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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 $\mathrm{d}\vec{U}/\mathrm{d}t$ 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:

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

where the resulting Reynolds number is:

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

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 specified as an area of interest. These outputs supported the formation of a Research Group (GDR) jointly supported by CNES and CNRS on Fluids in Microgravity.

The GDR 1028 "*Fluid mechanics and transport phenomena in microgravity*" (Fμg) was created in January 1992. Among the constituting teams, three were concerned by combustion:

- *Combustion and turbulence* (LCSR, Orléans), led by I. Gökalp,
- *Combustion, reactive fluids* (Aérothermique, Meudon), led by R. Prud'homme,
- *Physical Chemistry of Combustion* (LCD, Poitiers), led by P. Joulain.

This research continued its evolution from 1996 to 1999 to the GDR-PRC 1185 "Critical phenomena, chemical reactions and heterogeneous media in microgravity". The GDR added a fourth combustion team working on *Supercritical combustion* (IRPHE, Marseilles), led by P. Haldenwang and C. Nicoli.

The Research Group 2258 "*Transport phenomena and phase transitions in microgravity*" followed the previous one from 2000 to 2004. In addition to the inclusion of physicists investigating materials growth, a new team joined the group. This new team investigated the *spread of flame in suspensions* (LCD, Poitiers) and was led by B. Veyssière.

Since 2005, the Research Group 2799 "*Fundamental and Applied Microgravity*" (MFA) continued filling the microgravity research area, holding regular meetings and seminars. Research topics of the combustion teams have continued to evolve as it can be seen in the minutes of the seminar held in 2009 by CNES for the preparation of a scientific roadmap for the field of material sciences [18]:

> "Combustion is also an area where compressible reactive phases benefit from microgravity studies to reveal mechanisms and isolate basic behaviors that feed more accurate models. Several areas have been cleared in recent years. The first involves the spray mist (CNRS Orléans, C. Chauveau), which has been modeled by drops interacting regularly spaced on carrier fibers. The interaction in the absence of convection is sufficient to alter the rate of vaporization. A second line developed in Poitiers (CNRS, B. Veyssière) relates to the combustion of solid particles by controlling the dispersion of particles, thanks to sedimentation reduction. Effective diagnoses have been implemented in both the ground and in parabolic flight. The team of P. Haldenwang (Marseilles University) developed a model adapted to the mists, explaining the origin of pulsed movements that were observed by Japanese teams in experiments in microgravity. The team also developed an approach that couples the acoustic disturbance with the two-phase combustion, since these disturbances are suspected to be a possible origin of the pulsations. The theoretical approaches have also been directed toward the combustion near a critical point by R. Prud'homme in Paris. Finally, the study of flames representative of fires was continued in Poitiers (CNRS, Joulain P. and Wang Hy), where the distribution of soot and other chemical elements was recorded versus severity level.
>
> The prospects of combustion in microgravity are obscured by safety concerns that led to the prohibition of microgravity experiments to date.[1] Furthermore, the thematic dispersion of the teams has not allowed the emergence of a leading theme that could have benefited, given its importance in modeling, by the interest or support from engine industries. Nevertheless, we observe thematic rapprochements as the announced applicability of the P. Haldenwang modeling to experiments by C. Chauveau and B. Veyssière, or the transposition of the results of R. Prud'homme to certain experiments dealing with supercritical vaporization under magnetic compensation. It therefore seems urgent to define with the actors some clear perspectives, presumably including them in a European framework and/or in connection with industrial players. Without such an action, we could fail to capitalize the effort by CNES in recent years and discourage young researchers who could be involved now in the theme." (Text based on the report of the preparatory meeting of the prospective seminar dedicated to combustion.)

In the 2008–2012 activity report of the GDR MFA, the following studies dealing with reacting systems were presented:

- hydrodynamic instabilities at the interface of reactive systems;
- chemical coupling reaction – hydrodynamics during the propagation of a chemical wave front;
- two-phase combustion, propagation of a flame in an aerosol;
- propagation of fog flames.

Within the colloquium held in Carqueiranne in 2014, combustion presentations were about:

- flame spread on samples of cylindrical revolution [19];
- propagation of a flame in a two-phase medium (Mist): characterization of cellular instabilities [20];
- rich mists flames [21].

[1] This ban is now lifted, as shown in the experiments presented in 2014 in Carqueiranne.

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2.3. The last fifteen years

Various international events have taken place in the last period, including:

- the 5th International Seminar on combustion in microgravity, organized by NCMR/NASA in Cleveland (Ohio, USA) from 18 to 25 May 1999. Seventy-eight papers and 40 posters were presented, with a significant French contribution [22].
- the First International Symposium on Microgravity Research and Applications in Physical Sciences and Biotechnology, organized by ESA in Sorrento (Italy) from 10 to 15 September 2000 [23], in connection with the future International Space Station (ISS). The program included a "Combustion" session.

