HETEROGENEOUS COMBUSTION PROCESSES UNDER MICROGRAVITY CONDITIONS

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1. EXPERIMENTAL PROGRAMME*

1.1. Introduction

An experimental programme on flame spreading over the surface of PMMA (plexiglass) samples has been conducted under microgravity conditions in the NASA KC-135 aircraft laboratory.

A few experiments (three) were conducted in 1986 under the preceding contract no. 6284/85/F/FL, but the largest part of the experimental programme has been carried out under the present contract in two parabolic flights campaigns.

A total of 36 experiments were performed, most of them successful. From the results of these experiments the flame-spreading velocities over PMMA samples have been obtained, as well as their laws of variation with pressure and mixture composition. Both cylindrical (axial symmetry) and flat (bidimensional symmetry) samples have been investigated.

These results were compared with those obtained under the same conditions of pressure and composition on the ground at 1 g, and it was shown how gravity does influence the spreading process and how this influence was affected by pressure and mixture composition.

It must be pointed out that flame spreading under microgravity conditions has been observed for the first time and that this ESA research programme has therefore been of a pioneering nature.

1.2. Selection of the experiments

The heterogeneous combustion process of a flame spreading over the surface of a condensed (solid or liquid) fuel and a reacting gaseous atmosphere is strongly influenced by gravity. Firstly, the characteristics of the spreading flame depend strongly on free convection, and secondly the spreading mechanism, especially the diffusion process of the fuel vapours into the reacting atmosphere is also altered by gravity.

On the other hand, flame spreading would constitute the basic mechanism of fire propagation in a spacecraft.

As a consequence, flame spreading can be considered as a combustion process highly appropriate and of great interest for the study of the influence exerted by gravity. In addition these types of experiments were considered suitable to be carried out during parabolic flights.

Although several fuels were initially studied**, considerations of simplicity, and above all, safety dictated the selection of PMMA.

As has already been mentioned, cylindrical and rectangular samples were investigated.

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1.3. Test equipment

1.3.1. Combustion chambers

The flame-spreading experiments were carried out in closed chambers.

Reloading of the chambers in flight is very difficult, and in order to avoid this reloading procedure before each parabolic flight it was decided to use several identical combustion chambers; three in the first campaign and six in the second and third campaigns (see Figs. 1.1 and 1.2).

Figure 1.1. Combustion chambers in the NASA KC-135 aircraft laboratory. First campaign.

Figure 1.2. Combustion chambers in the NASA KC-135 aircraft laboratory. Second and third campaigns.

Maintaining a constant composition of the atmosphere in the chambers during the combustion process would have implied the design of a complex system of gas extraction and mixture supply with a complicated control system.

Therefore it was decided to design the combustion chamber with a minimum volume in such a way that the composition of the atmosphere would not change substantially during the combustion process under microgravity conditions. Parabolic flights were of the order of 15—20 s. The amount of PMMA burnt during ignition and the 20 seconds of spreading combustion was measured on the ground by quenching the flame with nitrogen and by weighing the sample.

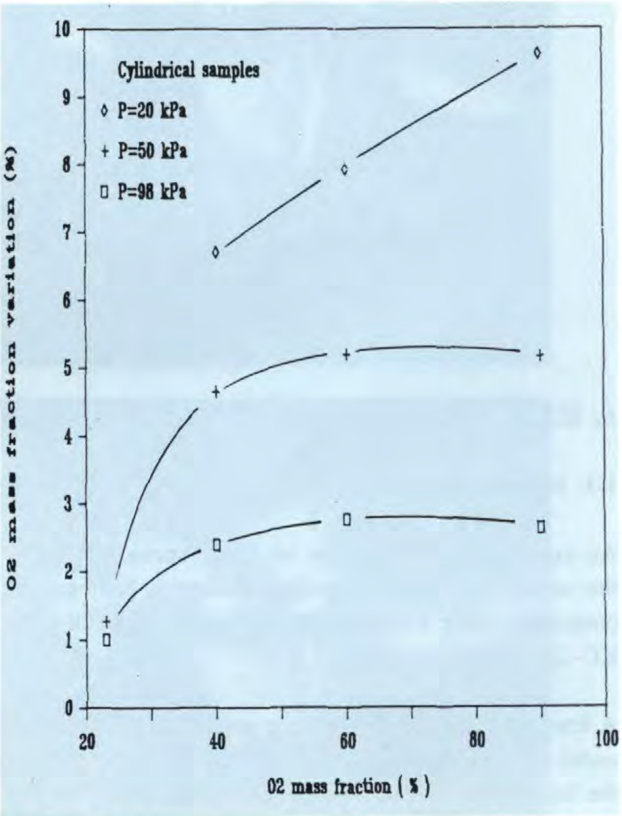

Figure 1.3. Variation of 02 mass fraction for a burning time of 20 s at 1 g.

Fig. 1.3. shows that for a chamber of 25 dm^3 in volume the gas composition does not change substantially during the process. This volume was selected since larger chambers were excluded due to problems of volume and weight.

NASA safety regulations specify design pressures of the chamber as function of both, maximum measured pressure and adiabatic combustion conditions of the total amount of fuel contained in the chamber (Fig. 1.4). This last condition implied the use of low mass samples (1—2 g). Maximum recorded pressure during the combustion processes was of the order of 140 kPa.

The chambers were designed and tested at 800 kPa according to those values.

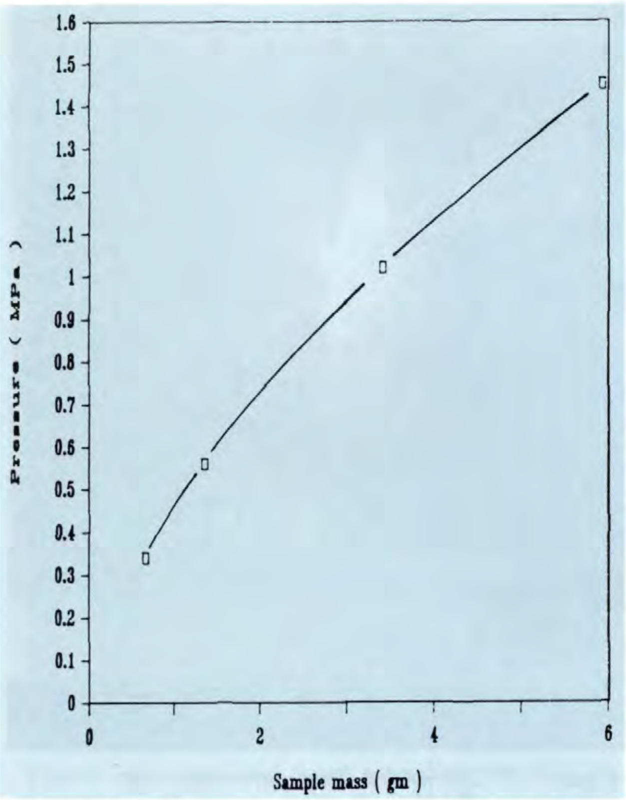

Figure 1.4. Maximum pressure for adiabatic and complete combustion.

