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Is frying possible in space?

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A B S T R A C T

Dietary nutrition and uptake of earth-like foods are extremely important aspects for the health and performance of astronauts, especially during future planned long-term space missions. Despite the major progress in studying and designing systems for crop cultivation in microgravity conditions in the last years, there hasn't been equal interest in food preparation processes and cooking. There are several reasons for this but it is chiefly because at present astronauts stay in space for a few months at most, so there is no serious nutritional or psychological need for earth-like food habits. This, however, will change drastically in long-term missions, e.g., to Moon and Mars. French fries are a very popular food commodity across many cultural backgrounds on earth and as such they may be appreciated by long-term space travelers of different origin. The process of frying in hot oil is associated with complex heat and mass transfer along with the growth and detachment of water vapor bubbles. These phenomena are strongly affected by buoyancy and gravitational acceleration making the study of frying at space conditions a challenging task. The present work examines potato frying in hot oil during the short duration low gravity conditions achieved in a Parabolic Flight Campaign organized by the European Space Agency. An innovative device has been constructed, allowing the simultaneous observation of bubbles dynamics above the potato surface and the thermal behavior inside the potato flesh. It is seen that even in the absence of buoyancy i.e., during parabolas, vapor bubbles still detach and depart from the surface of potato permitting hot oil to maintain contact with the potato surface and leading eventually to a fried product. Instantaneous overpressure inside potato pores due to vapor formation upon boiling of potato water is suggested as the mechanism generating the force for bubbles detachment and departure. Moreover, the amount of produced vapor is comparable among the examined values of gravitational acceleration, including the low gravity conditions during parabolas. All in all, the results of the present study provide primary experimental evidence that frying can occur in space.

1. Introduction

Travels in deep space (i.e. human presence in Mars and long-term manned missions) is the priority concerning the next major planned steps in space exploration (Nangle et al., 2020). During long-term space missions, dietary nutrition is extremely important to the life quality of astronauts, not **only** because the intake of appropriate nutrients is necessary for maintaining their proper nutrition, but also because appropriate food plays an important role in social psychology (Bychkov et al., 2021; Jiang et al., 2019). The current strategy for food support during low earth orbit missions based on direct supplies from Earth, is practically an inapplicable approach for future manned deep space missions and especially for planned Mars colonization and for a permanent lunar base (Finetto et al., 2008). NASA is planning a mission to send humans to Mars in the next five to ten years and spends 22.6 billion dollars annually researching and developing space food (Pandith et al., 2022). Experimental and theoretical data from MELISSA and BIOS projects suggest that the high system mass and volume of extraterrestrial food production becomes cost-effective only for missions lasting in excess of 2–3 years (Ellery, 2021).

Several novel ideas have been proposed for providing enough sustenance in space travel. These concepts start from the point that the mass of food that must be shipped in support of a long duration space mission food system can be substantially reduced with the incorporation of in situ crop production (Cooper et al., 2012). The in-situ production of food would reduce the mass, energy and resource costs of sending food directly from Earth. Furthermore, food grown in situ offers the possibility of fresh production with many benefits for the astronauts' health (Cockell & McLaughlin, 2019). This approach is attractive as it removes the need for resupplies and would also regenerate oxygen and water in the process while removing carbon dioxide (Cahill & Hardiman, 2020). However, these in situ produced raw materials must be first properly processed or in other words be cooked to make them suitable for human consumption.

Regarding food preparation processes, there is an increasing interest the last years in proposing innovative food technologies and systems to solve the challenges of food production in space (Obrist et al., 2019; Space Food, 2020). A bit earlier, NASA has carried out pre-research of

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the on-orbit[1] processing technology of food and has designed a prototype of the principle (Perchonok et al., 2011) Sometime ago, Zasypkin and Lee (1999) suggested a device that includes many food processes (i.e. drum dryer/separator, compact mill, combined food processor, forced-air microwave/convection oven, high air velocity oven, bread maker, multifunctional cooking pan, extruder, flaking rolls, homogenizer, compact centrifuge, and refrigerator and freezer) to outfit an isolated, inhabited station in a hypogravity environment. These researchers proposed that using this equipment a wide variety of foods could be produced at reduced time and labor requirements. Ruminsky and Hentges (2000) stated that ingredient processing equipment, including an extruder, expeller, centrifuge, soy hull floater, microwave/convection oven, and incubator, are required to produce just the peanut oil and tempeh from raw peanut and soybean crops, respectively, but at a significant time cost (Perchonok et al., 2011). Recent emerging technologies for food production in space, consider the production of food from hydrogen-oxidizing bacteria (Alvarado et al., 2020).