On the French side, successive meetings from 1998 until 2008 led to publications in scientific journals. The CNES prospective seminar in Arcachon, from 9 to 12 March 1999, following the meeting organized by the Research Groups "µg" on Île d'Oléron in May 1998, gave rise to publications in the *Journal de chimie physique et de physico-chimie biologique* [24]. Then the Proceedings of the meeting held in Paris in May 2001 were published in the *Journal de physique IV* [25]. Finally, the Symposium "Microgravity and transfers" incorporated into the 16th French Congress of Mechanics resulted in the publication in 2004 of the work in simultaneous thematic issues of the Proceedings of the Academy of Science and Mechanics & Industries [26,27].

3. Concepts and basic problems

Before describing the current trends for combustion in µg and the main research programs, it is important to review some basic concepts and key issues.

3.1. Diffusion flames, premixed flames, and triple flames

Although in some cases, diffusion flames and premixed flames coexist or, in the laminar regime in the presence of concentration gradients, lead to triple flames, these flames are generally treated as separate. In the turbulent regime flame propagation is not of the same nature and has to be treated in an independent manner. We constrain here the following review to the laminar regimes.

For the *diffusion flame*, the fuel and the oxidizer are initially separated and the flame takes place in the gas phase at the location of their mutual contact. If the flame is thin enough, its position is given by the locations where the reacting species are found to be at the stoichiometric concentrations. For practical configurations, this reflects the way this type of flame finds its position.

Generally, diffusion flames are established in different potential configurations that are dependent on the nature of the fuel, oxidizer, and geometrical considerations. Some examples are illustrated below:

- the flame resulting from the vaporization of droplets of fuel in a gaseous oxidizer (often a hydrocarbon in oxygen or air) or the reverse configuration (LOX drops in gaseous hydrogen). The flame can take place either around each drop or around a cloud of droplets;
- the flame resulting from injected flows, parallel or not, of oxidizer and gaseous fuel;
- candle flames, where the fuel changes phase before gasification occurs and different physical processes compete to deliver fuel to the flame (often a complex matter);
- pool fires, where fuel and oxidizer carry no momentum other than buoyancy and where gravity unstably interacts with density gradients;
- flames resulting from the sublimation of plates or fuel rods (polystyrene for example) where the geometry and nature of the fuel allow for simplifications.

Premixed flames – as explicitly suggested by their name – involve mixtures of fuel and oxidizer, mixed in a stable state at room temperature (the time required for chemical reactions is then virtually infinite). After ignition (e.g., by an external energy deposit like the one generated by a spark), the reaction zone releases energy as heat, which heats up the fresh reactants mainly by conduction (although radiation can also play a role). Simultaneously, molecular diffusion occurs, i.e. the combustion products diffuse into the reactants and conversely the fresh gases diffuse towards the reaction zone, supplying the reaction with reactants and releasing further energy. A flame (or deflagration wave) is the result of the coupling and competition that takes place between reaction, thermal and mass diffusion, and convection, and once it starts to propagate. Propagation velocity is that of a wave. For free propagation, it is the eigenvalue of the above-described problem.

Two cases emerge as eigenvalues, as evidenced by the Rankine–Hugoniot theory [28,29], i.e. a deflagration wave corresponding to a subsonic propagation – the only one relevant to microgravity conditions – and a detonation wave corresponding to supersonic propagation. Both regimes can successively exist within the same mixture, initially at rest in a pipe: after ignition, a deflagrative flame appears that is substantially isobaric and almost flat under certain conditions of heat transfer to the wall. This flame may turn after a lapse of time into a detonation wave. The latter is a strong shock that induces compression and convection and completely obscures the effects of gravity.

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The canonical problem addressed in these studies is that of the plane adiabatic flame [29–31]. The asymptotic expansions allow the identification of curvature, non-adiabaticity, and unsteadiness effects on the flame speed in the case of relatively low stretch rate [32]. Gravity is generally neglected in these baseline studies.

