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# Cyclic pattern along the downward flame spread over cylindrical samples in partial gravity

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## Abstract

Downward flame spread over thin electrical wires is investigated at reduced gravity. The wire is made of a Nickel/Chrome (NiCr) core coated with Low Density PolyEthylene (LDPE). The flame spreads in an opposed flow and the conditions of the free stream, i.e. oxygen content, pressure, and forced flow velocity, are varied. Parabolic flights allow experiments to be performed at various gravity levels to reproduce conditions met on Earth, Mars, the Moon, or in microgravity. Past studies showed that dripping of the molten coating occurs at Earth gravity but disappears in microgravity. A new process is here systematically observed at intermediate gravity levels: while the flame front spreads at a steady rate, a molten droplet of the LDPE coating exhibits a cyclic motion ahead of the flame front. This is driven by the balance among the gravitational, viscous, and adhesion forces. Gravity primarily powers the force driving the droplet away from the flame front, while the adhesion force ensures the droplet's attachment to the wire. The viscous force critically influences the droplet's velocity, which shows an inverse relationship with viscosity. This specific cycle can be decomposed into two stages where the aforementioned balance can be evaluated to clarify the conditions of the cycle's existence. Experimental results show that increasing the oxygen content tends to shorten the cycle by increasing the velocity of the flame front, while increasing the pressure also shortens the cycle by increasing the cooling rate of the droplet. This cyclic behavior can trigger flame extinction at Martian gravity levels, even in scenarios where flames propagate under normal and microgravity conditions. These findings can significantly impact fire safety strategies in environments with intermediate gravity levels.

*Keywords:* Fire safety; Partial gravity; Flame spread; Dripping; Cyclic spread

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## **Information for Colloquium Chairs and Cochairs, Editors, and Reviewers**

### **1) Novelty and Significance Statement**

The novelty of this research is the investigation on the phenomenon of downward flame spread over electrical wires under various gravitational conditions, including Earth, Mars, the Moon, and in microgravity. It is significant because it uncovers a unique cyclic process at intermediate gravity levels, shedding light on the intricate interplay of gravitational, viscous, and adhesion forces on molten droplets preceding the flame front. This discovery not only enhances the understanding of flame spread mechanisms but also has practical implications for fire safety, particularly in spacecraft and extraterrestrial habitats. By elucidating the factors influencing flame behavior in different gravity environments, this work contributes to advancements in fire prevention and safety measures in space exploration and future human settlements beyond Earth.

### **2) Author Contributions**

- First author's contributions: Performed research, analysed data, wrote the paper.
- Second author's contributions: Designed research, analysed data, wrote the paper.
- Third author's contributions: Designed research, performed research.
- Forth author's contributions: Analysed data, wrote the paper.
- Fifth author's contributions: Analysed data, wrote the paper.
- Sixth author's contributions: Designed research, performed research, analysed data, wrote the paper.

### **3) Authors' Preference and Justification for Mode of Presentation at the Symposium**

The authors prefer **OPP** presentation at the Symposium, for the following reasons:

- An oral presentation would allow us to showcase the intricate details of our experimental setup and instrumentation.
- Using video presentations would facilitate a better description of the intricate interplay between droplets and flames.
- A PPT format would enable a more comprehensive display of the mechanisms driving the cycling motion.

## 1. Introduction

Electrical wires are identified as a primary cause of fires both on Earth [1] and during space missions [2]. When an electric current flows through a wire, the polymeric protective coating can melt, drip, and ignite due to the overload current effect [3]. Extensive research has been conducted in both normal gravity and microgravity conditions, investigating factors such as wire core properties, orientation, and surrounding conditions affecting ignition and flame spread [4, 5]. Notably, experiments in microgravity have highlighted the key role of buoyant flows in flame extinction, spread rate, and soot production [6–9]. In microgravity experiments, steady opposed-flow flame spread rates have been achieved over thin Low-Density Polyethylene (LDPE) coated wires with a metallic core of low conductivity, such as Nickel-Chrome (NiCr). This ability to record steady spread has been critical in studying flame spread properties and the underlying heat transfer mechanisms. In this configuration, microgravity flame spread is governed by conduction through the metallic core. A molten droplet is generated during the thermal degradation of the polymer material, spreading steadily at the same rate as the flame front [10]. In contrast, normal gravity experiments show that downward flame spread is primarily driven by the heating caused by the dripping flow of hot molten insulation [11]. This dripping occurs through a competition between, on the one hand, gravitational forces and, on the other hand, surface tension and viscous forces [12].

As national space agencies ambition future missions to the Moon and to Mars [13], fire safety issues must be addressed in environments that feature intermediate gravity levels of  $0.16g_0$  for the Moon and  $0.38g_0$  for Mars,  $g_0 = 9.81m/s^2$  being the gravitational acceleration observed on Earth. Experiments that investigated the effect of oxygen content on flame spread over thin cellulosic solid fuel in partial gravity established that the upward flame spread rate, as well as the flame length and pyrolysis length, increased linearly with the gravity level [14]. However, investigations on downward flame spread showed the existence of a peak spread rate at partial gravity [15]. This situation is problematic in the context of space exploration, preventing extrapolation from existing results obtained at normal and micro-gravity. This specific combustion behavior at an intermediate gravity level also affects flammability, and drop tower experiments established that some materials can burn at partial gravity for oxygen contents lower than that recorded at both normal and microgravity conditions [16]. Recent findings suggest that adding flame retardants to LDPE can be a safe strategy [17]. Comparative experiments conducted under both microgravity and normal gravity conditions have demonstrated that flame retardants reduce the dripping phenomena caused by gravity. However, the results reveal that under microgravity, the flame retardants exhibit a lower effectiveness than under normal gravity. This dis-

crepancy is linked to the gravity-dependent nature of dripping phenomena, underscoring the importance of understanding the fundamental mechanisms of flame spread under varying gravity conditions.

There consequently is a need to identify the mechanisms driving the flame spread process in partial gravity [18]. To shed light on this issue, experiments are conducted in parabolic flights to further investigate downward flame spread in lunar and Martian gravity levels over thin wires. Flame spread and material temperature are recorded under various ambient flow conditions. The experiments reveal a distinct flame spread process at Martian gravity, with the flame front spreading almost steadily behind a droplet of molten fuel exhibiting a cyclic motion. This paper aims to report experimental data on this unique flame spread behavior, to identify and analyse governing forces, and to investigate the effects of the ambient oxygen content and pressure.

