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An Experimental Programme on Flame Spreading at Reduced Gravity Conditions

An experimental programme on flame spreading over the surface of polymethylmetacrylate (PMMA) samples has been conducted at reduced gravity conditions in the NASA KC-135 aircraft laboratory. A total of 36 experiments were performed. 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 and flat samples have been investigated. These results were compared with those obtained for the same conditions of pressure and composition on the ground at 1 g. In this way it was shown how gravity does influence the spreading process and how this influence was affected by pressure and mixture composition.

1 Introduction

The heterogeneous combustion process of flame spreading over the surface of a condensed (solid or liquid) fuel and a reacting gaseous atmosphere it is strongly influenced by gravity. In the first place, the characteristics of the flame that spreads depend strongly on free convection, and in the second place the spreading mechanism, specially the diffusion process of the fuel vapors into the reacting atmosphere is also altered by gravity.

On the other hand, flame spreading would be an essential part of the mechanism of fire in a spacecraft.

As a consequence, flame spreading can be considered as a combustion process appropriated and of positive interest for the study of the influence exerted by gravity. In addition, these types of experiments are suitable to be carried out by means of parabolic flights. However, the information available on these processes is very scarce.

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

2 Test Equipment

Combustion Chambers

The flame spreading experiments were carried out in closed chambers.

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Fig. 1. Combustion chambers in NASA KC-135 aircraft laboratory

Reloading of the chambers between parabolic flights is very difficult. In order to avoid this problem it was decided to utilize several equal combustion chambers (fig. 1).

Maintaining a constant composition of the atmosphere within 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.

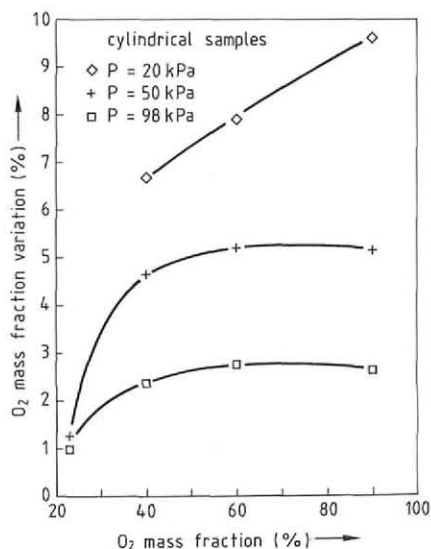


Fig. 2. Variation of the O₂ mass fraction in the oxidizing mixtures for a burning time of 20 s at 1-g

Therefore, it was decided to design the combustion chambers with a minimum volume such that the composition of the atmosphere would not change substantially during the combustion process at reduced gravity conditions.

For a chamber of 25 dm³ in volume, it is shown in fig. 2 that the gas composition does not change substantially during the 20 seconds combustion characteristic time of a parabolic flight. This volume was selected since larger chambers were precluded 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. This last conditions implied the utilization of low mass samples (1-2 g). Maximum recorded pressure during the combustion processes was of the order of 135 kPa.

According to those values the chambers were designed and tested at 800 kPa.

Samples

The cylindrical samples were of 60 mm in length and 4 mm in diameter. They were designed with a central hole of 2.0 mm in diameter utilized to hold the sample with a wire. The surface of this hole was inhibited with asbestos to prevent combustion acting at the same time as heat transfer insulator of the wire.

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

3 Test Procedure

Ignition presented special problems in the environment of the tests. Typical liquid fuels ignitions systems, normally used with PMMA could not be utilized at the conditions of the tests.

A very effective ignition system utilizing a plastic double base propellant and an electric spark was developed and tested on the ground. Unfortunately, it had to be discarded due

to safety considerations. Therefore, ignition had to be carried out by means of an electric heated wire, coiled at the extremity of the sample. This type of ignition was relatively slow, specially at low oxygen concentrations, and it has to be started slightly before the flight reaching reduced gravity conditions. This ignition system originated some lack of precision in the results.

A photographic camera taking photographs every two seconds was utilized 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 temperatures 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 during the processes.