Triple flames can develop in a mixture with inhomogeneity in concentrations. In an inhomogeneous mixture, a premixed flame will arise at the location of stoichiometric conditions. If the conditions are appropriate, it can coexist with a lean branch and a rich branch. The flame curves on each side of the tip where the concentrations are stoichiometric. The normal propagation velocity is lower when the mixture is leaner or richer than stoichiometric. However, there is a difference, downstream of the flame, between the lean side and the rich side. In the lean side, the unburnt oxidizer is mixed with combustion products, and in the rich side the unburnt fuel is mixed with combustion products. As a result, in a hydrocarbon flame, some oxidizing intermediate species can be found in the lean side, while carbonaceous species are found in the rich side. These components may react downstream of the premixed flame, establishing a diffusion flame attached to the stoichiometric line of the premixed flame. If the flame is small, its position is determined by the locations where $Z = Z_{\mathrm{st}}$, Z being the mixture fraction and Z_{st} its value in the stoichiometric conditions. This is the phenomenology of triple flames [33,34]. In some circumstances, both parts, lean and rich, of the premixed flame disappear and there remains only the stoichiometric top. The triple flame has degenerated only into the part of "diffusion flame" [35]. This was originally studied by Buckmaster [36]. The circumstances of occurrence are associated with stretching rates that need to be high enough to let the diffusion thickness be of the same order of magnitude as the thickness of the preheating zone in the premixed flame.

3.2. Vaporization and combustion of droplets

Let us now consider a drop of pure fuel, at rest in an infinite atmosphere. Such a situation may be attained at normal gravity with a sufficiently small drop given that the size L involved in the Grashof number of section 1 is the diameter of the drop. Nevertheless, for sufficiently low pressures, i.e. well below the critical point, the absence of surface tension prevents the droplet from being attached to any suspender. Therefore, an upward flow is necessary to compensate for gravitational forces. This upward flow will compromise the spherical symmetry of the flame. It is therefore almost always necessary to conduct these studies in microgravity if the idealized theories are to be validated.

The following basic theory corresponds to an ideal situation observable only in weightlessness. We consider the case of a diffusion flame surrounding the droplet. The key assumptions are the following ones:

- the pressure is uniform;
- the evolution of the system is quasi-steady in the gaseous mixture which follows the ideal gas law;
- the droplet is spherical, r_{S} being its radius;
- the droplet temperature T_{S} is uniform;
- the reaction rate per unit volume $\dot{\zeta}$ characterizes a single chemical reaction $\nu'_{\mathrm{O}}\mathrm{O} + \nu'_{\mathrm{F}}\mathrm{F} \to \nu''_{\mathrm{P}}\mathrm{P}$ of the fuel F with the oxidizer O, producing the combustion products P. The heat released per mole of fuel consumed is ΔH;
- constant conductivity coefficients k/c_{pf} and diffusivity ρD;
- the so-called Shvab–Zeldovich assumptions[2] are supposed verified [29]. Among these, a major one is about Lewis number $Le = k/\rho D c_{\mathrm{pf}}$ that is set equal to unity and one calls a the identical value of ρD and k/c_{pf}.

To derive the equations for a conserved scalar, one defines the quantities β_j and β_T as follows:

$$\beta_j = Y_j/\nu_j M_j$$

$$\beta_T = \sum_j Y_j \int_{T_0}^{T} c_{p,j}\,\mathrm{d}T/\Delta H$$

where the subscript j stands for the jth species considered ($j = 1, \ldots N$). Y_j is its mass fraction, $\nu_j = \nu''_j - \nu'_j$ its algebraic stoichiometric coefficient in the combustion reaction, M_j its molar weight, $c_{p,j}$ its specific heat capacity per unit mass at

[2] Within the framework of this approximation, the following assumptions are permitted:
there is a steady flow in a suitably chosen reference frame
- there is no thermal diffusion; $D_T = 0$
- external forces are negligible
- viscosity is negligible
- to a first approximation, the static pressure is constant
- Fourier's law holds for thermal conduction
- Fick's law holds for diffusion, and there is a single diffusion coefficient for all species
- the Lewis number is close to unity
- there is only one chemical reaction
- a mixture of N perfect gases is present.

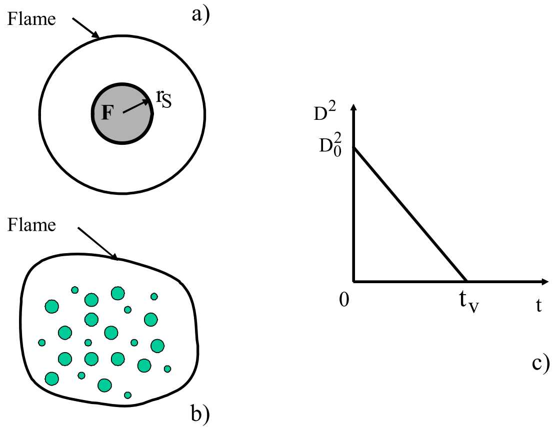

Fig. 1. a) Individual droplet burning; b) packet drops combustion, each drop being vaporized; c) evolution with time of the droplet diameter D following the D^2 law.