## 2. Methodology

The DIAMONDS rig, described in detail in Ref. [19], is used to investigate downward flame spread over cylindrical samples in a controlled atmosphere. DIAMONDS is loaded aboard the Novespace A310 ZeroG plane which performs reduced-gravity parabola. A Martian gravity environment ( $0.38g_0$ ) and a Lunar one ( $0.16g_0$ ) can then be replicated to conduct experiments lasting 34s and 27s, respectively. Both gravity levels are obtained with a precision below  $5 \times 10^{-2}g_0$ . DIAMONDS is assembled around a cylindrical combustion chamber with an inner diameter of 190 mm, providing a controlled laminar nitrogen-diluted air stream flowing from the bottom to the top. Flow velocity,  $u_\infty$ , oxygen content,  $x_{O_2}$ , and pressure,  $P$ , can be set in the ranges 0-300 mm/s, 0-21%, and 50-150 kPa, respectively. In the present experiments,  $u_\infty$  varies from 60 to 150 mm/s,  $x_{O_2}$  from 17 to 21%, and  $P$  from 50.7 kPa to 141.8 kPa, respectively.

The flame spreads over 150 mm long cylindrical samples, which consist of a 0.5 mm in diameter NiCr core coated with a 0.3 mm thick layer of LDPE. Before each parabola, a new sample is placed at the centre of the combustion chamber. Once the chamber is closed, the coating is ignited by an incandescent Kanthal wire located at its upper end to initiate a downward flame propagation.

A JAI AT-140CL digital 12-bit tri-CCD camera records the flame propagation. The camera is equipped with a telecentric lens to restrict the light collection to light beams parallel to the optical axis, and thus prevent image distortion. The frames are captured at 39.06 fps with a resolution of  $72.6 \mu\text{m}$ . To enable simultaneous observation of both the flame spontaneous emission and the profile of the sample surface, a controlled uniform LED backlight located behind the sample is alternatively set on and off during image acquisition. Simultaneously, an infrared camera collects the infrared emission from the surface of the sample to track the evolution of the sur-

1 face temperature during the flame spread. The camera 59  
2 is set behind a germanium window and is equipped 60  
3 with a passively athermalized lens. The radiative in- 61  
4 tensity emitted over the spectral band spanning from 62  
5  $8\ \mu\text{m}$  to  $14\ \mu\text{m}$  is collected on the array of pixels 63  
6 with a resolution of  $86\ \mu\text{m}$  at a rate of 30 fps. The 64  
7 infrared camera is calibrated with a blackbody, and 65  
8 the LDPE emissivity is assumed to be constant over 66  
9 the expected range of temperature and equal to 0.92 67  
10 [20]. The temperature evaluated from the IR images 68  
11 is associated with the reported emissivity of melted 69  
12 LDPE uniformly set to the whole sample as this study 70  
13 is dedicated to the molten LPDE upstream the flame 71  
14 front. Therefore, the total uncertainty of  $\pm 10.2\ ^\circ\text{C}$  72  
15 on the temperature is the cumulated contribution at- 73  
16 tributed to the calibration procedure, estimated to be 74  
17  $\pm 1.5\ ^\circ\text{C}$ , and the estimated emissivity fluctuation, 75  
18 leading to an additional uncertainty of  $\pm 8.7\ ^\circ\text{C}$ . The 76  
19 line-of-sight of the infrared camera is orthogonal to 77  
20 that of the tri-CCD camera. In doing so, the possible 78  
21 3D effects breaking the axisymmetry of the studied 79  
22 configuration are captured when comparing the vis- 80  
23 ible and infrared information. In order to minimize 81  
24 the influence of the ignition process, the observation 82  
25 period starts 15 s after ignition.

### 26 3. Results

#### 27 3.1. Initial observations

28 Figure 1 illustrates opposed-flow downward flame 89  
29 spread in both micro- and Martian gravity, for  $u_\infty$  90  
30  $= 60\ \text{mm/s}$ ,  $x_{\text{O}_2} = 21\%$ ,  $P = 121.6\ \text{kPa}$ . In micro- 91  
31 gravity, an axisymmetric bulb-shaped pyrolysis zone 92  
32 forms ahead of the flame front, as depicted in Fig. 1 93  
33 (a). This zone progresses at the same rate as the flame 94  
34 front. Furthermore, a steady flame spread rate is ob- 95  
35 served, since the flame front position progresses lin- 96  
36 earlyly with time, while the flame length and the ax- 97  
37 isymmetric bulb remain constant throughout the prop- 98  
38 agation [10]. However, at Martian gravity, new mech- 99  
39 anisms introduce unsteadiness. The droplet dripping 100  
40 ahead of the flame causes irregular motion through- 101  
41 out the observation period, making the steady flame 102  
42 spread definition and following analyses developed 103  
43 for microgravity inapplicable.

44 Figures 1 (b) and (c) illustrate two cycles of droplet 104  
45 motion upstream of the flame front. In the first cycle, 105  
46 the droplet quickly moves ahead of the flame from 106  
47  $t = 0\ \text{s}$  until  $t = 2.6\ \text{s}$ , then slows down and stops 107  
48 between  $t = 2.6\ \text{s}$  and  $t = 3.9\ \text{s}$ . During this cycle, 108  
49 the luminous flame undergoes dynamic changes that 109  
50 require close observation. Initially, during the accel- 110  
51 eration phase, it elongates, increasing from  $10.5\ \text{mm}$  111  
52 at  $t = 0\ \text{s}$  to  $11.5\ \text{mm}$  at  $t = 1.3\ \text{s}$ . Subsequently, 112  
53 it shortens to  $10.1\ \text{mm}$  at  $t = 2.6\ \text{s}$ , only to elon- 113  
54 gate once more, reaching  $11.18\ \text{mm}$  at  $t = 3.9\ \text{s}$ . 114  
55 These fluctuations highlight the intricate variations in 115  
56 heat transfer within the flame, influenced by the pres- 116  
57 ence of the upstream droplet. The second cycle occurs 117  
58 from  $t = 5.1\ \text{s}$  til  $t = 9\ \text{s}$ ) and follows a sim-