The aforementioned processes focus more on the production of sufficient amount of food in space rather than on preparing food with taste, flavor and other organoleptic characteristics alike to those experienced on earth. The psychological need to provide in space food similar to what we consume on earth, is known (Bychkov et al., 2021; NASA, 2021) and the astronauts have already expressed their preference for tasting earth-like food in space missions (Volkov, 2011). Hence, several configurations have been proposed and tested in microgravity conditions that can produce food that is popular on Earth. For example, a device has been developed for cooking in zero gravity and tested during parabolic flights campaign (2014), an oven designed from Zero G Kitchen (2019) to hold and bake food samples in microgravity conditions and an espresso production device has been successfully operated on ISS during Expedition 43 (Tana & Hall, 2015). Nevertheless, the above devices do not examine systematically the difficulties expected to be encountered when preparing food in actual zero gravity conditions. The absence of earth gravitational acceleration creates additional complexities to the process of food cooking and preparation (Jiang et al., 2019). A recent review concerning the current processing and packing technology for space foods (Jiang et al., 2019), suggests that the development of devices for food processing in space (e.g. heating and refrigeration) should be further carried out in the future. To our best knowledge, there are no systematic studies on space food process engineering, concerning the influence of low gravity conditions on the physico-chemical processes involved in the cooking of food as we know it in terrestrial conditions (i.e. heat and moisture transfer and shrinkage deformation, heat transfer by combined convection, conduction, radiation and chemical reactions accompanying heating).

The present study examines the hypothesis whether French fries, one of the most popular foods on Earth, can be also produced in space conditions. Astronauts have already expressed their desire for French fries in their space menu (Volkov, 2011). Moreover, one of the candidate foods recommended to support NASA habitat missions is sweet potato and white potato (Esther et al., 2018). Recent studies have provided preliminary evidence that the cultivation of potatoes in Martian environment could be achieved under certain soil properties and lighting conditions (Ramirez et al., 2017; Wheeler, 2011). Therefore, the process of frying, if feasible, could become a very popular cooking method appropriate for long distance space travels and future colonization on Mars or/and Moon.

Potato frying in hot oil is one of the most complex food preparation processes, since it involves unsteady heat and mass transfer phenomena in porous media (a porous structure develops gradually in potato crust with frying), phase change of water to vapor, growth and detachment of vapor bubbles on the food surface, natural heat convection in the oil bulk combined with forced heat convection induced by the violent bubble departure from the food surface (Bouchon, 2009; Mallikarjunan et al., 2009; Sahin & Sumnu, 2009).

Understanding the heat and mass transfer phenomena during frying, to investigate the possibility of producing fried foods in zero gravity conditions, has been the goal of a large series of ongoing ESA (European Space Agency)-supported chain work in our laboratory over the last decade. Initially, large-scale experiments (deep fat frying) under terrestrial-gravity conditions have shown how the heat and mass transfer mechanisms in the crust region of crucial importance for the frying process and the characteristics of the final product (Lioumbas, Kostoglou, & Karapantsios, 2012a). Then small-scale experiments designed to focus on understanding the phenomena that take place at the small region inside the crust (Lioumbas & Karapantsios, 2014, 2015; Lioumbas, Kostoglou, & Karapantsios, 2012b). These experiments considered the buoyancy force as a design parameter (performing lab experiments at different potato orientations with respect to the gravity vector Lioumbas & Karapantsios, 2012c and under hyper gravity conditions by performing tests in the Large Diameter Centrifuge at ESTEC/ESA; Lioumbas & Karapantsios, 2014; Lioumbas, Kostoglou, & Karapantsios, 2017) and demonstrated how the bubble dynamics play a crucial role in the mass and heat transfer phenomena during frying and consequently in the quality of the produced crust.[2] Specifically, a moist, less crispy, crust was produced when the bubbles detachment from the potato surface was artificially prohibited (to simulate frying conditions as the ones expected to meet in micro-gravity conditions), and bubbles created a gas blanket inhibiting contact of hot oil with the potato. The present work is the culmination of all previous efforts to better understand the heat and mass transfer processes that take place during frying and to investigate how frying would be possible under conditions of zero gravity, where buoyancy forces are practically annihilated, and bubble dynamics have completely different characteristics from those on Earth.

