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Laurent Jamonet and Anne Pacros
Department of Aeronautics and Astronautics
MIT, Cambridge MA 02142

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REVIEW OF A COMBUSTION EXPERIMENT PERFORMED DURING A PARABOLIC FLIGHT

Laurent Jamonet*, Anne Pacros*,
Department of Aeronautics and Astronautics, MIT, Cambridge MA 02142

Abstract

Space exploration is becoming severely limited by propulsion systems that, most of the time, rely on the complex phenomenon of combustion in microgravity. Hence, improving the combustion of condensed phase fuels in sprays would increase the performance of rocket engines. But the study of spray combustion is so complex that modeling and experimental approaches are necessary. Therefore a microgravity combustion experiment has been designed and successfully flown in two parabolic flights during the 3rd ESA Student Parabolic flight campaign in Bordeaux, France (October 23 and 24, 2000). This experiment, named COSMIC for COmbustion around a Sphere in MICrogravity, consists of igniting a porous sphere fed with ethanol under controlled atmosphere and to observe the flame in microgravity by way of a camera recorder. Additionally, post-flight observations of the spheres provide important information about the formation of soot in microgravity. Parabolic flights provide 30 second-long periods of acceptable microgravity that allow ignition stabilization and observation of the almost round-shaped flame. Flight data are currently being analyzed to propose a correlation between the fuel flow and the diameter of the flame. This paper presents the conception and realization of this experiment, as well as the first conclusions of the experimental data analysis.

1 - Introduction

Many experts agree that the mastery of energy will be a major challenge in the future. Combustion of condensed phase fuels in sprays particularly needs to be improved; as it is used in many propulsion devices (car engines, liquid fuelled rocket engines...), it is necessary to increase their efficiency and to reduce the emission of soot. But as the members of an ESA topical team put it, the study of spray combustion is so complex that "experimental and modeling approaches are necessary. [...] Such modeling studies require experimental information on the local phenomena in order to simplify the conservation equations and to model the local phenomena that cannot be simulated numerically" [12]. That is why we proposed this experiment to study the combustion around a porous sphere, which is a good approximation of a constant diameter droplet.

More precisely, the problems at stake are:

- Ignition and stability limits
- Flame propagation velocity
- Flame instabilities (oscillations)
- Extinction
- Soot formation

Microgravity is very relevant to study these problems. The first point is that the absence of gravity leads to a phenomenon that has the spherical symmetry. Hence the experiment is as close to the theory as possible. Moreover, the aim of this experiment is to observe temperature and flame instabilities during the combustion. As the flame is only faced with natural convection forces and viscosity forces, the experiment is led by the ratio of those forces, which is called the

* Graduate students Ecole Centrale Paris/MIT, AIAA student members
Contact: ljamonet@mit.edu, pacros@mit.edu

Grashof number Gr. It can also be written as a combination of physical parameters which interfere with the combustion: $Gr = g L^3 \Delta T / T \nu^2$ where g stands for gravity, L for the characteristic dimension such as the drop diameter, ΔT for the temperature range, T for the temperature, and ν for the cinematic viscosity. We would like to have steady conditions during the combustion, with the less natural convection possible, which means the lowest Gr. We can only act upon g and L to modify Gr. But the measurements we want to do require spatial and temporal resolution that are impossible to obtain with small particles. Therefore one is obliged to move to larger droplet sizes and L cannot be reduced too much. The only remaining parameter we can modify is g: the lower g we have, the lower Gr will be and the better results we will obtain. That is why microgravity is required. Moreover, in microgravity, fundamental characteristics such as ignition and long-term stability limits can be determined independently of flow and turbulence conditions and then used for model validation.

Consequently, performing this experiment on a parabolic flight opens up new avenues for scientific research, which are long awaited by scientists and also fully relevant for applications. We will study the influence of the incoming flow on the combustion around the sphere (it is possible to find a relation between this flow and the evolution of the diameter in a "real" droplet). We will first describe our experimental device, and then we will explain the results that we have already obtained on earth and in parabolic flight. We will conclude on the future developments of our experiment. This flight campaign showed many interesting aspects of combustion that really deserve being explored further in upcoming flights.