ilar pattern. Infrared observations in fig. 1 (c) show 59  
surface temperatures above  $350\ ^\circ\text{C}$  at the flame lead- 60  
ing edge, consistent with previous observations over 61  
LDPE. Upstream of this region, the droplet's surface 62  
temperature remains much lower, fluctuating between 63  
 $135\ ^\circ\text{C}$  and  $200\ ^\circ\text{C}$ . It is important to note that the 64  
droplet moves on one side of the wire and eventually 65  
rotates at the end of the second cycle. This highlights 66  
the need for careful evaluation of quantities of inter- 67  
est, such as droplet temperature, which can be influ- 68  
enced by its position relative to the infrared camera. 69  
Figure 2 illustrates the time evolution of critical data 70  
extracted from both visible and infrared camera ob- 71  
servations, including the distance travelled by the 72  
droplet in a cycle ( $d$ ), the flame leading edge position 73  
( $y_f$ ), the droplet front position ( $y_d$ ), and the maxi- 74  
mum droplet surface temperature ( $T_{d,max}$ ). To evalu- 75  
ate  $y_f$  and  $y_d$ , the positions of the leading edge of the 76  
droplet and of the leading edge of the visible flame 77  
were extracted from visible camera images with and 78  
without backlight, as indicated in Fig.1 (b).  $T_{d,max}$  79  
was estimated by matching the droplet's position from 80  
the visible camera with the maximum temperature 81  
recorded by the infrared camera in that region, as 82  
shown in Fig.1 (c). The evolution of  $y_f$  (see Fig.2) 83  
displays a linear relationship with time, supported by 84  
a coefficient of determination exceeding 0.99, provid- 85  
ing strong evidence of steady flame spread rate. 86  
In contrast, the droplet's characteristics exhibit cyclic 87  
behavior throughout its motion, with its temperature 88  
consistently above the  $130\ ^\circ\text{C}$  melting point of LDPE 89  
but well below  $400\ ^\circ\text{C}$ , suggesting LDPE flows as 90  
a liquid with negligible vaporization [21]. However, 91  
the temperature of molten droplet undergoes contin- 92  
uous changes during the propagation process, and its 93  
presence predominantly acts as a barrier to heat trans- 94  
fer upstream of the flame. This impacts the flow and 95  
the amount of heat distributed to the pyrolysis pro- 96  
cess and, in turn, the flame length. Additionally, it 97  
can be observed that the peak temperature over the 98  
cycles is damped. This phenomenon is attributed to 99  
the increase in the droplet's mass at the onset of suc- 100  
cessive cycles, as illustrated in Fig. S1 (a) in the sup- 101  
plementary material. This cyclic behavior and the as- 102  
sociated temperature variations were observed in all 103  
experiments conducted under Martian gravity, across 104  
different oxygen contents, pressures, and flow veloc- 105  
ities. The corresponding data on droplet temperature 106  
variations, presented in the supplementary material, 107  
further support the occurrence of this distinct behav- 108  
ior. 109

Such a cyclic motion has not been reported in nor- 110  
mal gravity, where gravity causes the droplet to drip 111  
and slide far away from the flame. Similarly, this has 112  
not been observed in microgravity, where the axisym- 113  
metric pyrolysis zone spreads at the same rate as the 114  
flame front. However, at Martian gravity level, these 115  
mechanisms compete, resulting in the unique pattern 116  
initially reported by Konno et al. [18] when assess- 117  
ing gravity's impact on Limiting Oxygen Concentra- 118  
tions (LOC) and flame spread rates in DIAMONDS. 119

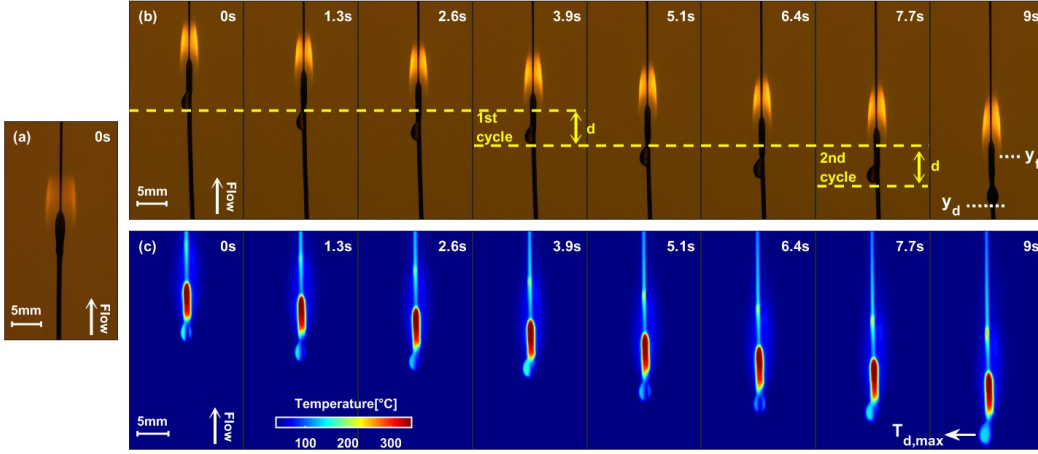


Fig. 1: Opposed-flow flame spread over laboratory wire samples at low gravity, for  $u_\infty = 60$  mm/s,  $x_{O_2} = 21\%$ ,  $P = 121.6$  kPa. The blue portion downstream the pyrolysing coating reveals the bare nickel-chrome surface. (a) backlighting frames show a steady rate spread mechanism in microgravity, while (b) backlighting and (c) infrared frames evidence a cyclic behavior of the spread in Martian gravity.

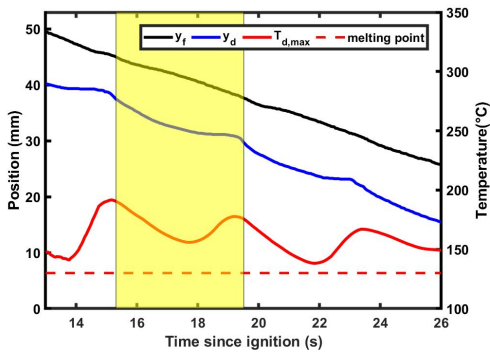


Fig. 2: Evolution during the parabola presented in fig. 1 for the same ambient conditions of the flame front position,  $y_f$  (black), droplet front position,  $y_d$  (blue), and maximum droplet temperature,  $T_{d,max}$  (red line). The melting point of LDPE is indicated with a red dotted line. The highlighted area covers one cycle.

1 In addition to gravity and surface tension, fluctuations  
 2 in viscosity with temperature have been suggested as  
 3 potential contributors to these thermoplastic deformation  
 4 observations. To better understand the associated risk,  
 5 it is worth mentioning that observations at Lunar  
 6 gravity show a similar cyclic pattern. However, limited  
 7 observation time during parabolic flight prevents  
 8 reporting successive cycles at Lunar gravity in this  
 9 configuration. In Lunar conditions, dripping typically  
 10 occurs around 20 seconds after ignition, delaying the  
 11 second cycle's occurrence. An in-depth analysis of a  
 12 cycle is conducted to highlight Martian gravity's driving  
 13 mechanisms before studying the influence of ambient  
 14 flow conditions on the cyclic propagation features.  
 15

### 3.2. Droplet's dynamics

17 The motion of the droplet results from a balance between,  
 18 on one hand, the gravitational force,  $F_g$ , and,  
 19 on the other hand, the adhesion force,  $F_{ad}$ , the drag  
 20 force due to the ambient air flow resistance,  $F_D$ , and  
 21 the internal viscous forces,  $F_\tau$  [22, 23]. It can be written  
 22 as follows:

$$\frac{d}{dt}(\rho_p V_d \frac{dy_d}{dt}) = F_g - F_{ad} - F_D - F_\tau \quad (1)$$

23 where  $\rho_p$  is the density of the molten LDPE and  $V_d$  is  
 24 the droplet volume.

