European Microgravity Combustion Science, from Drop Towers to the Space Station

Christian Eigenbrod

Center of Applied Space Technology and Microgravity
ZARM, University of Bremen, Germany

Abstract

Combustion is an interdisciplinary science spreaded in the fields of thermodynamics, fluid mechanics, transport processes and chemical kinetics. Combustion processes can be described as exothermal transformation of chemical energy into thermal energy. In atmost cases this transformation leading to a reasonable temperature rise is accomplished by a decrease of local density, generally by a factor between two and ten. As density driven buoyancy affects many terrestrial combustion processes, microgravity experiments, suppressing buoyancy and thus reducing the number of degrees of freedom, can be of great benefit for the observation of new combustion phenomena. In most cases this problem reduction leads to a better understanding of the fundamental processes as well as to more accurate data about combustible materials properties. Numerical simulations taking advantage of the increasing calculation capacity of modern computers became the most important tool to develop new or better combustion technologies. As the quality of results depends on the quality of the basic data as well as the models accuracy data from microgravity experiments assist the simulations development by offering a vast stuff properties data base and help for the models validation at a state of development where natural convection driven buoyancy has not yet been included.

Introduction

The first basic and systematic combustion experiments under microgravity conditions were performed by S. Kumagai [1] in the 1950´s. Kumagai studied droplet burning in a free-fall facility between the ceiling and the floor of his laboratory. There he achieved almost 1s of microgravity duration. The relevance of gravity to combustion phenomena is implicit in even much earlier studies, such as the observation of a candle flames weakening under reduced gravity (Fig.1) [2] or the observed differences in flammability limits for upward and downward premixed flame propagation [3]. Since then, microgravity combustion studies have led to a number of discoveries such as the existance

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of flame balls as stable burning seperate flames resulting from flame front instabilities during premixed flame propagation [4], the slow regime of droplet burning [5], the staged regimes in autoignition of fuel droplets [6] and self-extinguishing flames [7].

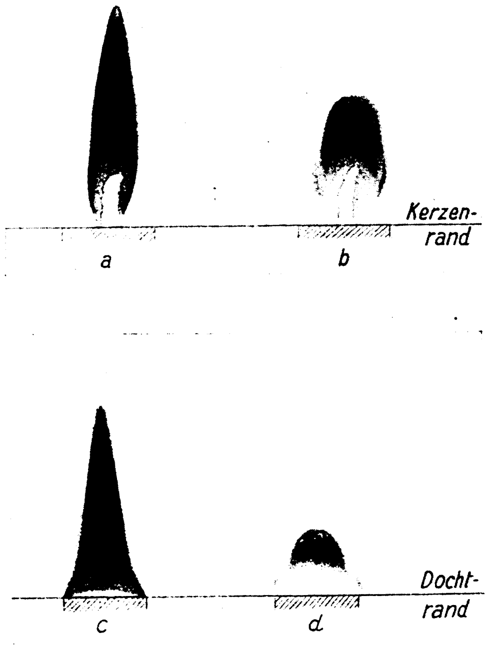


Bild einer Kerzen- und einer Petroleumdochtflamme in Ruhe (*a* bzw. *c*) und in freiem Fall (*b* bzw. *d*) bei gleichen Belichtungszeiten (natürl. Größe). Belichtungszeit = Fallzeit = 0,7 sec.

Fig. 1: Photografic images of a candle flame and a petroleum flame under 1g- and µg-conditions from 1934 [2]

Significant European activity in microgravity combustion began in 1984, when ESA issued a first call for proposals. A number of European microgravity combustion experiments were performed on parabolic aircraft flights in 1986 and 1987 [8]. Worthwhile scientific contributions to combustion are now coming from these and subsequent European microgravity investigations. Even though most combustion processes are of short time scales, compared to other research branches, the decision of the ESA member states to participate to the International Space Station (ISS) recently fostert the scientific communitiy to install a consolidated European microgravity combustion research program. This research will enhance both, industries interests in getting quick answers by applying short term facilities that are easy to access like drop towers, parabolic flight aircrafts or sounding rockets as well as the scientists requests for comprehensive parametric studies onboard the permanently available ISS.

