Fostering Research in Aerospace and Mechanical Engineering Undergraduate Curricula

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Over the last five years the University of Tennessee Mechanical, Aerospace, and Biomedical Engineering (MABE) Department has offered undergraduate students enrolled in senior capstone design "microgravity" projects as part of NASA Reduced Gravity Student Flight Opportunities Program. In comparison with traditional design projects these projects also include a well-developed research portion, which include experiments onboard NASA "Vomit Comet", data analysis, and scientific reporting. During the 2002-2003 academic year three projects were completed with a focus to investigate two-phase fluid flows and mass transfer under reduced gravity conditions. The main features of this approach to implement a research component in undergraduate curriculum are: involvement of students in cutting edge areas of science and technology; fostering student interest in science; providing the opportunity to use basic knowledge in real scientific research; and recruiting talented students for graduate programs. Five years of participation in NASA Reduced Gravity Student Flight Opportunities program have demonstrated amply that program is not only simply suitable as capstone design project, but that it also provides senior students the unique opportunity to apply their knowledge to real scientific problems, improve their analytical abilities and research skills.

Keywords: Microgravity, research, design, project.

INTRODUCTION

Typically, mechanical and aerospace engineering curricula are very structured with major portions devoted to mathematics, physics, material science, thermal science, mechanical system, and courses in other areas. This leaves little time to implement a research component in the two programs. One opportunity to facilitate undergraduate research and involve students' skills in solving non-traditional engineering problems is in senior design projects. Five years ago the University of Tennessee's Mechanical, Aerospace and Biomedical Engineering Department offered a senior capstone course involving "microgravity" projects. These projects require participation, on a competitive basis, in a unique NASA program: "The Reduced Gravity Student Flight Opportunities Program" [1]. This program provides a unique academic experience for undergraduate students to propose, and successfully design, fabricate, fly, and evaluate a reduced - gravity experiment of their choice. The overall experience includes scientific research, hands-on experimental design, test operations, and educational/public outreach activities. The Reduced Gravity Program usually begins in October and has the following milestones:

(a) In the middle of October, a Letter of Intent is submitted that marks the first level of communication between the student team and the program coordinator;

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(b) Toward the end of October, a proposal for participation in the competition is submitted. It contains various parts including theoretical background of proposed research, test objectives, test descriptions, apparatus and equipment descriptions, structural design, electrical and hazard analyses, and description of the data acquisition system;

(c) In early December, the teams receive feedback about their proposal;

(d) During January and February months, flight physicals are submitted;

(e) From January through March, the students submit a test - equipment data package which must include detailed test apparatus and equipment description, calculations, plan of experiment, and any additional specific information that may be required;

(f) From March through July, the experimental package is flown;

(g) During August and September months, a post flight final report is written and submitted.

During the flight week, the selected team normally undergoes physiological training in classroom and hypobaric chambers, completes construction of the experimental equipment, passes test - readiness review and technical inspection, loads equipment onto aircraft, flies two consecutive days with their experiment package, and collects data. Each team is assigned to two consecutive flight days with one flight scheduled per day. Each flight lasts an average of 60 to 80 minutes and has approximately 30 reduced - gravity parabolic maneuvers over the Gulf of Mexico. The trajectory flown on each parabolic maneuver will provide approximately 25 seconds of near - zero gravity condition for each team's experiment. At the end of the reduced gravity maneuvers, teams/experiments are also treated to approximately 30 seconds of lunar-g (1/6-g) and approximately 40 seconds of Martian-g (1/3-g) environments. In order to encourage experiments that could address issues and find solutions as NASA travels back to the Moon, the Reduced Gravity Student Flight Opportunities Program in 2007 decided to provide also a special flight to give research teams the opportunity to fly student-designed experiments in lunar gravity. One of the special requirements for the flight crewmembers is that they should be U. S. citizens. Ground crew membership is unrestricted, and it may include students (high school, undergraduate, graduate), faculty members, and professional consultants. The proposed experiments can cover a wide area of research in mechanical and aerospace engineering, electrical engineering, material science, biomedical engineering, biomedicine, and many other fields. The same test facility could be used for a maximum of 3 years if needed to complete the proposed research. A significant component of the Reduced Gravity Program is the outreach component of the program, which is designed to engage the team members in outreach activities in their own university, community, and region.