25 To facilitate further analysis, it is essential to derive  
 26 each term from experimental data and investigate the  
 27 relationship between the acting forces and the droplet  
 28 dynamics. The analysis is conducted over a full cycle  
 29 to highlight the different stages of the droplet motion,  
 30 and relate the associated variations of each force as a  
 31 function of time.

32 The dynamic motion of the droplet is measured as  
 33 the most obvious tracer of this cyclic motion. Analyzing  
 34 the time evolution of the droplet velocity,  $u_d = dy_d/dt$ ,  
 35 the successive peaks in velocity are used as a distinctive  
 36 marker identifying the start and end times of each cycle.  
 37 Using the velocity peak, the original positions of  $y_f$   
 38 and  $y_d$  can be established at the same moment. This  
 39 reference point enables the observation of changes in  
 40 the flame and droplet over the course of a cycle. A  
 41 cycle of interest is selected and highlighted in yellow  
 42 in fig. 2. This specific cycle has been selected due to  
 43 the lack of rotation of the droplet around the wire,  
 44 allowing for an accurate observation of its outline to  
 45 formulate the following theoretical framework.  
 46

47 Looking at the droplet motion along the wire axis,

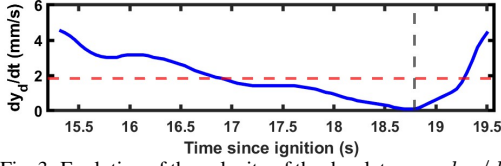


Fig. 3: Evolution of the velocity of the droplet  $u_d = dy_d/dt$  during the cycle highlighted in fig. 2. The horizontal red dashed line represents the average spread rate of the flame during this cycle. The vertical gray dashed line delineates the phases of deceleration and acceleration of the droplet.

1 a detailed description of the droplet velocity evolu-  
 2 tion within the highlighted cycle is provided in fig. 3.  
 3 The data on droplet position over time is extracted  
 4 from images and smoothed. The droplet velocity is  
 5 then calculated by deriving these data using the Euler  
 6 scheme. The trends followed by the droplet velocity  
 7 can be divided into two parts, namely one phase of  
 8 deceleration followed by one phase of acceleration.  
 9 The change between phases occurs at 18.8s, 3.7s af-  
 10 ter the beginning of the cycle, as highlighted by the  
 11 grey dashed line. The end of the cycle is recorded at  
 12 19.1s.

### 13 3.2.1. Description of each force

14 The forces on the right-hand side of Eq.(1) can then  
 15 be expressed individually. The gravitational force  
 16 applied to the droplet can be simply evaluated from  
 17 the droplet's mass  $\rho_p V_d$  and the Martian acceleration  
 18 field,  $0.38g_0$ :

$$F_g = \rho_p V_d 0.38g_0 \quad (2)$$

19 The volume is estimated by integrating the droplet's  
 20 height  $h_d$  along its width  $w_d$ , assuming a spherical ge-  
 21 ometry.  $h_d$  and  $w_d$  are extracted from droplet profile  
 22 and the snapshots of the droplet contour with geomet-  
 23 ric details are provided in the supplementary material.  
 24 The polymer density is evaluated as  $809 \pm 20 \text{ kg/m}^3$   
 25 based on the droplet temperature measured from the  
 26 infrared camera.

27 The adhesion force  $F_{ad}$  is estimated using Furmidge's  
 28 law, considering the length of the contact line on the  
 29 perimeter of the wire [24]:

$$F_{ad} = k (\cos \theta_R - \cos \theta_A) \gamma_p 2 \pi r_w \quad (3)$$

30 where  $k$  is a numerical constant that depends on the  
 31 shape of the droplet, which can be estimated as  $k =$   
 32  $0.23 + 1.04\beta$  [24] and  $\beta$  is the length-to-width as-  
 33 pect ratio of the contact line. In the present study,  
 34 the droplet is assumed to be circular ( $L_d = w_d$ ),  
 35 which leads to  $\beta = 1$ .  $\theta_A$  and  $\theta_R$  are the advanc-  
 36 ing and receding contact angles, respectively, which  
 37 are extracted from the droplet profile. The detailed  
 38 extraction method is described in the Section 1 of  
 39 the supplementary material.  $\gamma_p$  is the surface tension  
 40 of LDPE, and  $r_w$  is the radius of the electrical wire.

41 The applied surface tension of the droplet is based on  
 42 the results of linear polyethylene measured by Roe  
 43 [25]. Following these measurements, the surface ten-  
 44 sion is found to decrease linearly with temperature.  
 45 Based on the infrared measurements,  $\gamma_p$  varies from  
 46  $24.4 \times 10^{-3} \text{ N/m}$  at  $T = 152^\circ \text{ C}$  to  $26.8 \times 10^{-3} \text{ N/m}$   
 47 at  $T = 193^\circ \text{ C}$ .

48 To estimate the drag force,  $F_D$ , due to the ambient  
 49 flow resistance when the droplet slides over the elec-  
 50 tric wire, the Reynolds number of the flow around the  
 51 droplet,  $Re_{flow}$  is first computed. This characteristic  
 52 Reynolds number is defined as follows:

$$Re_{flow} = \frac{\rho_{air} (u_\infty - u_d) h_d}{\mu_{air}} \quad (4)$$

53 where  $\rho_{air}$  and  $\mu_{air}$  are the density and the dynamic  
 54 viscosity of the forced flow, respectively. Within the  
 55 discussed cycle, the Reynolds number of the ambient  
 56 airflow surrounding the droplet  $Re_{flow}$  is of the order  
 57 of 10, meaning  $F_D$  can be estimated with Stokes' law  
 58 [26]:

$$F_D = 6 \pi \mu_{air} (h_d/2) (u_\infty - u_d) \quad (5)$$

59 where  $\mu_{air}$  is the dynamic viscosity of the forced  
 60 air flow. Finally, the viscous force  $F_\tau$  acting on the  
 61 droplet can be expressed as follows [27]:

$$F_\tau = A_c \mu_p \frac{dy_d/dt}{h_d} = k_p \mu_p (dy_d/dt) \quad (6)$$

62 where  $A_c \approx \pi r_w w_d$  is the approximated contact  
 63 area of the droplet with the wire. According to the  
 64 droplet profile, it is observed that the changes in  
 65 droplet height and width during a cycle are very small.  
 66 The variations under 0.1mm for both terms lead to  
 67 variations of  $\pm 9.4\%$ . Thus  $A_c$  can be treated as a  
 68 constant in this analysis, and the steady geometric  
 69 features of the system are combined in a new constant  
 70  $k_p$ . The viscosity of the molten LDPE,  $\mu_p$ , is obtained  
 71 from data measured by Bird et al. using the Weis-  
 72 senberg rheogoniometer and the capillary viscometer  
 73 [28]. The molten LDPE is a non-Newtonian fluid, so  
 74 its viscosity depends on both the shear rate  $\dot{\gamma}$  and tem-  
 75 perature. The shear rate of the droplet is estimated as  
 76 the droplet velocity divided by its height [29], indi-  
 77 cating the rate at which adjacent layers of the droplet  
 78 move relative to each other. On the other hand, the  
 79 temperature is determined using  $T_{d,max}$ . As a results,  
 80 the dynamic viscosity of the droplet ranges from 3875  
 81  $\text{Pa}\cdot\text{s}$ , at  $T = 193^\circ \text{ C}$  and  $\dot{\gamma} = 3.25 \text{ s}^{-1}$  to 14670  $\text{Pa}\cdot\text{s}$   
 82 at  $T = 172^\circ \text{ C}$  K and  $\dot{\gamma} = 0.14 \text{ s}^{-1}$ .

### 83 3.2.2. Dimensionless analysis

84 A dimensionless analysis is applied to assess the bal-  
 85 ance among the forces driving the droplet's behavior.  
 86 Among the external forces, the gravitational one pri-  
 87 marily powers the observed downward motion. Grav-  
 88 itational effects are thus compared to other contri-  
 89 butions to identify the balancing mechanisms. The

1 droplet acceleration  $\Gamma_d = d^2 y_d / dt^2$  can be estimated  
 2 from fig. 3 to  $-1.32 \text{ mm/s}^2$  in the deceleration stage  
 3 and  $5.62 \text{ mm/s}^2$  in the acceleration one. This estimation  
 4 shows that  $\Gamma_d \ll 0.38 \times g_0$ . Consequently,  
 5 the time derivative of momentum in the left-hand side  
 6 of Eq.(1) can be neglected. The adhesion force, calculated  
 7 using Eq. (3) with experimentally measured  
 8 contact angles, is contrasted with the gravitational  
 9 force. Their ratio, depicted in fig. 4(a), is approxi-  
 10 mately 0.42, indicating that gravity's overall influence  
 11 on the droplet is twice that of the adhesion one. Never-  
 12 theless, the localized action of the adhesion force  
 13 plays a significant role in counteracting vertical gravi-  
 14 tational effects. In contrast, the drag force, estimated  
 15 using Eq. (5), is about three orders of magnitude  
 16 lower than  $F_g$ . The drag force from the ambient flow  
 17 can thus be neglected in comparison to the gravi-  
 18 tational one.

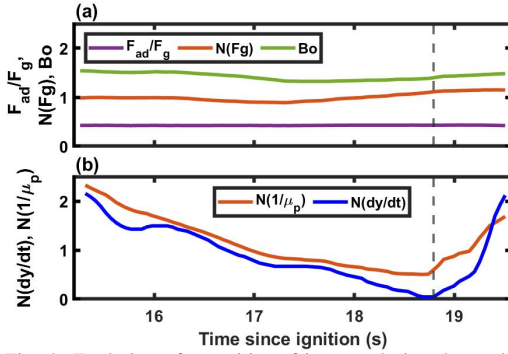


Fig. 4: Evolution of quantities of interest during the cycle highlighted in fig. 2: (a) Ratio of adhesion to gravitational forces,  $F_{ad}/F_g$ , gravitational force normalized by its average value over a cycle,  $N(F_g)$ , and Bond number,  $Bo$ ; (b) Droplet velocity normalized by its average value over a cycle,  $N(dy/dt)$ , and inverse droplet viscosity,  $N(1/\mu_p)$ . The deceleration and acceleration stages of the cycle stand on the left and the right, respectively, of the dashed line ( $t = 18.79s$ ).

19 Considering the analysis and Eq. (1), the gravitational  
 20 force emerges as the dominant force responsible for  
 21 the downward acceleration of the droplet, while the  
 22 variations in viscosity are the primary counteracting  
 23 force responsible for droplet deceleration. The adhe-  
 24 sive forces slow the downward motion of the droplet  
 25 throughout the cycle, with an almost constant effect.  
 26 Based on the previous analysis, Eq. (1) can then be  
 27 expressed as:

$$F_g - F_{ad} - F_\tau = 0 \quad (7)$$

28 Combining Eqs. (6) and (7), the droplet velocity takes  
 29 the following form:

$$\frac{dy_d}{dt} = \frac{(F_g - F_{ad}) k_p}{\mu_p} \quad (8)$$

30 The key factors influencing the droplet's motion can  
 31 then be elucidated based on this last relationship. The

32 normalized gravitational force, as shown in Fig. 4(a),  
 33 remains close to 1 throughout the cycle, and can be  
 34 considered constant. Similarly, the ratio of adhesion  
 35 force to the gravitational one remains unchanged and  
 36 is then treated as a constant parameter. Furthermore,  
 37 as discussed in Eq. (6),  $k_p$  is also constant. Therefore,  
 38 it can be inferred that viscosity is the primary factor  
 39 affecting the variation of the velocity over the cycle.  
 40 To support this statement, fig. 4(b) shows the normal-  
 41 ized droplet's velocity and the inverse of the dynamic  
 42 viscosity of the molten LDPE,  $\mu_p$ . These two prop-  
 43 erties exhibit a similar time evolution over one cy-  
 44 cle, confirming the inverse relationship between the  
 45 droplet's velocity and its viscosity. A plot of the re-  
 46 lationship between the non-Newtonian viscosity and  
 47 the droplet motion is provided in the supplementary  
 48 material. Furthermore, the relevance of this relation-  
 49 ship is supported by its extension to different levels  
 50 of oxygen content and pressure, as presented in Fig.  
 51 S4 of the supplementary material.

52 Though the gravitational and viscous forces domi-  
 53 nate the vertical motion of the droplet, it should be  
 54 noted that adhesion force also plays a critical role  
 55 in the radial direction, maintaining the attachment to  
 56 the wire's surface. In addition, the droplet's ability  
 57 to keep its shape depends on the surface tension and  
 58 gravity. The Bond number, which characterizes the  
 59 ratio between the gravitational force and the surface  
 60 tension, is defined as:

$$Bo = \frac{0.38 \rho_p g_0 w_d^2}{\gamma_p} \quad (9)$$

61 Throughout the cycle, the Bond number remains  
 62 greater than 1, as highlighted in Fig. 4(a). This in-  
 63 dicates the dominant role of gravity in shaping the  
 64 droplet, with surface tension playing a secondary role.  
 65 This implies that the surface tension remains a con-  
 66 tributing factor in maintaining the overall shape and  
 67 stability of the droplet.