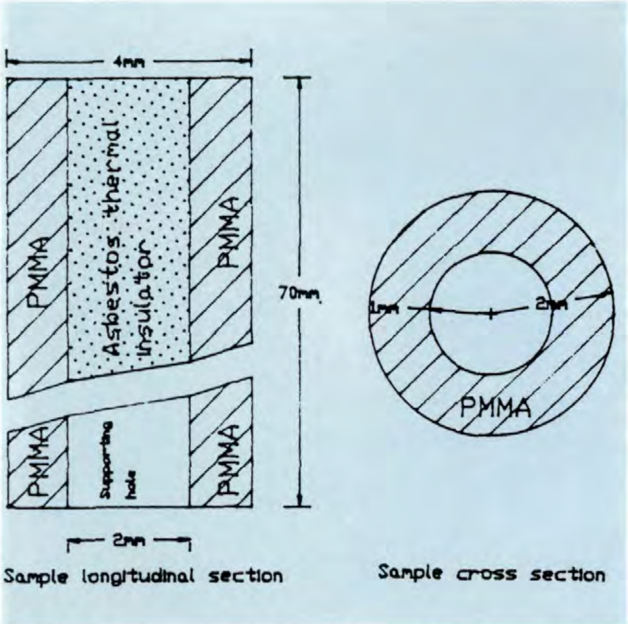

Figure 1.5. View of longitudinal and cross sections of a cylindrical sample.

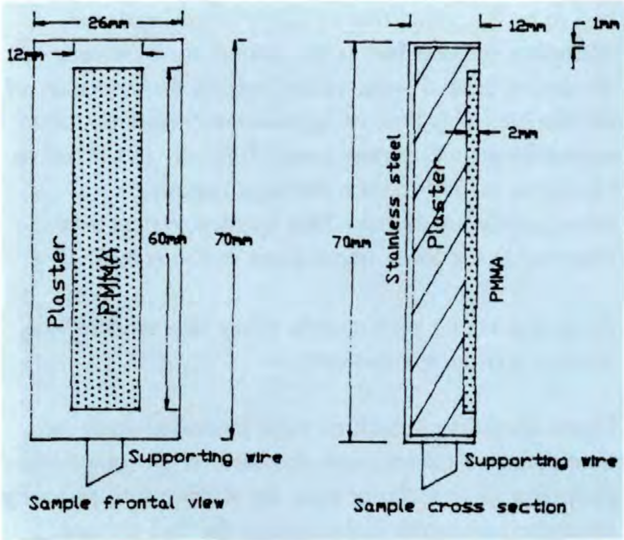

Figure 1.6. Frontal and cross-section view of a flat sample.

1.3.2. Samples

The cylindrical samples had a length of 60 mm and a diameter of 4 mm for the first and second campaign. They were designed with a central hole of 2.0 mm in diameter which was used for holding the sample with a wire. The surface of this hole was inhibited with asbestos to prevent combustion (Fig. 1.5), acting at the same time as heat transfer insulator of the wire.

The flat samples had a length of 60 mm, a width of 12 mm and a thickness of 2 mm. They were embedded in low thermal conductivity plaster* and contained in a rectangular stainless steel box (Fig. 1.6), leaving only a flat surface exposed to the combustion-spreading process. Plaster was used in order to prevent heat transfer along the metallic box which might have significantly altered the flame-spreading process.

1.4. Test procedure

Ignition presented special problems in the environment of the tests. Typical liquid-fuels ignition systems, normally used with PMMA, were unsuitable due to the conditions of the tests.

A very effective ignition system utilising a plastic double-base propellant and an electric spark was developed and tested on the ground. Unfortunately, it

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** Thermal conductivity of plaster is 2—3 orders of magnitude smaller than that of metallic materials.*

had to be discarded due to safety considerations. Therefore ignition had to be carried out by means of an electric heated wire, coiled around the extremity of the sample. This type of ignition was relatively slow, especially at low oxygen concentrations, and it had to be started slightly before the light reaching microgravity conditions. This ignition system was responsible for some imprecision in the results.

A camera taking photographs every two seconds was used as well as a video camera.

Flame-spreading velocities were measured from the time-recorded photographs and also on the ground by recording as function of time the temperature given by three thermocouples embedded in the fuel surface.

Pressure in the chamber was also recorded during the flame-spreading processes. However, it only varied slightly, and therefore results are not shown since they were practically not influenced by it.

1.5. Results

1.5.1. Experiments on the ground

An experimental programme was conducted on the ground, aimed at achieving the following objectives:

- Obtaining information on the order of magnitude of the flame-spreading velocities by carrying out experiments at low pressure in order to reduce the Grashof number. It allowed to select appropriate dimensions of the samples. These preliminary data were later to be verified during the first parabolic-flights campaigns.
- Development and testing of ignition systems, photographic equipment and recording devices.
- Obtaining the values of the flame-spreading velocities with the same samples and for the same range of pressures and mixture compositions that would later be obtained in flight under micro-gravity conditions.

Downward-spreading velocities were measured, taking average values of several experiments for each case.

Photographs of the flames are shown in Figs. 1.7, 1.8, 1.9 and 1.10 and the results of the spreading velocities as a function of mixture composition are shown in Figs. 1.11 and 1.12.