During the 2002/03, 2003/04, and 2005/06 academic years, three Reduced Gravity Projects where initiated:

“Making A Mixing Measurement Of Two-Phase Flow- MAMMOTH Flow” was started in fall 2001 by a group of volunteering students and completed in spring 2003 as a senior capstone design project. The objectives of this experiment were to simulate film boiling in reduced gravity using air injected in a liquid flow in a vertical pipe.

“Heat Exchange Research And Condensation Evaluation By Utilizing A Liquid/Fog Experimental Set Up - HERCULES” was started as a senior capstone - design project in fall 2002 and completed in spring 2004. The objectives of this project were to investigate the peculiarities of the forced - flow condensation in reduced gravity using saturated air-water mixture flow.

“Simulation For Confirmation Of The Onset Correlation Of Liquid Potassium Entrainment – SCOPE” started in fall 2004 with first flight in spring 2006. The delay was, in part, due to temporary suspension of Reduced Gravity Program in spring 2005 to switch aircraft used in the program from a KC-135 to C-9. The SCOPE objectives were to simulate liquid droplet entrainment in vapor flow using an air-water mixture and investigate the entrainment interaction between air and water in annular - flow regime under reduced gravity condition.

PROJECTS’ ACCOMPLISHMENTS AND RESEARCH RESULTS

As described by the objective of each project, the research projects were focused on specific features of fluid flow and heat and mass transfer under reduce gravity environment. However, each project required considerable design activity prior to and during the flight and data collection phases. This provided an opportunity to cover outcomes required in accreditation of engineering programs such as those conducted by US Accreditation Board for

Engineering and Technology. These projects also provided means and resources to foster research in undergraduate programs. Brief descriptions of the accomplishments in each program are discussed below.

Film Boiling Experiment (MAMMOTH Flow Project)

The objectives of this experiment were to simulate film boiling by injecting air near the surface of a vertical pipe filled with liquid flow. As the gravity level is reduced, the hydrodynamics of the two-phase flow was expected to change resulting in the creation of circumferentially concentrated vapor bubbles between the liquid and the pipe wall. Once this was accomplished, the study focused on investigating the utility and effectiveness of pipe cross section modification (inserts) and the resulting mixing of the flow and its impact on heat transfer under microgravity conditions. Two pipe augmentation inserts were tested: a helical ribbon and a variable diameter insert. It was assumed that the helical ribbon would create a desirable phase distribution for heat transfer applications under microgravity conditions by disrupting the simulated vapor phase from the pipe wall/heating surface. This disruption is caused by the swirling of fluid, thus centrifugally pressing the water flow onto the wall of the pipe. Similarly, the variable diameter insert were expected to create flow turbulence resulting in mixing of the two-phases and enhancement of fluid contact (and hence heat transfer) with the heating surface. The effectiveness of these heat transfer augmentation devices (HTAD) were compared with a control section (smooth pipe) in order to determine their usefulness in promoting two-phase flow heat transfer under microgravity conditions. Heat transfer effectiveness was measured by measuring change in temperature before and after a section of the pipe that was heated for this purpose.

The experimental apparatus consisted of four components. They were fluid transfer, air injection, two-phase separation (combined with cooling), and data acquisition. The fluid transfer section, containing a total of two and one half gallons of de-ionized water shown in Fig. 1, consisted of a centrifugal pump that is controlled by a precision adjustable flow regulator that fed to a 1-inch ID clear PVC pipe. After passing through a flow straightener, the liquid was passed through an air injection system. The two-phase mixture was then passed through one of the inserts (HTAD). After the flow was passed through the test section for data acquisition, it entered the Gas-Liquid Separation Module (GLSM) for phase separation. The GLSM was encased in an ice bath in order to help cool the fluid. From the GLSM, liquid was returned to the pump thus closing the fluid transfer loop. The air injection system, shown in Fig. 2, consisted of compressed air that was injected circumferentially through a ring manifold at the pipe surface. In these experiments air simulated vapor generated from film boiling near the pipe surface.