### 68 3.2.3. Thermally driven cyclic motion

69 Because the shape and volume of the droplet re-  
 70 main constant through the cycle, most variations oc-  
 71 cur through changes in its temperature. The thermal  
 72 balance of the droplet can be expressed as:

$$\rho_p V_d c_p \frac{dT_d}{dt} = \dot{q}_{g,c} + \dot{q}_{g,R} + \dot{q}_s \quad (10)$$

73 with  $c_p$  the specific heat of LDPE. The heat ex-  
 74 changed with the surrounding gas through convection  
 75 and net radiation (including droplet surface radiation)  
 76 are expressed as  $\dot{q}_{g,c}$  and  $\dot{q}_{g,R}$ , respectively, while  
 77  $\dot{q}_s$  represents the heat exchanged with the underlying  
 78 solid through conduction.

79 At the beginning of the cycle, the droplet is close to  
 80 the flame. The recorded high temperatures, as shown  
 81 in Fig. 2, are associated with a low dynamic viscosi-  
 82 ty, resulting in low viscous forces. The gravita-  
 83 tional forces dominate the motion, and the integra-  
 84 tion of the acceleration in time leads to an increase in



1 downward velocity. As the droplet velocity is greater  
2 than the flame front velocity, it moves away from the  
3 flame. This relative displacement of the droplet is  
4 accompanied by a cooling process owing to convective  
5 and radiative loss to the surrounding and conductive  
6 losses to the cold underlying solid. The droplet  
7 temperature gradually decreases, leading to increased  
8 viscous forces which eventually overtake the gravitational  
9 forces. As the velocity of the droplet goes  
10 down, the reduction in its internal shear rate effectively  
11 lowers the viscous forces. The droplet could  
12 consequently reach a low, steady velocity if only  
13 gravitational and viscous forces were at play. However,  
14 the complete stop of the droplet motion is triggered  
15 by the adhesion force, which can account for half of  
16 the gravitational forces. As the distance between  
17 the flame and droplet reduces, the heat received  
18 from the flame increases, and overtake the conductive  
19 and radiative heat losses. The droplet's temperature  
20 consequently increases, and  $\mu_p$  decreases. The  
21 reduction in dynamic viscosity offsets the influence of  
22 the low shear rate on viscosity, eventually decreasing  
23 the overall viscosity. Gravitational forces eventually  
24 overtake the combined effect of viscous and adhesion  
25 forces, and the velocity of the droplet increases again  
26 until it reaches that of the flame front and the cycle  
27 can be repeated.

### 28 3.3. Effects of ambient conditions

29 Now that the cyclic behavior has been reported for a  
30 given flow condition, the effect of variations in oxygen  
31 content and pressure are analysed. It is worth noting  
32 that due to the limited number of parabolic flights,  
33 each experiment was conducted only once. Nevertheless,  
34 similar profiles were observed in all the conditions  
35 studied below, indicating a fine level of reproducibility  
36 of this distinct cyclic behavior. To characterize the  
37 variations caused by oxygen content and pressure,  
38 the period  $\tau_{exp}$ , indicative of the duration of each  
39 cycle, is reported.  $\tau_{exp}$  is influenced by two  
40 main factors: the flame front velocity  $u_f$  and the  
41 distance  $d$  traveled by the droplet over a complete  
42 cycle.  $d$  can be expressed as  $d = y_d(t = t_0 + \tau_{exp}) - y_d(t_0)$ .  
43 To assess the validity of this assumption, a characteristic  
44 time  $\tau_c$ , representing the time it takes for the  
45 flame front to catch up with the droplet, is introduced:

$$36 \tau_c = \frac{d}{u_f} \quad (11)$$

#### 46 3.3.1. Effect of oxygen content

47 Experiments were performed at Martian gravity by  
48 varying the oxygen content in the oxidizer stream  
49 from 18 to 21% at atmospheric pressure and for two  
50 levels of flow velocity, i.e.  $u_{\infty,1} = 150$  mm/s and  
51  $u_{\infty,2} = 60$  mm/s. The main characteristics of the  
52 spread process, namely cyclic period,  $\tau_{exp}$ , flame  
53 spread rate,  $u_f$ , travel distance,  $d$ , and characteristic  
54 time,  $\tau_c$ , are summarized in Tab. 1.  
55 Table 1 shows a decrease in cycle period with increasing  
56 oxygen content and an increase in flame spread

Table 1: Cyclic flame spread characteristics as a function of the oxygen content at a pressure of 101.3 kPa. The gravity is  $0.38 g_0$ . Cyclic behavior can still be observed under conditions where the oxygen content are 18% and 19%, which are close to the LOCs corresponding to  $u_{\infty,1}$  and  $u_{\infty,2}$ .

		$x_{O_2} [\%]$				
		17	18	19	20	21
$u_{\infty,1} =$ 150mm/s	$\tau_{exp}$	×	×	6.25	3.99	3.53
	$u_f$	×	×	1.38	1.51	1.69
	$d$	×	×	9.92	6.82	6.71
	$\tau_c$	×	×	7.19	4.52	3.97
$u_{\infty,2} =$ 60mm/s	$\tau_{exp}$	×	7.53	4.48	-	4.28
	$u_f$	×	1.22	1.44	-	1.80
	$d$	×	9.55	6.97	-	8.57
	$\tau_c$	×	7.83	4.84	-	4.82

× : flame extinction, - : no experiment

57 rate under both flow velocities. A detailed discussion  
58 on the LOC can be found in Ref. [18]. For the conditions  
59 investigated here, the LOC is hardly affected when  
60 moving from normal to Martian gravitational level.  
61 Increasing the ambient oxygen content increases the  
62 flame temperature, which in turn enhances the heat  
63 flux from the flame to the unburnt solid ahead of  
64 the pyrolysis front. This results in an increased  
65 flame spread rate, reducing the droplet's travel time  
66 ahead of the flame front and naturally decreasing  
67 the travel distance. This trend aligns with the  
68 experimental variations in  $\tau_{exp}$ , reflecting a similar  
69 pattern in  $\tau_c$ .

70 As the oxygen content is decreased down to 18% at  
71 a flow velocity  $u_{\infty,1} = 150$  mm/s and a pressure  
72  $P = 101.3$  kPa, extinction happens in Martian  
73 gravity. This extinction would not have been  
74 extrapolated from existing results. Under the same  
75 flow conditions, flames can propagate at normal  
76 gravity [30], despite intense dripping carrying fuel  
77 away from the flame. They can also propagate in  
78 microgravity [8], where the molten fuel droplet  
79 moves at the same pace as the flame front. In  
80 Martian gravity, self-extinction occurs when the  
81 flame catches up with the droplet, due to the  
82 increased heat losses from the flame to the cooled  
83 droplet. This mechanism is illustrated in the movie,  
84 namely "Movie S1", provided in the supplementary  
85 material.