4 Results

Experiments on the ground

An experimental programme was conducted on the ground, directed to the achievement of the following objectives:

- Information of 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 appropriated dimensions of the samples, which were later verified in the first parabolic flights.
- Development and testing of ignition systems, photographic equipment and recording devices.
- Finally, a series of experiments were carried out in order to obtain the values of the flame spreading velocities with the same samples and for the same range of pressures and mixture compositions that would be later obtained in flight at reduced gravity conditions.

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

Results of the spreading velocities as function of mixture composition and pressure are shown in figs. 3 and 4.

Experiments at Reduced Gravity Conditions (KC-135 NASA Aircraft Laboratory)

The experiments were carried out in two flight campaigns, with a total of 36 experiments.

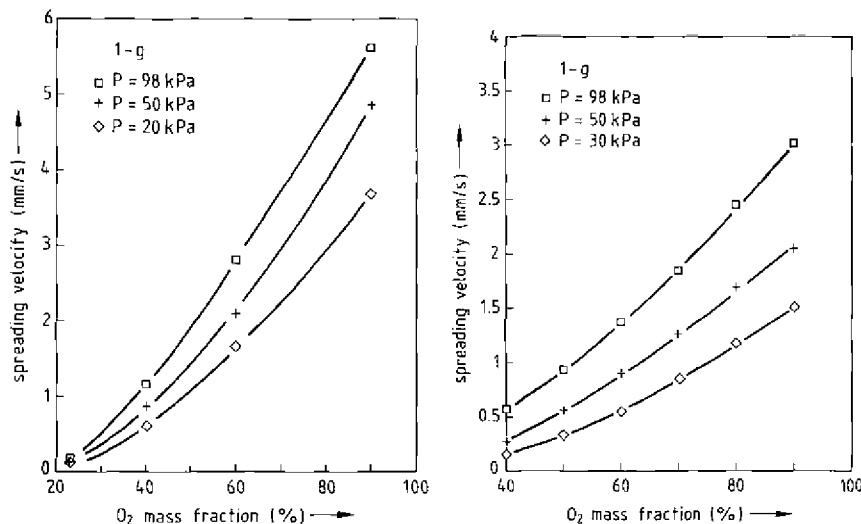


Fig. 3 (left). Downward flame spreading velocity over cylindrical samples at 1-g and at different pressures

Fig. 4 (right). Downward flame spreading velocity over flat samples at 1-g and at different pressures

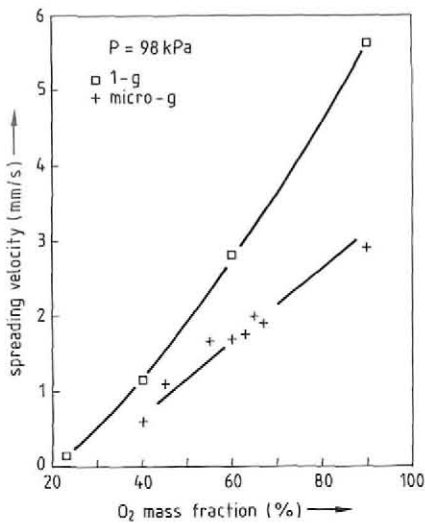


Fig. 5. Flame spreading velocity over cylindrical samples at 1-g and at reduced gravity

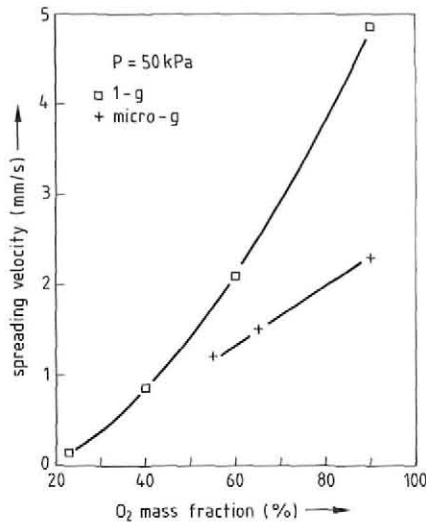


Fig. 6. Flame spreading velocity over cylindrical samples at 1-g and at reduced gravity

