Considerations for Material Properties and Processes in Space and their Impact

Professor Marcello Lappa,
University of Strathclyde, UK

Dr Andrew Kao,
University of Greenwich, UK

Overview

Gravity dominates everything on Earth, from the way life has developed to the way many types of materials are formed. Onboard spacecrafts orbiting the Earth or other vehicles in free-fall conditions; however, the influence gravity is barely felt. In this "microgravity environment", scientists can investigate phenomena, which are impossible on Earth or are masked by the presence of gravity. In this condition various effects are significantly altered, in particular convection, buoyancy, hydrostatic pressure and sedimentation.[26] [27] In this virtual absence of gravity as we know it, therefore, space flight gives scientists a unique opportunity to study various states of matter (solids, liquids and gases), and discern forces and processes that are interwoven or overshadowed in normal gravity. Accordingly, microgravity can be regarded as an important tool for improving our fundamental understanding of several complex phenomena, which are of great interest in several technological fields.

Notably, research conducted in space is also supporting current efforts to identify new principles and strategies for the "active control" of many phenomena or processes. As an example, in such a context, of special interest are the dynamics of the so-called complex fluids, i.e. media characterized by the coexistence of two phases, namely, two immiscible liquids, a liquid and a gas or a liquid and a solid (in the form of dispersed fine particles). These multiphase systems and the related "interfaces" are omnipresent in several fields of engineering (especially materials, chemical, nuclear, pharmaceutical, and food engineering, just to cite a few). UK researchers (e.g., from the University College London and the Universities of Southampton and Strathclyde) are currently involved in relevant international collaborations with ESA, CNES, NASA and even JAXA for the design of new experiments in parabolic flight, in the ISS, and in unmanned orbital vessels to collect new relevant experimental data. Critical knowledge gained from these microgravity experiments is contributing to validate new, more complex models, accelerating the current trend towards predictable and reproducible phenomena, and enabling the development of new "manipulation" strategies or criteria.

Similar concepts also apply to many materials that we use in their final solid state. Before being solid, many of these materials pass through a liquid state and the properties that they display in the final state often depend on the convective phenomena that are established in their liquid state. Whether it is the case of a mould filled with liquid metal to produce a cast component, a permanent joint created by fusion welding between metal plates, a complex component printed from metal powder by laser-based additive manufacturing (3D printing), or a high-quality crystal of a semiconductor or superconductor material being crystallised from a melt, all of these processes depend on a successful solidification step to generate the solid structure from liquid. In the liquid phase, mass and heat transport occur by thermo-solutal convection and/or gravitational separation of the involved phases.

Clarifying the cause-and-effect relationships at the root of these phenomena is key to a full understanding of microstructure development during solidification. During microgravity, the thermo-solutal, buoyancy-driven convection and/or sedimentation phenomena induced by the different density of the involved phases are suppressed and comparison with ground data, enables increased understanding of all these effects. Over the past few decades, UK researchers from the University of Greenwich have actively taken part in relevant ESA activities (e.g., the Peritectic Alloy Rapid Solidification with Electromagnetic Convection – PARSEC - project) and topical teams (e.g. the Solidification of Containerless Undercooled Melts (SOL-EML)). Moreover, researchers from the University of Ulster have already benefitted from microgravity experimentation onboard soundings rockets (MAXUS and TEXUS) and the International Space Station (ISS). The opportunity for the UK materials science sector to utilise the unique microgravity environment to undertake R&D, however, continues to grow, with current and future launch providers (e.g., Virgin Orbit, Lockheed Martin, SpaceForge) and integrated service operators (e.g., Kayser Space, Lodestar Space, Gravitilab) increasing the capacity and availability for payloads.

Along these lines, in addition to the remarkable benefits described above in terms of fundamental knowledge and "know-how", microgravity-based research being conducted in UK is also serving another important objective, that is, enabling the important technological developments required to allow deep space exploration missions and the colonisation of other planets. Many materials used for various applications need to be tested directly in space (e.g., to verify their ability to withstand the adverse effect of radiations or of space debris or other environmental effects), and there are relevant UK national, industrial and academic entities (such as, the National Physical Laboratory – NPL, the Satellite Application

[26] M. Lappa (2009), Thermal Convection: Patterns, Evolution and Stability", 700 pages - John Wiley & Sons, Ltd (2009, Chichester, England).

[27] M. Lappa (2012), Rotating Thermal Flows in Natural and Industrial Processes, 540 pages, John Wiley & Sons, Ltd (2012, Chichester, England).

There are plans to use regolith as a kind of building material for the construction of lunar bases, feedstock for 3D printing or for oxygen extraction. As food and water shall also be produced in situ, engineers are also investigating the possibility to use regolith as a solid-support substrate for plant growth, a source for extraction of essential plant-growth nutrients, a substrate for microbial populations in the degradation of wastes, a source of O2 and H2, which may be used to manufacture water. With increasing commitments from both global governments as well as private companies in the coming decades to colonise space and nearby bodies, there is still critical fundamental R&D to be done and several UK academic entities have already started to deal with such specific aspects (e.g., the University of Cambridge, the University of Surrey and the University of Strathclyde).