Fields of European Activities

Combustion research usually is represented through the three subareas, premixed flames, diffusion flames and condensed-fuel combustion. With the rapid developments of modern non-intrusive laser based diagnostic methods and its special requirements for microgravity applications it appears meaningful to add this fourth area. This the more as these techniques are the same in most parts for the different combustion areas but quite different from non-combustion applications and even different from non-microgravity combustion diagnostics.

Premixed Flames

In premixed gaseous flames, the reactants are well mixed prior to initiation of the combustion process. Premixed combustion is the major goal of many industrial combustion processes. This is because premixing is the only solution between the two contradicting aims: high flame temperature for high thermal efficiency - low flame temperature for low emissions of nitric oxides that are both, poisenous and environmentally harmful. The amount of nitric oxides in the exhaust gas strongly depends on local flame temperatures and the values are the highest, the closer the mixture approaches stoichiometric conditions. Therefore the homogeneous premixture enables the highest flame temperatures at lowest nitric oxide emissions as local temperatures and mean temperature are then mostly the same and the engine can operate at lean conditions close to the flammability limits.

The reason for performing microgravity experiments in this area is, that there are a number of mechanisms for stabilizing or destabilizing premixed flame propagation that proceed on relatively long time scales and that therefore can be masked by buoyancy. The onset of buoyancy takes a time in the order of the square root of the ration of a lenght to the acceleration of gravity. On earth this is typically between 10ms and 100ms. These mechanism include various diffusive, thermal hydrodynamic and radiative effects. As an example, Fig. 2 depicts the lean flammability limits of methane/air mixtures under 1g- and µg-conditions. The µg- flammability limits are between 0.15% and 0.28% leaner as for terrestrial flames. The difference is increasing towards higher pressure values. Fig. 3 shows the tendency to cellular structures and gives a good impression on how slow such lean flames can propagate without buoyant effects .

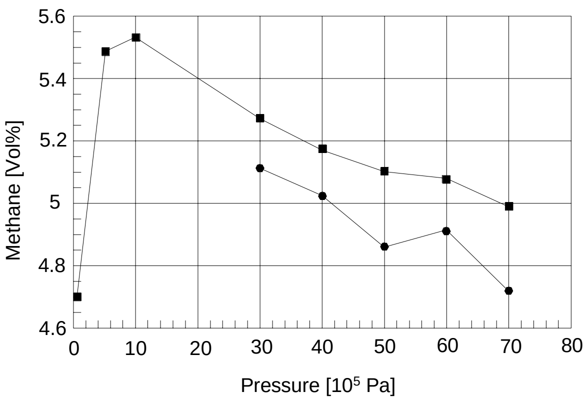


Fig. 2: Lean flammability limits for Methane/Air under 1g (top) and µg [9]

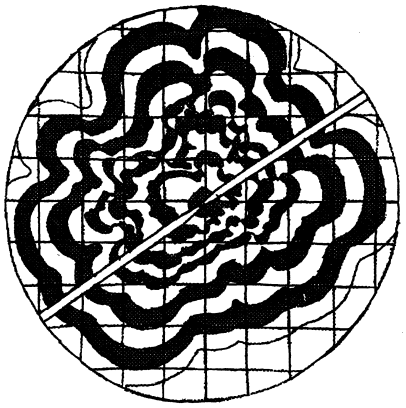


Fig. 3: Flame Propagation for 60 bar and 5.01 Vol% Methane (Front recorded at 0.05; 0.1; 0.2; 0.3; 0.4; 0.5; 0.7; 0.9; 1.1; 1.3; 1.5 s, ∅ = 50 mm) Schlieren Image [9]

On the other hand, lean and homogeneous flames are very sensitive against perturbations. As turbulence in terrestrial combustion is necessary to stimulate combustion, there should a limit of turbulence intensity exist beyond which vorticies might split the flame front leading to local extinguishments and the formation of pockets of unburnt gas. Even though this interaction has never been observed directly, the effects are assumed to be responsible for the induction of hazardous humming of gas-turbines which is connected with strong pressure oscillation. Microgravity experiments can deliver unique conditions under which these thermoacoustic interactions can be ideally investigated. The time being related experiments with industrial co-operation are under preperation.

