participant Information Forms

All forms submitting electronically.

Participant Signature Forms

See attached pages.

Photo Identification Copies

See attached pages.

Proof of Undergrad Status

See attached pages.