constant pressure. c_{pf} is defined as the "frozen" specific heat, i.e. $c_{\mathrm{pf}} = \sum_j Y_j c_{p,j}$. The β quantities can be shown to be governed by the following equation:

$$\dot{M}\frac{\mathrm{d}\beta}{\mathrm{d}r} - \frac{\mathrm{d}}{\mathrm{d}r}\left(4\pi r^2 a \frac{\mathrm{d}\beta}{\mathrm{d}r}\right) = 4\pi r^2 \dot{\zeta}$$

where $\dot{M} = -\mathrm{d}M/\mathrm{d}t$ is the vaporization rate of the droplet whose mass is $M = \frac{4}{3}\pi\rho_{\mathrm{L}} r_{\mathrm{S}}^3$. ρ_{L} is the uniform density of the droplet.

Then the set of coupling variables α such that $\alpha_{\mathrm{F,O}} = \beta_{\mathrm{F}} - \beta_{\mathrm{O}}$ and $\alpha_{\mathrm{O}} = \beta_T - \beta_{\mathrm{O}}$ obey the following equation, which does not include any source term, i.e. no specific reaction rate:

$$\frac{\mathrm{d}^2\alpha}{\mathrm{d}\xi^2} + \frac{\mathrm{d}\alpha}{\mathrm{d}\xi} = 0$$

where $\xi = \dot{M}/4\pi a r$ is an intermediate variable.

The boundary conditions required to close the mathematical formulation are as follows:

$Y_{\mathrm{O}} = Y_\infty$, $Y_{\mathrm{F}} = 0$, T_∞ at infinite
$Y_{\mathrm{OS}} = 0$, Y_{FS}, T_{S}, $\frac{\mathrm{d}Y_j}{\mathrm{d}\xi}|_S = Y_{j\mathrm{L}} - Y_{j\mathrm{S}}$, $\frac{\mathrm{d}T}{\mathrm{d}\xi}|_S = -\frac{\ell}{c_{\mathrm{pf}}}$ at the droplet surface S ($r = r_{\mathrm{S}}$ or $\xi = \xi_{\mathrm{S}}$), with $j = \mathrm{F}$, O and ℓ the latent vaporization heat.

Once the equations are solved, the steady mass flow rate can be derived either from the evolution of Y_i or from that of T:

$$\dot{M} = 4\pi a r_S \ln(1 + B_{\mathrm{M}}) = 4\pi a r_{\mathrm{S}} \ln(1 + B_T)$$

This latter expression leads to the following identification:

$$B_{\mathrm{M}} = B_T = B$$

where $B_{\mathrm{M}} = \frac{M_{\mathrm{F}}}{1-Y_{\mathrm{FS}}}\left(\frac{Y_\infty}{M_{\mathrm{O}}} + \frac{Y_{\mathrm{FS}}}{M_{\mathrm{F}}}\right)$, $B_T = \frac{\Delta H}{\ell}\frac{Y_\infty}{M_{\mathrm{O}}} + c_p \frac{T_\infty - T_{\mathrm{S}}}{\ell}$.

Note that the mass flow rate $\dot{M} = -\mathrm{d}M/\mathrm{d}t$ is proportional to the droplet's radius. As $M = \frac{4}{3}\pi\rho_{\mathrm{L}} r_{\mathrm{S}}^3$, the well-known "$D^2$ law" can be inferred (see Fig. 1c): $D^2 = D_0^2 - Kt$, where $D = 2r_S$ and $K = 8a\ln(1 + B)$.

Generally, the conditions at infinity can be monitored, but we do not know the fuel concentration at the droplet surface, Y_{FS}, or the drop temperature, T_{S}. To determine the latter, the relationship $B_T = B_{\mathrm{M}}$ is used together with the vapor–liquid equilibrium relationship on the surface of the droplet: $pX_{\mathrm{FS}} = p_{\mathrm{Fsat}}(T_{\mathrm{S}})$, where p is the pressure, X_{F} the mole fraction of the species F, connected to the mass fraction Y_{F} and $p_{\mathrm{Fsat}}(T)$ the saturated vapor pressure of F, which is a function of temperature (this is equivalent to equalize the chemical potentials of species F in both liquid and gaseous phases).

Many numerical studies allowed the vaporization and combustion of drops to be modeled under more realistic assumptions than the ones described above [37,38]. Nevertheless, the previous analytical model remains a reference.