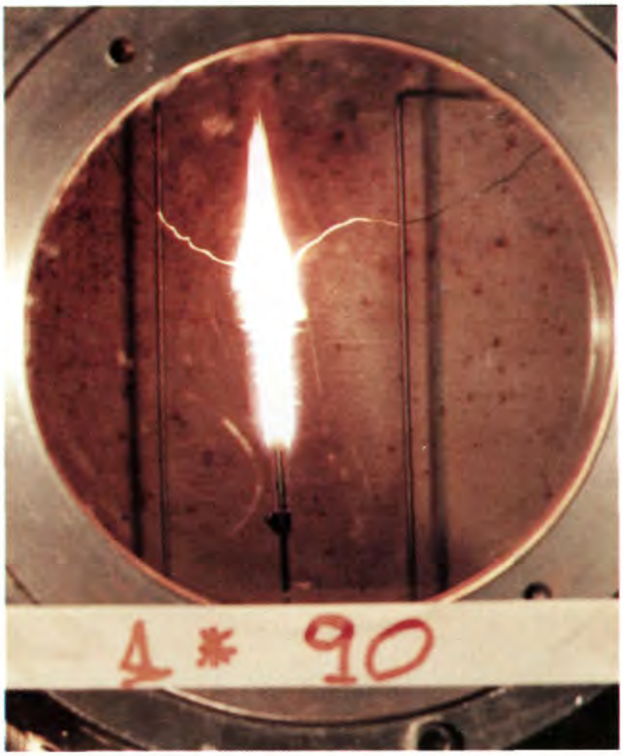

Figure 1.7. Downward flame spreading over cylindrical samples at 1 g. $Y_{02} = 0.9$, $P = 98$ kPa.

Figure 1.8. Downward flame spreading over cylindrical samples at 1 g. $Y_{02} = 0.9$, $P = 20$ kPa.

Figure 1.9. Downward flame spreading over flat samples at 1 g. $Y_{O2} = 0.90$, $P = 98$ kPa.

Figure 1.10. Downward flame spreading over flat samples at 1 g. $Y_{O2} = 0.90$, $P = 30$ kPa.

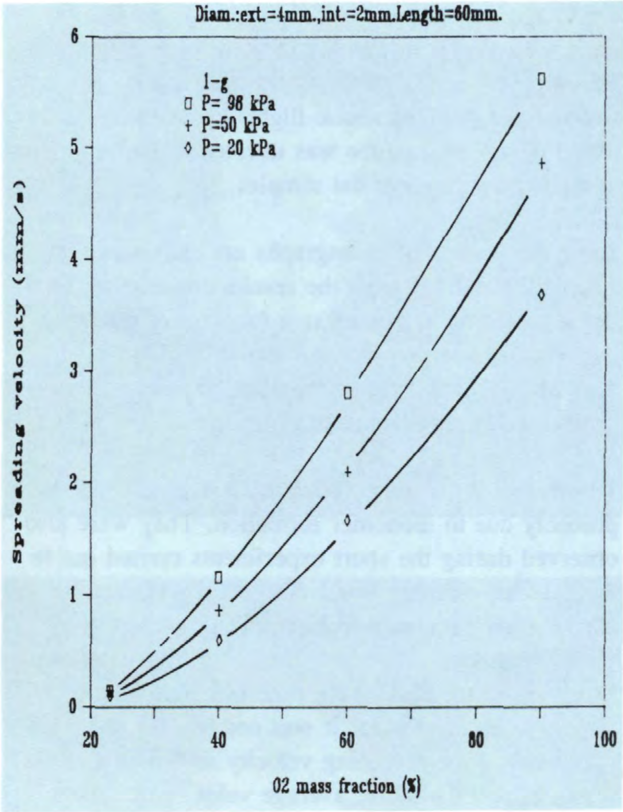

Figure 1.11. Results of measurements of flame-spreading velocities for cylindrical sample.

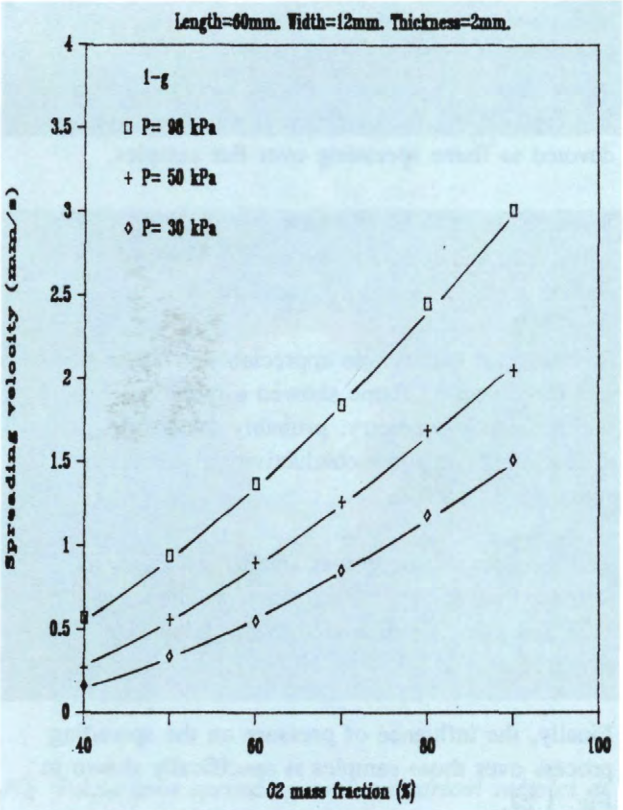

Figure 1.12. Results of measurements of flame-spreading velocities for flat sample.

1.5.2. Experiments under microgravity conditions (parabolic flights in the NASA K-135 aircraft laboratory)

In the April 1987 parabolic-flights campaign the experimental programme was devoted to flame spreading over cylindrical samples.

Some representative photographs are shown in Figs. 1.13, 1.14 and 1.15 and the results obtained of the flame-spreading velocities as a function of mixture composition and pressure are shown in Figs. 1.16, 1.17 and 1.18. Results of the 1986 parabolic-flights campaign are also included.

The flames show some radial irregularities which are probably due to monomer formation. They were also observed during the short experiments carried out in the free-fall chamber test facility of the Instituto Nacional de Tecnica Aeroespacial*.

Due to the shortness of the time available under microgravity conditions, it was not feasible to detect variations of the spreading velocity as function of the distance, and therefore, average values were taken.

There was some discrepancy between the results, but it was moderate except at low pressure and low concentrations. The very low spreading velocities at such conditions made obtaining meaningful results impossible, as shown in Fig. 1.18.

In October 1987 the parabolic-flights campaign was devoted to flame spreading over flat samples.

