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Two Phase Flow and Space-based Applications

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Abstract

A reduced gravity environment offers the ability to remove the effect of buoyancy on two phase flows whereby density differences that normally would promote relative velocities between the phases and also alter the shape of the interface are removed. However, besides being a potent research tool, there are also many space-based technologies that will either utilize or encounter two-phase flow behavior, and as a consequence, several questions must be addressed. This paper presents some of these technologies missions. Finally, this paper gives a description of web-sites for some funding.

The Reduced Gravity Tool

The use of a reduced gravity environment, in effect, negates the buoyancy force. This is manifested in one of two ways: the shape of the gas-liquid interface and the suppression of flows that are generated because of density-difference between the phases.

As identified by Dukler, et al. (1988)[1], the flow regimes are axi-symmetric which is similar to normal gravity vertical flows. However, there are some significant differences: First, in normal gravity bubble flow, the bubbles are ellipsoid shape and traverse axially in a spiral fashion. In microgravity, the spherical bubbles move in a rectilinear fashion[2]. In normal gravity slug upflow, the cylindrical shaped bubbles overtake smaller bubbles with significant coalescence and breakup occurring in the recirculation zone at the tail of the cylindrical bubbles. In microgravity, the spherical bubbles present within the liquid slug move at about the same velocity as the cylindrical bubble and there is very little interaction within the liquid slug between the tail of the cylindrical bubble and spherical bubbles. Closer examination of the liquid film adjacent to wall has revealed that in microgravity, the liquid is accelerated with the passage of liquid slugs or large disturbance waves and slows, sometimes even stopping, in between these slugs and waves[3]. For normal gravity upflow, the liquid film will actually reverse direction between roll waves and liquid slugs.

Finally, the last major difference between normal and microgravity is that there are no hydrostatic pressure effects since the acceleration term becomes very small.

There are several ways to attain microgravity. Ground-based studies have utilized the NASA 2.2 Second Drop Tower and 5 second Zero-G facility to study capillary phenomena and pool boiling behavior. Aircraft flying parabolic trajectories can provide 20 seconds of acceleration levels of 0.01, 0.10, 0.17 (lunar), 0.25, 0.38 (martian), or 0.50 g's.

There are two proposed space-based two phase flow facilities. The first is the Fluids Integrated Rack (FIR), which is part of the Fluids Combustion Facility (FCF) and will be part of the US Lab Module on the International Space Station. Because of volume constraints, the maximum straight length possible is 1 m. so it would not be practical to study the flow development within larger tube diameters. However, studies that utilize experimental hardware, such as rotating couettes, heliocoils, and heat pipes, are being pursued for inclusion within this facility. The second facility is the Two Phase Flow Facility (TPFF) and will be mounted on the truss structure external to manned modules on the space station. The concept involves a permanently attached portion, consisting of pumps, compressors, separators, data acquisition systems, etc, that would mate to experiment-specific hardware such as test sections, optics, and fluid supply containers. The maximum straight length available for the test section would be about 3 m, and there would a maximum available power of only 3 kW which be used for heating, pumping, acquiring data, control.

Space System Design

The primary concerns about the design of any two phase flow system used for space applications is whether or not the system will work reliably and can the response to changes in the setpoints such as heat load, flowrates and pressures be predicted. Phase separation is also a concern, particularly since buoyancy can not be used to take advantage of the phase difference. Almost no work has been done on flow distribution through splitting tees and manifolds, and yet parallel paths are being used in a host of applications. The boiling crisis is of concern since some work has shown that critical heat flux can be much lower than in normal gravity. Furthermore, dryout of the liquid film can occur because of hydrodynamic conditions whereby the contact angle between the tubing wall and liquid are not as highly wetting as desired, Weislogel and McQuillen (1998).

The heat transfer coefficient and pressure drop are needed for sizing heat exchangers and pumps; however, given the requirements for reliability versus a minimal penalty for launch mass, it is good engineering practice to oversize the pumps and heat exchangers, although this still doesn't obviate the need for developing better predictive techniques.

Two-phase flow data obtained using ground-based reduced-gravity facilities has been subject to several criticisms by designers of space systems. There is a concern that the fluid and/or power levels may not be similar to those being anticipated for the space system and that the scaling analysis to apply the data may be questionable. Because of the limited time duration of the reduced gravity period, there is insufficient time for the system to come to steady-state or for fluid sloshing to dampen out as the system transitions from high or normal gravity to low gravity. Finally, there is a concern that the systems being tested are "simplified" and do not account for all the parallel paths, manifolds, or space environmental conditions that the actual system will encounter versus that being tested.

Space Based Applications

Space-base applications are usually categorized as follows: Power and thermal management, fluid and propellant management, and environmental control and life support systems (ECLSS). These applications are discussed further below.

Power Management

There are several current and futuristic systems that will encounter two phase flows.

