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Fundamental and Applied Microgravity Capillary Flows, Phenomena, and Transport

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Abstract

Shortfalls in our understanding of capillary phenomena are amplified in reduced-gravity environments of space where their impacts occur over truly macroscale length scales many orders of magnitude larger than on earth. Based on practical experience, it can be argued that nearly all fluid systems aboard spacecraft are or become multi-phase capillary fluid systems. This fact has been known to NASA and the aerospace community for many decades, which is why the topic remains the highest priority within the Fluid Physics subcategory of the Physical Sciences. It is both 'enabling' and 'enabled by.'

The Need Repeated

We remain unaccustomed to the behavior of low-g liquids and gases together such that even the most mundane fluids operation on earth cannot be treated as such in space. The routine challenges of space toilets provide a case in point[3,5,13,16].

In total, there is no broader, more important, and perhaps more interesting fluids research field within the fluid physics discipline than capillary flows and phenomena in microgravity. Such flows are vast and include the configuration, stability, and flow of free- and wall-bound liquid surfaces, droplets, bubbles, films, jets, and rivulets. Both fundamental and applied objectives require knowledge of key aspects such as flow regimes, phase separations, phase change, spontaneous migrations, degassing, coalescence (bubble and drops), and said behaviors in the presence of myriad multi-physics effects including fields such as acousto-, magneto-, electro-, thermo-, soluto-, accelero-, chemico-, surfacto-capillary phenomena[21]. High inertia multi-phase flows are also critical to NASA's mission in space, but beyond a certain inertial threshold such flows behave like those on earth and are thus ground testable. It is the small-intermediate-large length scale moderate-to-low-inertia flows that are particularly unearthly because they cannot be ground tested and must rely far more on un-benchmarked numerical modelling or rare low-g experimental evidence. Add to the difficulties the presence of myriad wetting conditions, surface heterogeneity, and geometric complexity it is no wonder that even something as terrestrially simple as watering plants in space has posed serious challenges that persist to this day[19].

The need for an ever-increasing fundamental and applied experiential, theoretical, and numerical knowledge of capillary phenomena is proven by the fact that fluids experiments were of the first, if not the first, experiments performed in space[23]. Fundamental subfields within the capillary discipline include topics such as impacts of the moving contact line, partial wetting, transitional wetting (90°±…), non-wetting, as well as super-hydrophilic and super-hydrophobic wetting and surfaces. Flows in complex geometries including backed beds, filters, porous materials, structures, flexible and hemi-wicking surfaces are frequently routine for systems on earth. But these must become routine for applications in space. Unfortunately, space applications require far greater understanding of capillary fluid phenomena than is currently in hand. Such systems range broadly from the mundane to the high tech, including valves, irregular closed and open conduits, manifolds, expansion, contractions, fittings, condensers, evaporators, reservoirs, accumulators, and many more for myriad process-specific operations such as containment and control for bio-regenerative systems, but also water management for food, hygiene, plant and animal habitats, medical procedures, and experiments of all kinds—BPS and beyond. Capillary systems with ideal wetting and fluid purity such as cryogenic and storable liquid fuels and propellants, thermal fluids in thermal control systems, and others have made significant progress in recent decades. But continued advancement is required to keep pace with new 'green' poorly wetting fuels[20], large tank thermal control and gaging, and large self-gravitating fluid masses with acceleration fields.

The Need Re-Cited

The case for continued fluids research and development has been clearly made via each decadal survey over the last 50 years. The various fluids research sub-topics have also not changed significantly. This does not mean significant progress has not been made. Rather, it proves the need for continued progress in this field for the benefit of NASA and the commercial aerospace community[17]. Special emphasis on critical applications can be made highlighting numerous examples where shortfalls in fundamental understanding or experience led to system failures which have proven costly in crew take and replacement parts, to outright dangerous[17,18]. [Watching Ref. 17 is strongly recommended.]

For example(s), a single bubble lodges in a circular tube preventing the flow of water in the primary hydrolysis oxygen generator[1]. A capillary flow is halted by a 'fitting' deactivating a large thermal control system[2]. Contamination of rotating machinery leads to fouling and failure of the primary waste (water) control system[3-5]. Routine operation of a condensing heat exchanger[6] in a water recovery loop leads to dry out, coating failure, and ejection of liquid droplets into the cabin air stream. Condensate droplets in astronaut backpacks corrupt the output of a CO_2 sensor leading to the premature termination of EVAs[7,8]. A flight experiment is irretrievably ruined at initiation when a fluid interface is destabilized following an initial retraction of a sliding lid[9]. Plant habitats are perpetually foiled by lethal root-water management issues[10]. The list goes on, demonstrating a strong need to address fluids engineering shortfalls in low-gravity environments. Could we assure safe passage to Mars with our present understanding and level of experience? Maybe not, but probably not.