2 - Experimental set-up

General description

We chose to use ethanol as the fuel, because it is cheap, easy to procure, and it can be carried with relatively few precautions. Ethanol is injected continuously in a porous sphere via a syringe, as shown on figure 1. It diffuses from the center to the surface of the sphere where it is vaporized because of the heat of the flame. So the combustion does not take place on but around the surface of the sphere, which decreases the problems of soot.

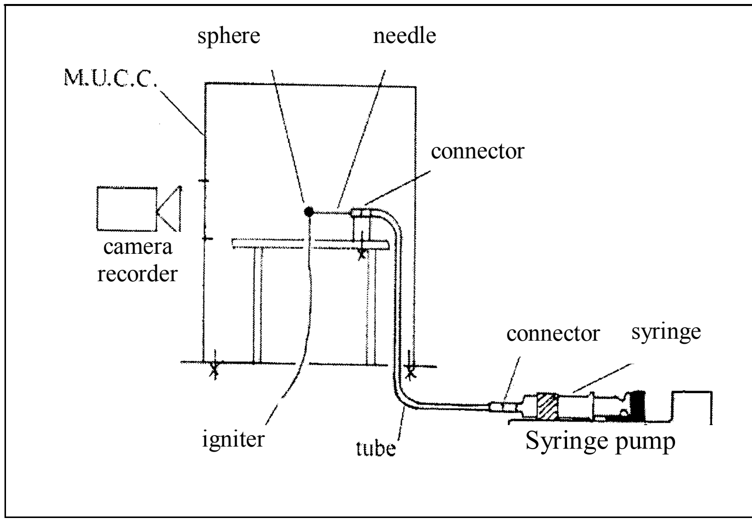


Figure 1 - Principle of the experiment

The core of the experiment has three parts:

- *The sphere*: it is a 8-mm diameter ceramic sphere. Its main characteristics are regularity of the surface in order not to have disturbances in the flame, high porosity (80%) to have a good diffusion of the ethanol and resistance to high temperatures.
- *The needle*: the needle is introduced to the center of the sphere and is stuck to the sphere. One major issue was the resistance of this link at high temperatures, because the dilatation coefficient of the needle and the sphere are very different.
- *The syringe*: the syringe is linked to the needle via a pipe. A syringe pump allows us to regulate the flow.

Flight equipment

Parabolic flights impose many security standards, especially for experiments including combustion because of the obvious fire hazard. Thus, the whole experiment has to be carried out in a certified combustion chamber. We used the CNES combustion chamber called "MUCC" (Multi-User Combustion Chamber, figure 2) that had already been certified and has flown combustion experiments in many parabolic flights. The MUCC has are four portholes. One can be opened during the flight and gives access to the experiment inside the MUCC. Another one is dedicated to observation: a camera records the experiment through this porthole. The third one is used for visual

control by the operators for increased safety and the fourth one was condemned. An air-regenerating system is also included in the MUCC. We designed the experiment so that only two operators are required to perform it.

