



Basic and applied researches in microgravity / Recherches fondamentales et appliquées en microgravité Combustion in microgravity: The French contribution



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ABSTRACT

Microgravity (drop towers, parabolic flights, sounding rockets and space stations) are particularly relevant to combustion problems given that they show high-density gradients and in many cases weak forced convection. For some configurations where buoyancy forces result in complex flow fields, microgravity leads to ideal conditions that correspond closely to canonical problems, e.g., combustion of a spherical droplet in a far-field still atmosphere, Emmons' problem for flame spreading over a solid flat plate, deflagration waves, etc. A comprehensive chronological review on the many combustion studies in microgravity was written first by Law and Faeth (1994) and then by F.A. Williams (1995). Later on, new recommendations for research directions have been delivered. In France, research has been managed and supported by CNES and CNRS since the creation of the microgravity research group in 1992. At this time, microgravity research and future activities contemplated the following:

- Droplets: the " D^2 law" has been well verified and high-pressure behavior of droplet combustion has been assessed. The studies must be extended in two main directions: vaporization in mixtures near the critical line and collective effects in dense sprays.
- Flame spread: experiments observed blue flames governed by diffusion that are in accordance with Emmons' theory. Convection-dominated flames showed significant departures from the theory. Some theoretical assumptions appeared controversial and it was noted that radiation effects must be considered, especially when regarding the role of soot production in quenching.
- Heterogeneous flames: two studies are in progress, one in Poitiers and the other in Marseilles, about flame/suspension interactions.
- Premixed and triple flames: the knowledge still needs to be complemented. Triple flames must continue to be studied and understanding of "flame balls" still needs to be addressed.

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1. The relevance of microgravity

A very low gravity provides ideal conditions for some experimental configurations that may allow the associated fluid mechanics problems to be solved. The effects of gravity are negligible if the fluid is almost incompressible, or if forced convection is very large compared to natural convection.

However, in some situations, the effects of gravity cannot be neglected, e.g., when the density gradients are important and/or forced convection is moderate or weak. These conditions are common for reacting flows. The importance of natural convection is often assessed by using the Grashof number [1]:

$$Gr = \Delta\rho g L^3 / \nu^2$$

For a reacting flow, $\Delta\rho$ is the local difference of density ($\Delta\rho = \rho - \rho_\infty$, where ρ_∞ is the density of the surrounding fluid far away from the combustion zone and ρ the density in the combustion zone), g the acceleration of gravity, L a characteristic length, and ν the kinematic viscosity. The Grashof number compares the effects of buoyancy, which is the source of natural convection, to the strength of viscous friction. We can obtain this dimensionless number by writing the momentum equation, with p' for the deviation from the hydrostatic equilibrium pressure, \vec{U} and $d\vec{U}/dt$ for the local velocity and acceleration and μ for the dynamic viscosity, $\mu = \rho\nu$.

The speed resulting from buoyancy is easily scaled using the following approximation:

$$\rho U \partial U / \partial x \cong g \Delta\rho \Rightarrow \rho U^2 / L \cong g \Delta\rho \Rightarrow U \cong \sqrt{L g \Delta\rho / \rho}$$

where the resulting Reynolds number is:

$$Re = UL/\nu = \sqrt{gL^3 \Delta\rho / \rho \nu^2} = \sqrt{Gr}$$

When the Grashof number is of order 1 or greater than 1, it is no longer possible to ignore natural convection. This usually happens in diffusion and premixed flames. As a result, multiple studies have been conducted in France and worldwide in microgravity to analyze these flames away from the complications induced by buoyancy. These studies aimed to a better understanding of specific phenomena such as disturbances occurring under normal gravity conditions, e.g., flame flickering, or as a means to explore, in an idealized environment, the fundamental combustion processes. This is the case of droplet studies relevant to chemical space propulsion systems and engines for various vehicles. A final illustration corresponds to studies aiming at the control of fire safety in manned spacecraft, in particular the study of flammability and combustion of materials in microgravity.

2. A brief history

2.1. Pioneering works

According to a report by F.A. Williams [2] to the “Grand Jury” of ELGRA (European Low Gravity Association), the first studies on the effect of gravity on combustion processes have focused on the flammability limits of premixed flames propagating upwards or downwards [3]. Later on, Kumagai et al. [4] studied droplets burning in free fall for half a second and provided with results that have long remained the only ones available, confirming the “ D^2 law” whose theoretical derivation is attributed to Godsave [5] and Spalding [6]. Kimzey [7] highlighted the specific behavior that a fire exhibits in a spacecraft. Cochran [8] investigated diffusion flames in drop tower. Pelce and Clavin [9] theoretically determine the effect of acceleration on premixed flames. Ronney [10] studied the ignition and extinguishment of non-buoyant flames.

In 1984, a call by the European Space Agency for microgravity projects had a stimulating effect all over Europe, and especially in France, where the “Centre national d'études spatiales” (CNES) [11] supported several initiatives. Among these, the following ones tackled combustion issues.

- In 1987, a team lead by R. Prud'homme in Meudon (France) investigated the problem of flickering of premixed Bunsen flames [12] in parabolic flights and in centrifuge facility, while Gökalp's team in Orléans (France) studied the vaporization and combustion of droplets in parabolic flights [13]. Simultaneously, Carleton and Weinberg, in the United Kingdom, assessed the effect of an electric field on a candle flame [14].
- In 1988, flame spread established in microgravity over flat and cylindrical samples was investigated by Tarifa et al. in Spain [15].
- In 1990, Choi et al. (in the USA) studied the slow burning of droplets in microgravity [16].

2.2. French research structures

In the year 1991, CNES held a *prospective seminar* in Aix-en-Provence [17] that directed future French activities in microgravity. This meeting emphasized the need for the study of droplet combustion, and in particular encouraged projects that mixed combustion and critical phenomena. Fire safety aboard orbital stations and flammability of materials was also

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