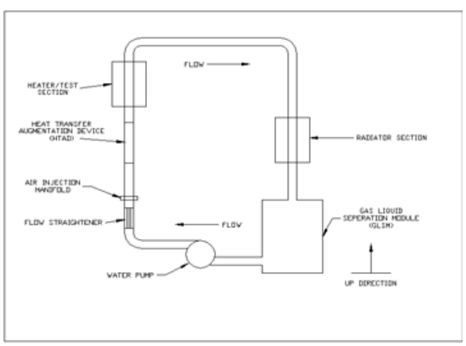

Fig. 1. Schematic of the Water Flow Loop

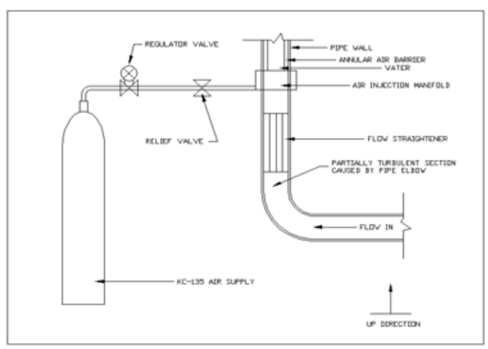

Fig. 2. Schematic of the Air Injection System

The two-phase separation system (GLSM) was cooled by ice packs to keep the fluid temperature in the loop from rising excessively. Through cooling it was possible to keep the overall rise in the fluid loop temperature to 12°F as opposed to an expected value of 70 °F. The data acquisition system included visualization and data collection. Flow visualization was accomplished through a video camera and a still camera positioned to view the HTAD and the resulting flow. The heating section consisted of a resistance heater wrapped around the pipe to heat the fluid. Thermocouples were placed fore and aft of the heating section to measure the change in temperature within the fluid flow. There were two sets of thermocouples each consisting of four thermocouples located circumferentially at the inlet and the exit of the heated section, respectively. The output of the accelerometer and the two sets of thermocouples (after amplification) were then recorded by a laptop computer in real time. HPVEE code was used for data collection and analysis. Ground testing included experimentally optimizing the liquid and gas flow rates and resistance heater input power. The temperature measurements were used to compare the change in fluid temperature (ΔT) across the heater section in microgravity for the two different HTAD inserts and the control section (smooth pipe).

MAMMOTH flow test apparatus flew twice in spring 2002 and 2003. Only a couple of typical results obtained by students flight crew are presented here. They include flow visualization results demonstrating different flow patterns and temperature difference measurements for the smooth pipe and pipes with HTAD inserts demonstrating heat transfer enhancement. Bubbly flow was observed immediately following the injection of air. The air bubbles expanded in size until they finally broke free from the ports drilled in the air injection manifold. The continuation of slug flow into the control section after air injection manifold may be seen in Fig. 3. This figure indicates large concentration of vapor bubbles along the inner surface of the pipe wall. As was intended the variable diameter insert and swirling-helical (plastic) mixer HTADs generate turbulence in gas/liquid mixture flows. Fig. 4 shows flow change due to swirling-helical mixer HTAD.

Fig. 3. Flow in smooth pipe

Fig. 4. Flow with swirling-helical HTAD

The change in temperature across each HTAD and the control section (smooth pipe) are presented and compared in Fig. 5. Aircraft acceleration profile is also presented in the same figure. Although the numerical difference between the ΔT's shown in this figure are small (less than 0.05° F), there is a distinct and repeatable difference observed in the HTAD performance. One can see from Fig. 5 that temperature rise for the test section with variable diameter insert (squares) is higher than temperature rise for the control section (rhombus). Fig. 5 shows also that variable diameter insert is more effective for the heat transfer enhancement compared to the swirling-helical mixer. Over the entirety of each flight, the HTADs did show consistently an increase in heat transfer as measured by rise in ΔT. Hence a large number of flight confirmed repeatedly that the variable diameter HTAD provides the highest heat transfer rates as compared to the swirling-helical HTAD and the control (smooth pipe) section. These observations and data collected confirmed the variety of possible ways to increase the rate of film boiling under reduce gravity environment using different kinds of inserts. The results of flight test were presented and published in the proceedings of AIAA Aerospace Science Meeting and Exhibit [2].

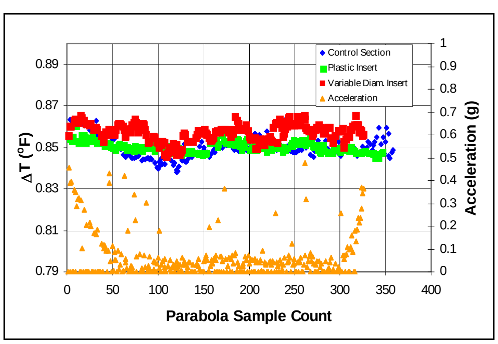

Fig. 5. Performance Comparison of HTAD Inserts

Fig. 6. MAMMOTH flow onboard KC-135

Forced Flow Condensation in Reduced Gravity (HERCULES Project)