Specifically, the last part of our ESA related work is devoted to frying experiments in the low gravity conditions achieved during a Parabolic Flight Campaign. It is well known from conventional pool boiling experiments in microgravity conditions that the absence of gravity dramatically changes heat transfer coefficients (Di Marco & Grassi, 2009). This might affect frying in space but, till now, there is no direct experimental evidence whether the frying process is indeed feasible at reduced gravity conditions. Aim of the present study is to fill this gap and provide such evidence. For this, an innovative experimental device has been employed for the frying experiments onboard the parabolic flight. The device is operated automatically based on a prescribed scenario that is activated by the flying team through a computer. The device provides experimental data concerning bubble dynamics (concerning the bubble growth, bubble rising velocity and detachment velocity) on the external potato surface and temperature profiles inside the potato flesh during frying. Finally, the interpretation of the results of this work should contribute to our understanding of the processes of frying in near-zero gravity conditions and answer the question whether frying would be feasible in space.

[1] Food preparation in non-terrestrial gravity (on-orbit processing technology) refers to the concept that the raw material of the food will be grown exclusively either on board or/and on the destination planet, while the preparation of the food to be eaten will be carried out entirely after the spacecraft has left Earth.

[2] Based on all this knowledge, a frying device has been tested and patented (patent no. 20170100130/30.03.2017 Hellenic Industrial Property Organization) that confirms that when additional gravitational forces are employed during deep fat frying (frying pots counter rotate around two vertical axes) the frying process completes in about half the usual time and uses hot oil at lower temperatures than routinely.

2. Materials and methods

2.1. Apparatus description and experimental procedure

The design of a frying experiment for parabolic flights faces several challenges, since the experimental apparatus should maintain some minimum requirements:

- Suppress any potential oil leakage.
- Maintain the pressure inside the hermetically closed frying chamber constant (~0.9 bar) because any increase of pressure (due to volume expansion by bubble formation) shifts boiling of potato water to a higher temperature and so alters the frying process.
- Avoid sloshing of hot oil in the test vessel during low gravity conditions. To achieve this, no free space should exist in the test vessel (closed chamber).
- Minimize the power requirements for heating the oil by thermally insulating the whole system.

To deal with the above challenges, a device is designed and constructed that ensures both the automatization of the experimental procedure and the necessary safety conditions for the operators and the crew by minimizing human interference. The device is furnished with diagnostics that provide information on the:

- Bubbles dynamics (i.e., bubbles size and rising velocity) concerning their path from their appearance on the potato surface to a distance of ~1.5 cm above it.
- Temperature profiles in the hot oil as well as in the potato flesh, at three distances below the potato surface.

The above information time-stamped in synchronization with the gravitational acceleration profile recorded during the flight. A sketch of the conceptual design of the device is shown in Fig. 1a. Its description follows.

The heart of the experimental device is a carousel disk (1) which accommodates six separate frying units (2); each one holding a potato specimen. The potato specimen is a cylindrical piece of potato (diameter 1 cm, Agria variety, average moisture content 80 % wet basis). Each frying unit has the form of an insulating Teflon double-trough, one trough inside the other. The potato specimen is fixed inside the inner Teflon trough with its top surface only free exposed to hot oil. The employed specimen placement excludes complications induced by exposure of the potato side surfaces, edges and corners and so reduce the heat and mass transfer problem to an approximately-one-dimensional one. Extra virgin olive oil ($T_{oil,\ boil} = 299$ °C) is employed as the frying agent. This oil is popular for domestic frying in Mediterranean countries and is known for its high nutritional value and high antioxidants content. For flight safety, the employed oil temperature is limited to maximum $T_{oil} = 120$ °C.

A triplet of miniature hypodermic probe thermocouples, HYP0, with a needle diameter of 0.2 mm (OMEGA) that do not disturb the surrounding insertion area, are mounted in well-defined positions (at three distances below the potato surface; i.e. 0.5, 1.0 and 1.5 mm) below the potato surface. Thermocouples are placed with a ±5 % accuracy on their X-Y positioning plane. These specific locations were chosen in a region where the crust will develop and significant changes are expected to take place in the potato structure during frying (Lioumbas & Karapantsios, 2012b). Moreover, the temperature profiles at these locations provide a good indication of the intensity of the heat transfer phenomena occurring during frying which determine the different stages of frying (Lioumbas & Karapantsios, 2012b).