The work of a recently installed ESA Topical Team (TT), titled “Flame-Vortex Interaction“, deals with that premixing related problems and open questions, that are both, microgravity relevant as well as of technical application importance. The TT´s purpose is to establish a common platform for the activities of different European institutes and institutions in order to aim for a common Space Station hardware as a long term goal.

Diffusion Flames

In diffusion flames, the fuel and oxidizer are unmixed prior to initiation of combustion. Even though many liquid- and solid fuel combustion processes happen in the diffusive combustion regime, they are accordingly treated as condensed matter combustion later. In diffusion flames buoyancy exerts appreciable influences on the flame shape, on soot production and formation and on conditions for extinction.

In Europe, the number of microgravity projects on this item is quite low even though the number of ground based projects on soot formation is comparably high. Nevertheless there is a significant potential for future advancements of scientific knowledge through microgravity investigations and the community is just about to discover the potential of microgravity to answer basic questions in this field.

One of these open questions is, whether or not a diffusion flame in a Burke-Schumann configuration (central fuel flow and concentric oxidizer flow with identical flow velocities at the burners exit) must have a closed flame contour or can be open-tipped. Existing theory does not allow for an open-tipped flame due to conditions of continuity, but first experiments unvealed such flames through videographic monitoring of the visible flame emissions. In order to get more reliable informations, experiments monitoring the CH-radicals chemoluminescence indicating the raction zone were made using an intensified camera. As a result, fig. 4 shows the development from 1g to the steady-state burning µg-structure as an open-tipped methane diffusion flame.

Condensed-Fuel Combustion

As including the areas of droplet- and spray combustion, particle- and particle cloud combustion and the combustion of solid fuel e.g. as wall fires the condensed fuell combustion research is the most active one not only in Europe. Besides, the microgravity research on these items is closesd to application and therefore application research and industry are involved into the related projects.

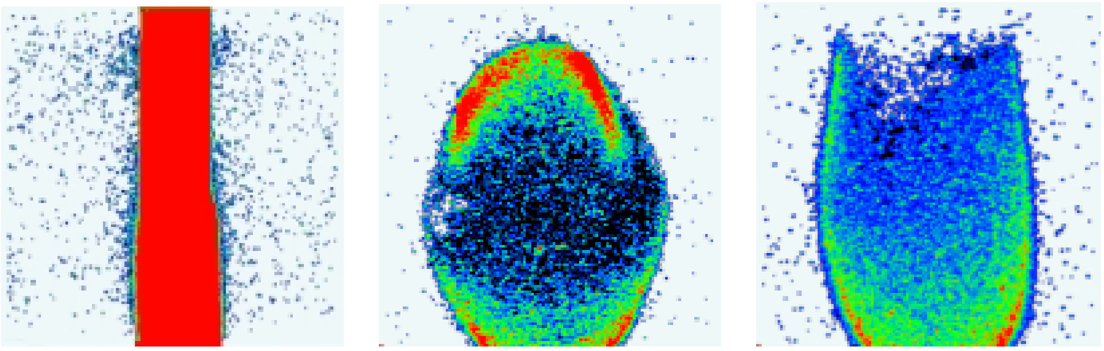


Fig. 4: CH-radicals chemoluminescence of a laminar methane diffusion flame. From left to right: before the drop (saturated by soot precursors), during transition, µg-steady state 3s after release of the capsule [10].

The investigations on flammability limits, flame propagation and flame-vortex interactions of particle cloud flames, both for combustible particles in an oxidizing ambient and in a reactive gaseous ambient are covered by the same TT as for the premixed flames. Besides the explosion safety aspects these items are of great importance for the development of new rocket boosters based on metal particles combustion in a CO_2 atmosphere.

Research programs on droplets, groups of droplets and sprays are represented through groups in France and Germany. The investigations in France focus on the evaporation and combustion of multicomponent fuel droplets and of monocomponent fuels under conditions close to- or above the critical pressure of the fuel. It has been shown, that the mass burning rate reaches a maximum at critical pressure and therefore the droplet lifetime has a minimum. As the sensitivity of this phenomenon on residual accelerations is very high, due to the third power effect of g to the Gr-number, this phenomenon can only be observed under high-quality µg-conditions as in drop towers or an orbital facility. Whether this behaviour can also be observed for multicomponent fuel droplets, like technical fuels, has not been tested yet.

