

Topical: Challenges and Research Needs for Micro- and Partial-Gravity Fires

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Introduction

Spacecraft fire safety has always been an essential component for any successful space mission. The importance increases exponentially for longer duration missions, such as the upcoming Artemis missions to the Moon and the “next giant leap” to Mars. If fire occurs in the spacecraft, terrestrial help for recovery may not be possible. Crew members have limited options to suppress and escape the fires and the associated vitiated atmosphere. The partial gravity conditions after landing on the Moon or Mars, as well as the high oxygen concentration proposed for the Lunar habitat, bring in additional challenges for spacecraft fire safety. To ensure safety and mission success, there is an urgent need to advance the knowledge of fire behavior in micro and partial gravity. This will also improve the understanding of how buoyancy flow plays a role in fire behavior, leading to a more complete theory of fire dynamics for Earth applications.

Fire is a multi-physics process which includes fluid dynamics, thermal and species diffusion, gas radiation, chemical kinetics, solid decomposition, and buoyancy effects. Each fire scenario warrants extensive fundamental research as well as practical standardized testing procedures. On Earth, this burning process is always accompanied by buoyant flow, which is caused by a temperature-driven density gradient in a gravity field. The buoyant flow accelerates as the flame grows and entrains an increasing volume of fresh air. In other words, this gravity-induced buoyant flow increases with the fire size.

For solid materials, the geometry and orientation of the burning surface with respect to gravity determines the flame growth, and, due to its acceleratory nature on Earth, the case of upward spreading flames is usually considered the most dangerous configuration¹. Early theories predicted that the controlling mechanism for this type of burning scenario is the heat transfer from the flame to the unburned solid fuel in the preheat region ahead of the burning and to the pyrolysis regions¹⁻³. When convection dominates, the buoyancy flow has a significant effect on both the flame length and the flame spread rate. For upward flame spread, the flame spread rate is found to be proportional to the pyrolysis/flame length⁴ and most experiments show a continuously growing process^{2,5} (with exceptions such as for sufficiently narrow and thermally thin samples^{6,7}, when convective or radiative heat losses become a limiting factor⁶, and for very long samples in reduced pressure environments⁸). With practical sample lengths (< 1m), the flame length and spread rate typically increase throughout the experiments.

Multiple phenomena must be fully understood to ensure the crew safety and mission success as NASA and other explorers venture out into the solar system. The fire dynamics in both microgravity and partial gravity must be fully understood to encompass fires that could be sustained during all phases of the mission profile. Fundamental study of the thermal fluid process and chemical kinetics that are illuminated by microgravity will also further advance predictive tools to determine the fire growth and spread for both space and Earth applications. Understanding the dominant forces in a particular fire and being able to ignore other phenomena that least affect the fire can greatly increase the speed and accuracy of modeling and improve fire safety. *Any incremental changes in how microgravity and partial gravity flames are understood will lead to transformative practices in fire safety* (e.g., material selection, oxygen limits, sensing, extinguishing, post-fire cleanup).

Flame spread over solid materials in microgravity

In microgravity, the flow from buoyancy is essentially eliminated, and without an external flow, molecular diffusion controls the mixing of fuel and oxidizer. Research has indicated that solid and gaseous fuels can burn in quiescent microgravity⁹⁻¹¹, especially in enhanced oxygen

environments. This quiescent environment is extremely important for studying the chemical and heating processes without the influence of buoyancy. However, from a fire safety point of view, this configuration does not necessarily represent the worst burning scenario due to the relatively slow flame growth, at least for the oxygen concentrations proposed for the Lunar missions. The heating, ventilation, and air conditioning (HVAC) systems onboard space vehicles generate a low speed forced flow ($\sim 10\text{-}20$ cm/s), which can bring in fresh oxidizer to the combustion zone when a fire occurs. In the past few decades, research has been carried out to understand how materials burn in microgravity in low-speed flows. These include experiments using drop towers¹²⁻¹⁶, parabolic flight¹⁷⁻¹⁹, sounding rockets²⁰, space vehicles²¹⁻²³, and the International Space Station (ISS)²⁴⁻²⁷. For flame spread in low-speed forced flows, experiments showed that flames eventually reach a steady spreading state with a constant flame length²⁸⁻³⁰. For thin samples, the flame spread rate is controlled by the burnout of the solid sample²⁸. For thick samples that do not burn out, the mechanism for a limiting length to be achieved is the balance between heat input from the flame and heat loss from the solid surface in the preheat region²⁸. The steady flame spread rate was shown to be a function of forced flow velocity^{13,22,25}, ambient pressure¹³, oxygen percentage^{3,13,25}, flow confinement^{26,27}, sample thickness¹⁵, and sample arrangement (e.g., discrete patterns¹⁶).