Condensation can also be different in microgravity conditions when compared with terrestrial gravity conditions. There are two basic forms of condensation that are of interest: drop-wise and film-wise. Drop-wise condensation occurs when the cooling surface is not easily wetted, or when the vapor does not contain enough liquid to sufficiently form a liquid film over the entire inner surface of the cooling pipe. The film-wise condensation occurs when the cooling surface is easily wetted. The liquid film on the inside of the pipe poses a problem in the area of heat transfer because it does not allow the vapor inside the pipe to come in contact with the wall as is the case in the normal gravity condition. This is mainly because the liquid annular flow establishes a liquid barrier on the inner surface of the pipe preventing vapor contact with the cooling surface further reducing rate of condensation. This leads one to expect that the heat flux from vapor to wall would be smaller under the reduced gravity conditions. Therefore the anticipated results are that there will be a decrease in the temperature of the condensate in microgravity and that the temperature difference, defined as the change in temperature from the inlet to the exit of the cooling section, will be smaller in the vapor flow. The observation of the gas and liquid temperature differences and experimental confirmation of anticipated phenomena of the condensation in the reduced gravity was the main goal of HERCULES experiment.

Experimental apparatus consisted of four systems comprised of five major components that operated automatically and continuously throughout each test cycle with no human intervention (Fig. 7): the fluid transfer system, water/fog injection system, condensation system (test section), and the data acquisition system. The five major components were: the separation module (SM), pump, fluid heaters, atomizer, and cooling module. The fluid transfer system begins and ends at the separation module (SM) (6). From SM, water was pumped through an incremental flow valve and through a series of heating bands (7), which raised the water temperature and kept it stable in the inlet of the cooling module. After the flow regulator and divider (10) the water was separated into two flows with variable flow rates. One path traveled to the atomizer (5) intake to develop the water fog for the simulation of the saturated water vapor and the other path went directly to the flow loop where it was injected into the flow stream by an injector nozzle (13). Thermocouples were used for water temperature drop measurement (two for the fog temperature drop measurement and eight for water temperatures drop measurement and two for the water and fog absolute temperature measurement) and were placed before and after the cooling section (19). By using this setup it was possible to measure the change in temperature of the condensate (water) and vapor (fog) in reduced gravity conditions, which could then be compared to those gathered in normal gravity conditions and absolute temperatures of the fog and water in the test section outlet. SM is a cylindrical tank and the air-water mixture is forced to follow the curvature of the tank to provide preliminary separation of water from air. Air is removed from the tank through a drain valve. To provide the main cycle of separation, the tank was fitted with a mesh system at the bottom that holds the water at the inlet of the pump through wetting force and surface tension.

Visual observations with digital video and pictures of test section demonstrated three flow patterns in reduced gravity. In the early stages of parabolas the regular (stratified) flow pattern changed to bubbly flow, consisting of discrete, nearly spherical gas bubbles surrounded by a continuous liquid phase. In the middle stages the flow pattern underwent a transition to slug flow pattern that was characterized by bullet-shaped Taylor bubbles separated by slugs of water. It was observed that for comparatively small flow rates of water the length of air bubbles increased and flow had a tendency to transform in a short period of time into annular flow (Figure 8). The annular flow was not very stable for small water flow rates. Measurements of air and water temperature drops confirmed the expectations concerning the reduction of the condensation rate in microgravity environment. For example, Figure 9 demonstrates the history of the water and fog temperature difference along the test section. This figure shows that temperature difference of fog (dTf) is less then temperature difference of water (dTw). While this observation does not prove directly the insulation effect of water film (because of the difference of heat transfer coefficients for saturated air and water), it points out to possible evidence in support of water insulation effect. The same results were observed for different water flow rates. Ground tests were conducted for comparison purposes and to confirm the above hypothesis. Fig. 10 shows a comparison of ground and microgravity results for water mass flow rate of 1.1 gallons per minute. It is observed that under normal gravity the results show higher fog (vapor) temperature change as expected. Hence, the experiments on a simulated condensation process confirmed expectations for

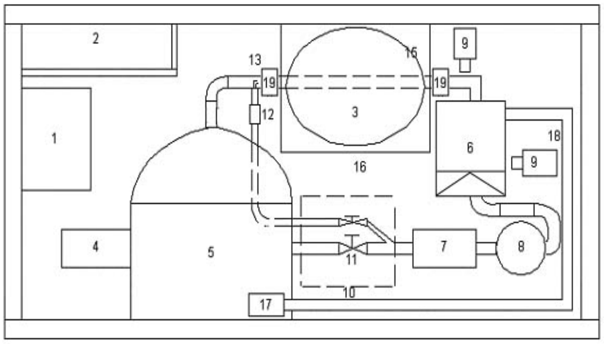

Fig. 7. Schematic of test apparatus.