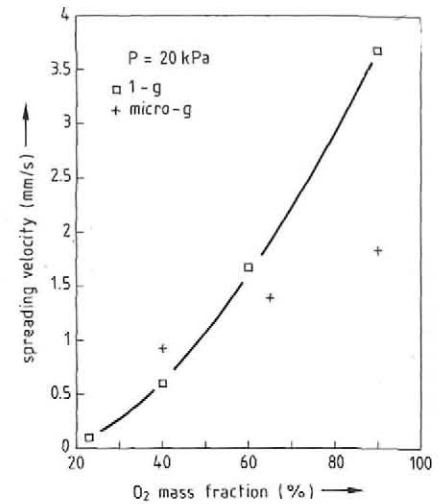


Fig. 7. Flame spreading velocity over cylindrical samples at 1-g and at reduced gravity

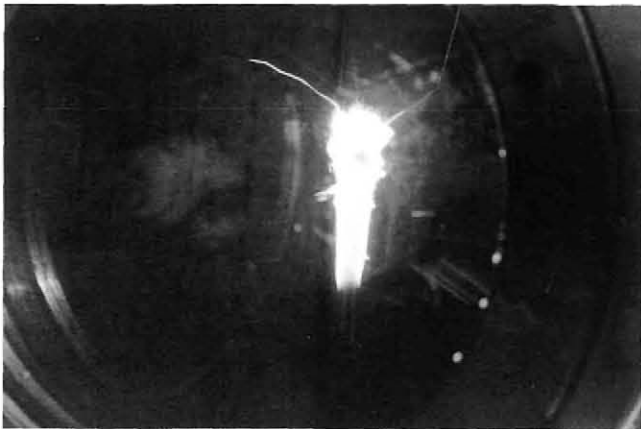


Fig. 8. Flame spreading over cylindrical samples at reduced gravity conditions in the NASA KC-135 aircraft laboratory. $Y_{O_2} = 0.90$, $P = 98$ kPa

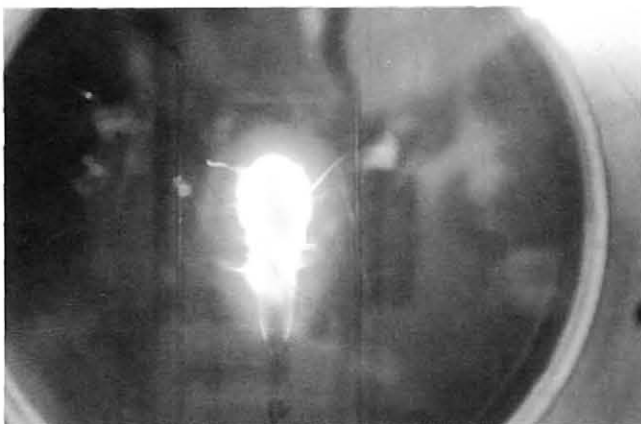


Fig. 9. Flame spreading over cylindrical samples at reduced gravity conditions in the NASA KC-135 aircraft laboratory. $Y_{O_2} = 0.80$, $P = 20$ kPa

The first flight campaign was devoted to cylindrical samples and the results obtained are summarized in figs. 5, 6 and 7. Two representative photographs are shown in figs. 8 and 9, and for comparison a flame at 1 g is also shown (fig. 10).

The flames show some radial irregularities which are probably due to monomers formation.

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

There were some scattering of results, but they were moderate except at low pressure and low concentration. The very low spreading velocities at such conditions prevented to obtain meaningful results, as shown in fig. 7.

The second experimental flight programme was devoted to flame spreading over flat samples.

Some representative photographs are shown in figs. 11, 12 and 13 and the results obtained are summarized in figs. 14, 15 and 16.



