# An Overview of PERWAVES: A Sounding Rocket Experiment to Examine Flame Propagation in the Discrete Regime

Jan Palecka, Samuel Goroshin, Jeffrey Bergthorson, and Andrew J. Higgins
McGill University
Montreal, Quebec, Canada

## 1 Introduction

Theoretical studies over the last decade have identified a unique regime of combustion in particulate suspensions for which flame propagation is controlled by the diffusion of heat from particle to particle, now termed *discrete combustion* [1]. Unlike traditional heterogeneous combustion, which can be well described by continuum-based models wherein the particulate nature of the fuel is embedded in a volumetric source term, in discrete combustion the spatial discreteness of the fuel particles cannot be treated using an averaging procedure. The fact that fluctuations in particle concentration can occur on a scale comparable to the flame thickness itself means that the flame dynamics will reflect the inherent statistical variation in particulate concentration and spacing. Theoretical studies to date have identified a number of interesting phenomena unique to the discrete combustion regime:

1. Flame propagation speed independent of particle burning rate or oxygen concentration [2]
2. A limit to flame propagation occurring in the absence of heat losses and associated chaotic dynamics when this limit is approached in 1-D [3, 4]
3. A strong dimensional dependence of models: Results of 1-D, 2-D, and 3-D arrays and arrays of regularly vs. randomly positioned particles exhibit fundamentally different dynamics [4, 5]
4. An interaction with the inherent thermo-diffusive instability of the large Lewis number regime (pulsations), resulting in a cascade of period doublings and chaotic solutions [6]
5. Front roughening behavior that, in the limit of low ignition temperature and fast burning particles, can be shown to fit in to the KPZ universality class of statistical physics [7]

Preliminary experimental verification of the first prediction on the above list has been obtained in ground-based [8] and parabolic flight-based experiments [2]. The behavior enumerated above points to a regime

Correspondence to: andrew.higgins@mcgill.ca

of propagation sharing many features with percolation, a branch of statistical mechanics wherein local connectivity of elements determines how a given domain can be spanned by, in this case, a reactive front.

Recognition of this unique behavior has led to the selection of an experiment examining the propagation of flames in lean suspensions of heterogeneously burning fuel in low thermal diffusivity oxidizer to fly on the European Space Agency (ESA) MAXUS 9 sounding rocket in the spring of 2017. The experiment is entitled, "Percolating Reactive Waves in Particulate Suspensions (PERWAVES)." This abstract will present an overview of the PERWAVES experiment, and the accompanying presentation will be the first public release of the results of the sounding rocket experiment.

## 2 Conditions for Discrete Combustion and the Rationale for Microgravity

The hallmark of the discrete combustion regime is heat release times of individual burning particles occurring faster than the timescale of diffusion between particles. This can be expressed as a nondimensional parameter [4]

$$\tau_{\mathrm{c}} = \frac{t_{\mathrm{c}}}{l^2/\alpha} \tag{1}$$

where $t_c$ is the timescale of particle heat release (burning time) and $l^2/\alpha$ is the timescale of interparticle diffusion of heat. When $\tau_{\mathrm{c}}$ is less than unity, the flame propagation is "bottlenecked" by interparticle heat diffusion, the flame speed becomes independent of burning time, and the front morphology is controlled by the spatial distribution of the particles. In order to realize this regime, iron has been selected as the fuel, since it burns entirely via heterogeneous surface reaction, essentially remaining a point-like heat source. Iron particles of approximately 30 $\mu$m (selected to be easily visualized using CCD-based cameras) in 20% oxygen are expected to burn over a timescale of 20 ms [9]. Thus, in order to realize the discrete regime, a low thermal diffusivity medium must be used. A mixture of 20%/80% oxygen/xenon is expected to have a sufficiently low thermal diffusivity due to the presence of the heavy noble gas xenon, with $\alpha_{\mathrm{Xe}} = 6 \times 10^{-6}$ $\mathrm{m}^2$/s. The thermal flame speed of the mixture can be estimated via

$$v_{\mathrm{f}} = \sqrt{\frac{\alpha}{t_{\mathrm{c}}}} \tag{2}$$

Note that while this relationship is not strictly valid for the discrete regime, it can provide guidance in estimating the experimental parameters. Flames with such a low flame speed cannot be observed under normal gravity conditions, due to the disrupting influence of buoyancy. Previous studies by the authors have demonstrated that flames as slow as 10 cm/s could be observed on board parabolic flight aircraft, but at lower propagation speeds, the flames became disrupted by g-jitter on board the aircraft of the order of 0.05 g. Since buoyancy-driven convective flows scale with the body-force term (gravity) to the 1/3 power ($\sim g^{\frac{1}{3}}$), a reduction in the observable flame speed by an order of magnitude necessitates a three order of magnitude reduction in gravity, a condition that can only be achieved in a space-based environment [10]. In addition, particles in the 20 to 30 $\mu$m size range cannot be suspended in normal gravity, as they would rapidly settle and induce convective cells [11]. Thus, there exists two rationales for a microgravity experiment: creation of the suspension and observation of the low speed flame.