Case Experiences

The UK has leading expertise and capabilities covering several of the subjects described above, ranging from the characterization and control of multiphase fluid systems to the production of several inorganic and organic materials, including a number of active related space research projects:

Fundamental studies on multiphase systems and material solidification:

- Researchers at the University of Southampton are carrying out fundamental studies on the stability of the interfaces between miscible fluids in microgravity conditions to achieve long-term control of multiphase systems and management of interfacial heat and mass transfer, needed for the development of new chemical engineering and materials processing technologies in space.
- Researchers at the University of Strathclyde are looking at the potential use in space of ferrofluids, i.e., a class of smart materials composed of magnetic particles dispersed in a conventional carrier liquid, which can be forced to target desired locations using magnetism and may therefore lead to innovative lab-on-a-chip devices, microrobots technologies, and even new methods to delivery drugs inside the human body.
- Researchers in the Department of Civil, Environmental and Geomatic Engineering at University College London are currently involved in two international collaborations (CNES-JAXA and ESA-NASA) for the design of experiments in parabolic flight, in the ISS, and in unmanned orbital vessels to collect new experimental data on fire ignition mechanisms, flame spread, and particulate/smoke emission over a range of materials. These will be used to develop new theoretical models and improve existing space fire safety systems.

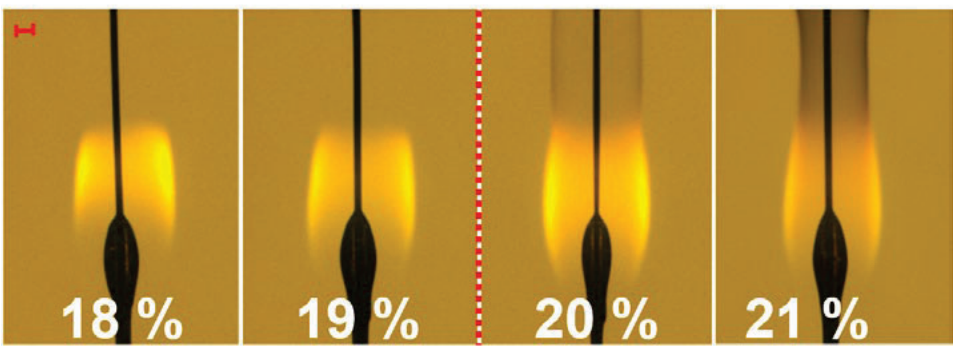

Figure xii. Flames spreading over electrical wires in microgravity at standard pressure for a range of oxygen contents. As oxygen content is increased, the flame starts to emit thick smoke.

- Researchers at the Department of Bioengineering of the University College London are interested in exploring the opportunities offered by research conducted in microgravity to optimise 3D bioprinting and develop tissue models that would otherwise be impossible to manufacture on Earth.
- Researchers at the University of Ulster have benefitted from microgravity experimentation onboard soundings rockets (MAXUS and TEXUS) and the International Space Station (ISS), which they conducted to investigate metal alloy microstructure development. Through comparison with terrestrial results, this endeavour has led to the elaboration of a new theoretical model to account for the impact of thermo-solutal convection.
- Yet, with regard to the solidification of metal alloys and the need to understand how convective current being present in the fluid phase can influence their final properties, researchers at the University of Greenwich have derived a novel approach to measure precisely the thermophysical properties of these alloys in the fluid phase through the use of contactless levitating devices that can imitate microgravity conditions.
- The UK-based company “Gravitilab Aerospace Services” has been leveraging, in collaboration with the University of Manchester, its suborbital rockets (such as the ISAAC) and remotely controlled miniaturised microgravity platforms to investigate the conditions leading to “high entropic inorganic materials” in space. These are a new class of substances with increased disorder at a microscopic (atomic) level and are currently being considered as candidates for a range of different applications in physics (superconductors, optoelectronic materials), materials science (battery materials, thermoelectric materials, nanomaterials), and chemistry (catalysis, electrocatalysis).
- Engineers at Lodestar Space aim to develop Directed Energy Deposition (DED) techniques for additive manufacturing, welding, and repair within the space environment. These methods, which rely on a plasma arc, a laser, or an electron beam, can deposit material on a substrate within the microgravity environment in a safer way with respect to other powder-based techniques. Engineers have already conducted research into DED within space, specifically for constructing improved efficacy micrometeorite and orbital debris shielding.
- At British Telecommunications, engineers aim to develop technologies which can increase the efficiency of electronic components through the integration of high-quality, space-grown heatsink substrates with embedded microfluidic cooling. This technology will lead to unprecedented high power efficient GaN (gallium nitride) RF devices for high frequency 5G “terrestrial” communications.
- Researchers in the Department of Materials Science and Metallurgy of the University of Cambridge are considering silicon carbide (SiC) and gallium nitride (GaN) as Wide-bandgap semiconductors for use in specific space-based applications, e.g., for the development of transistors to be used inside interstellar probes or low-earth orbit satellites. They are therefore interested in exploring the electrical activity of these materials and their properties (such as the radiation immunity) in the space environment.