#### 86 3.3.2. Effects of pressure

87 To investigate the effects of pressure on the cyclic  
88 flame spread, experiments are performed for  
89 pressure levels ranging from 50.7 to 141.8 kPa,  
90 at a given oxygen content of 21% and a flow  
91 velocity of 60 mm/s. The effect of pressure  
92 variations on  $u_f$ ,  $d$ , and  $\tau_c$  are reported in  
93 Tab.2.

94 In agreement with previous findings [8, 9],  
95 pressure modifications have minor effects on  
96 the flame spread rate. Using the same scaling  
97 analysis, the data in Tab.2 show that:

$$98 u_f \sim P^\beta \quad (12)$$

99 with  $\beta = -0.09$  over a wide range of conditions.

Table 2: Cyclic flame spread characteristics as a function of the pressure investigated at  $x_{O_2}=21\%$  and  $u_\infty=60$  mm/s. The gravity is  $0.38 g_0$

	$P$ [kPa]				
	50.7	70.9	101.3	121.6	141.8
$\tau_{exp}$	6.49	5.41	4.28	4.12	3.99
$u_f$	2.02	1.88	1.91	1.82	1.92
$d$	16.12	10.98	8.67	8.14	8.05
$\tau_c$	7.98	5.84	4.82	4.47	4.20
$dT_d/dt$	8.8	13.6	14.6	15.4	16.3
$dT_d/dt$ : droplet temperature drop rate [ $^{\circ}C/s$ ]					

On the other hand, Tab.2 shows that  $d$  decreases with increasing pressure. This trend is linked to enhanced heat transfer coefficient  $h$  between the air and the molten LDPE at high pressure, increasing its cooling rates through  $\dot{q}_{g,c}$ . This process is further illustrated in Tab.2 through the rate of cooling of the droplet,  $dT_d/dt$ . This quantity is averaged using the time required for the droplet to cool down from its initial temperature of  $T_{d,max}$  at the beginning of the cycle to the lowest temperature experienced during the cycle.  $dT_d/dt$  increases from  $8.8^{\circ}C/s$  at  $P = 50.7$  kPa to  $16.3^{\circ}C/s$  at  $P = 141.8$  kPa. Since the cooling rate increases with pressure, the droplet's temperature is lower. This increases the viscosity and, ultimately, reduces the travel distance. Since the flame front velocity is not affected, the flame is able to catch up with the droplet faster, as highlighted by the good agreement between the experimental period measurement  $\tau_{exp}$  and the characteristic time scale  $\tau_c$ . Additionally, pressure influences mainly droplet motion through the heat transfer coefficient as follows:

$$h \sim P^{1/2} \quad (13)$$

Thus, pressure affects the cyclic behavior of the droplet. Consequently, the cycling period,  $\tau$ , can be estimated as the time required to cool the droplet from the pyrolysis temperature,  $T_p$ , to a temperature close to the melting temperature,  $T_m$ :

$$\frac{dT_d}{dt} \sim \frac{T_p - T_m}{\tau} \sim h \sim P^{1/2} \quad (14)$$

Therefore, the cooling rate,  $\frac{dT_d}{dt}$ , and the cycling period vary as  $P^{1/2}$  and  $P^{-1/2}$ , respectively, as observed in Tab.2. Finally, Eq. (11) leads to the following trend:

$$d \sim u_f \tau \sim P^{-0.5+\beta} \quad (15)$$

where the exponent is close to  $2/3$ , in agreement with the data in Tab.2. This further supports the explanation of the impact of pressure on the cyclic behavior described above.

#### 4. Conclusions

Downward flame spread over melting material displays a unique behavior at partial gravity. Though steady flame spread is reported over thin NiCr-LDPE

wires at Martian gravity, a molten droplet of polyethylene regularly accelerates and decelerates ahead of the flame front. Tracking the motion and temperature of the droplet, it can be observed that its volume and geometry remain constant, while the velocity and temperature oscillate. Non-dimensional analysis shows that gravitational forces are the primary drivers of the downward movement. The droplet's velocity then varies under the influence of viscous forces, and the inverse correlation between velocity and viscosity is established. As velocity decreases due to increased viscosity, vertical adhesion forces eventually stop the droplet's motion. Infrared imaging highlights that the alternation of accelerations and decelerations is driven by the thermal properties of the droplet. When the droplet cools, its viscosity increases, reducing its velocity. As the flame front catches up, the droplet heats up, its viscosity decreases, and it consequently accelerates until its velocity overtakes that of the flame front. The droplet then cools again, triggering the next cycle. Cycle duration is influenced by the oxygen content and the pressure of the ambient flow. Increasing oxygen content shortens cycles primarily by boosting flame spread rates, allowing the flame to catch up with the droplet faster. Increasing pressure reduces cycle duration by enhancing gas-phase convective cooling when the droplet moves away from the flame front, reducing the travel distance of an undisturbed flame front. This cyclic dripping mode can eventually trigger flame extinction at Martian gravity, in flow conditions when flames are reported to spread at normal and micro-gravity. This will impact fire safety strategies at intermediate gravity levels.

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#### Supplementary material

The video *Movie S1* and the extraction procedure of the droplet's geometric characteristics are provided as supplementary materials to share the flame extinction in Martian gravity.

#### References

- [1] V. Babrauskas, Research on electrical fires: The state of the art, *Fire Safety Science* 9 (2008) 3–18.
- [2] A. Guibaud, G. Legros, J.-L. Consalvi, J. Torero, Fire safety in spacecraft: Past incidents and deep space challenges, *Acta Astronaut.* 195 (2022) 344–354.
- [3] H. He, Q. Zhang, R. Tu, L. Zhao, J. Liu, Y. Zhang, Molten thermoplastic dripping behavior induced by flame spread over wire insulation under overload currents, *J. Hazard. Mater.* 320 (2016) 628–634.