Some representative photographs are shown in Figs. 1.19, 1.20 and 1.21 and the results obtained are shown in Figs. 1.22, 1.23 and 1.24.

Scattering of results was appreciably lower in this case and the spreading flame showed a remarkable bidimensional symmetry, probably due to the utilisation of very low conductivity material surrounding the sample.

The spreading velocity was smaller for these flat samples than for cylindrical ones, as shown in Figs. 1.25 and 1.26 and discussed in the following paragraph.

Finally, the influence of pressure on the spreading process over those samples is specifically shown in Fig. 1.27.

$t = t_0$ s

$t = t_0 + 0.40$ s

$t = t_0 + 0.80$ s

Fig. 1.13 Flame spreading over cylindrical samples at microgravity conditions in the NASA KC-135 aircraft laboratory. $Y_{O2} = 0.90$, $P = 98$ *kPa.*

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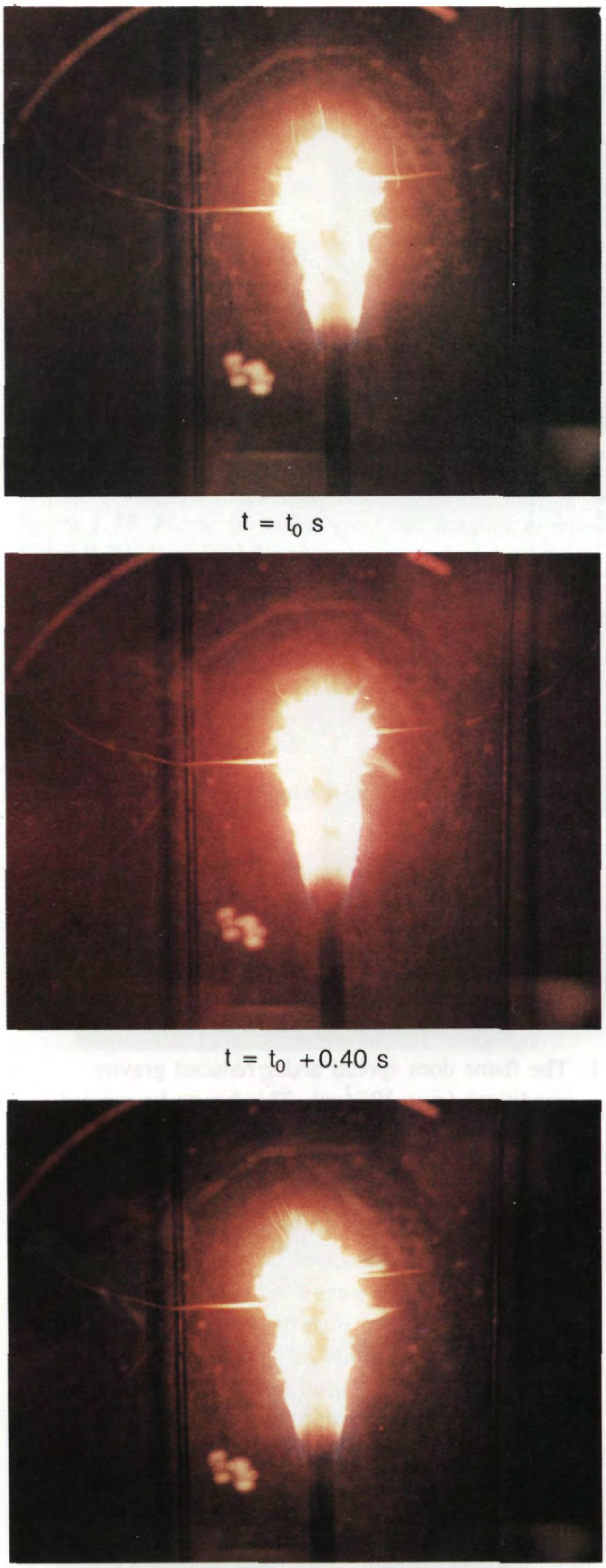
* *Contract no. 6284/85/F/FL, Final Report*



$t = t_0$ s

$t = t_0 + 0.40$ s

$t = t_0 + 0.80$ s

Fig. 1.14 Flame spreading over cylindrical samples at microgravity conditions in the NASA KC-135 aircraft laboratory. $Y_{02} = 0.90$, $P = 50$ *kPa.*

Fig. 1.15 Flame spreading over cylindrical samples at microgravity conditions in the NASA KC-135 aircraft laboratory. $Y_{02} = 0.80$, $P = 20$ *kPa.*