One of the six frying units every time, enters into a chamber (3) below the bottom of the oil container (4). The oil container contains hot oil (at 120 °C) and is separated from the chamber by a valve. A stirrer and a cartridge heater (500 W) keep the oil temperature steady inside

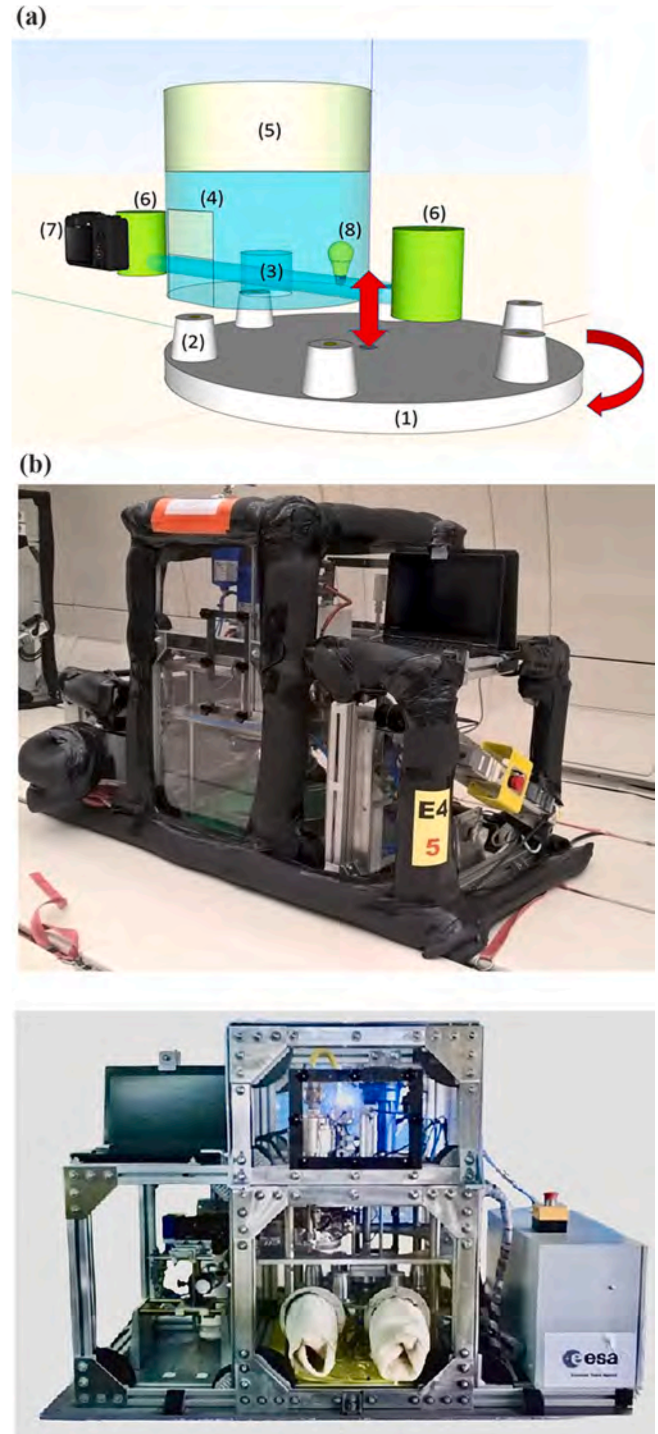

Fig. 1. (a) Conceptual design of the experimental device; (b) The experimental device mounted to the airplane cabin floor during the 66th Parabolic Flight Campaign.

the oil chamber. A bellows system (5) is placed at the top of the oil container to absorb pressure differences (by expanding their length; sensitivity 0.01 bar; maximum pressure 1.5 bar abs.) (Witzenmann - HYDRA diaphragm bellows with normal profile, 87 × 103 × 1 × 0,15 material no. 1.4571 (AISI 316Ti)) due to bubbles formation. A pressure transducer measures the absolute pressure inside the chamber. Both the chamber and the bellows system are thermally insulated with a Teflon gasket aiming to minimize thermal losses. As soon as a frying unit enters the chamber, the valve opens, hot oil gradually fills the chamber and contacts the exposed potato surface leading to initiation of the frying process. This heating approach circumvents the problem of non-uniform heating of the exposed potato surface that could triggered by convection currents (Lioumbas & Karapantsios, 2012b). When the frying process is completed after a five parabolas sequence, hot oil is automatically removed from the chamber using a cascade system of vacuum pumps (6) and returns to the oil container which is isolated again from the chamber by closing the separating valve. Once the chamber is isolated, the frying unit is dispatched from it. Then, the carousel disk rotates automatically until a new frying unit takes position under the oil chamber and the process takes over again (details on the automated process can be found in Suppl. material A.