Power aboard launch and some orbiting vehicles, including the space shuttle, is often provided by a fuel cell, which must operate in normal gravity prior to launch through the high acceleration periods associated with the launch, microgravity in orbit, and, in some cases, with the high and normal acceleration of landing. Typically, liquid oxygen and hydrogen are vaporized and then mixed, in controlled quantities and the resulting chemical reaction is use to provide electricity. Because of the high reactivity of both gases, it is desired to mix non-stoichiometric amounts in order to deplete one of the reactants. Because the product is water and the desire to remove the reaction product, the water vapor is condensed and must be removed before any residual reactants are recycled back into the fuel cell. These fuel cells tend to involve flow within micro-channel networks.

Gas evolution within electrochemical batteries is a problem given the explosive nature of the gas that is usually generated, spillage and electrical short circuits caused by displaced electrolyte and blockage of the effective area around the electrodes.

During the early design phases of the space station, considerable effort was looked into using "dynamic" power systems in order to eliminate the need for huge solar arrays by using smaller sized solar concentrators. There were studies regarding the benefit and practicality of using of liquid metal vs. organic fluids as the heat transfer medium and the Rankine vs. Brayton Cycle. Because of the reduction in size and power levels on the space station, as well as concern about two-phase flow in general, it was decided to postpone and, later, cancel the solar dynamic portion of the effort.

Although there are safety concerns about the use of nuclear power in space-based systems, they offer significant benefits. For example, any permanent presence on the lunar surface is going to require some effort in developing a system that can function well in both the 14-day long days and nights. Nuclear power can provide a constant source of power on the lunar surface; whereas solar power would only be available for 14 days and batteries, or some other power storage method, would be required to provide power for the other 14 days of the month. The size of a nuclear-powered spacecraft is much smaller than solar-powered spacecraft since huge solar arrays are not required to gather sunlight. Nuclear power may also be used to superheat propellants in order to achieve additional thrust.

Thermal Management

Thermal management is the transport of heat from one location to another and is usually attained by heating a working fluid both sensibly and by vaporization. This is usually done to cool electronics or other temperature sensitive equipment by maintaining a temperature usually from 0 to 25°C.

There have been two methods for pumping the working fluid through the system: wicks and mechanical pumps. Heat pipes and capillary pumped loops rely on wicks to drive the flow. Unfortunately, they have a limited pressure rise and thus are severely limited by the total fluid transport distance attainable. Mechanical pumped loops can overcome the limited pressure rise of wicking systems, but require either a two phase flow pump, or a phase separator, and given their complexity and number of moving parts, have significant reliability issues. One new concept is the Pulsed Thermal Loop (PTL) which utilizes only a couple of check valves and shutoff valves and can deliver significant pressure rises[4].

Fluid Management

Fluid management is the transfer of fluids, in particular liquids from one location to another. Positioning of the gas ullage within a liquid tank must be accomplished to draw only liquid into the transfer line. Cryogenic and other volatile liquids will vaporize as the liquids encounter warm surfaces and quickly pressurize the receiving tank thus slowing the delivery. In order to prevent this, the vapor needs to be either vented or re-condensed.

Transfer of storable liquids (those at room temperature) can also pose problems because of the desire to minimize gas bubble ingestion into the liquid transfer line from the supply tank. Furthermore, bubble-free filling of the receiving tank and positioning of the gas-liquid interface in a desired location are other technical concerns.

Mass gauging to assess the liquid level within tanks need to account for the placement of the two phases within the tank and is one means of detecting leakage of fluid. Methods of clean-up and recovery of leaking fluid is required not only for reasons of safety, but also maintaining adequate supplies of liquid during long duration space missions.

Propellant Management

Propellant management is for the most part, a specialized class of fluid management. For the cryogenic propellants in particular, line diameters may be as large as 30 cm. Some additional applications including cooling engine nozzles by vaporizing propellant in tubing surrounding the nozzle prior to the propellant entering the combustion chamber. One futuristic concept that was examined during the space station development was to use water-based resistojets. Waste water would be vaporized by heating a packed bed and flowing the water through it. The merit of the idea was to reduce the amount of propellant that was annually launched to the space station for re-boosting the station's orbit by having this capability of disposing of the waste water.

Environment Control and Life Support Systems

The primary focus of ECLSS is to control the humidity and temperature within the environments of a crewed vehicle for reasons of comfort and safety. Because of desire for long duration missions and recycling resources , there have been additional efforts that require an understanding of two phase flows. One concept is to growing plants for food, consumption of carbon dioxide and oxygen production. As such fluid management within the "soil" is required to supply the plants with water and nutrients. Another concept is the waste water bioreactor which consumes waste water containing soap, urine and other wastes into potable water via packed bed reactor with an immobilized bacteria. Mixing the gas and water to promote the dissolution of the oxygen, flow distribution with the packed bed so that the bacteria receive a sufficient amount of waste water and oxygen, and gas-liquid separation are items that need to be addressed.