3.3. Combustion over plates and cylinders

A flame can be established inside a boundary layer over an ablating surface as illustrated by the diagram in Fig. 2. The difference between the droplet scenario and this configuration is the presence of a forced flow that induces a boundary

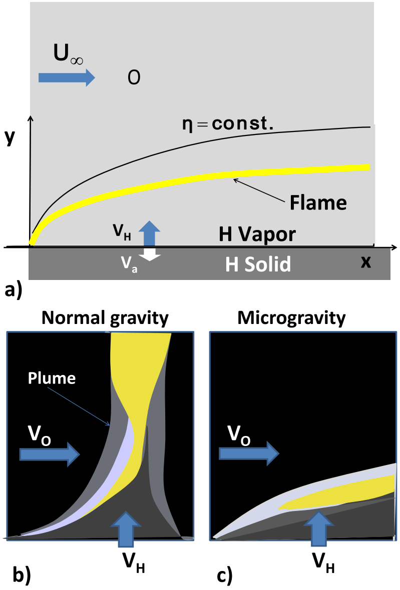

Fig. 2. a) Flat plate of a solid fuel H burning in the presence of an oxidizing flow O. b) Schematic of a buoyant flame experiencing normal gravity. The gaseous fuel is here injected through a horizontal porous plate at a velocity V_{H} inside an oxidizing flow of velocity V_{O}; c) same configuration as b) but in microgravity.

layer. This problem was first described by Emmons [29,30] in very similar terms as the droplet combustion problem, but providing a solution to the fluid mechanics problem of a boundary layer. In the Emmons problem considered here [29, 30], the same transformations of the energy and mass transport equations are performed, leading to the Shvab–Zeldovich approximation for the chemical reaction in the gaseous phase: $\mathrm{H} + \mathrm{O} \to \mathrm{P}$.

In addition, the Prandtl number is assumed to be unity. A similar solution as that characterizing the conventional boundary layer over a flat plate can be found but for the gasifying flat plate the Blasius function, $f(\xi)$, is not zero at the wall. The main steps of the analysis are reminded below. The coordinates are those specified in Fig. 2a):

- a self-similar solution is derived from the Blasius equation:

$$f''' + ff'' = 0, \quad f'(0) = 0, \quad f'(\infty) = 1, \quad f(0) = -Bf''(0), \quad B = (\beta_{T\infty} - \beta_{TP} - \beta_{\infty})\Delta H/\ell$$

  where ΔH is the heat released per mole of fuel in the chemical reaction and $\beta_{\mathrm{O}} - \beta_{\infty}$ at infinite
- the ablation velocity of the wall:

$$v_a = -(U_{\infty}/2\xi)^{1/2} f(0)(\rho\mu)_P/\rho_H, \quad \xi = \int_0^x \rho\mu \mathrm{d}x, \quad \zeta = \int_0^y \rho \mathrm{d}y$$

  where μ is the shear viscosity
- the quantities of interest such as the friction tension on the plate and the concentration profiles are functions of $\eta = \zeta(U_{\infty}/2\xi)^{1/2}$.

Microgravity allows the assessment of this kind of solution, as shown in Fig. 2b) and 2c). With gravity, the plume's features are governed by buoyancy, which is neglected in the theory of Emmons. In microgravity, the flame's shape is very similar to Emmons' solution. This solution is of importance because it allows us to elucidate the competing effects of diffusion, fuel injection, and oxidizer flow velocity in the characteristics of the flames. An important finding associated with these studies is the role of soot production and consumption in quenching and the relative importance of fuel injection [39–42].

4. Results and outlook

Combustion studies at different levels of microgravity have been fruitful. The results obtained in France have contributed to unveil new flame behaviors in microgravity that are better connected with fundamental theories. These results have opened the door for new studies that will answer many of the questions that have emerged.

In general, as for other fields in physics of fluids, outputs can be directly applied to the adaptation of technology to the space environment. "This research is necessary for the conduct of planetary exploration programs, microgravity is an essential component." (See [43], p. 23.) As an illustration, the implementation of the DECLIC instrument (in French: "Dispositif d'étude de la croissance et des liquides critiques", i.e. "A study of the growth and critical liquids"), used in the International Space Station, allowed other basic research to be extended in the field of vaporizing drops and bubbles in the vicinity of the critical point (see pp. 1066–1073 in [24]). This research is meaningful for applications to thrusters [43]. In addition, microgravity, as a privileged place for the study of heterogeneous media, should facilitate the study of interaction between a flame and suspensions [20,44].

A report of the ELGRA [2] highlighted the need for the intensification of European research in combustion with sustainable financial support (over one to three years). Among the topics carrying the following are specifically mentioned:

- premixed flames,
- diffusion flames,
- combustion of droplets, metal, dusty gas, plates.

Let us examine more precisely the results and perspectives, and more particularly those delivered by the French laboratories on a few topics. We can now state that the perspectives take better account than in the past of complex or stringent configurations such as turbulence, heterogeneous environments, radiation, and high pressures.