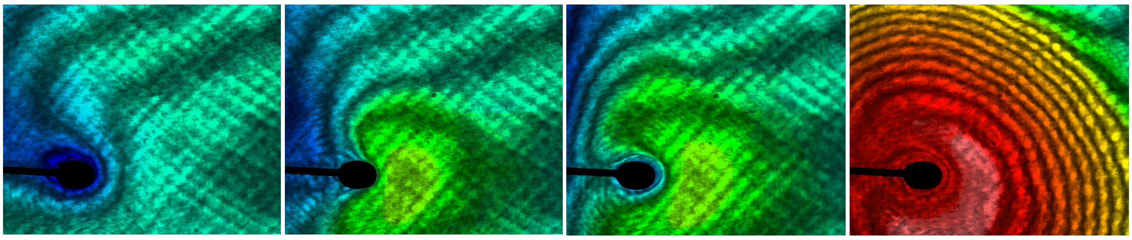


Fig. 5: False coloured interferograms of a selfigniting suspended n-heptane droplet (µg). From left to right: cool vapour area around the droplet, bright green cool-flame above ambient temperature, cool-flame expanding, hot ignition. [11]

In Germany investigations focus on the autoignition behaviour of droplets and droplet groups under elevated pressure- and temperature conditions, as occuring in adiabatically compressing engines. The fuels of interest are technical fuels like kerosene and light-oil and its bicomponent model-fuels. It was found, that at engine operation conditions, droplets ignite in a staged regime with exothermal precursor reactions affecting the total induction time until hot ignition. Fig. 5 displays the temperature distribution around an igniting droplet at different stages. These results led to the definition of new model fuels for kerosene and light-oil, enhancing the staged ignition behaviour. The model fuel data are needed in order to enable direkt numerical simulations to transfer those findings into process simulations. These data are needed in order to develop lean-prevaporized-premixed combustion (LPP) technology for stationary gas-turbines and aircraft propulsion. As the time for prevaporizing and premixing of liquid fuel is very limited under compressor-end-temperature conditions (up to 600°C), to avoid ignition inside the intake dukt or flashback to happen, detailed knowledge about the autoignition process is necessary. This international research is covered under another ESA TT since 1998.

The investigations on flashing and flame spreading over solid spacecraft materials is directely related to space technology. On one hand, fires in space are the worst accident scenario as no escape is possible, on the other hand, wall fires or fires along cable insulation materials proceed quite different compared to ground fires. These slowly spreading fires can burn invisible and undetected for very long periods producing harmful gases and toxic aggregates. Investigations on such materials are ongoing in France [12] and Spain.

Non-Intrusive Combustion Diagnostics

Modern laser based non-intrusive diagnostics become more and more important in combustion research. Since the beginning of developments in the 1970 many new findings were enabled. As microgravity research is fundamental research and expensive in any way, the equipment to answer the related questions must be appropriate and as effective as possible. On the other hand, the application of such techniques is connected with quite a lot of restrictions concerning volume, mass, power consumption, rigidity etc.. Therefore special developments are necessary in order to facilitate the use of laser diagnostics. These developments are at the very beginning and in a definition phase. On that way, drop towers enable a combination of ground based techniques applied to microgravity experiments. Fig. 6 depicts the installation of an excimer laser based diagnostic system (LDS) at drop tower Bremen. There, the laser system is attached to the vacuum tube and the beam is mirrored into the falling capsule. Light-sheet forming optics, the intensified camera and the data acquisition system is dropped together with the experiment. Besides its benefit for drop tower combustion research it has led to some new developments that are of terrestrial use. These are e.g.: high-speed LIF, automatic resonance calibration, fast wavelenght switching etc.. In the meantime the LDS system has been applied to most of the above mentioned projects. As an example, fig. 7 shows some images from a high-speed sequence of an autoigniting n-heptane droplet and is quite comparable to fig. 5.