Due to the large number of controlled parts (i.e. 7 electrical valves, 3 DC motors, 1 light source and 1 cartridge heater), the many temperatures (i.e. 25 miniature thermocouples) and one pressure sensor that are used in the experiment, an industrial based Control and Data Acquisition system (PLC – SCADA - SIEMENS) has been programmed (sampling frequency 5 Hz, the diagram of electrical block diagram is depicted in Suppl. material B). The whole system is fully PC controlled. An image of the device ready for parabolic flights is presented in Fig. 1b. In the latter, a glovebox is seen meant to allow operations on the carousel disk without removing the external liquid-proof Plexiglas cover of the apparatus.

2.2. Design of experiments in microgravity conditions

The experiments are conducted in May 2017 during the European Space Agency (ESA) 66th Parabolic Flight Campaign totaling 3 daily flights on board an Airbus A310 Zero-G operated by NOVESPACE. Each flight contains 31 parabolic maneuvers (parabolas), an initial trial one for newcomers onboard and then 30 regular ones. Each parabola starts with an initial high-g (1.8 g/g_{earth}) pull-up phase, followed by a low-g (0.01 g/g_{earth}) period of 22 s, and ending with a high-g (1.8 g/g_{earth}) pullout phase. Data are obtained in all time during the flight, i.e., during normal g, high-g, and low-g phases. According to the usual parabolic flight protocol, the 30 regular parabolas are split in 6 sets of 5 parabolas sequence per set. Each 5 parabolas sequence last 15 min. Each one of these sets is interrupted by a 5–8 min break. The approximately 20 s duration of low gravity conditions during a parabola is deemed sufficient, as the experiment is tailored so that statistically enough bubbles are generated during this period. Specifically, previous frying experiments have shown that the duration of different frying stages (i.e. heating, boiling and not boiling), in an experimental configuration similar with the one of this study, increases as the oil temperature (Lioumbas & Karapantsios, 2012c) and gravitational acceleration decrease (Lioumbas & Karapantsios, 2012c; Lioumbas & Karapantsios, 2014). Considering the findings of the above studies, and preliminary on-ground experiments, the duration, between the first and last appearance of bubbles during frying in microgravity conditions, is expected to last ~ 500–700sec. Therefore, special care has been taken to synchronize the boiling initiation with the onset of 1st parabola.

Fig. 2, presents a typical example of the data recorded (oil temperature, three temperatures in the potato flesh, pressure, synchronized with the gravitational acceleration levels) during a typical set of five parabolas. According to literature, the frying process can be separated into various phases based on the events of heat and mass transfer (Farkas et al., 1996). Specifically, recent studies (Lioumbas & Karapantsios, 2012b and 2014) have shown, the temperature profiles in a region very close to proximity of the potato – oil interface (inside the region where the crust develops) are indicative of the crust thickness evolution, of the evaporation front propagation inside the potato flesh, the moisture loss and of the bubble behavior during frying. The boiling regime[3] is designated by a slight increase at the potato temperature, then T_p, values attain a considerable period of constant temperature values and as soon as the T_p values start considerably increasing, the boiling period ends. For the present study, the temperature profiles at various locations inside the potato flesh are presented in Fig. 2, and they present the same characteristics as those previous described and measured during earth experiments. Specifically, both the temperature profiles and visual observations confirm that boiling initiates during the 1st parabola of the sequence (blue arrow in Fig. 2); and finishes during the 4th parabola (red arrow in Fig. 2; after that point only, sporadic bubbles appear).

Each experimental run (using the same potato specimen) is executed during a five parabolas sequence. This means that the potato surface is in contact with hot oil during the whole duration of the five parabolas sequence and not only during the low gravity period of each parabola At the end of every sequence of five parabolas, the frying unit that contains the potato specimen is replaced by a new one. In total six potato specimens are fried using six different frying units one for each of the five parabolas sequence of a daily Parabolic flight.

2.3. Description of data analysis

2.3.1. Video recording

A cube beam splitter provides the image source at two cameras having different purposes:

i. A digital video camera (Canon PowerShot G9 X Mark II) is employed for recording bubbles population and bubble growth during low gravity conditions (60fps at image resolution 1920X1080pixels).
ii. A fast video camera (MotionBLITZ EoSens® mini2 High-Speed Recording Camera System) that is employed to record at high-speed (1000fps at image resolution 1024X768 pixels) the intense bubble dynamics during hypergravity conditions.