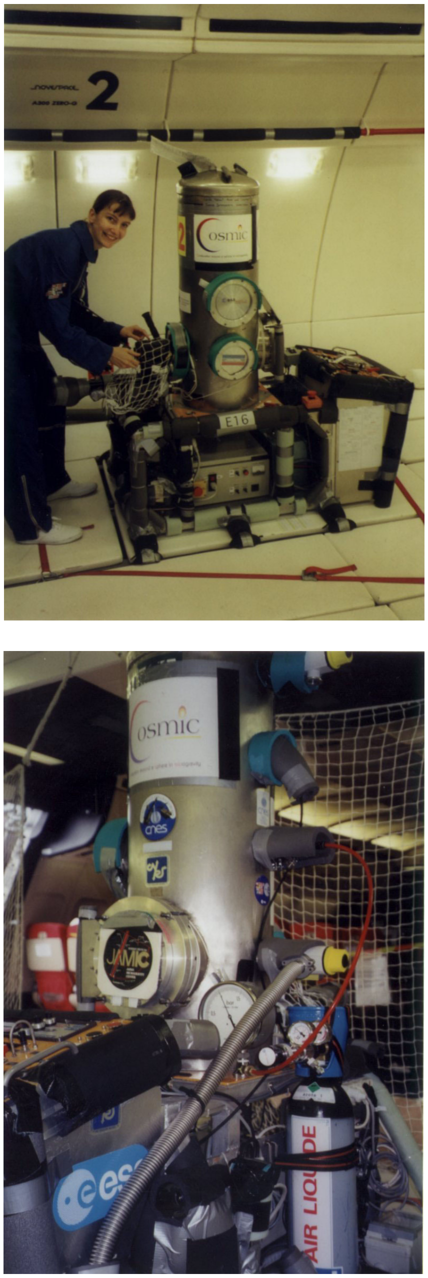


Figure 2 - Views of the combustion chamber (MUCC) onboard the A300 Zero-G"

The flame will be ignited with an electrically heated filament attached on an arm controlled by an electro-magnet. The arm has two possible positions: when the sphere has to be ignited, the arm brings the heated filament next to the sphere; as soon as the flame appears, the arm returns to its original position in order not to disturb the observation of the flame and filament electricity supply is turned off.

The materials in the chamber have to resist high temperatures. We chose brass and aluminum to build the support plate (figure 3) that strongly holds all the elements that go inside the chamber. This plate is then fixed on the MUCC in an airtight way. We checked by a calculation of materials strength that the system sphere-needle resisted +6 g. All the connections (needle-pipe, pipe-syringe, pipe-pipe when crossing the surface of the chamber) are secured using Luer Lock ® connectors.

Figure 3 - The support plate before its mounting inside the MUCC

The electric generators, the syringe pump and the syringe filled with ethanol are confined in a box (figure 4) outside of the MUCC to be kept away from the flame and high temperatures.

Figure 4 - The supplying box, containing the syringe pump and the power supply.

3 - Experimental protocol

Assumptions

For our calculations and interpretations we assume that:

- The combustion around the sphere has the spherical symmetry; we assume that the needle does not break this symmetry.
- All the injected fuel is burned
- The vaporization rate is constant (because the surface of the sphere remains constant).

Studied phenomena

With this experiment we attempt to:

- Understand how the flow and the periodical fluctuations of the flame are linked: the experiment carried out on earth had shown this phenomenon, but could not find a precise relationship.
- Study the non-stationary phases (ignition time and flame vanishing) qualitatively.

In-flight protocol

The parameter that varies is the flow. The same fuel (ethanol, C_2H_5OH) was used in all the experiments. We performed experiments for 13 different flows within a range of 10.6 to 36.1 mL/h with an accuracy of 2%. Observations have been conducted at least two times for each flow, and more for flows that demonstrated interesting properties.

Here is a typical sequence of operations. At the beginning of the observation period:

1) Safety Electro valve ON
2) Syringe pump ON
3) Igniter ON
4) Filament ON
5) Verify that the filament heats and that ignition occurs
6) Filament OFF
7) Igniter OFF

After the end of the observation period:

8) Syringe pump OFF
9) Electro valve OFF
10) Air regeneration.

We also had emergency procedures in case of fire or leaks.

4 - Results on Earth

Test of the experimental material

We wanted to be sure that the sphere and the needle glued together would resist the high temperatures caused by the flame. With the glue we used, the system resisted a 10-minute experiment. Figure 5 shows what the on-ground experimental set up looks like.

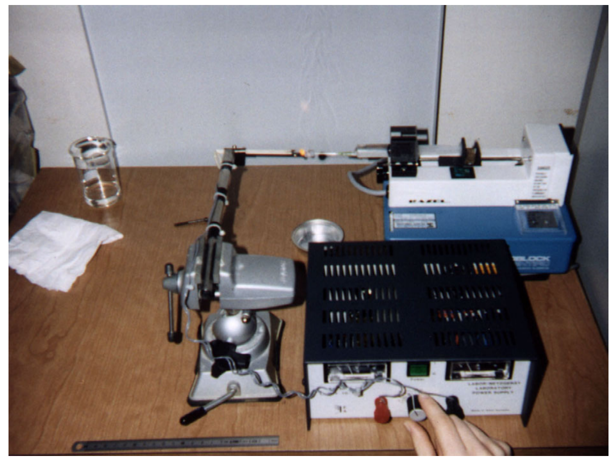


Figure 5 - The ignition process tested on earth

We also tested the filament (the igniter) and the ignition time. We tested different distances between the sphere and the filament, and different tensions, to determine what was the situation in which the ignition occurred first. We also compared two possibilities: either we turned the syringe-pump on first, or the filament. We concluded that the best situation was:

- To turn on the push-syringe first
- To have a distance of 3 mm between the igniter and the sphere
- To use a tension of 6V (the filament melts when the tension is 8.5V and the intensity 6 A)

The flame appears approximately 2 seconds after switching on the syringe pump and the filament (the filament warms very quickly but we must wait for the ethanol to fill the sphere).

Influence of the flow; optimal flow

We tried different values of the flow thanks to the push-syringe. When it was lower than 27.8 mL/hour, it was not enough to maintain the combustion, the flame came closer to the surface, soot was formed, and finally the flame vanished. The best value of the flow appeared to be 28.6 mL/hour. If the flow is greater, liquid ethanol comes to the surface and burns there, which damages the sphere.

Observations

On Earth, we recorded our experiments thanks to a CCD camera, with a Schlieren device. We observed the variations of the size of the flame and the phenomenon called "flickering", shown on figure 6.

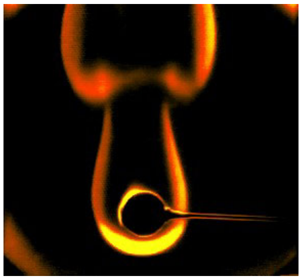


Figure 6 - Flickering flame around the sphere.

5 - Results from flights: qualitative analysis

Two parabolic flights were performed in the framework of the ESA 3rd Student Parabolic Flight campaign in Bordeaux, France (October 23 and 24, 2000). Indeed our experiment was selected along with 30 others among about 150 proposals from all over Europe. The plane we used to perform the parabolas was the Airbus A300 Zero-G (figure 7).

Figure 7 - Airbus A300 Zero-G

Our experiment worked very well and we were able to identify three main phases: Ignition, Microgravity and Hypergravity.

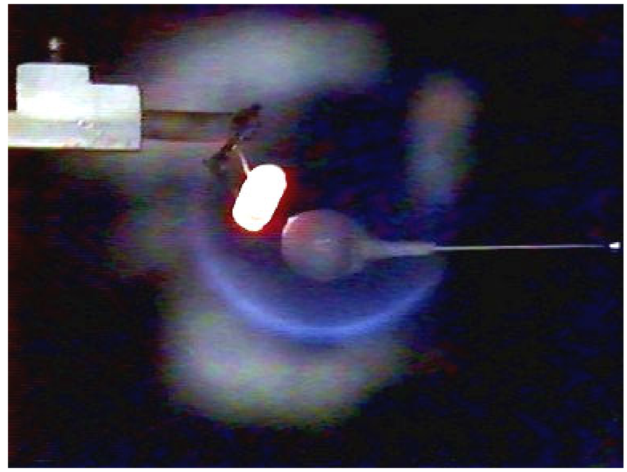


Figure 8 - Ignition

Fuel (ethanol) flow into the sphere was initiated about 20 to 40 seconds before the pull-up phase of each parabola depending on the fuel flux. This allowed for the ethanol to completely soak the sphere. The heating wire was turned on during the initial phase of hypergravity but due to gravitational drag, the ethanol vapor formed around the sphere was not enough concentrated within the area heated by the wire, so ignition conditions were not reached in the vicinity of the wire. Another effect of hypergravity is also to increase natural convection around the heated wire and thus to reduce its temperature. This is probably why ignition could not be achieved during hypergravity phases. Once the plane entered the phase of microgravity, gases quickly distributed themselves evenly around the sphere and provoked a rapid ignition (figure 8).