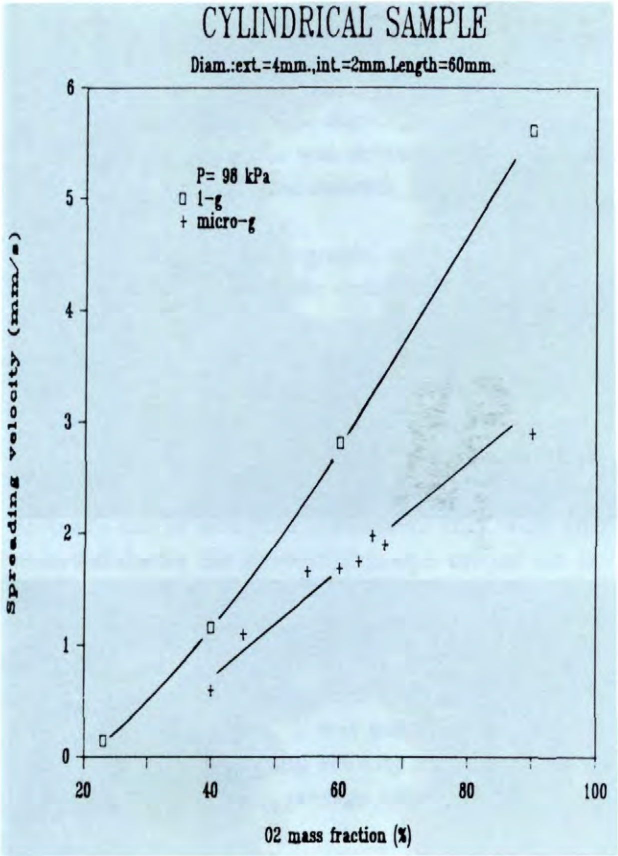


Fig. 1.16

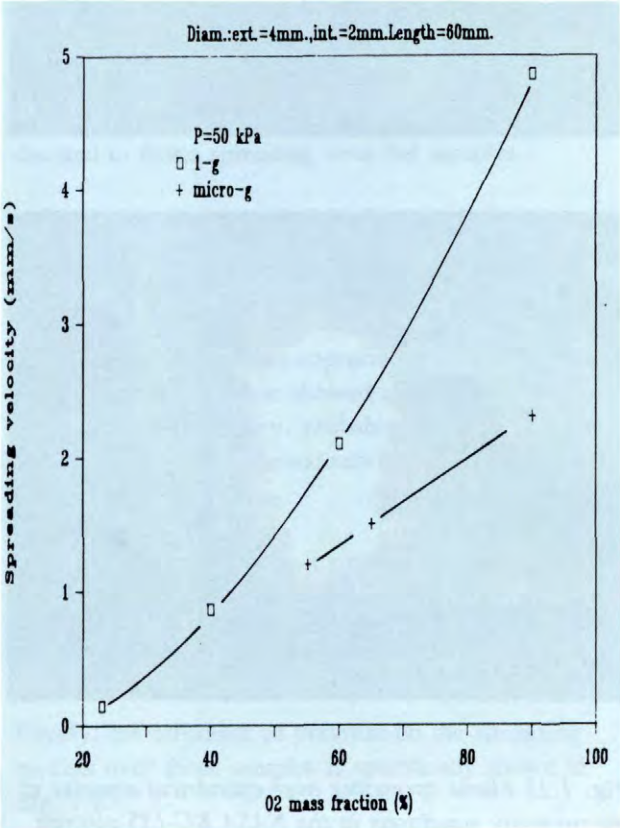


Fig. 1.17

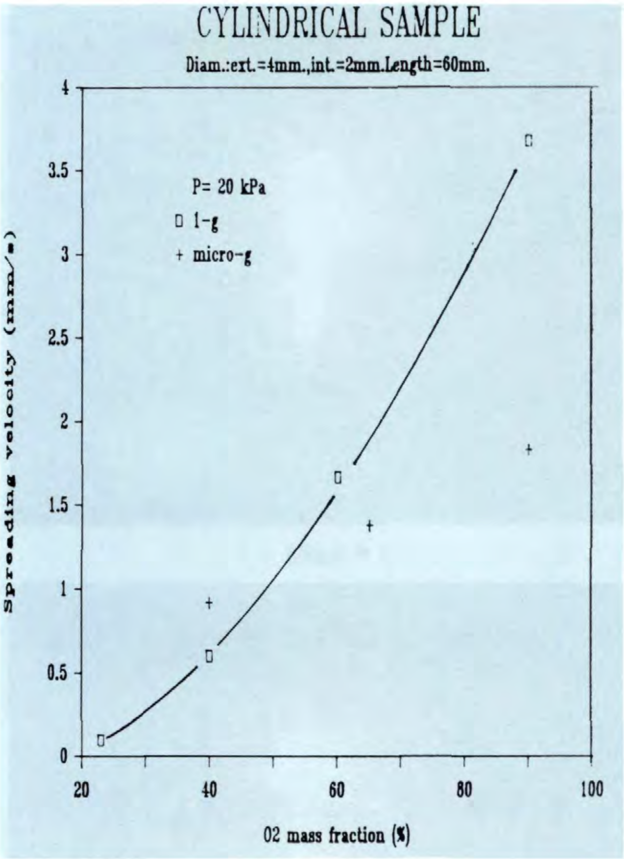


Fig. 1.18

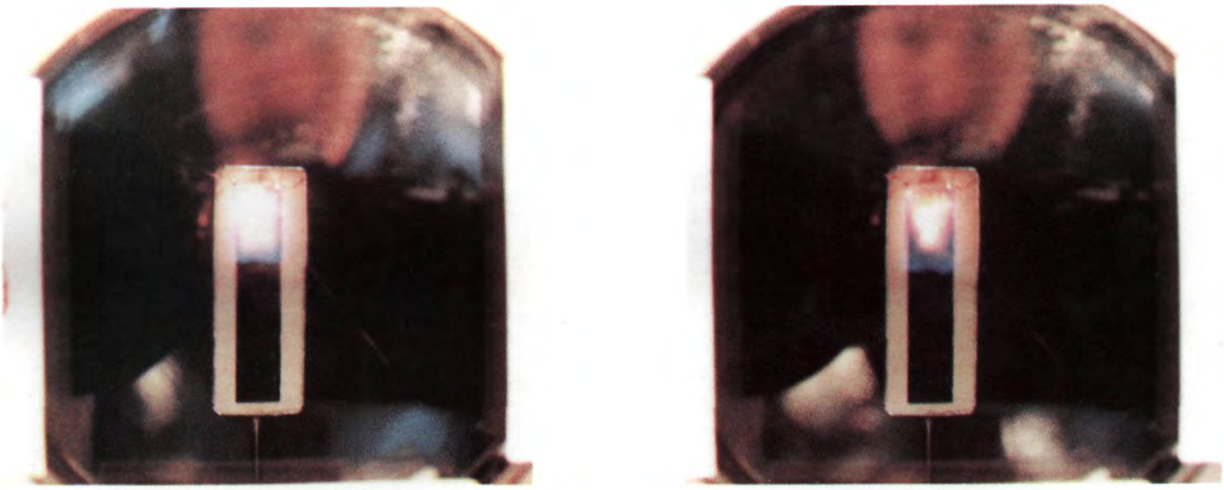
(Figures 1.16, 1.17, 1.18): Results of measurements of the flame-spreading velocities as a function of mixture composition and pressure.

1.6. Conclusions

1. The flame does spread under reduced gravity conditions (g = 10^{-2}go). This has to be pointed out since there had been doubts about the possibility that a flame might or might not spread under microgravity conditions.

2. Flame-spreading velocities are considerably lower under microgravity conditions, but within the same order of magnitude, than flame-spreading velocities at 1 g. Therefore it has to be considered that the Grashof number at 1 g is small owing to the small size of the samples tested.