## 3 Sounding Rocket Experimental Package

The experimental module (Fig. 1), designed and developed by Airbus Defence and Space (formerly Astrium), allows for the observation of flames in transparent 34-mm-wide and 332-mm-long glass tubes. At the beginning of each test run, the tube is filled for 6 s with the suspension of iron particulates in gaseous oxidizer. The dispersion system consists of a step motor feeding the iron powder onto a rotating brush, which deposits the powder into a fast inlet $O_2$/Xe flow of 4.2 L/min. The concentration of the powder in the flow is proportional to the step motor rate.

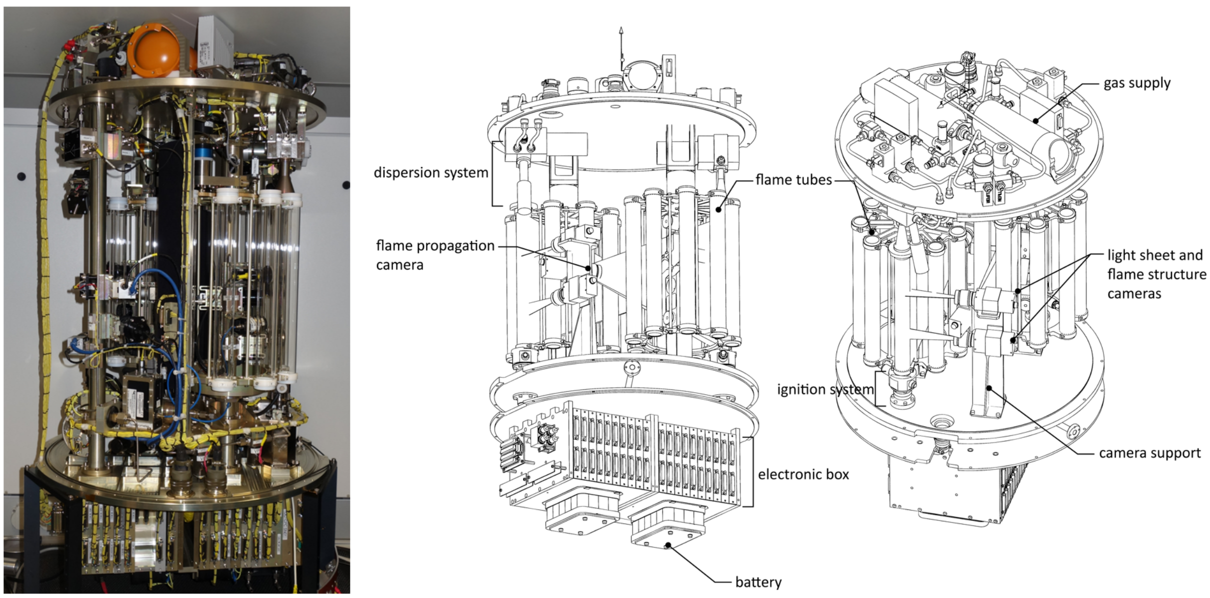


Figure 1: Experimental module schematics showing the carousel configuration, the dispersion and ignition systems, and the position of diagnostics and their field of view.

The flame in the suspension is initiated by igniting a small amount of propane, injected into one end of the tube, by means of a high voltage/low energy spark (15 kV - 5 mJ). After each test run, the tube is cleaned with a flow of gas and the exhaust mixture is conveyed through filters, and vented into outer space. Laboratory and parabolic flight experience shows that particle deposition on the walls prevents clear optical access already after two test runs. Thus, the tubes are mounted on two carousels that independently rotate clean tubes into the dispersion/ignitions systems and into the field of view of the diagnostics. With 9 glass tubes per carousel and two carousels, a total of 41 combustion experiments was achieved within the 12 minutes of microgravity conditions in the sounding rocket flight.