Fig. 8. Annular flow in reduced gravity

air/liquid flow patterns (annular, slug, and bubble flows) under reduced gravity. The temperature measurements indicated that less condensate is expected to form under reduced gravity in annular flows than under normal gravity condition. Detailed description of the test facility and analysis of the flight test data were published in the proceedings of AIAA Aerospace Science Meeting and Exhibit [2,3].

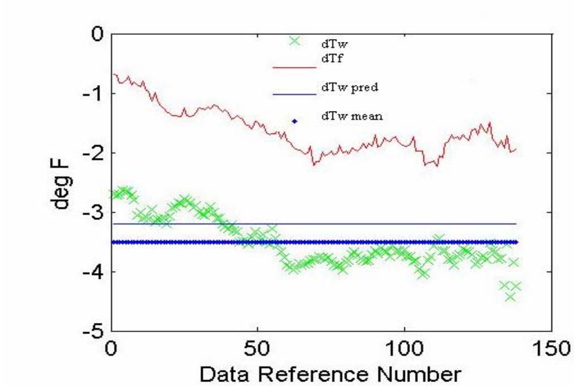

Fig. 9. History of the temperature difference of the fog and water for reduced gravity condition

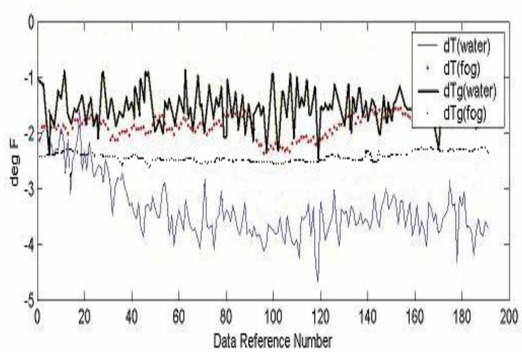

Fig. 10. Comparison of the history of temperature difference of the fog and water for reduced gravity and normal gravity condition

Simulation of the Liquid Droplets Entrainment (SCOPE Project)

Higher nuclear electric power generation require the application of effective thermodynamic cycles for power conversion. In US space programs Rankine cycle was pursued as an approach for achieving extremely high specific powers. However, in a reduced gravity environment, the lack of buoyancy can alter the physics of a two-phase fluid interaction and thus the performance of a Rankine cycle. An important phenomenon specific to the Rankine power cycle involves fluid entrainment in the boiler. In two-phased flow, the vapor flow has a higher velocity than the liquid flow. The drop flow is thus a direct product of droplet entrainment from liquid film by the higher velocity vapor flow. These liquid droplets, carried along in the central vapor core, do not come into contact with the heated wall surface and are not vaporized reducing effectiveness of the heat exchange. In addition, and more importantly, the primary detriment in liquid droplets occurs in the turbines downstream of the boiler. The liquid droplets entrained in the vapor flow impinge upon the turbine blades at high relative velocities and thus induce more wear over time. This also creates a serious design issue in space reactor applications where the turbine must operate for long periods of time in microgravity without any opportunity of inspection or repair. These specific issues suggested following research goals: to investigate the droplet entrainment in microgravity environment and to compare relationships predicting droplet entrainment onset for normal gravity with data obtained under reduced gravity environment.

Data on droplet entrainment onset for normal gravity condition were obtained experimentally by Ishii et al. [4,5]. The onset of droplet entrainment was treated as a sudden change in the test section pressure drop versus gas velocity for different flow rates of water (Fig. 11). Theoretical entrainment onset criteria were compared with experimental data for numerous liquids and gases.

In SCOPE experiments, mixed water/air flow was selected as test fluid because of the complexity of the testing of liquid metals in microgravity conditions. The experimental apparatus consisted of five systems that operated automatically and continuously throughout each test cycle. The five systems are: the fluid injection system, gas injection system, liquid/gas injector, test section, and the data acquisition system as seen in Figure 12. The fluid transfer system begins at the end of the test section. The liquid and gas mixture leaves the testing section and travel toward the liquid-gas separator. The water is then pumped out of the tank and into the system. The water passes through a flow meter where its mass flow rate is measured and is then fed to the liquid-gas injector where it is injected in an annular fashion into the pathway of the injected gas. In the test section, the separated water and air flow through the flow development section. The two-phase flow enters the actual section of the transparent tube where entrainment will begin, and then passes by a pressure transducer. The data acquisition system consists of one accelerometer, two thermocouples for the measurement of the temperature of air and water, one orifice flow meter for air, water flow meter, two differential pressure transducers to measure pressure drop in the test section, video camera, and a laptop computer.