4.1. Spherical droplets

The evolution with time of a vaporizing droplet's diameter is assessed in microgravity, its generality covering conditions extended beyond the case of the adopted assumptions. However, the experimental evolution departs from the theoretical predictions due to unsteady effects (drop in unsteady thermal evolution at an injector outlet, for example), and at the end of the combustion process. The theory especially predicts the existence of a steady premixed flame exhibiting a constant diameter, which is not what is observed in microgravity experiments. In contrast, spherical symmetry is well verified. Finally, we note that in the presence of the only vaporization, the "D^2 law" is still valid for a drop that is a part of a fog surrounded by a flame (see Fig. 1b) but with simpler definitions of B_T and B_{M}. The vaporizing droplet behavior in the presence of a radial thermal field has been studied [42] as well as the possibility of vaporization disequilibrium and instability of vapor recoil [45].

Among the most significant results related to vaporization at high pressure, a very significant increase in the vaporization characteristic time has been measured in the subcritical regime for pressure above the critical pressure of the fuel, while the reverse trend has been evidenced for the subcritical regime for temperature above the critical temperature [43]. However, experiments conducted on methanol by the LCSR Orléans and the DME Osaka show an increase in the firing rate coupled with an increase in the surrounding pressure. These studies do not demonstrate the existence of a maximum at the critical pressure of methanol as one might expect. The same experiments show an evolution of the burning rate as $Gr^{1/4}$ (Chauveau et al. in [24] pp. 1031–1037). The latter law is assessed experimentally using three levels of gravity, i.e. g_0 (on ground), 10^{-2} g_0 (in parabolic flights), and 10^{-4} g_0 (in drop tower). The evolution of a supercritical fluid bag has been studied numerically later on [46].

Two directions of research are in progress. These are:

– *vaporization near the critical point*, since we cannot be satisfied, as we used to be in the past, with considering only the critical point of pure liquids. Studies were conducted on this topic in Marseilles (I. Raspo and P. Bontoux), in Paris at LMM (S. Préau, R. Prud'homme, and B. Zappoli), and Bordeaux (D. Beysens and Y. Garrabos), where experiments were designed for the ISS;
– *collective effects*, as these are present in the combustion of sprays. We thus observe the presence of two conflicting effects in the vicinity of drops: a rise in temperature tends to accelerate the vaporization and chemical reactions, while, due to the significant amount of combustion products, dilution of reactants occurs, which reduces the reaction rate. Usually the latter trend prevails (Borghi and Lacas [47], Dietrich et al. in [22], pp. 281–284);
– in this field, the experimental design needs to tackle the problem of positioning the droplets, which involves suspenders, especially if one wants to study the effect of an external flow. Drops are commonly delivered on quartz fibers or glass fibers, and potentially on networks of these. Significant results have recently been obtained by the team of C. Chauveau in Orléans [48–50] (see Fig. 3). One of the problems is the possible wetting of the fiber by the liquid of the drop, which can happen especially in microgravity. Wu et al. [51] improve the experimental procedure to better stabilize the drop. These authors designed a spherical inverted cup coated with epoxy adhesive that is located at the end of a quartz fiber (100 μm in diameter). This ensures the stability of the drop delivered by the fiber, especially in the presence of an external flow. Another problem is the heat leakage through the support, though this phenomenon can be fairly well modeled.

4.2. Plates, sheets, and cylinders

The experiments conducted in microgravity can also show a very complex behavior. The experimental studies by the LCD team in Poitiers (Vietoris et al. in [24] pp. 1022–1030) are related to the *combustion of a PMMA plate subject to a flow forced*

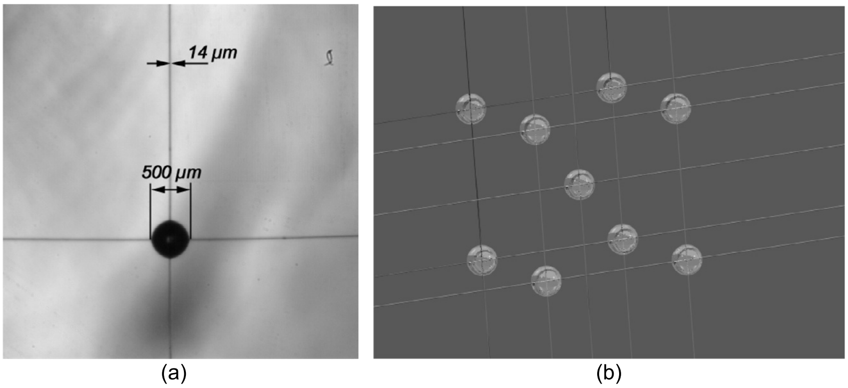

Fig. 3. (a) A drop delivered at the intersection of quartz fibers; (b) network of drops [48], reproduced with the permission of the authors (see also [49,50]).