Cameras intended to observe the flame structure record at 60 Hz and have a narrow field of view ($3 \times 3$ cm$^2$) with a spatial resolution of 30 $\mu$m per pixel, sufficient to enable individual burning particles to be registered. Another camera focused upon a laser light sheet (520 nm green laser sheet of height of 20 mm and a thickness of 0.4 mm) has a $3 \times 2$ cm$^2$ field of view and 23 $\mu$m per pixel to observe laser-illuminated particles. This camera serves to verify the uniformity of the particulate suspension and permits direct determination of particulate density with 10 Hz sampling during the tube filling cycle. The flame speed camera views the entire tube (30 x 4 cm$^2$ field of view) with 60 Hz sampling and a spatial resolution of 150 $\mu$m per pixel. In order to view the entire tube, this camera is located on the opposite side of the flight package from the tube it is observing, requiring an optical path that passes through the carousel. Finally, light emission data of the flame at various wavelengths were recorded via a spectrometer with a resolution of 1.5 nm and a rate of 20 spectra per second.

The PERWAVES experiment was automated according to a pre-set algorithm to reach the low particle concentration limit of flame propagation as fast as possible. Thus, a successful flame propagation was followed by a decrease of powder concentration (through the rate of the step motor) in the next test run, and, conversely, flame quenching led to a concentration increase. Each test was allowed a 25 s duration. The operator on ground was provided with a possibility to override the pre-set concentration in the next run or to postpone the cleaning phase beyond the allocated time.

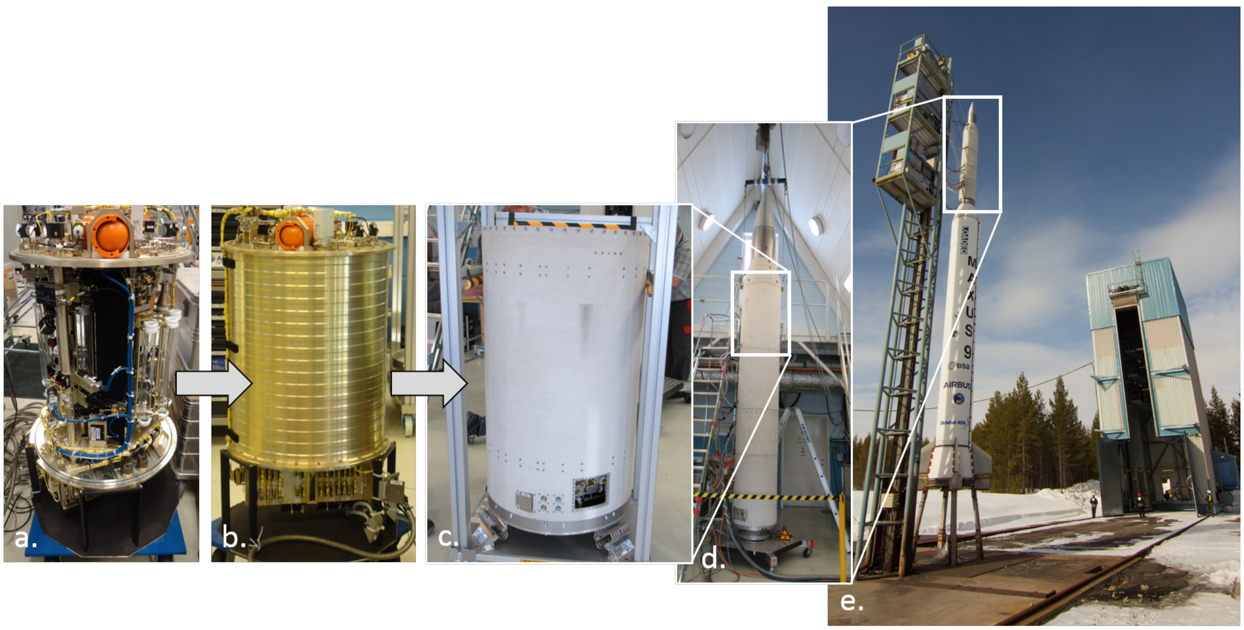


Figure 2: Integration of the experimental module into the MAXUS sounding rocket: (a) the apparatus is closed inside (b) a sealed dome, pressurized with argon, and secured inside (c) a section of the payload, which is connected with the other experiments in (d) the payload, and is assembled and integrated with (e) the rocket motor (photos by Antonio Verga and Neil Melville, ESA).

The experimental module is 1.08 m long, 0.64 m in diameter, and has a mass of approximately 130 kg. Before the launch, it was sealed and filled with argon gas at atmospheric pressure, and was placed and secured in a section of the rocket payload (Fig. 2), thus ensuring both a pressure-controlled and a low-vibration environment for the tests. Prior to the campaign, the components of the module were tested in short-time microgravity drop-tower tests in the ZARM facility at the University of Bremen, Germany, on an experimental prototype containing a single tube.