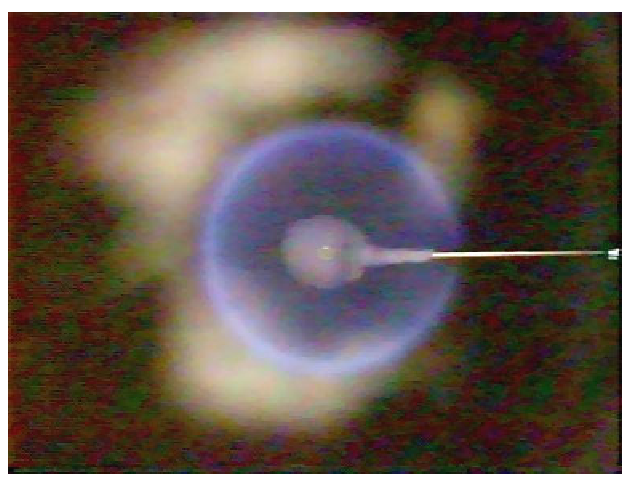


Figure 9 - Flame in microgravity.

During microgravity (figure 9), the flame around the sphere took - as predicted - an almost spherical shape. The influence of the needle seemed negligible. The diameter of the flame was about three times as big as observed during trial runs on Earth.

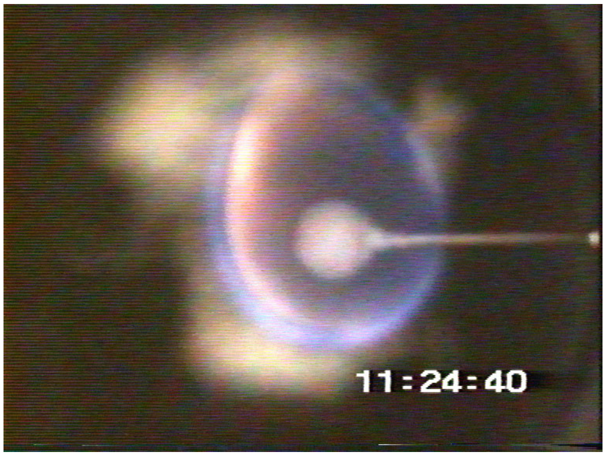


Figure 10 - Flame in 0.08g.

Fluctuations in the shape of the flame resulted mostly from varying g-levels as the flight accelerometers data proved it. These variations are related to small fluctuations of the g-level from perfect microgravity. The rapid change from 1.8g to 0g was also responsible for large natural convection flows in the MUCC and thus modified the flame shape (figure 10).

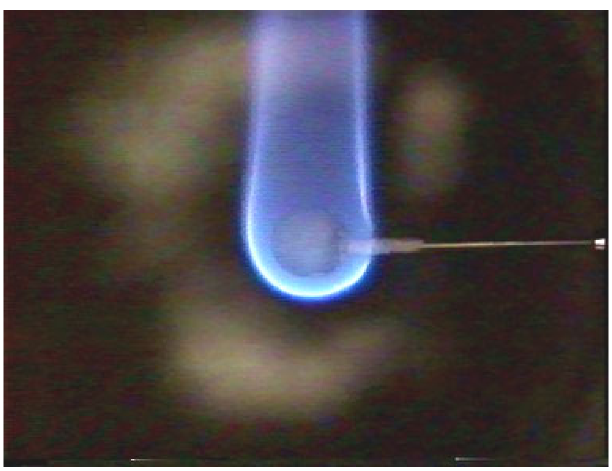


Figure 11 - Hypergravity

At the end of microgravity the effects of gravity quickly came back into play and gave the flame a more conventional shape (figure 11). Closer examination shows that during the following phase of hypergravity the flame forms an even more cylindrical shape than observed during a regime of 1g. The flame comes closer to the sphere at the bottom and tends to move aside from the sphere on the side. This is again caused by gravitational effects, which confine the hot gases to an area directly above the sphere. We can also point out that the flame in hypergravity is much brighter than the flame in microgravity. At high flows, a drop forms under the sphere and falls. Most of the time the flame extinguished itself during hypergravity phase or shortly after, when all the ethanol contained in the sphere was consumed. It was also noticed that the presence of soot was enhanced during the hypergravity phases.