Some studies focused on characterizing the extinction limits of flame spread in terms of ambient oxygen percentage and flow velocity^{12,17,25,31}. The extinction (or the flammability) boundary consists of a low-velocity quenching limit and a high-velocity blowoff limit³². The quenching limit is a condition at which the rate of heat generation during combustion becomes comparable to the heat loss (e.g., radiative loss on the sample surface, radiative and conductive heat loss from the flame³³). The blowoff limit is due to insufficient residence time of the reactants (the residence time is smaller than the reaction time i.e., low Damkohler number) in the flame anchor zone. As the oxygen percentage increases, the low-velocity quenching limit decreases and the high-velocity blowoff limit increases³⁴. At a given ambient oxygen level, there exists an optimal flow rate for flame spread over a thick fuel.

While previous studies provided abundant data, the majority of the microgravity tests have focused on idealized fuels (PMMA, cellulose-based materials). Practical materials that have non-ideal burning behaviors (such as melting, intumescence, thick char layers, or a combination of these burning behaviors) need to be studied to better understand how to mitigate fires in spacecraft. Another topic that is under-studied is the smoke release in fires. In microgravity, the increased residence time modifies the radiative structure of the flame, supporting local extinction of the flame and the massive release of smoke^{35,36}, which is a major issue in the enclosed environment of a spacecraft. Further studying of the relationship between fire characteristics and environmental conditions (e.g., oxygen, pressure, flow speed, and confined conditions) especially for non-idealized materials that are used in space application (e.g., Nomex), will ensure best practices for preventing, identifying, and extinguishing spacecraft fires.

Flame spread over solid materials in partial gravity

In partial gravity, the buoyancy flow is expected to be weaker than that on Earth, leading to smaller convective heat loss and a longer residence time of reactants in the flame stabilization zone during flame spread. These may imply that a material is combustible in a wider range of oxygen and pressure in partial gravity than in normal gravity. The limited available experimental data obtained at different gravity levels suggest a direct proportionality between flame spread rate and gravity in the upward configuration for very thin fuels¹⁸. The proportionality depended also on sample width and ambient pressure. On the other hand, downward spreading flames showed a non-

monotonic behavior with gravity, which was attributed to the competition between chemical kinetics and radiative losses.

Current methods for materials selection for use in space vehicles rely on ground tests in Earth gravity (e.g., NASA 6001 tests). However, the different gravity levels between ground tests and space missions can result in unexpected fire behaviors. For instance, the study of extinction limits as a function of gravity has shown that combustion could be sustained at partial gravity levels, while extinction of the same solid materials occurred at both micro- and normal gravity. *Fire behavior in partial gravity (e.g., on Moon and Mars) cannot be expected to be interpolated between the data obtained in normal and microgravity conditions* (which themselves are not yet fully understood). In addition, the proposed atmosphere for habitable structures in future space missions requires an oxygen concentration higher than sea-level conditions and at a reduced pressure to lower the preparation time for Extravehicular Activities (EVA)³⁷. The Lunar modules are expected to have an oxygen concentration of 34% and a pressure of 56.5 kPa and the Lunar Gateway is expected to have an oxygen concentration of 26.5% and a pressure of 73.5 kPa. Despite the reduced ambient pressure which can slow down the flame chemical kinetics and increase its heat losses³⁸, ground based experiments of upward flame spread in Normoxic conditions have shown higher flammability, proportional to the oxygen concentrations, even for fire resistant fabric such as Nomex³⁹⁻⁴¹.