Fig. 10. Downward flame spreading over cylindrical samples at 1-g $Y_{O_2} = 0.90$, $P = 98$ kPa

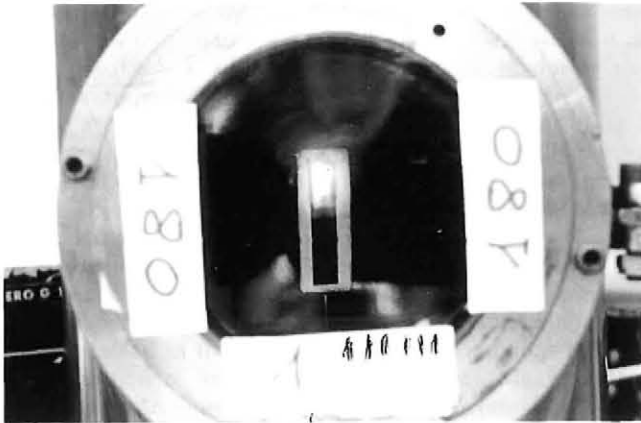


Fig. 11. Flame spreading over flat samples at reduced gravity conditions in the NASA KC-135 aircraft laboratory. $Y_{O_2} = 0.80$, $P = 98$ kPa

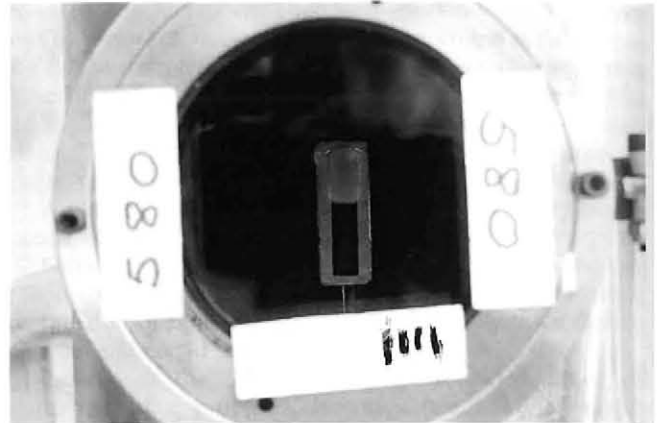


Fig. 12. Flame spreading over flat samples at reduced gravity conditions in the NASA KC-135 aircraft laboratory. $Y_{O_2} = 0.80$, $P = 50$ kPa

Scattering of results was appreciably lower for these flat samples and the spreading flame showed a remarkable bidimensional symmetry, probably due to the utilization of very low conductivity material surrounding the sample.

The spreading velocity was smaller for these flat samples than for cylindrical ones, as shown in the preceding figures. This effect is discussed in the following paragraph.

Finally, the influence of pressure on the spreading process over those samples is specifically shown in fig. 17.

5 Conclusions

1. Flame spreading velocities are considerably lower at reduced gravity conditions $\sim 10^{-2}$ g, but within the same order of magnitude than flame spreading velocities at 1 g. At this respect, it has to be considered that the Grashof number at 1 g is small, owing to the small size of the samples tested.

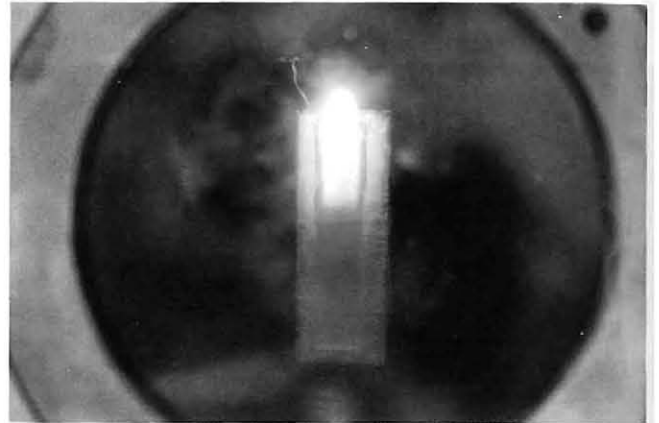


Fig. 13. Downward flame spreading over flat samples at 1-g. $Y_{O_2} = 0.90$, $P = 98$ kPa

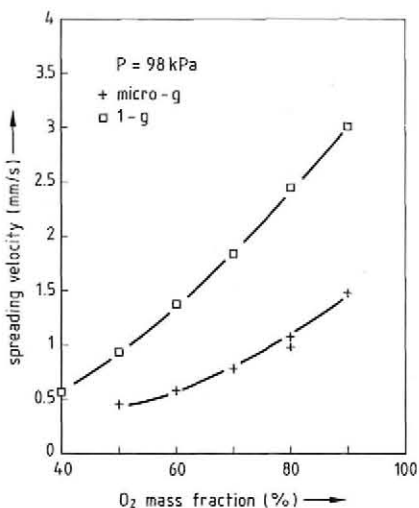


Fig. 14. Flame spreading velocity over flat samples at 1-g and at reduced gravity