The first portion of the tests was performed under normal gravity condition to establish flow rates and velocities applicable to Ishii, et al. tests. Experimental data showed good quantitative comparison with Ishii 's results and demonstrated the increase of the pressure drop with the increase of the water flow rate (Figure 13) for the fixed values of the velocities of air in the range from 5 m/s to 30 m/s. One difficulty is that it is generally not easy to identify the break in the pressure drop for different water flow rates (see Figure 13), which corresponds to the onset of droplet entrainment in accordance with Ishii and Grolmes research criteria (the velocity that corresponds to the break in the pressure drop was named "critical velocity".) This is, of course, also true for results in Figure 11, where the break in the pressure is also difficult to pinpoint exactly. Because of the complexity of such "geometrical identification" of the break it was suggested that the maximum of the second derivative to be identified as the point of break in the pressure drop. The calculation of the second derivatives for each water flow rate from the set of 0.0063 kg/s, 0.0189 kg/s, 0.0315 kg/s, 0.0631 kg/s, and 0.0852 kg/s corresponding to 0.1 GPM, 0.3 GPM, 0.5 GPM, 1.0 GPM and 1.35 GPM, respectively, gave the gas flow velocity values (critical gas velocities) which could identify the location of the break.

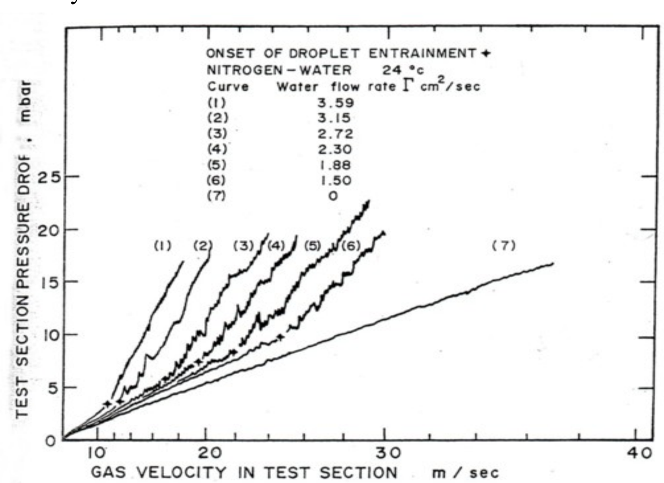

Figure 11 : Test section pressure drop for concurrent gas-liquid flow with onset of droplet entrainment [4]

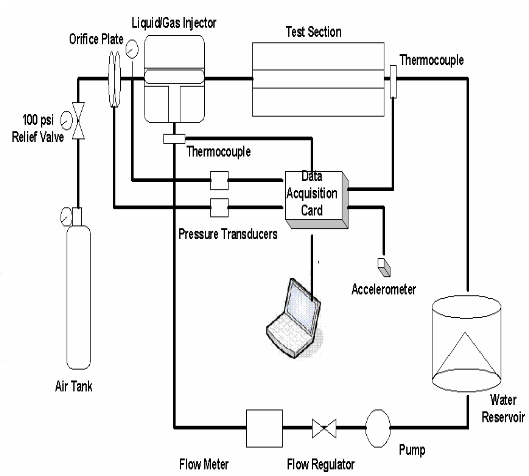

Figure 12: Diagram of experimental apparatus

Microgravity tests were performed for two water flow rates, and demonstrated that the pressure drop in the test section for microgravity conditions is higher than the pressure drop for normal gravity (Figures 14, 15) at the corresponding water flow rates of 0.0063 kg/s; 0.0189 kg/s (corresponding to 0.1 GPM and 0.3 GPM). Preliminary conclusion shows that for horizontal or slightly inclined channels in normal gravity, gravity plays a stabilizing role whereas the relative velocity between phases destabilizes the film through variation in pressure distribution over the liquid wave. The critical gas velocities for the microgravity tests are lower than the normal gravity results at the same water flow rates. This difference may be explained again by the absence of the stabilizing effect of gravity in microgravity conditions, when less gas velocity is needed, in comparison with normal gravity, to provide the entrainment onset. Additional microgravity experimental data collection is planned for spring 2007 to provide more information about the differences in reduced gravity and normal gravity environment.