6 - Results from flights: quantitative analysis

Observations

Before each flight we took some pictures of a test pattern (a ruler) so that it is easier to measure the diameters of the sphere and the flame (see figure 12). We also synchronize precisely the clock so that we can check on the onboard flight data that the microgravity level is acceptable during the periods when we observe the flame.

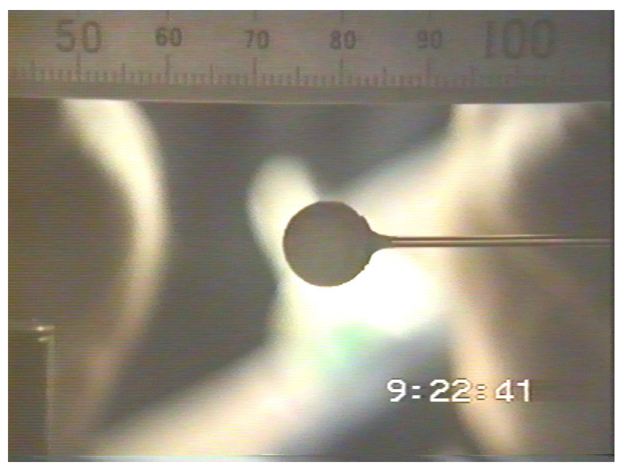


Figure 12 - Test pattern

The post-flight data analysis that we have done so far consists in digitalizing the videos, applying color treatment to highlight edges, averaging the flame and sphere diameters and correlating flame diameter and flow. Only a very small amount of data has been exploited at this point. The data we show here come from parabolas 11, 12, 16 and 17 in the first flight (flows of 27.6, 25.5, 17.0 and 14.9 mL/h respectively). We will soon have many more data points as we finish to extract images from the tapes. Since the sphere and

the flame may not be perfectly spherical, we took for the diameter an average value of two measures (see figure 13).

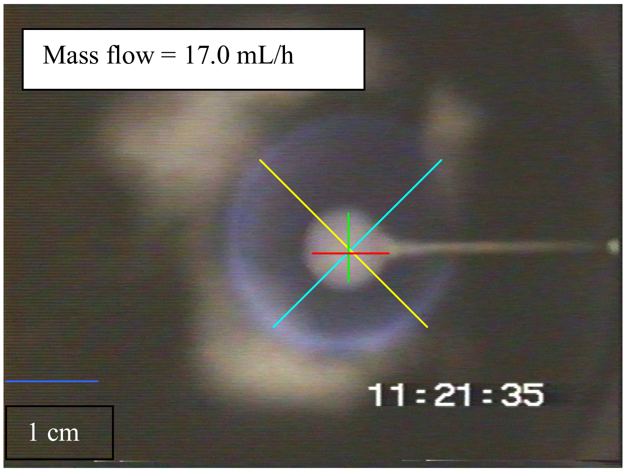


Figure 13 - Measuring the diameters

We did the same measurements on a total of four pictures. The results are shown in the table 14.

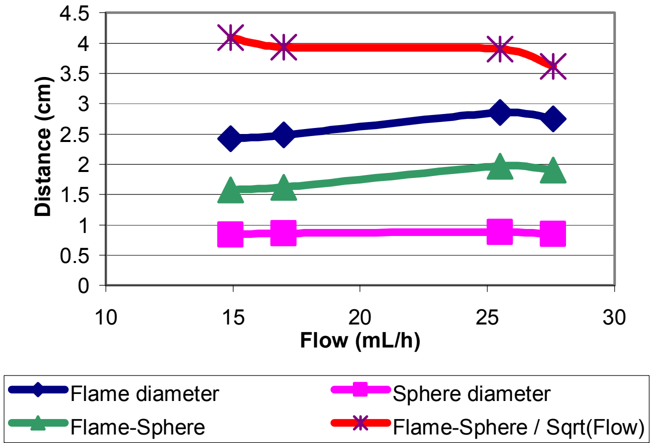
Parabola	11	12	16	17
Flow (mL/h)	27.6	25.5	17	14.9
Flame diameter	2.75	2.85	2.48	2.42
Sphere diameter	0.85	0.88	0.86	0.84
F-S diameter	1.9	1.97	1.62	1.58
F-S diameter/flow	0.36	0.39	0.39	0.41