To belabor the point, even such a simple task as fluid volume measurement is complicated by the ever-present effects of wetting, surface tension, and container geometry. For example, NASA, JAXA, and RSA flight surgeons cannot record accurate urine sample volume measurements without consuming unnecessary crew time and ISS resources. For similar reasons, critical space suit liquid cooling water inventories are not known accurately due to contamination from bubbles in flexible bags. In extreme cases, poor fluid system design can lead to disastrous consequences[11], but for the most part, and for life support systems in general, crew time[12-14] is consumed by repair and maintenance of mundane life support equipment to keep operations at acceptable, if not tolerable levels. A perfect example is the approximately 5 hours per month of crew time spent simply bleeding bubbles from Teflon CWC-I and PWR water supply bags[15]. Such conditions are not satisfactory for NASA's near future and longer duration Moon and Mars exploration missions.

From our perspective, the common theme of these problems is a lack of familiarity with large length scale microgravity (aka capillary) fluidic phenomena that precludes robust designs. If future long-term missions are to be successful and efficient, something as mundane as plumbing must be well understood and effectively managed[17]. System level investigations are nearly absent. To quote a recent mid-decadal review[22]:

"The most significant progress expected for applied science research within the fluid mechanics discipline targeting design needs for exploration will most likely come by way of practical stability limits, regime limits, onsets, transitions, and low-g benchmarked numerical methods…It is reasonable to expect significant 'component-level' progress along these lines by the 2024-time frame. However, it is not certain whether such phenomena may be adequately studied at the system level (i.e., entire systems including evaporators, conduits, condensers, filters, valves, manifolds, parallel paths, reservoirs, etc.) and plans do not appear to be in place to pursue such research in the near term. System level stability and interactions are critical to every fluid system aboard spacecraft with special concerns during start-up, shut-down, safing, and transient response to excursions and off-nominal events. Benchmarked methods to model such processes must be developed to reduce risks of advanced system performance at an accelerated pace if hoping to deliver significant design products by 2024. The development of such system level fluid physics experiments will likely require more resources than currently available for this physical sciences subdiscipline."

Summary

Mission critical fundamental and applied experimental, theoretical, and numerical research in the broad field of capillary flow and phenomena continues to define and contribute to the 2020 NASA Technology Taxonomy sections: Propulsion Systems (TX 01), Human Health, Life Support, and Habitation Systems (TX06), and Thermal Management Systems (TX14). Such investigations are both 'enabling to' and 'enabled by' space exploration. Based on the proven track record (i.e., Ref. 17), continued vital investigations in the field of capillarity is the only way to uniquely advance the needed scientific knowledge, meet human and robotic exploration mission needs, and provide the terrestrial benefits that often result from new outer-space research frontiers.

References

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[9]The authors are aware of dozens of experiments investigating interfacial phenomena, phase change heat transfer, crystal growth, bio-reactors, thermocapillary flow, LOC/OOC, droplet deployment, interface oscillations, and capillary thermal devices that have encountered significant fluids difficulties that during the design phases of these experiments appeared for all practical purposes as mundane operations. The troubling fluid phenomena are predominantly uncontrolled bubble/void formation,

irregular capillary flows and wetting issues, and interfacial instabilities. The misleading results of ground or low-g aircraft tests have also contributed to poor performing low-g fluid systems designs.

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[14]NASA JSC STTR 2016 Topic T6.02, Liquid Quantity Sensing Capability, TA6 Human Health, Life Support and Habitation Systems; Flexible space suit Feedwater Supply Assembly (FSA).

[15]On ISS, Teflon-covered water storage bags are either of 22 L CWC-I or 12 L PWR types. If the bags are not de-gassed properly and air bubbles get into the water processor, it can shut the respective systems down and require many hours of ground commanding to get the system working again.

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[18]APS/DFD (2020), The APS Div. of Fluid Dynamics meets annually with thousands of presentations provided covering the most terrestrially relevant topics. Included are many hundreds of papers each year covering topics in capillary phenomena such as drops, bubbles, films, biofluids, biofilms, surface tension effects, self-assembly on surfaces, multiphase flows, instability, CFD, micro-capillarity, nano-capillarity, porous media, wetting, wicking, the moving contact line boundary condition, reacting flows, medical fluids, multi-physics, fundamentals, applications, and more. This level of terrestrial work testifies to the pressing need for advances in the science as well as to the wealth of terrestrial applications of the research.

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