A camera positioner allows the cameras to move vertically and longitudinally; the cameras are fixed at a constant position throughout the experiments. The cameras are fixed on a stand very close to the area of observation in such a way that the potato specimen is located between the camera and an appropriate lighting system (white light, 100 W, 12DC). A light diffuser is placed between the light source and the object to be recorded. The image recording procedure is automated with the help of macro recording software (JitBit™) which allows having a video that corresponds to a total frying video with duration of several minutes (0.7Gbyte file). It must be also noted that the optical system offers a very narrow depth of field (a few hundreds μm). The calibration of the measuring system, needed to ensure the accurate measurement of the bubble size, is accomplished by measuring the known diameter of a cylindrical metal rod (Ø0.2 mm) placed at the focusing plane.

2.3.2. Image analysis

Available commercial image analysis software is not efficient in analyzing the chaotic and extremely complex bubbles patterns observed during frying. Consequently, the image analysis presented in this work is performed after each bubble has been digitized manually by using appropriate software (Redlake MotionScope® and ImagePro®). A typical image used for image processing along with the bubble diameters marking annotation is presented in Fig. 3a and a typical video which has been used for the data image analysis is presented in Suppl. Material C. Bubble growth has been calculated by measuring the bubble diameter in

[3] The Boiling regime begins the moment the first vapor bubble emerges from the potato surface due to surface water evaporation and ends when bubbles at the potato surface are so scarce and their growth so slow that do not give the impression of boiling anymore (Lioumbas & Karapantsios, 2012b).

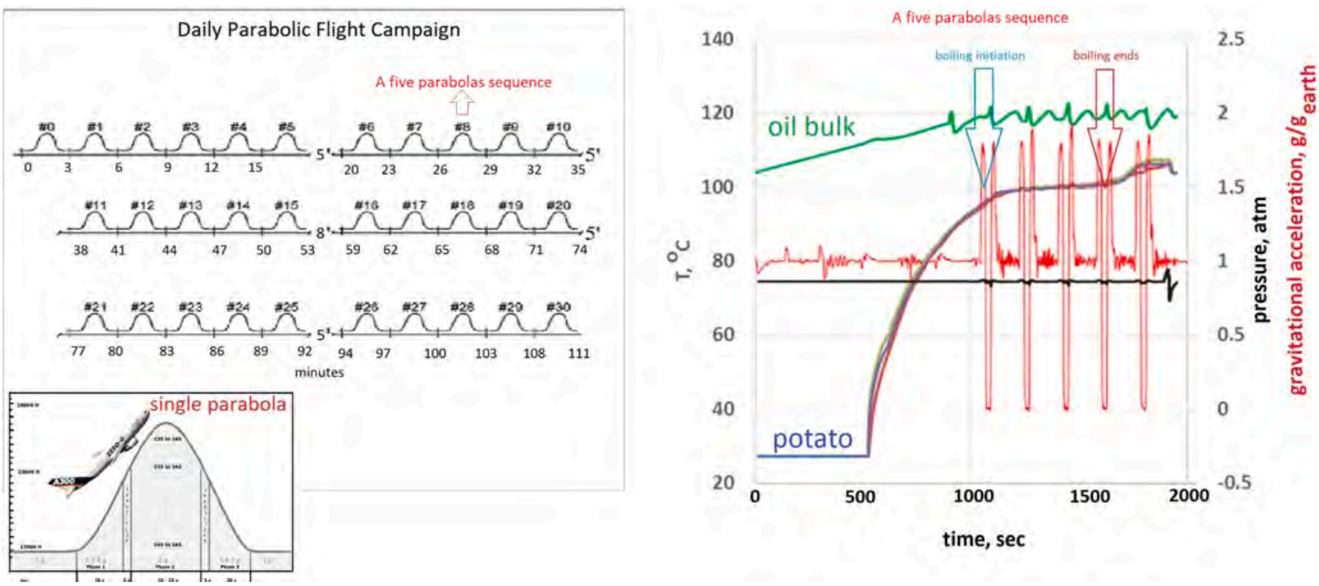

Fig. 2. Description of the parabolic flight campaign and typical measurements acquired during a five parabolas sequence. Profiles of data obtained during the initial set of five parabolas of the flight; the left axis stands for the temperatures (inside bulk oil; green colored lines and potato flesh; light green, blue and purple lines); the right axis stands for the pressure; black line and the gravitational acceleration values; red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

images sequences as obtained from corresponding videos. In particular, the growth of a bubble as measured during an experiment in near-zero gravity conditions is schematically represented in a 3d graphic (Fig. 3b). The numbers on the left, relate the time values associated with each of the bubble growth stages, while the numbers on the right relate the recorded gravity acceleration values to these time values.