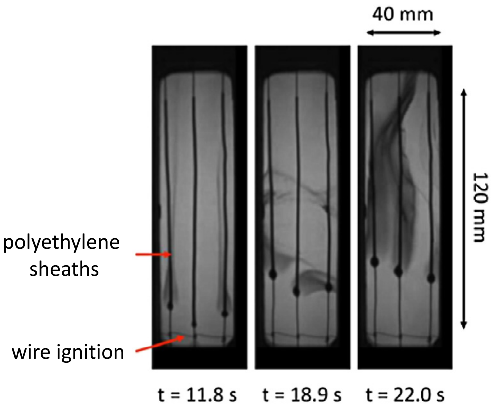

Fig. 4. Set of frames obtained by the absorption technique at different times after the beginning of the microgravity period ($t = 0$) [19]. The air flow and flame spread are oriented from the bottom to the top in these pictures.

parallel to the plate surface. Experiments conducted on ground, in parabolic flights, and in a drop tower have identified two stable burning regimes:

- a regime exhibiting blue flames where the fuel supply is governed by diffusion: in this case, the flame stand-off distance corresponds to that predicted by the Emmons theory (see § 3.3);
- a regime leading to yellow flames, indicating the presence of soot (note that it was recently shown that blue flames could produce soot also), where fuel convection is of significance (neglected by Emmons) and where experimental and theoretical results do not match [19]; some simplifying assumptions must then be questioned and radiative feedback to the fuel surface becomes of significant relevance;
- finally, losses by radiation and heat conduction in the solid have to be accounted for to predict the flame length [42] (see also [30] and [52]).

Evidence has also been made that the absence of the air flow induced by buoyancy leads to a reduction of the minimum oxygen content required for ignition of the solid fuel. This statement supported the need for the ongoing review of *fire safety standards aboard space vehicles, especially in terms of flammability* [43].

Experiments took place recently in parabolic flights by the team lead by Legros at the Institut d'Alembert of UPMC in Paris [19] to study the interaction of flames spreading along parallel cylinders coated with polyethylene. At the beginning of the test, the ignition of the central coating was intentionally delayed. Two reverse trends may be evidenced. On the one hand, the combustion products that the lateral flames release can induce a dilution of the oxidizer flowing along the central wire. On the other hand, the radiative transfer from the lateral flames towards the central coating can heat it up. As shown in Fig. 4, the central spread finally catches up, evidencing that the latter effect prevails in microgravity. Interestingly, this sequence never occurs at normal gravity.

Eventually, in the absence of forced convection but in the presence of gravity, the combustion of a liquid sheet causes above its surface explainable characteristic flickering due to a Rayleigh–Taylor mechanism. The experimental simulation of the phenomenon was performed using a circular porous burner through which ethane was injected into air at pressures ranging from 0.03 to 0.3 MPa. The effect of the acceleration field was studied between 0 and 12 g_0. The radiation is taken into account in some cases. Good agreement with a model of "integral type" was obtained [43].

4.3. Heterogeneous mixtures

The following studies were covered by the Research Group "Transport phenomena and phase transitions in microgravity."

- The presence of solid particles alters the spread of flames and the ambient acceleration field acts in two ways, i.e. hot thus less dense areas are affected while the particles are generally much denser than the gas. Microgravity can generate better controlled suspensions. It should allow us to better study the propagation of turbulent eddies whose characteristic sizes are lower than flame thickness. A study has been initiated at the PPRIME laboratory in Poitiers on this topic (B. Veyssière).
- The spread of a flame through a high-pressure fuel mist may be facilitated in microgravity. In the real case of diesel engines and rocket engines with a high compression ratio, the thickness of the flames considered is small as compared to the inter-droplet distance. In the numerical simulations at ordinary pressure, which is generally used, one is led to consider large drops of up to 100 μm in diameter, which is difficult to set on ground. A study conducted by the team of P. Haldenwang in Marseilles is in progress in this field [53,54].
- Experiments of flame propagation in a two-phase medium were presented recently at the yearly conference of the GDR MFA by the team of C. Chauveau [20] in Orléans (ICARE Laboratory). This research activity includes a comparative approach with numerical studies conducted by the team of P. Haldenwang [21,55] in Marseilles at M2P2 and IRPHE laboratories, thus echoing the prospects drawn along the seminar held in Biarritz in 2009 [18].