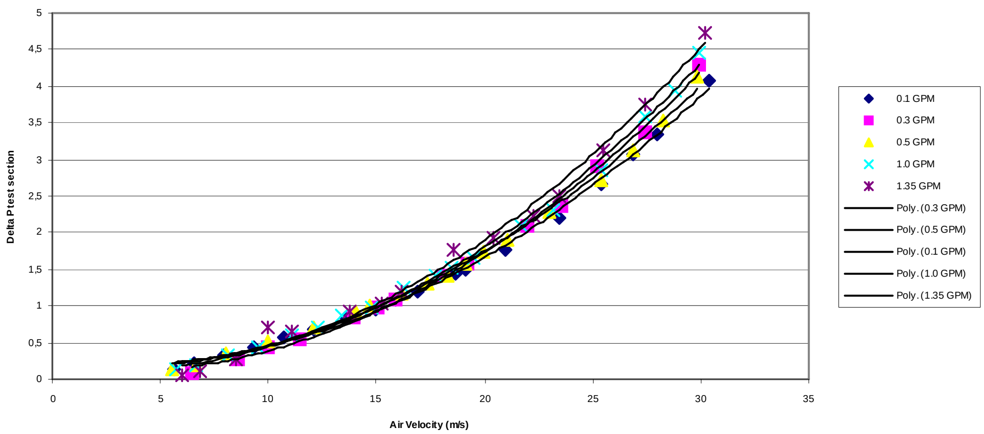

Figure 13: Ground test. Test section pressure drop for concurrent gas-liquid flow in the ¾ inch horizontal pipe (pressure drop in the test section is measured in Psi).

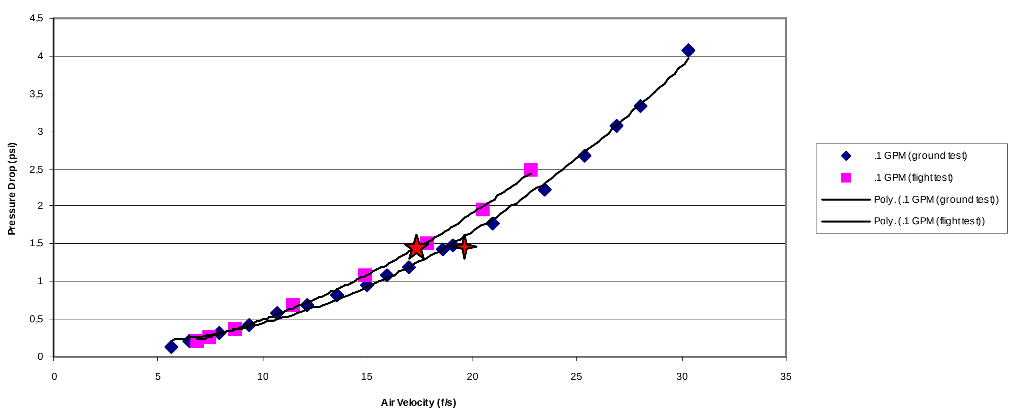

Fig. 14: Critical velocities(microgravity; microgravity) at the onset of entrainment (water flow rate: 0.1GPM)

The description of the entrainment onset numerical and experimental investigation and first results of the SCOPE normal gravity and microgravity tests along with analysis can be found in [5].

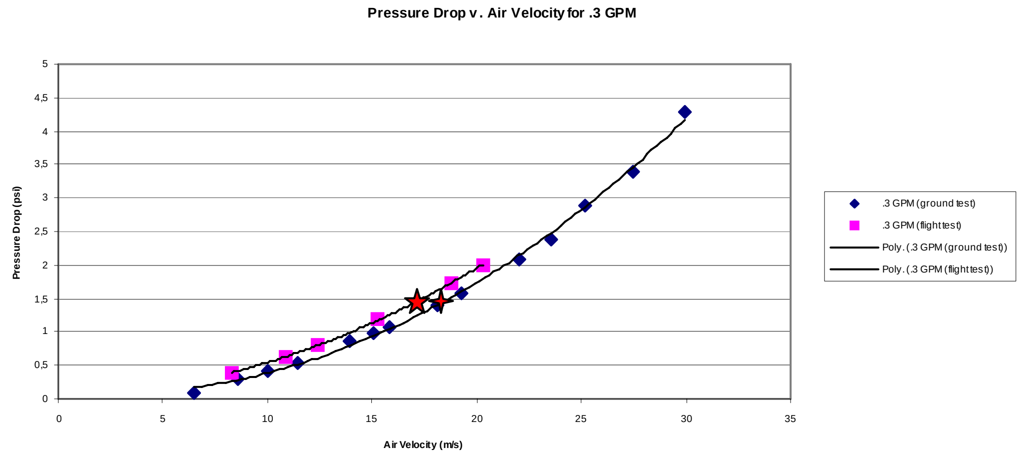

Fig. 15: Critical velocities (★microgravity; ✦ microgravity) at the onset of entrainment (water flow rate: 0.3GPM)