Supporting Space Exploration:

To support space exploration there are a number of other translational capabilities from research active groups that could address future exploration needs, but also drive further fundamental R&D terrestrially:

- Researchers at the National Physical Laboratory (NPL) have considerable experience in high precision measurement systems and methods for manufacturing. They can deliver detailed, independent analysis to accelerate development, increase performance and quality, and identify failure modes of many types of materials, products or structures. This may in time enable analogous capabilities to support in-space manufacturing technologies, especially those relying on the in-situ utilisation of locally available materials such as the Lunar and Martian regoliths.
- The company Yoursciencetech Ltd (Surrey), together with researchers from the University of Cambridge and in collaboration with ESA, have recently elaborated an innovative approach for the production of regolith-based aerogels that could be built directly in-situ with a minimal or reduced provision of Earth materials.
- The University of Strathclyde is collaborating with ESA in the framework of an OSIP project to explore the potential application of high-frequency vibrations as a new method to force lunar regolith, which is typically characterized by strong internal inter-particle friction, to behave as a ‘fluid’, thereby making its transportation and utilization in the context of several applications much easier.

- In partnership with ESA three UK industry specialists (Kayser Space ltd, Cellular Agriculture Ltd, and Campden BRI, with relevant skills in Cellular Agriculture, Space and Food and Drink, respectively), have assessed the viability of cellular agriculture and through modelling, sized a system utilizing a hollow fibre bioreactor capable of providing the nutritional protein requirements of a crew on long duration space missions.
- The University of Surrey has extensive experience in selecting and modifying materials and coatings for flight hardware destined for particularly challenging environments, such as polymer membranes, thin composites, and inflatables for use in drag-deorbiting from low Earth orbit. More recently this work has broadened to include parallel research on the manufacture and performance of metal matrix composites.
- Similarly, Researchers at Imperial College London are currently developing advanced new materials and surface treatments for hypersonic applications. This is being achieved through a multidisciplinary approach that relies on the ability to predict the severe conditions established during transitional and turbulent hypersonic flows and test experimentally the ability of metal alloys, ceramics of various types and their composites to withstand such conditions.
- Yet, with regard to the development of materials that can cope with extreme conditions in the context of space exploration, the Satellite Applications Catapult has recently exploited its in-house facilities to fabricate a variety of research and development thrust chambers utilizing Inconel 718, a nickel superalloy, which retains exceptional strength and corrosion resistance at high temperatures. This research, which has been funded through the Innovate UK Edge Program, relies on recent advancements in additive manufacturing methods.

Overcoming Challenges

Within the contributions there were a number of challenges critically discussed, which could be used for the definition of new opportunities, the implementation of adequate “countermeasures” and new strategies for producing “impact”.

Growing access: A number of groups highlighted that currently there are barriers to the development of this research in UK especially because of the lack of access to the required environmental conditions. This is in part due to the current excessive focus on orbital missions (especially experimentation on board the ISS), which have long lead times and huge costs and legislations associated with them. Improving access to research in microgravity through suborbital missions might be regarded as a viable option for many research institutions, however access is limited due to lack of services within the UK.

Creating relevant networks: So far, the USA, Japan and other European countries such as Germany, Belgium and France have dominated microgravity research targeting space-based electronics and various other materials or processes. However, UK academia has a strong history in these fields, especially with regard to the exploitation of various multiphase systems and the production of inorganic materials of great technological value and interest such as metal alloys and semiconductor substances, with activities led by Bristol, Cambridge, Sheffield, Strathclyde, Glasgow, Cardiff, and other universities. As an example, the recent ‘National Semiconductor Strategy’ roadmap pointed out, know-how for semiconductor design and high-throughput manufacturing already exists in companies clustered throughout the UK. Hence, as the race-to-space intensifies, strategically coordinated industry-academia efforts are needed to fill the gap with other countries.

Driving Research and innovation

There are many opportunities for research and innovation in space, including studying the effects of gravity-independent forces (and, indirectly, of gravity) on the properties and behaviour of many fluid and solid “terrestrial systems”, and developing new manipulation strategies and materials in space (as well as new in lab-on-a-chip devices and microrobots technologies) with properties or functionalities that cannot be obtained in normal gravity conditions. Moreover, from an ISRU (in-situ resource utilisation) standpoint, the development of new and improved materials is the driving force behind the definition of novel closed-loop processing cycles that address the paucity of accessible resources in space. These simple arguments clearly indicate that the unique environment of space offers many opportunities to create new “principles”, technologies and materials that can benefit both space exploration and life on Earth. Because of this breadth, contributors highlight the need for dedicated funding, facilitation mechanisms to access the microgravity environment and the creation of new and more extended links among researchers, manufacturers, and space agencies (to establish comprehensive guidelines, standards, and testing protocols).