Lastly, scales and confined conditions in standard tests and previous research are very different from realistic spacecraft fire scales. It is uncertain if the knowledge gained is applicable for realistic fire scenarios and for future space missions. To fill these knowledge gaps, in the next decade we propose to focus on: 1) advancing ***fire dynamics in micro and partial gravity***, and 2) developing ***reliable predictive tools*** for fire in space. Such tools include dimension modeling, numerical modeling, and machine learning models.

Scale Modeling

Scale modeling and its fire applications were discussed as early as the 1960s⁴²⁻⁴⁴. Williams identified 29 dimensionless groups constructed from the physical quantities that describe a fire system⁴⁴. Assumption here is that fire phenomena in different gravity fields can be correlated (at least partially) by preserving some of the dimensionless groups.

The complexity of combustion renders complete modeling practically impossible. Successful fire modeling requires identifying dominant invariant groups and deliberately ignoring some known phenomena that are deemed to least affect the fire under the scenario of interest. This approach is called partial modeling and has been successful in yielding empirical equations for various fire systems. For example, many studies employ Froude modeling where the dimensionless group gL/u^2 is kept constant. This approach relates small and full-scale fires through the buoyancy flow term u . Rich data for empirical equations/correlations exists in literature for various fire scenarios⁴⁵. Some studies apply pressure modeling where P^2L^3 is kept constant^{46,47}. The concept is to replicate buoyancy flows encountered in real fires by controlling density (inversely proportional to pressure in the ideal gas approximation) in reduced-scale fire tests. This partial modeling technique is based on the assumption that, compared to dimensionless groups for buoyancy and viscosity, other dimensionless groups that contain density terms are insignificant.

Another possible approach is to use reduced pressure, and consequently reduced density, to reproduce the burning characteristics observed in partial and microgravity conditions. As the pressure is reduced, flames tend to move away from the fuel surface and the boundary layer along the solid fuel becomes thicker. Furthermore, this behavior causes a reduced heating of the fuel surface by the flame, which results in lower spread rate and flame length. Thus, the effect of

reducing the ambient pressure has similar consequences as reducing the buoyant flow velocity in low gravity. Previous experiments suggest that reduced pressures ranging between 20-40 kPa may be able to simulate flames in microgravity in terms of flame spread rate and flame length^{48,49}, at least for thin combustible materials. Furthermore, models involving a constant Grashof number ($P^2g \sim \text{constant}$) have been successful in correlating partial gravity results⁵⁰. However, there are some limitations to the comparison between low gravity and low pressure, especially since pressure showed a significant effect on flame spread even in the absence of buoyant flows¹³. Moreover, pressure and gravity affect the laminar to turbulent transition of the flame, with implications on the heat released by the flame⁵¹. Numerical studies and scaling analyses highlighted the importance of radiation losses in reduced pressure environments^{32,38,52}. At the same time, diffusion processes become more important because of the lower molecular density. This, in combination with different heating mechanisms and pressure effects on chemical kinetics, can change the flame structure⁵³⁻⁵⁵.

Considering the multi-physics nature of fires, several aspects of the fire behavior (laminar vs turbulent flame, soot formation, thermal and chemical processes) are affected by the ambient conditions in different ways, depending on the specific burning configuration. Long-term and realistic experiments in partial gravity will be required to develop robust scale models of fires and to examine the validity of existing models. A successful scale modeling approach will allow the design of new flammability tests for future space exploration.

Comprehensive Database and Machine Learning

Several combustion and fire experiments from previous NASA investigations have been added in recent years to the Physical Sciences Informatics (PSI) repository. On the PSI website, researchers can find experimental data along with detailed information for each investigation (e.g., ambient conditions, visual and thermal images and videos). Such a database is extremely valuable to transfer past knowledge and accomplishments to new researchers, as well as to validate theoretical and numerical models. Furthermore, additional information could be extrapolated from previous experiments with new technological advancement (e.g., image analysis techniques, which drastically improved over the last two decades), or simply be used differently to answer additional questions. However, the current version of the PSI is far from completion. Combustion investigations before the 2000s are missing. A more comprehensive database, in addition to the published data in the literature, could allow more researchers to access the limited low gravity experiments, and validate models with a larger amount of results. A large dataset would also open the possibility of using “new” optimization techniques such as machine learning algorithms. Genetic algorithms and neural networks have already been used to better understand some aspects of combustion such as the flammability of acrylic materials⁵⁶, and the chemical kinetics of cellulosic fuels⁵⁷. However, the applications to microgravity are rare and require an intense literature review of the available data⁵⁸. Machine learning models with input such as ambient conditions and gravity level, could provide additional and powerful tools to study material flammability and predict the fire behavior for Lunar and Martian gravity levels, providing invaluable insights driving the design of future experiments.