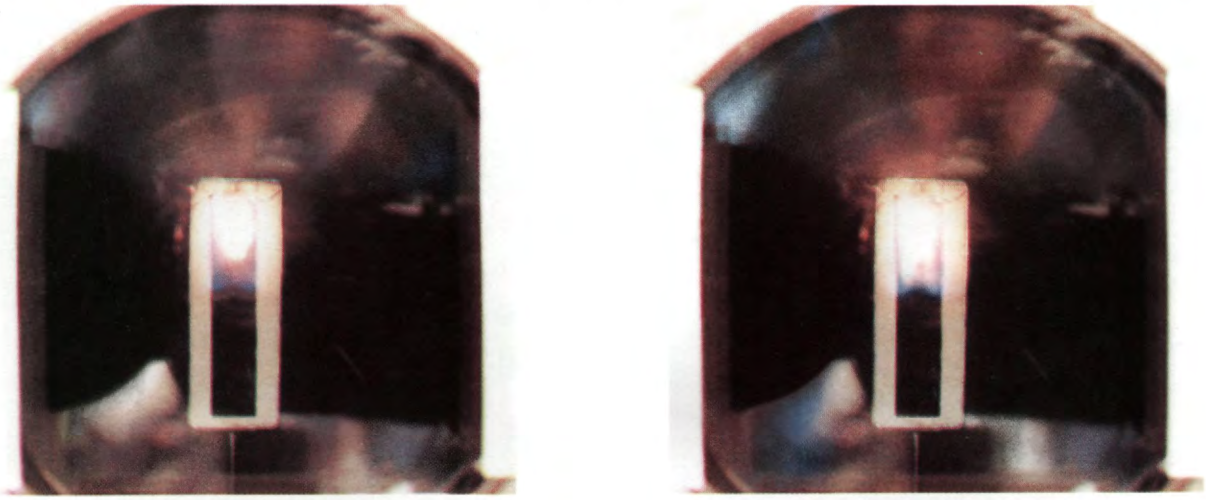
3. The influence of gravity decreases when the mixture pressure is reduced, a conclusion explained by the fact that at 1 g the Grashof number is proportional to the square of the pressure if temperatures are constant. On the other hand, under microgravity conditions the influence of pressure is small, since it is only exerted through its direct influence on the combustion process.



$t = t_0$

$t = t_0 + 2$ s

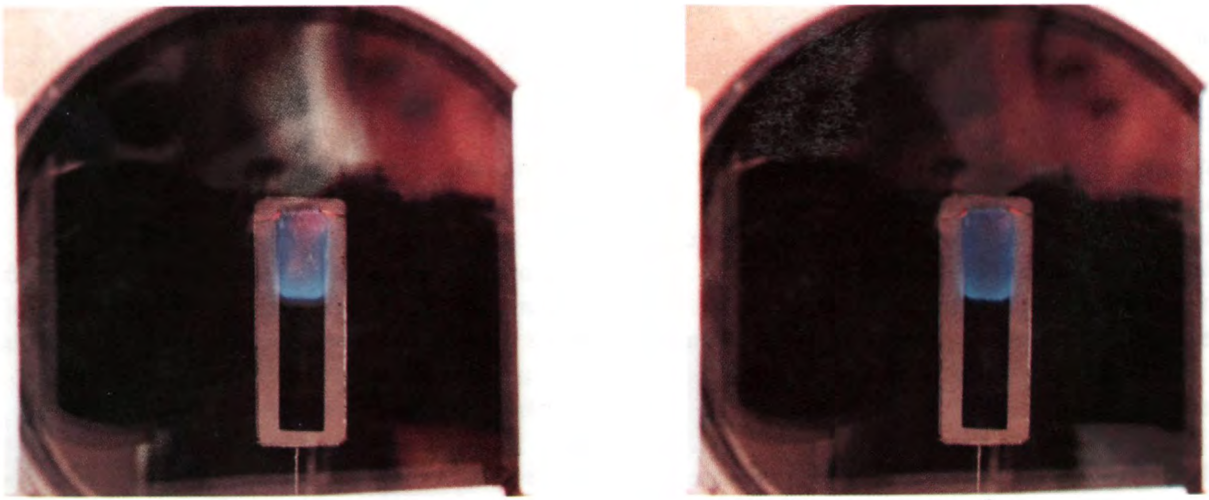
Figure 1.19. Flame spreading over flat samples at microgravity conditions in the NASA KC-135 aircraft laboratory. $Y_{02} = 0.80$, $P = 98$ *kPa.*



$t = t_0 + 4$ s

$t = t_0 + 6$ s

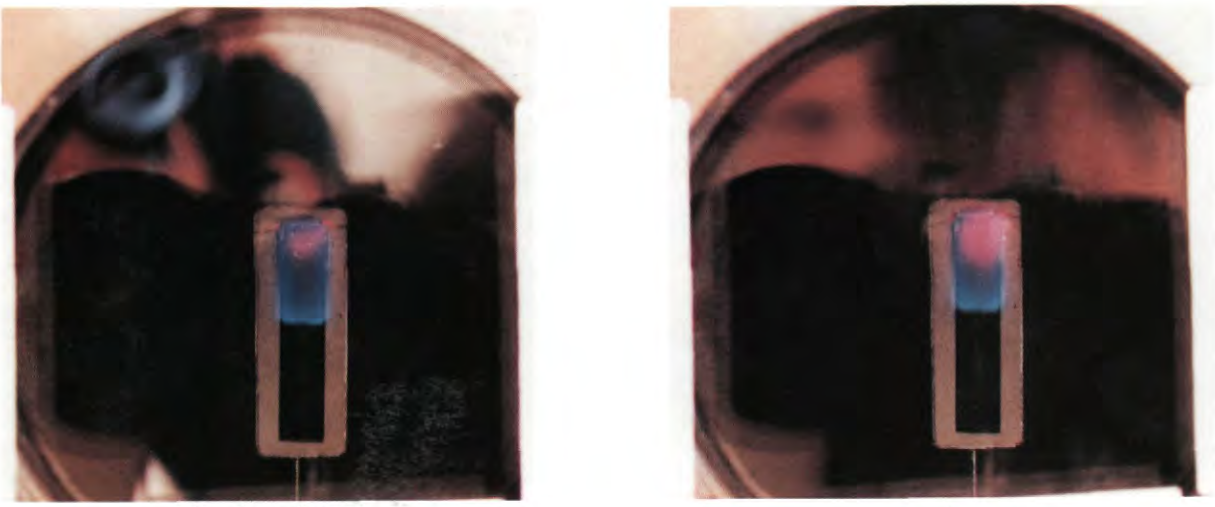
Figure 1.19. (cont.) Flame spreading over flat samples at microgravity conditions in the NASA KC-135 aircraft laboratory. $Y_{02} = 0.80$, $P = 98$ *kPa.*



