**Title**

Topical: Continuous online measuring, monitoring, and imaging of multiphase flows in micro-gravity using non-invasive, light weight, and low power capacitance based technology.

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# Proposed research area

The proposed research area is to advance capacitance-based measuring, monitoring, and imaging technology and develop application based implementations to assist researchers and industrial users in understanding multiphase flows in space and microgravity environments.

# Need for multiphase flow measuring and monitoring in space

Multiphase flows are all around us on earth and are used in nearly every industrial process that involves mixing, chemical reactions, or transportation of material from one location to another. As we move to space, many of these operations are coming with us and the fluid behaviors of these processes can be radically different in a space/micro-gravity environment. Fluids no longer simply stratify by density, and coalescing forces become much more important in dictating fluid behavior.

In order to adapt these processes for operation in space, there is a lot of research that needs to be done to understand the fluid behaviors and how to take advantage of the natural phenomena that occur in space. New tools and methods are required to measure and monitor these multiphase flows to advance the field of micro-gravity fluid behavior research. Some applications of multiphase flow in space that would benefit from new measuring and monitoring tools/techniques are listed below:

* Phase separators
* Packed bed reactor
* Cryogenic fuel gauges
* Cryogenic fuel transfer
* Combustion
* Biological processes
* Filtration
* Phase change processes

Capacitance based imaging systems [1,2,3,4] play a critical role in the design of vital instruments for space applications [5]. For example, recycling critical fluids requires phase separation and filtration. The design of those instruments is based on the understanding of the hydrodynamics of a phase separator and a packed bed reactor through real-time imaging of the fluid inside. Other uses include custody transfer of fuels in long term space voyages. Such spaceships require refueling from cryogenic fuel stations. Here again, capacitance-based flow measurements can provide real-time measurements of mass flow rates of fuels.

Another major frontier that is yet to be addressed is the imaging of biological processes in a feasible and reliable means. Ground based technologies such as MRI and CT Scans suffer from practical limitations related to size, weight, power consumption, and safety. Capacitance based imaging can be developed to become a viable alternative to those technologies by overcoming their limitations and providing good enough imaging resolution.

# Challenges of measuring and monitoring multiphase flows in space

Due to unique fluid behavior, traditional methods of measuring multiphase flows do not work in space. Many multiphase measurements devices work based on assumptions of stratified fluids and are not applicable in space.

Additionally, space-deployed systems have further requirements for hardware and physical tools. These tools need to survive harsh vibration, shock, and radiation environments as well as meet tight weight and size specifications. Meeting these requirements can require complete redesign of existing solutions and in some cases require going back to more fundamental research to deploy the tool in space.

# Advantages of capacitance-based solutions

Capacitance based technology is a ready candidate for providing solutions to many of the challenges in measuring and monitoring multiphase flows in space[1]. It has already been used to provide the following metrics in varying multiphase flow research and industrial applications across a variety of flow regimes including those that appear in the space environment.

* 3D imaging
* Velocity measurement
* Volume fraction measurement
* Mass flow rate measurement
* Phase distribution monitoring

Capacitance based solutions are a feasible technology to send to space as they are inherently low power, light weight, adaptable, and small profile as sensors can be thin films of electrically conductive material fabricated into tanks, pipes, and other vessels.

# Current technology gaps and focus of research

The primary technology gaps between capacitance-based solutions and their space based applications are twofold: technology adaptations to specific applications and packaging development for space based missions. Over the next decade, funding should be allotted for research to shrink this gap.

## Technology adaptations to specific applications

Capacitance based measuring is an old measurement method that is under utilized in today’s research due to the lack of adaptation to the many possible applications. Capacitance measurement is simple in that only a voltage or current excitation and measurement on two conductive plates is required for operation. This makes it a good candidate for adapting to extreme industrial and research applications such as high temperatures, low temperatures, corrosive environments, and high pressure because conductive plates can be fabricated into a process vessel in a number of ways including printing, painting, milling, fasteners, and adhesives. Printed circuit boards are a very cost-effective way to fabricate capacitance plates with trace lines to connectors for easy connection to signal cables.

While capacitance lends itself to being adapted to these applications, it is not always a straight forward path to design such implementations of the technology and requires a collaboration of a dedicated technology development team and researchers who understand the application intimately. This can be a lengthy process and can require development of new materials, new manufacturing techniques, electronics design, and electronics packaging design.

Additionally, there is evidence that there is much more information embedded in the capacitance signal than traditionally known. Capacitance is a complex signal with both phase and magnitude and can provide information on the conductivity of a phase. This allows capacitance sensing to work with conductive or polar phases such as water, whereas in traditional capacitance methodologies, this is not feasible. Traditional capacitance can also only distinguish between two phases. Recent advancements, however, show promise in being able to distinguish between three phases within a flow. The information embedded in the capacitance signal could be very valuable to researchers studying multiphase flows in general, but especially in space because of the low profile of the imaging version of capacitance technology (ECT, ECVT) compared to MRI, X-ray, or other bulk imaging modalities.

Many of these techniques are still in research and development stages themselves and require more advancement to bring to practical applications. These advancements go hand in hand with the hardware developments for each application. To illustrate the complexity of the work that needs done to bring this simple technology to a deployable state for researchers or industry users and example of a cryogenic application is proposed below.

A cryogenic fuel two phase flow meter implementation would require examination of the application, safety requirements, environmental requirements, and performance requirements. A pressure vessel would need to be designed that allows the capacitance plates to be embedded and still get the signal out to the customer. An electronics system would have to be designed to measure the capacitance on the plates. It would have to be packaged to operate safely in the cryogenic fuel environment. An algorithm would have to be developed to extract the mass flow measurement data from the capacitance data. A communication system would need to be developed to deliver the information to the user. An investigation would need to be done on how cryogenic fluids and low temperature exposure could affect the capacitance in non-linear ways. Then all of this would need to be brought together in a single tool with the resources to manufacture and deliver to a researcher for use in their process in which they may be studying fuel transfer.

## Packaging development for space-based missions

In addition to the gaps listed in the previous section, one major gap for any technology to be deployed in space is packaging and qualifying the technology for space flight. This can be a significant endeavor that requires radiation hardening, design for shock and vibration, communications design, re-packaging to minimize size and weight, thermal management, and other factors that are not concerning for earth deployments. Nevertheless, the size, weight, complexity, and power consumption of a capacitance-based flow meter or imaging tool are significantly less when compared with competing technologies like radiation of nuclear based instruments. The packaging development involves less technical risk and with adequate resources this gap can be bridged.

Furthermore, capacitance-based imaging for biological applications can be developed into a portable of wearable instruments that human travelers can utilize for online monitoring and diagnosis, especially for long duration missions.

# Interested parties

Significant interest for this research has been fielded from multiple sectors of research and industry including NASA Glen, NASA Kennedy, and multiple private sector technology development corporations both large and small.

# References

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