3. Results and discussion

3.1. Visual observations

A first indication regarding the influence of gravitational acceleration levels on bubbles' behavior during frying, can be obtained from a typical raw video recorded during a single parabola and properly synchronized with the corresponding gravitational acceleration levels (Suppl. material C, video recording). Fig. 4 displays representative images retracted from the video presented in Suppl. material C. Each image corresponds to a typical bubbles behavior observed for the different gravitational acceleration levels:

- Phase A: Terrestrial gravitational acceleration level ($g/g_{earth} = 1$)

At this phase, the gravitational acceleration value corresponds to terrestrial conditions and vapor/bubbles behavior is the one customary observed in literature (Lioumbas, Kostoglou, & Karapantsios, 2012a). Specifically, bubbles grow and detach chiefly under the influence of the momentum of the vapor ejected through the potato surface and of buoyancy. In several occasions, bubbles at the surface of the potato merge to larger ones and then detach. Since bubbles activity cannot be adequately captured by the 30fps video recording camera, the fast video camera data are used to estimate the bubbles size and rising velocity which are similar to other terrestrial data in literature (Lioumbas & Karapantsios, 2014). All in all, bubbles detachment and departure from the potato surface occurs at a substantially fast rate allowing the renewal of contact between hot oil and potato surface, that is, frying to proceed.

- Phase B: Hypergravity acceleration levels ($1 < g/g_{earth} < 1.8$)

At this phase, the gravitational acceleration increases gradually from the terrestrial gravitational value to the maximum value that is attained during a parabola (i.e. 1.8 g/g_{earth}). After this maximum value, gravitational acceleration values start decreasing. It is observed that as the gravitational level increases, bubbles attain smaller diameter and detach with higher velocity from the potato surface. The other way around, as the gravitational acceleration values decline bubbles size increases and their detachment velocity decreases. High speed videos reveal that bubbles dynamics (bubbles size and rising velocity) present similar behavior to what has been observed in experiments performed with potato simulants (i.e. water saturated porous materials) at hypergravity conditions in the Large Diameter Centrifuge (LDC, Noordwijk ESA; Lioumbas, Kostoglou, & Karapantsios, 2012b). The findings of this work suggested that as the gravitational acceleration values increased, the bubbles size decreased with their rising velocity increasing, which results to higher heat transfer rates. Therefore, since bubbles detachment and departure from the potato surface, in the present work also occurs at extremely fast rate in hypergravity acceleration levels, this is expected to lead to significantly increased vapor production and consequently faster frying.

- Phase C: Low gravity levels ($0 < g/g_{earth} < 1$)

At this phase, gravitational acceleration values decrease until they are stabilized at values near zero. As gravity decreases, bubbles size progressively increases and the bubble production rate decreases. When near zero gravity value is achieved, bubbles detach from the potato surface only after they get large enough. Once they detach, new bubbles appear at exactly the same sites on the potato surface. This supports the notion that detachment is imposed by the new bubbles growing in the pores of the potato below the old bubbles. Instantaneous overpressure inside potato pores due to vapor formation upon boiling of potato water is suggested as the mechanism generating the force for bubbles detachment and departure. After detachment bubbles do not promptly depart from the potato surface, but wander nearby their nucleation site. As the process of frying continues in the absence of gravity (buoyancy), more and more such bubbles crowd above the potato surface. Due to the limited volume of the frying chamber, a moment comes where these bubbles cannot move freely anymore in the oil but touch each other forming a foam-like closely-packed structure with some of them