Experimental Capabilities

While many microgravity fire experiments exist, diagnostics were limited. For example, most of the past experiments relied on camera images for detecting the flame regions. However, these images pertained to the camera capabilities and settings and by no means fully resolved the flame structure. Improvements have been made to the optical diagnostics capabilities to probe the radiative

structure of the flame. However, such development is limited to specific axisymmetric configurations^{59,60}. These limitation prevents direct comparisons between different experiments. Measurement of low-speed flow in-situ in microgravity is another challenge. Without such data, the flame structure cannot be fully resolved. Novel approaches and advanced diagnostics are needed for a more comprehensive understanding of the underlying physics of the studied fire phenomenon.

Compared to microgravity, facilities for partial gravity are very limited. Parabolic flights have been used to achieve Lunar and Martian gravities^{17,18}. However, the test duration is limited to 20-30s and residual jitters from the plane trajectory and vibrations are inevitable. A Centrifuge operated in a microgravity facility (e.g., drop tower, sounding rockets, orbiting space vehicle) can also provide artificial partial gravity (through the centrifugal force). Currently, the only partial gravity centrifuge facility is at the Zero Gravity Research Facility (the 5.18s drop tower) at NASA Glenn Research Center. Consequently, the *dimension* and *duration* are limited to the drop tower capabilities. The Coriolis effect and gravity gradient present additional challenges. For burning experiments using a centrifuge facility, when hot combusting gases “rise” toward the rotating center, it experiences a decreased centrifugal acceleration and a tangential force. Novel experiment design will be needed to mitigate the Coriolis effect.

Conclusions and Recommendations

Future studies in micro and partial gravity flames are vital to ensure crew and mission safety in a wide variety of potential fire scenarios. Research recommendations include the following.

1. **Microgravity fire science.** Studying fire behaviors and their dependencies on ambient pressure, oxygen, and flow for *practical (non-idealized) materials* would lead to the best practices for preventing and minimizing risks for spacecraft fires.

2. **Partial gravity fire science.** Due to longer residence times materials are likely more flammable in partial gravity, giving the need to study flame spread in Lunar and Martian gravity. *Combination of experiments and numerical simulations* will not only reduce cost but also allow each parameter to be studied independently and systematically⁶¹⁻⁶⁴. This will lead to informed design of fire detection systems, mitigation strategies to stop flame spread and prevent flashover in Lunar habitats, fire extinguishment, and mission-preserving post-fire cleanup strategies.

3. **Scale modeling in partial and microgravity flames.** Studies are needed in scale (or dimension) modeling with emphasis in gravity and buoyancy effects on fires. The identification of dominant non-dimensional physics parameters will not only be a significant advancement of fire science but also enable simpler and more efficient computational models. Ultimately, this leads to robust, efficient, and realizable predictive tools for fires in space and Earth applications.

4. **Comprehensive fire database.** Such a database would accelerate model and theory development, as well as allowing the application of machine learning techniques that could lead to transformative discoveries in combustion and fire science.

5. **New platforms and techniques for partial gravity experiments.** Upgrading the Zero Gravity Research Facility for partial gravity testing, in addition to parabolic flights, could be used to create new standardized flammability tests. It will also create an *affordable* platform, accessible to the scientific community. This will enable a wide range of research topics, facilitate collaborations across universities, industries, and national labs, and provide training opportunities for college and graduate students. Ultimately, long-duration experiments will be required to validate fire models and suppression techniques, and the Lunar environment could offer this possibility. Novel in-situ diagnostics are also warranted to resolve the flame structure and temperature profiles and to achieve a complete understanding of the fire dynamics.

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