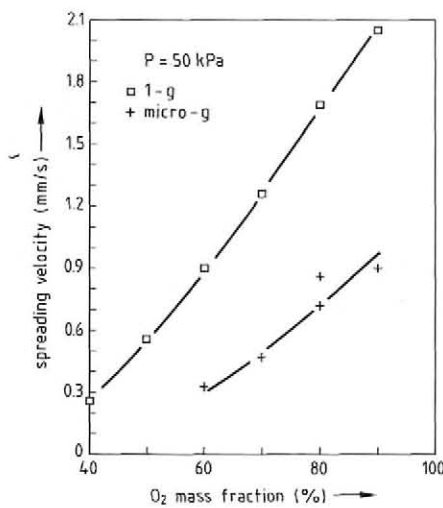


Fig. 15. Flame spreading velocity over flat samples at 1-g and at reduced gravity

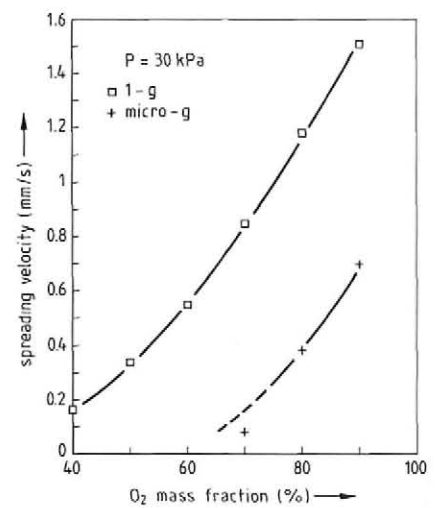


Fig. 16. Flame spreading velocity over flat samples at 1-g and at reduced gravity

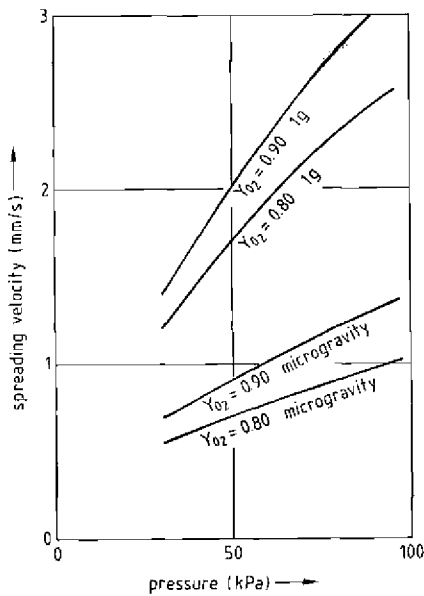


Fig. 17. Influence of pressure on flame spreading velocity over flat samples at 1-g and at reduced gravity

2. The influence of gravity decreases when the mixture pressure is reduced. This result could be expected since at 1 g the Grashof number is proportional to the square of the pressure if temperatures are constant. In ref. [2] it is shown that the pressure dependence of the flame spreading velocity is of the order of the $\frac{2}{3}$ power of the gas pressure.
3. When the oxygen concentration decreases the difference between results at 1 g and at reduced gravity also decreases.

This conclusion may be explained because when the oxygen concentration is lowered the combustion temperature

decreases reducing the flame spreading velocities in both cases, but more significantly at 1 g since in this case the Grashof number also decreases.

4. Flame spreading velocities are lower for the case of bidimensional symmetry than for the case of cylindrical symmetry. The main reason of this result is probably the difference in the fuel thickness of the samples, being only one half in the cylindrical samples as compared with the flat ones. At low pressure the difference in the spreading velocities is higher as it could be expected, since in this case the thermally heated layer in the samples becomes thicker.
5. Flame spreading over flat samples at test conditions showed a good approximation to real bidimensional conditions. Therefore, there are suitable to verify theoretical models.
6. Due to the test conditions and the short time available, some scatter of results has not been possible to avoid.

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References

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