$t = t_0$ s

$t = t_0 + 2$ s

Fig. 1.20. Flame spreading over flat samples at microgravity conditions in the NASA KC-135 aircraft laboratory. $Y_{02} = 0.80$, $P = 50$ *kPa.*



$t = t_0 + 4$ s $t = t_0 + 6$ s

Figure 1.20 (cont.). Flame spreading over flat samples at microgravity conditions in the NASA KC-135 aircraft laboratory. $Y_{02} = 0.80$, $P = 50$ *kP.*

a) $P = 98$ kPa, $Y_{02} = 0.80$ b) $P = 98$ kPa, $Y_{02} = 0.50$

Figure 1.21. Flame spreading over flat samples at microgravity conditions and different O_2 *mass fractions. NASA KC-135 aircraft laboratory.*

4. When the oxygen concentration decreases the difference between results at 1 g and under microgravity also decreases, since the combustion temperature decreases at lowered oxygen concentration, reducing the flame-spreading velocities in both cases, but more significantly at 1 g as in this case the Grashof number also decreases.

5. Flame-spreading velocities are lower in the case of bidimensional symmetry than in the case of cylindrical symmetry.
   This may be explained when considering that the heat transferred from the flame to the sample is higher per unit of volume in the case of the cylindrical flame, due to the thin diameter of the sample compared with a characteristic length of the flame. Therefore the sample temperature ahead of the flame is higher in the cylindrical case, resulting in a higher flame-spreading velocity. In addition, sample thickness was higher in the flat samples.

6. Flame spreading over flat samples at test conditions showed a good approximation to real bidimensional conditions. Therefore they are suitable for verifying theoretical models.