MAIN FEATURES OF THE IMPLEMENTATION OF MICROGRAVITY PROJECT AND RESEARCH COMPONENT IN THE AE AND ME CURRICULA

Various pedagogical problems were identified and resolved during this project. The experience showed that it would be more reasonable to distribute student activity uniformly during the fall and spring semesters. This would alleviate many of the problems exacerbated by the "time crunch" and by the complexity of the projects. The current course offering starts, depending on the project, with a two or three semester credit-hour course in the fall followed by a three or two credit-hour course in the spring. It is desirable to have a two - semester course to have additional flexibility due to NASA and deadline requirements. The experience also showed that teams of five to six students are optimal in the design or redesign and improving of the microgravity test apparatus. Another problem is that of the appointment of project leaders. The project leader is responsible for moderating meetings, scheduling the outside-class meetings, and tracking the design, procurement schedules, identifying and resolving subsystem integration issues. As with leadership and scheduling, the short time frame of the course exacerbates this problem. This is not an easy problem to solve but can be alleviated by early and frequent intervention and advice from the instructors.

Five years of participation in NASA Reduced Gravity Student Flight Opportunities program demonstrates that this program is very suitable to provide engineering design content, and to offer upper division students unique opportunities to apply their knowledge to real engineering problems, improve their analytical abilities, develop design skills, and work in multi-disciplinary teams. An additional important advantage of NASA microgravity projects is that they offer an opportunity to participate in a national competition, which strongly motivates students to do their best, provide a quality work in a timely fashion, and establish multi-year goals. Another important feature is that few programs provide students the opportunity to realize not only engineering and design skills, but perform real research and analysis. One of the specific features is "multi-subject" nature of the project. Microgravity team-members should have special orientation on the research and analysis. At the same time strong designer's skills are also required to develop the schematics and the design of the test apparatus. Moreover, microgravity team-members have to demonstrate knowledge in not only mechanical and aerospace engineering fields but also familiarity in electrical engineering and computer science too. The microgravity projects require the recruitment of talented students who have strong background in different areas of science and technology. Besides, during the participation in the projects students continue to develop their scientific and design skills. While working on the projects students considerably improve their knowledge in the cutting areas of science.

Even at the beginning of the study, students must read and analyze a large number of scientific papers in the specific research field needed to write a competing proposal to NASA. Our practice has been to engage students in discussions and debate in which students present the results of their research and decide on a selected topic for the project. Only after final decision all team members concentrate on the proposed topic of the research and start to develop schematic of the test facility. During the design process team-members face a number of "non-standard" problems forcing them to perform the research in different science and engineering fields. For example during the MAMMOTH flow, HERCULES and SCOPE projects students studied and determined a key problem: how to separate gas and liquid phases before pumping liquid under reduced gravity condition. This problem forced students to investigate and research various options in rocket fuel management under reduced gravity condition and find more effective ways for fuel/gas separation. Compared to many projects, these do not end with completion of flight tests. A large portion of the work needs to be done after the tests. At this point students have to perform data analysis, compare microgravity results with terrestrial ones, explain the collected data and make solid scientific conclusions. A significant time is also spent on the analysis of failures and suggestions for the test facility improvement and future flight tests. The final step of NASA microgravity project, i.e., final report writing, also takes a significant effort. As faculty advisors for microgravity project we observed considerable growth of the students' knowledge in such areas as Heat and Mass Transfer, Fluid Dynamics, Multiphase Flows during the completion of the project. The students are often encouraged to write about their research and experience in the form of a scientific paper for presentation to AIAA, ASME and other conferences and forums. For example, the scientific results of the MAMMOTH Flow, HERCULES and SCOPE projects were presented at 2004, 2005 and 2007 AIAA Meetings and published in corresponding AIAA Papers. This demonstrates the quality of the scientific results and the strong scientific experience that students have obtained from the microgravity senior capstone design classes in the past several years. It is also important to note that many of the team members often decide to continue their study and apply to many university graduate programs.

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