- 1 [4] N. N. Bakhman, L. Aldabaev, B. Kondrikov, V. A. Filippov, Burning of polymeric coatings on copper wires and glass threads: I. flame propagation velocity, *Combust. Flame* 41 (1981) 17–34.
- 2  
3  
4 [5] X. Huang, Y. Nakamura, F. Williams, Ignition-to-spread transition of externally heated electrical wire, *Proc. Combust. Inst.* 34 (2013) 2505–2512.
- 5  
6  
7 [6] M. Nagachi, J. M. Citerne, H. Dutilleul, A. Guibaud, G. Jomaas, G. Legros, N. Hashimoto, O. Fujita, Effect of ambient pressure on the extinction limit for opposed flame spread over an electrical wire in microgravity, *Proc. Combust. Inst.* 38 (2021) 4764–4774.
- 8  
9  
10  
11  
12 [7] O. Fujita, K. Nishizawa, K. Ito, Effect of low external flow on flame spread over polyethylene-insulated wire in microgravity, *Proc. Combust. Inst.* 29 (2002) 2525–2532.
- 13  
14  
15  
16  
17 [8] A. Guibaud, J.-M. Citerne, J.-L. Consalvi, G. Legros, On the effects of opposed flow conditions on non-buoyant flames spreading over polyethylene-coated wires – part I: Spread rate and soot production, *Combust. Flame* 221 (2020) 530–543.
- 18  
19  
20  
21  
22 [9] A. Guibaud, J.-M. Citerne, J.-L. Consalvi, G. Legros, On the effects of opposed flow conditions on non-buoyant flames spreading over polyethylene-coated wires – part II: Soot oxidation quenching and smoke release, *Combust. Flame* 221 (2020) 544–551.
- 23  
24  
25  
26  
27 [10] A. Guibaud, J.-M. Citerne, J.-L. Consalvi, O. Fujita, J. Torero, G. Legros, Experimental evaluation of flame radiative feedback: methodology and application to opposed flame spread over coated wires in microgravity, *Fire Technol.* 56 (2020) 185–207.
- 28  
29  
30  
31  
32 [11] Y. Kobayashi, Y. Konno, X. Huang, S. Nakaya, M. Tsue, N. Hashimoto, O. Fujita, C. Fernandez-Pello, Effect of insulation melting and dripping on opposed flame spread over laboratory simulated electrical wires, *Fire Safety J.* 95 (2018) 1–10.
- 33  
34  
35  
36  
37 [12] Y. Kobayashi, X. Huang, S. Nakaya, M. Tsue, C. Fernandez-Pello, Flame spread over horizontal and vertical wires: The role of dripping and core, *Fire Safety J.* 91 (2017) 112–122.
- 38  
39  
40  
41 [13] National Research Council, *Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era*, The National Academies Press, Washington, DC, 2011.
- 42  
43  
44  
45 [14] I. I. Feier, H.-Y. Shih, K. R. Sacksteder, J. S. Tien, Upward flame spread over thin solids in partial gravity, *Proc. Combust. Inst.* 29 (2002) 2569–2577.
- 46  
47  
48 [15] K. R. Sacksteder, J. S. Tien, Buoyant downward diffusion flame spread and extinction in partial-gravity accelerations, *Symp. (Int.) Combust.* 25 (1994) 1685–1692.
- 49  
50  
51  
52 [16] S. Olson, P. Ferkul, Evaluating Material Flammability in Microgravity and Martian Gravity Compared to the NASA Standard Normal Gravity Test, 42nd International Conference on Environmental Systems, 2012.
- 53  
54  
55  
56 [17] Y. Li, A. Guibaud, J.-M. Citerne, J.-L. Consalvi, A. Coimbra, J. Sarazin, S. Bourbigot, J. Torero, G. Legros, Effects of flame retardants on extinction limits, spread rate, and smoke release in opposed-flow flame spread over thin cylindrical polyethylene samples in microgravity, *Proceedings of the Combustion Institute* 39 (3) (2023) 3919–3928.
- 57  
58  
59  
60  
61  
62  
63 [18] Y. Konno, Y. Li, J.-M. Citerne, G. Legros, A. Guibaud, N. Hashimoto, O. Fujita, Experimental study on downward/opposed flame spread and extinction over electric wires in partial gravity environments, *Proc. Combust. Inst.* 39 (2023) 3785–3794.
- 64  
65  
66  
67  
68 [19] J.-M. Citerne, H. Dutilleul, K. Kizawa, M. Nagachi, O. Fujita, M. Kikuchi, G. Jomaas, S. Rouvreau, J. L. Torero, G. Legros, Fire safety in space—investigating flame spread interaction over wires, *Acta Astronaut.* 126 (2016) 500–509.
- 69  
70  
71  
72 [20] R. Sonnier, L. Ferry, B. Gallard, A. Boudenne, F. Lavaud, Controlled emissivity coatings to delay ignition of polyethylene, *Materials* 8 (2015) 6935–6949.
- 73  
74  
75 [21] A. Marcilla, A. Gómez-Siurana, A. Odjo, R. Navarro, D. Berenguer, Characterization of vacuum gas oil–low density polyethylene blends by thermogravimetric analysis, *Polymer Degradation and Stability* 93 (3) (2008) 723–730.
- 76  
77  
78  
79 [22] B. S. Yilbas, A. Al-Sharafi, H. Ali, N. Al-Aqeeli, Dynamics of a water droplet on a hydrophobic inclined surface: influence of droplet size and surface inclination angle on droplet rolling, *Rsc Adv.* 7 (2017) 48806–48818.
- 80  
81  
82  
83 [23] N. G. Kowalski, J. B. Boreyko, Dynamics of fog droplets on a harp wire, *Soft Matter* 18 (2022) 7148–7158.
- 84  
85  
86  
87 [24] C. W. Extrand, Y. Kumagai, Liquid drops on an inclined plane: the relation between contact angles, drop shape, and retentive force, *J. Colloid Interf. Sci.* 170 (1995) 515–521.
- 88  
89  
90  
91 [25] R.-J. Roe, Surface tension of polymer liquids, *J. Phys. Chem-US* 72 (1968) 2013–2017.
- 92  
93  
94  
95 [26] J. Xie, J. Xu, W. Shang, K. Zhang, Mode selection between sliding and rolling for droplet on inclined surface: Effect of surface wettability, *Int. J. Heat Mass Tran.* 122 (2018) 45–58.
- 96  
97  
98  
99 [27] A. Keiser, L. Keiser, C. Clanet, D. Quéré, Drop friction on liquid-infused materials, *Soft Matter* 13 (2017) 6981–6987.
- 100  
101  
102  
103 [28] R. B. Bird, R. C. Armstrong, O. Hassager, *Dynamics of polymeric liquids*. Vol. 1: Fluid mechanics, John Wiley and Sons Inc., New York, NY, 1987.
- 104  
105  
106  
107 [29] D. Bartolo, A. Boudaoud, G. Narcy, D. Bonn, Dynamics of non-newtonian droplets, *Phys. Rev. Lett.* 99 (2007) 174502.
- 108  
109  
110  
111 [30] F. Mitsui, M. Nagachi, J.-M. Citerne, H. Dutilleul, A. Guibaud, G. Jomaas, G. Legros, N. Hashimoto, O. Fujita, Effect of the ignition method on the extinction limit for a flame spreading over electric wire insulation, 47th International Conference on Environmental Systems (2017), paper 155.
- 112  
113