In this case, formaldehyde being a chemical tracer for the cool-flame of the first stage of ignition was excited to fluorescence at 352nm (XeF). With these data, the ignition radius and the delay times are much better to define as compared to the interferometric technique. The comparison with reaction kinetics enhanced numerical simulations became quite more reasonable by means of those data.
Beyond reasonable doubt, the diagnostics aboard ISS will be based upon solid state lasers as they are much smaller, less sensitive and developments towards higher output energy are rapidly evolving. But up to then, many scientific questions as well as technological ones can be answered utilizing ground based microgravity facilities.

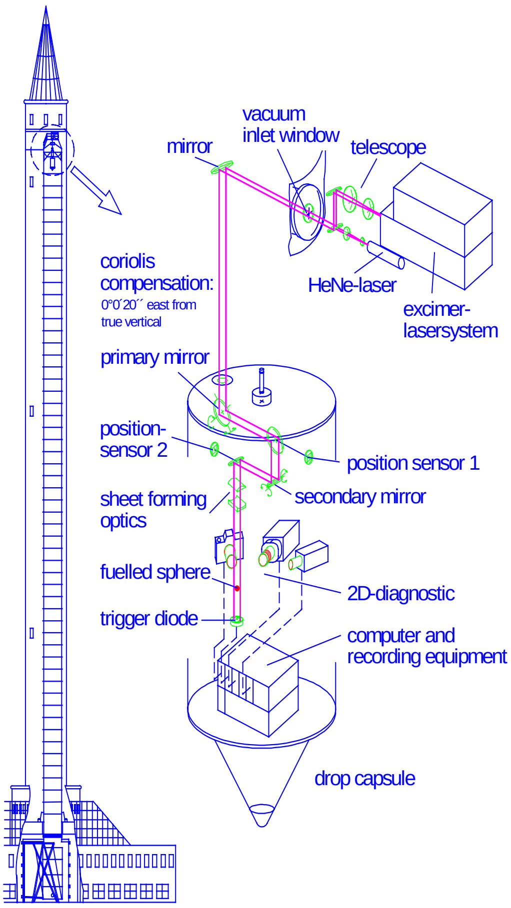


Fig. 6: Installation of the laser diagnostic system at drop tower Bremen

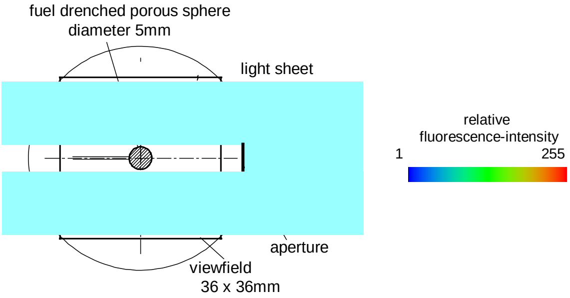
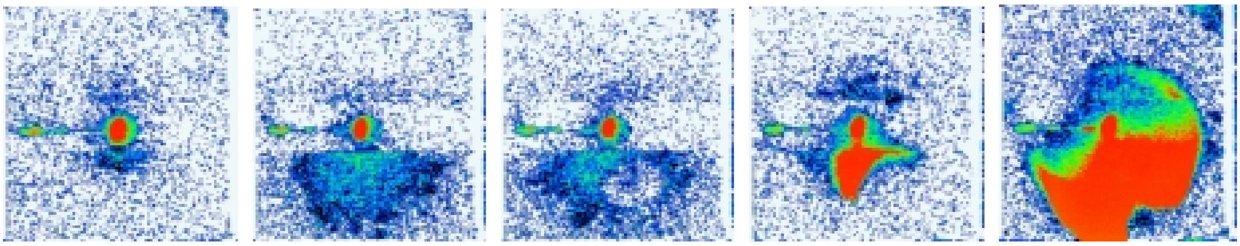


Fig. 7: Below: Formaldehyde-LIF images of a selfigniting n-heptane droplet. From left to right: 280, 1800, 1820, 1828, 1840 ms after insertion into hot ambient. First two images show the expanding cool flame, third image shows the point of hot ignition by a local consumption of formaldehyde, last two images show soot precursors during hot flame expansion.
Left: Optical configuration [13]



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