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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

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_∞ , 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_∞ 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 LDPE 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_∞ 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

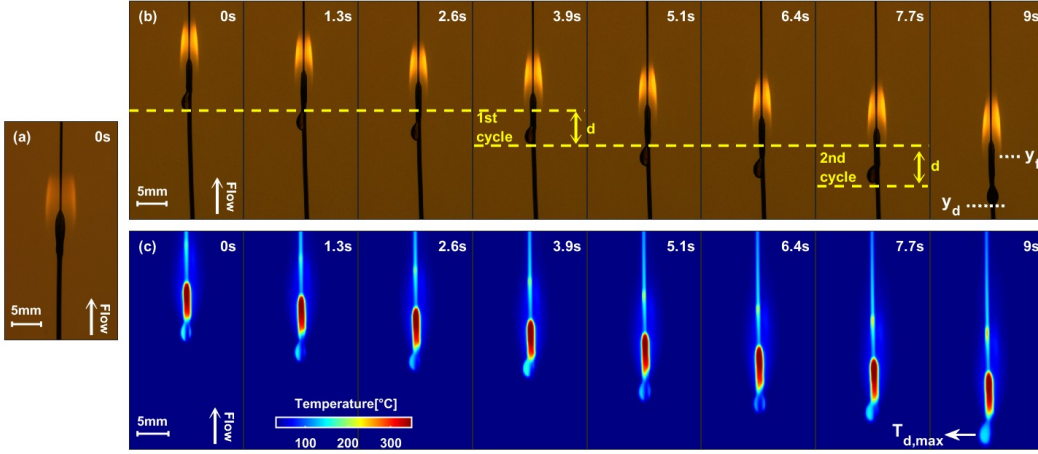


Fig. 1: Opposed-flow flame spread over laboratory wire samples at low gravity, for $u_\infty = 60$ mm/s, $x_{O_2} = 21\%$, $P = 121.6$ kPa. The blue portion downstream the pyrolysing coating reveals the bare nickel-chrome surface. (a) backlighting frames show a steady rate spread mechanism in microgravity,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

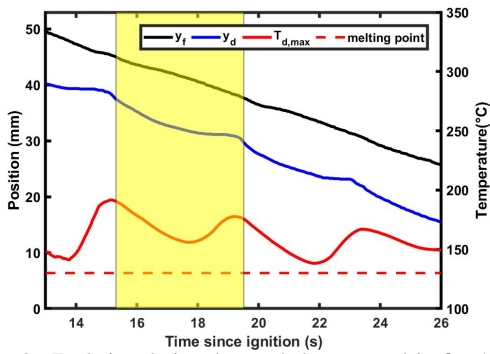


Fig. 2: Evolution during the parabola presented in fig. 1 for the same ambient conditions of the flame front position, y_f (black), droplet front position, y_d (blue), and maximum droplet temperature, $T_{d,max}$ (red line). The melting point of LDPE is indicated with a red dotted line. The highlighted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

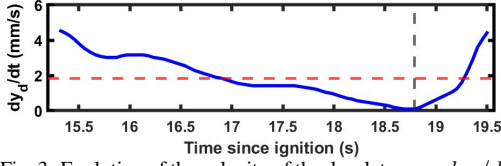


Fig. 3: Evolution of the velocity of the droplet $u_d = dy_d/dt$ during the cycle highlighted in fig. 2. The horizontal red dashed line represents the average spread rate of the flame during this cycle. The vertical gray dashed line delineates the phases of deceleration and acceleration of the droplet.

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 β 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 $\beta = 1$. θ_A and θ_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. γ_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, γ_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 ρ_{air} and μ_{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 μ_{air} is the dynamic viscosity of the forced
 60 air flow. Finally, the viscous force F_τ 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, μ_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 mm/s^2 in the deceleration stage
 3 and 5.62 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.