4.4. Premixed flames and triple flames

- The study of the effects of gravity on premixed flames is among the oldest set of studies. The experiments in parabolic flights and centrifuge were conducted on Bunsen-type flames by the team of Meudon. The theoretical and numerical studies have confirmed the $g^{1/2}$ law driving the frequency of the flame tip oscillations [12]. However, a conventional camera was often the only means of observation in this period. Sophisticated diagnostics were not available for microgravity applications. Therefore, the lack of more sophisticated experimental diagnostics did not allow some effects to be clearly described, such as that of the mixture equivalence ratio on the flow structure. Nevertheless, the nature of the instability is fairly well identified as a Kelvin–Helmholtz accelerated flow due to buoyancy forces. Extensive numerical computations are now expected to continue the exploration of premixed flames at a lower cost.
- The ignition of sprays or mixing layers often takes place in a medium of highly inhomogeneous composition and/or temperature, allowing triple flames to propagate. A numerical method implemented by Haldenwang et al. (see in [24], pp. 1016–1021) delivered interesting results. The triple flames are currently the subject of many studies [56]. Some configurations leading to combustion of interacting drops have also been published [57]. These triple flames studies should be further developed.
- The "flame balls" evidenced by P. Ronney [58] can also be a new topic of study. Ronney et al. were able to show the very first experimental evidence of steady spherical premixed flames. Until these experiments were conducted onboard the space shuttle, the existence of these flames had only been predicted theoretically by Zeldo'vich [28].

5. Conclusion

Combustion experiments at variable gravity begun in the 1970s and first made use of parabolic flights and drop towers [59]. Sounding rockets and satellites provide with longer periods of microgravity. The characteristic times encountered in combustion are often very small, allowing significant information to be extracted from short-duration microgravity facilities. While some problems, in particular those involving condensed phase fuels, require longer microgravity times, it has generally not been a simple task to conduct these experiments under sufficient microgravity time. For safety purposes, confinement needs to be guaranteed, thus resulting generally in very high experimentation costs. As of now, small satellites (so-called CubeSats) can be a solution when they are powered by small plasma thrusters (see, for example, [60]).

Alternatives to gravity compensation have been considered. These include acoustic levitation and magnetic compensation. The former is used as a means of support for a long time. However, the acoustic field acts on the vaporization of the droplets [61].[3] In addition, the high-frequency vibrations of the engines can lead to combustion instabilities, which is a subject of study by itself [62–64]. The latter means, i.e. the magnetic compensation, uses the sensitivity of materials to

[3] Schirmer et al. observed the following parasitic effects caused by this form of levitation in the case of evaporating water droplets in air:

- increasing of the evaporation rate due to the so-called "acoustic streaming";
- recirculation vortices enriched in steam which can be removed by purging with dry air.

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energy gradients attributed to the magnetic field. According to Shinoda et al. [65], the force acting on oxygen per unit mass is as follows:

$$\mathbf{f}_\mathrm{m} = \frac{\chi_{\mathrm{O}_2}}{2\mu_0}\nabla\left(B^2\right)$$

with $B = |\mathbf{B}|$, μ_0 being the magnetic permeability in vacuum, and χ_{O_2} the magnetic susceptibility per unit mass of oxygen.

This force contributes to the momentum balance written below for a steady flow:

$$\nabla \cdot (\rho\mathbf{v} \otimes \mathbf{v}) = -\nabla p + \nabla \cdot (\mu\nabla \otimes \mathbf{v}) + \rho Y_{\mathrm{O}_2}\mathbf{f}_\mathrm{m} + \rho\mathbf{g}$$

Thus, the magnetic force can balance buoyancy.

The magnetic field gradients are used for levitation [66,67], using for instance the paramagnetic or diamagnetic properties of vaporizing droplets [68–70]. The action of these gradients on flames is more complex given the different chemical species and their inhomogeneous distribution. In addition to the diversity of sensitivities involved, one can notice, like Chechulin does, that magnetic fields distort the electronic orbitals of molecules, thus changing their collision probability, which affects the rates of the reactions in which they operate [71]. Magnetic fields can also act on soot formation dynamics in flames [72,73].

We mostly talked about the studies conducted in France as part of projects funded by CNES and ESA. Experiments were supported by other space agencies. The book edited by Ross [74] in 2001 reported on the works especially funded by NASA and Bellan [75] reported on numerous configurations including drops, streams, shear and mixing layers, jets and sprays. Studies on combustion in microgravity have also been conducted in Japan, and more recently in China, and are also documented in the literature. There are many recent articles on biofuels combustion, showing how these can be characterized in microgravity [76–78].

We have presented here some meaningful illustrations of combustion in microgravity. This framework can be extended referring to other studies, and the reader can easily find satisfaction reading the other references [79–101] cited in addition at the end of the reference section.

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