Table 14 – Diameters (in cm)

Graph 15 shows the evolution of the diameter of the flame with respect to the ethanol mass flow. We also reported the difference

Δ = flame diameter – sphere diameter

(corrected flame diameter) as well as the ratio of Δ to the square root of the flow. From these few data points it seems that the flame diameter increases with the flow and that the ratio is approximately constant, but further analysis is required to draw a more precise conclusion.



Graph 15 - Correlation flow/Diameter

In addition, we notice that even if the flame is relatively spherical, it is not exactly centered on the sphere. We can also see that the dissymmetry is not always oriented on the same side. The flame can be closer to the needle or away from it. We assume that this is due to the combined effects of an imperfect microgravity causing the flame to move around the sphere and of the perturbation caused by the needle that destroys the spherical symmetry of the sphere.

<u>Correlation with theory</u>

A deeper analysis will be carried out using the model of a constant diameter fuel droplet. This model assumes that the ethanol evaporates at the surface of the droplet (constant radius R) in an oxidizer-rich environment (see figure 16). As a matter of fact, the flow fed to the sphere is equivalent to the variation of size of a real droplet.

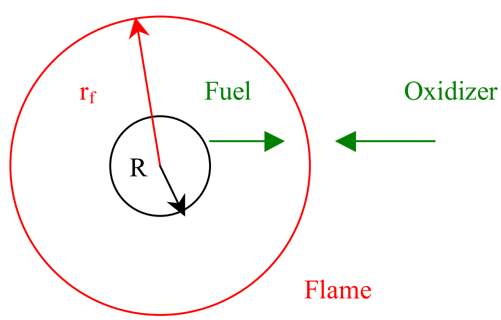


Figure 16 - Simplified droplet combustion theory

The fuel vaporizes and diffuses to the flame where it meets the oxidizer that has diffused from the outside. We assume that no oxidizer is present between the flame and the droplet. We can derive from this model and the conservation laws several different parameters driving the combustion. In particular, we plan to calculate the flame radius r_f and compare the results of the calculation with the measures taken during the flight. The corrected flame diameter should vary as the square root of the flow, assuming a constant evaporation rate at the boundary.

A limit to this model is that for high flow rates the saturation pressure is reached, which induces condensation. Then a drop forms and falls during hypergravity phases. An important point is consequently to find the limit value of the flow between these two models.

7 - Conclusion: future work

Many more post-analysis works are scheduled. They include:

- A much deeper exploitation the flame images (several thousands of pictures on two video tapes) correlated with the on-board records (microgravity level and its influence on the flame). This exploitation would enable a more quantitative evaluation of the mass flow rate effect on the ratio of flame to sphere diameter;
- A study of special phenomena such as extinction of the flame or non-ignition;
- A study of the soot formation on the spheres, based on both the nature and the amount of deposits.
- A CFD model using Fluent to check the influence of the needle. This simulation is difficult because of many special features: porous walls, phase transition, strong thermal gradients and flame contours.

Some future developments of the experiment are also planned in order to gain more data focusing on fields of great interest that are described below:

- Interesting improvements of our experiment would involve more sophisticated in-flight optical diagnostics such as a Schlieren device. It would enable us to see the distribution of hot gases and the temperature gradient. It requires a CCD camera, diaphragms and lenses. Moreover, it would be possible to compare the results with the ones obtained on Earth.
- Studying radiative heat transfer and temperature distribution within the sphere could also be a very interesting development of this experiment.
- Finally we could do systematic statistical analysis: the experiment is very sensitive to microgravity imperfections that occur during the parabolas. It results into a local deformation of the flame that no longer keep its perfectly spherical shape. Precision can be greatly improved by repeating the experiment many times keeping exactly the same flow. Then, using statistical analysis, it will be possible to compute the average shape of the flame in a much more precise way.

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