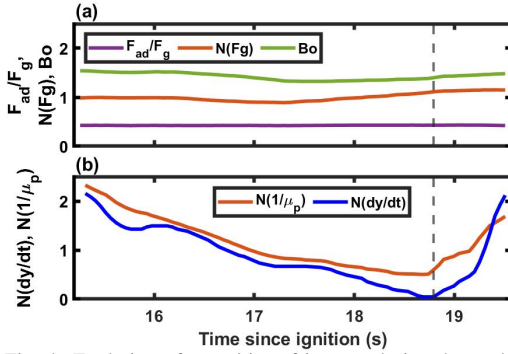


Fig. 4: Evolution of quantities of interest during the cycle highlighted in fig. 2: (a) Ratio of adhesion to gravitational forces, F_{ad}/F_g , gravitational force normalized by its average value over a cycle, $N(F_g)$, and Bond number, Bo ; (b) Droplet velocity normalized by its average value over a 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, μ_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 gravi-
9 tational forces. As the velocity of the droplet goes
10 down, the reduction in its internal shear rate effec-
11 tively lowers the viscous forces. The droplet could
12 consequently reach a low, steady velocity if only
13 gravitational and viscous forces were at play. How-
14 ever, the complete stop of the droplet motion is trig-
15 gered by the adhesion force, which can account for
16 half of the gravitational forces. As the distance be-
17 tween 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 μ_p decreases. The re-
21 duction 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 oxy-
31 gen content and pressure are analysed. It is worth not-
32 ing that due to the limited number of parabolic flights,
33 each experiment was conducted only once. Neverthe-
34 less, similar profiles were observed in all the condi-
35 tions studied below, indicating a fine level of repro-
36 ducibility of this distinct cyclic behavior. To char-
37 acterize the variations caused by oxygen content and
38 pressure, the period τ_{exp} , indicative of the duration
39 of each cycle, is reported. τ_{exp} is influenced by two
40 main factors: the flame front velocity u_f and the dis-
41 tance d traveled by the droplet over a complete cycle.
42 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 charac-
44 teristic time τ_c , representing the time it takes for the
45 flame front to catch up with the droplet, is introduced:

$$46 \tau_c = \frac{d}{u_f} \quad (11)$$

47 3.3.1. Effect of oxygen content

48 Experiments were performed at Martian gravity by
49 varying the oxygen content in the oxidizer stream
50 from 18 to 21% at atmospheric pressure and for two
51 levels of flow velocity, i.e. $u_{\infty,1} = 150$ mm/s and
52 $u_{\infty,2} = 60$ mm/s. The main characteristics of the
53 spread process, namely cyclic period, τ_{exp} , flame
54 spread rate, u_f , travel distance, d , and characteristic
55 time, τ_c , are summarized in Tab. 1.
56 Table 1 shows a decrease in cycle period with increas-
ing 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	τ_{exp}	×	×	6.25	3.99	3.53
	u_f	×	×	1.38	1.51	1.69
	d	×	×	9.92	6.82	6.71
	τ_c	×	×	7.19	4.52	3.97
$u_{\infty,2} =$ 60mm/s	τ_{exp}	×	7.53	4.48	-	4.28
	u_f	×	1.22	1.44	-	1.80
	d	×	9.55	6.97	-	8.57
	τ_c	×	7.83	4.84	-	4.82

× : flame extinction, - : no experiment

rate under both flow velocities. A detailed discus-
57 sion on the LOC can be found in Ref. [18]. For
58 the conditions investigated here, the LOC is hardly
59 affected when moving from normal to Martian gravi-
60 tational level. Increasing the ambient oxygen con-
61 tent increases the flame temperature, which in turn
62 enhances the heat flux from the flame to the unburnt
63 solid ahead of the pyrolysis front. This results in
64 an increased flame spread rate, reducing the droplet's
65 travel time ahead of the flame front and naturally de-
66 creasing the travel distance. This trend aligns with
67 the experimental variations in τ_{exp} , reflecting a simi-
68 lar pattern in τ_c .

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

84 3.3.2. Effects of pressure

85 To investigate the effects of pressure on the cyclic
86 flame spread, experiments are performed for pressure
87 levels ranging from 50.7 to 141.8 kPa, at a given oxy-
88 gen content of 21% and a flow velocity of 60 mm/s.
89 The effect of pressure variations on u_f , d , and τ_c
90 are reported in Tab.2.

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

$$95 u_f \sim P^\beta \quad (12)$$

96 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
τ_{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
τ_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 τ_{exp} and the characteristic time scale τ_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, τ , 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.

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