## 4 Preliminary Results

The high resolution videos, recovered from the payload capsule, show a rich set of propagation modes of the flames. Flames in both mixtures sometimes propagate with non-uniform fronts, forming cells, and display

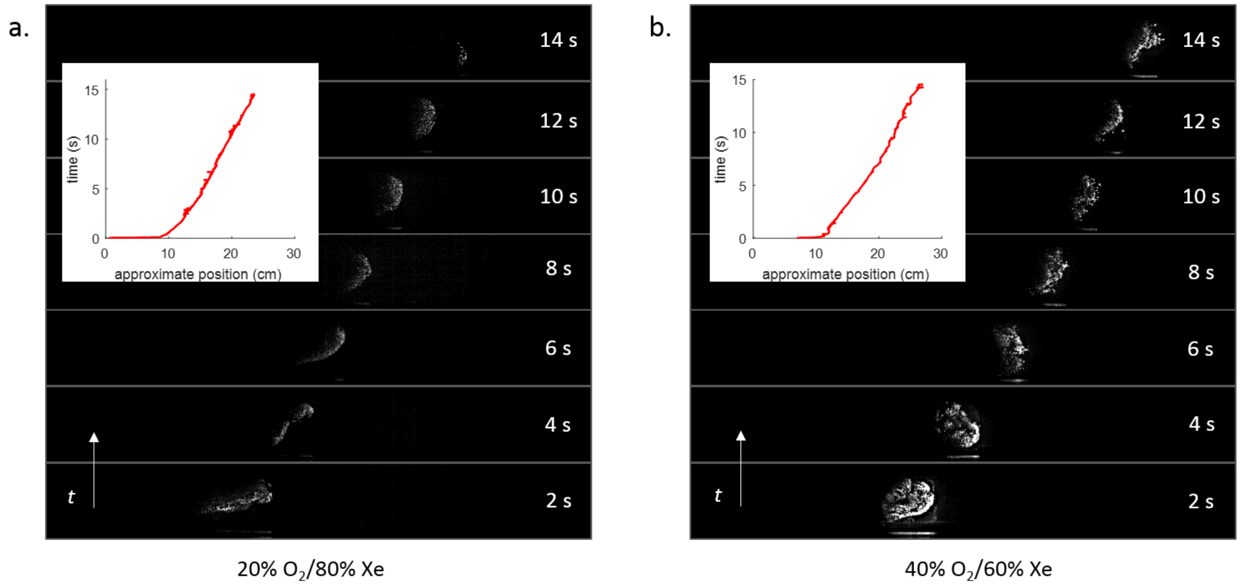


Figure 3: Flame propagation in a tube in a gas mixture of (a) 20% oxygen and of (b) 40% oxygen with time steps relative to ignition at $t = t_{\mathrm{ig}}$.

variations in speed, leading in some cases to virtually stationary combustion or even flames propagating in the opposite direction in some sections of the tube. Flames in the 20% oxygen mixture (Fig. 3a) usually possess a thinner front, sometimes on the order of less than 10 particles, and, in all cases, eventually extinguish before reaching the end of the test tube. As expected, particles in the 40% oxygen mixture (Fig. 3b) burn in a much brighter combustion process in slightly thicker flame fronts. Further data analysis is required to determine the particle combustion time and temperature, and thus the reaction rate of particles. Although the flame exhibits large changes in front surface structure and occasional non-uniform preferential propagation, more study is required to determine the causes of this behavior.

The preliminary results show a good agreement for the value of the average flame speed. In sections of the tube where the flame is undisturbed by effects of the ignition system or by large instabilities, almost all flames propagate at a steady state velocity of $\sim$1 cm/s. As this very low speed is consistently obtained in both carousels (one using 20% and the other 40% oxygen), it appears to be insensitive to oxygen concentration.

## 5 Conclusion

Flames of suspensions in gas were studied in a high-quality microgravity environment on board the ESA MAXUS 9 sounding rocket. The experiment (PERWAVES) used the microgravity environment on board to create a suspension of iron particles in a low thermal diffusivity oxygen/xenon mixture at 20% and 40% oxygen. Both mixtures exhibit flames with occasionally very low flame speeds, and even without the presence of gravity, display a rich set of physical behaviors. Two major observations can be drawn from the preliminary results: the average flame speeds in the mixtures are consistently low ($\sim$1 cm/s) and show virtually no sensitivity to the oxygen content in the gas.

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