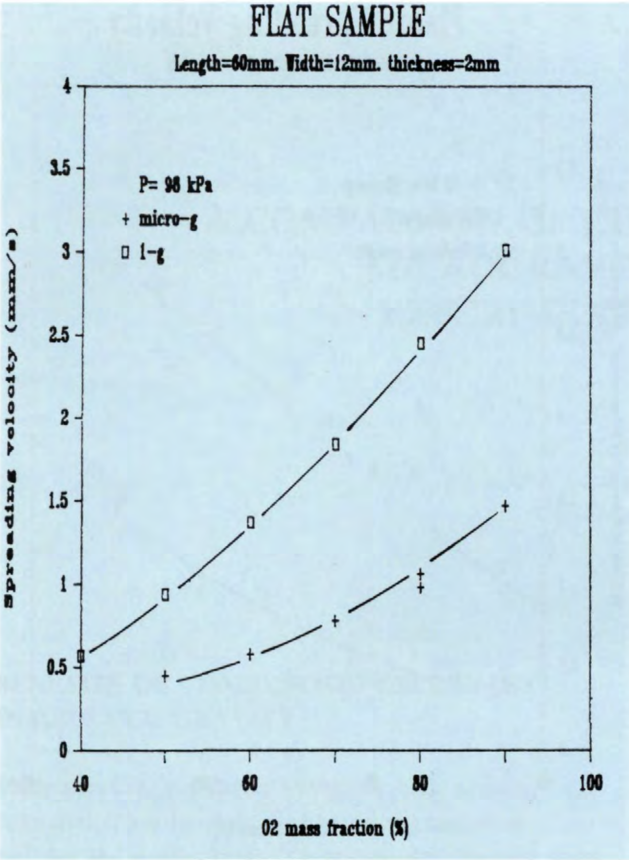


Fig. 1.22

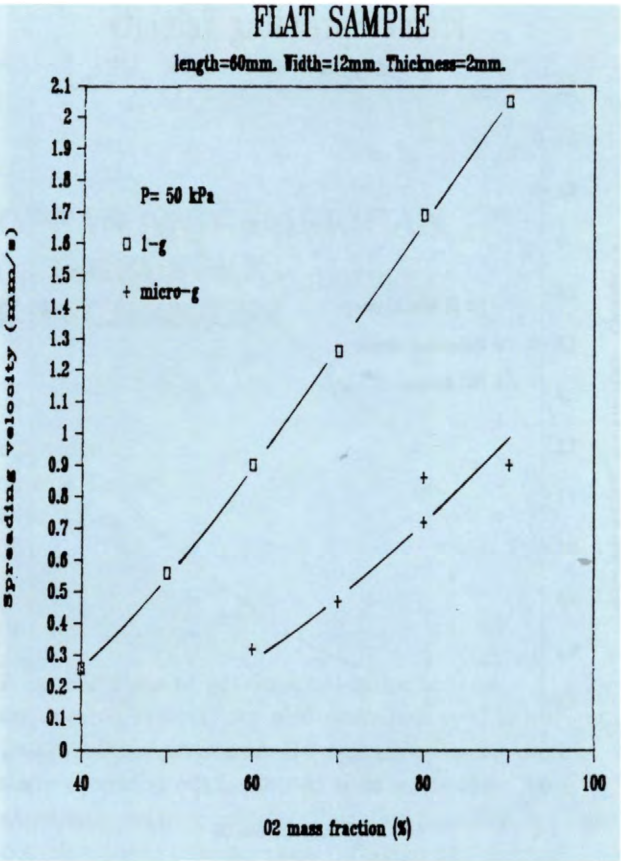


Fig. 1.23

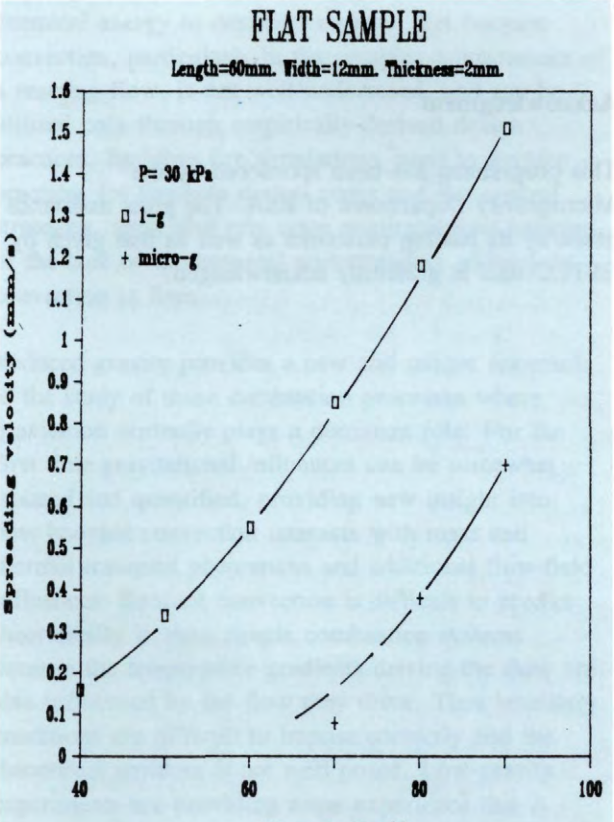
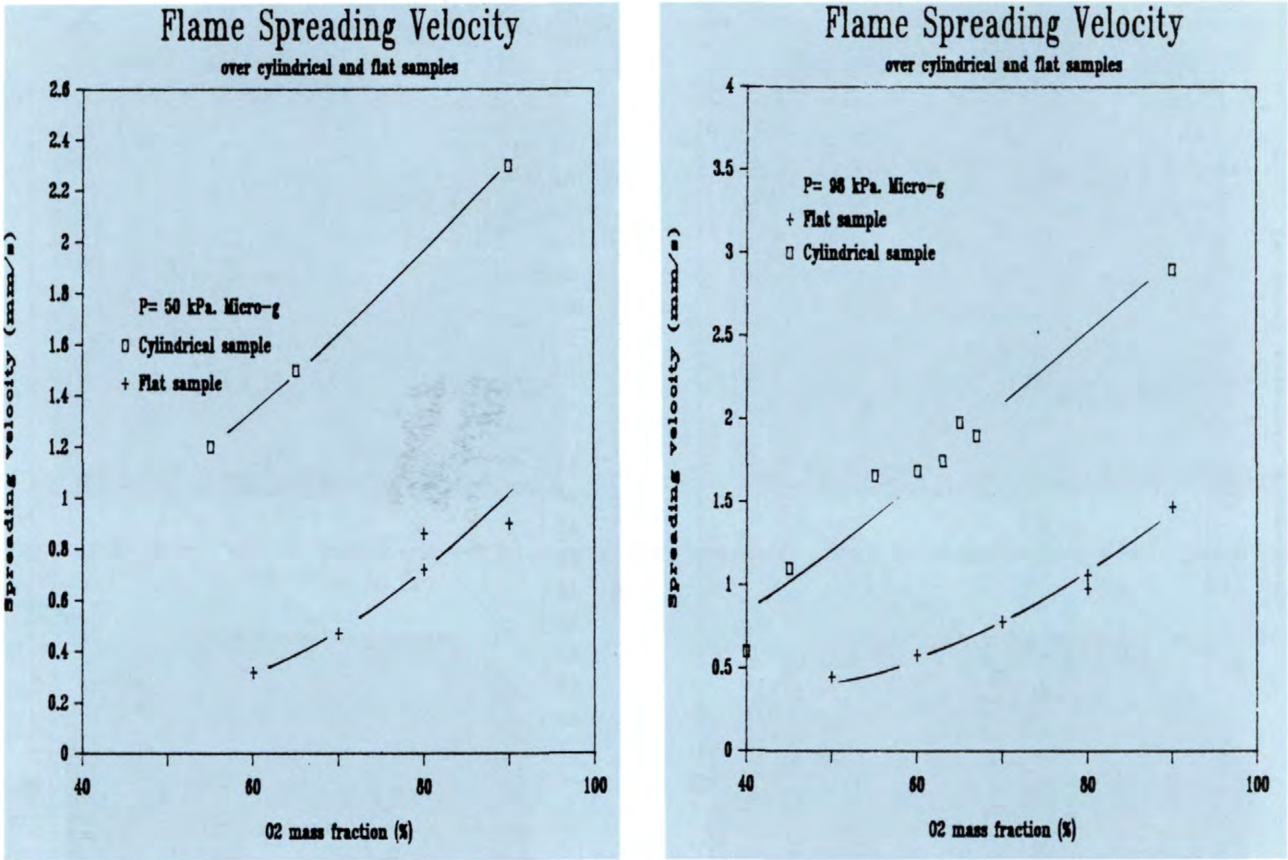


Fig. 1.24

(Figures 1.22, 1.23 and 1.24): Results of measurements of flame-spreading velocities over flat samples during parabolic flights in October 1987.



Figures 1.25 and 1.26: Results of measurements of flame-spreading velocities over cylindrical and flat samples.

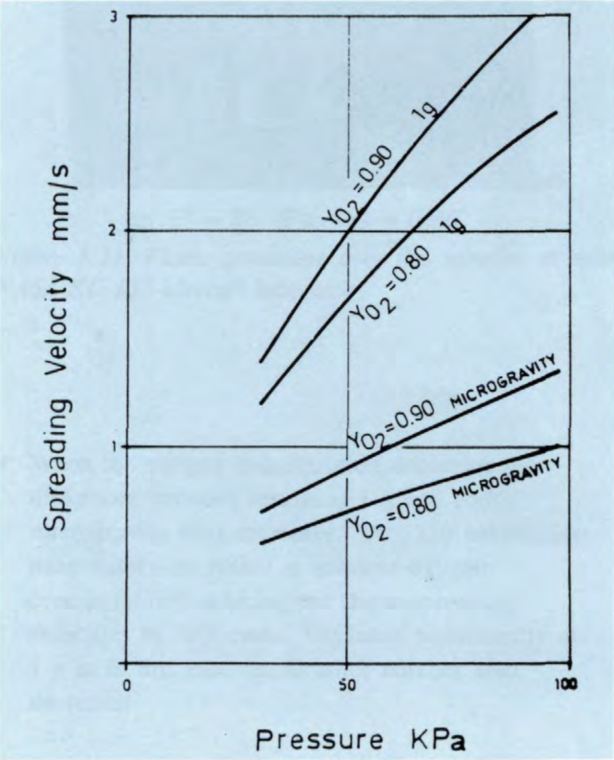


Figure 1.27. Results of measurements of the influence of pressure on the flame-spreading process over cylindrical and flat samples.

Acknowledgment

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