NASA Enterprises and Missions

NASA has four main "enterprises" or strategic thrusts: aeronautics, earth science or Mission to Planet Earth, Space Science and the Human Exploration of Space (HEDS) which includes life and microgravity science research. Both the earth science and space science require two-phase technologies to provide cooling for electronics and infrared sensors as well as for propellant management. The HEDS Enterprise currently has two major development efforts: the International Space Station in the near-term and a manned mission to Mars.

One of the major objectives for the space station include studying long-term effects of prolonged exposure to microgravity on humans and to test technologies for their suitability and reliability for the long missions to Mars. The requirements for a Mars mission are driven by the long duration (at least six months one way), include recycling resources such as air and water and "living off the land" or in-situ resource utilization, particularly when operations begin on the Martian surface, and have a preeminent driving force of minimizing risk of failure

Mars has a gravitational acceleration of 0.38 g's as opposed to Earth's 1.0 g's. Whereas the direction of the flow with respect to the direction of the gravitational vector in microgravity is irrelevant, this can not be in a Martian gravity environment. There will be buoyancy-related issues that will not be as strong as on earth because they will be tempered by viscous, surface tension, and inertial effects that dominate the microgravity flows. Therefore, scaling with respect to gravity needs to be verified.

While there will be some challenges with regards to gas-liquid flows, such as condensation of oxygen into a liquid cryogenic state, most of the two phase issues are for gas-solid or liquid-solid systems. Dust contamination of equipment and suits, in general, is an issue. Although there is very little data concerning the composition of the Martian soil, there are scenarios being developed to extract building materials such as concrete, water and oxygen from the soil, therefore excavation, transport, grinding and chemical processing of the soil. The current plans are to extract oxygen from the carbon dioxide atmosphere through a variety of means[5] including the use of Sabatier/water electrolysis, solid oxide electrolysis and a reverse water gas shift reactor. Not only will there be two phase issues with the propellant production, but each of these processes require power and the generation of the power will surely have the associated two phase flow issues. Finally, the separation of reactants and products from this reaction will require separation of the chemical gas species and this may entail condensation, distillation or other buoyancy-dominated two-phase separation processes.

Funding Opportunities

In Table 1, the NASA Enterprises, the appropriate organization at NASA Headquarters and responsible NASA field center associated with gas-liquid two-phase flow research and applications are listed.

NASA Enterprise	NASA HQ's	NASA Field Center	Location
Space Science	Office of Space Sciences		
Astronomy		Goddard Space Flight Center	Silver Spring, MD
Planetary		Jet Propulsion Lab	Pasedena, CA
Earth Science	Office of Earth Sciences	Goddard Space Flight Center	Silver Spring, MD
Human Exploration and Development of Space			
Space Shuttle	Office of Space Flight	Johnson Space Center	Houston, TX
		Marshall Space Flight Center	Huntsville, AL
Space Station	Office of Space Flight	Johnson Space Center	Houston, TX
		Marshall Space Flight Center	Huntsville, AL
Life Sciences	Office of Life and Microgravity Science and Applications	Johnson Space Center	Houston, TX
		Ames Research Center	San Jose, CA
Microgravity Sciences	Office of Life and Microgravity Science and Applications	Marshall Space Flight Center	Huntsville, AL
		Glenn Research Center	Cleveland, OH

NASA provides funding to study two-phase flows and develop systems through NASA Research Announcements (NRA's) and Announcements of Opportunity (AO's). In general all NRA's are listed at the following web-site http://www.hq.nasa.gov/office/procurement/grants/

However, the Office of Life and Microgravity Science and Applications (OLMSA) lists their specific NRA's at
http://peer1.idi.usra.edu/peer_review/nra/99_HEDS_01.html

The principle discipline in Microgravity Science that provides funding for two-phase flow research is Fluid Physics; however, there may be applicable technology developments for the other disciplines.

Although no date has been announced, there are plans being developed to have an NRA on Advanced Technology Development that would not only cover technologies for microgravity missions but for NASA space missions in general, space science, earth science and human exploration and development of space.

Conclusion:

A reduced gravity environment is a tool that offers the ability to reduce or eliminate the effect of buoyancy on two- phase flows. NASA hopes that the use of this unique tool will lead to a better understanding of two-phase flows, in both normal and reduced gravity, through better understanding of the governing mechanisms and improved modeling. However, this new environment also poses a challenge for many space-based technologies that will either utilize or encounter two-phase flow behavior with a wide range of tube sizes and geometries, from cryogenic liquids to liquid metals, and from flow loops to filling tanks. As a consequence, several questions concerning the feasibility and operability of these technologies need to be addressed.

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