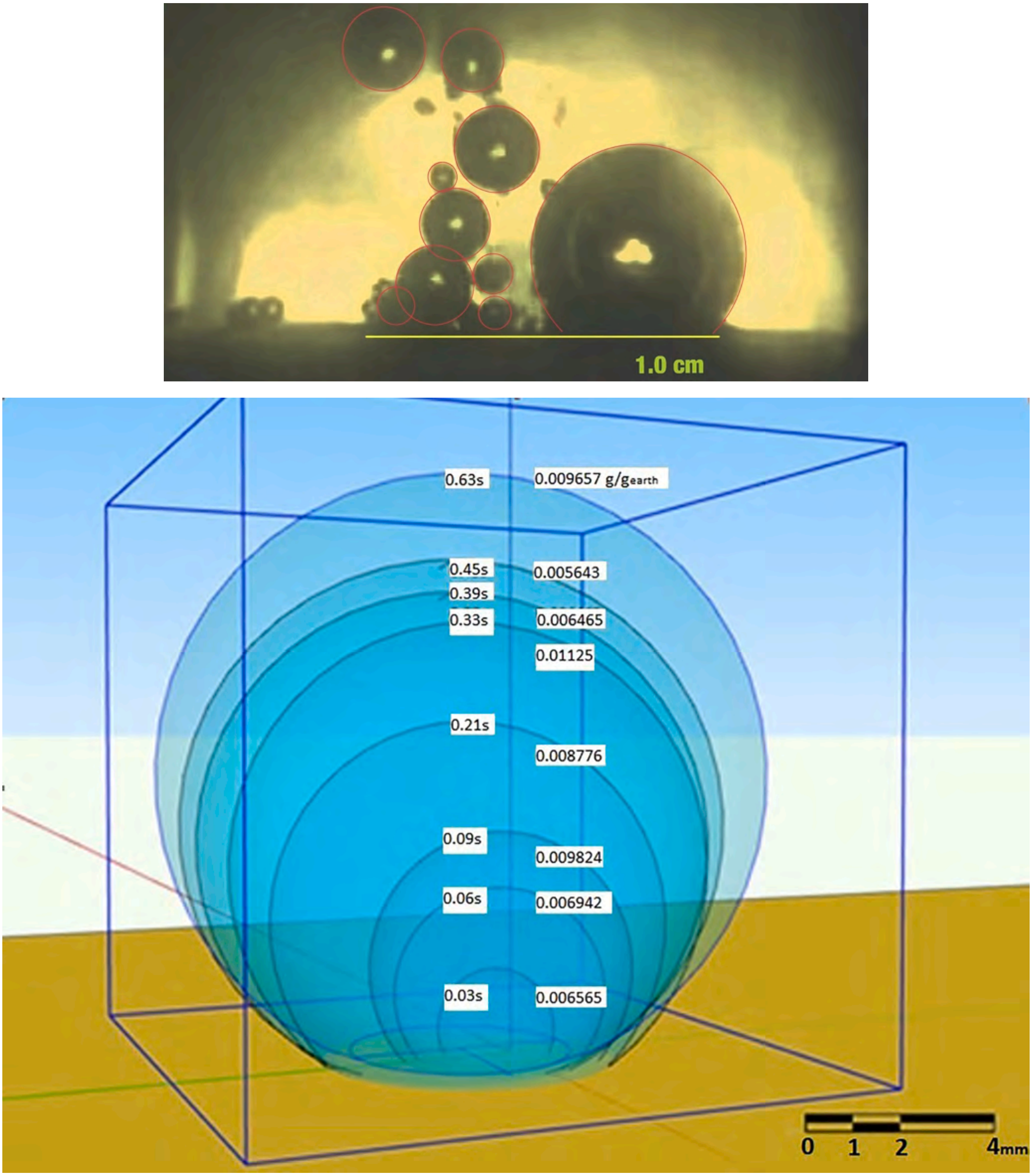

Fig. 3. Image analysis (a) Bubble diameter tracing in ImagePro®; the potato slab is pointed out with the yellow line, (b) A schematic description of bubble growth tracing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

touching the potato surface. Interestingly, new bubbles continue to emerge from the potato surface despite the force required to squeeze this foam-like structure. It is reminded that for safety reasons the present frying tests are conducted at low oil temperature (120 °C). At a realistic range of hot oil temperature (160–180 °C), the more intense heat transfer from hot oil to the potato would create more vigorous bubbles production in the potato. These bubbles do not coalesce to form a continuous vapor layer over the potato so there is always enough contact between hot oil and potato surface. As a result frying proceeds with new bubbles continuing to emerge even at near-zero gravitational acceleration. As soon as the gravity level increases from near zero to higher values, the bubbles accumulated at the potato surface, suddenly depart to the top of the frying chamber, due to buoyancy forces. Then the bubbles behavior follows the reverse line, from phase B to phase A.

The bubble behavior described above, is identical among parabolas and among all examined potato specimens. What actually changes is the

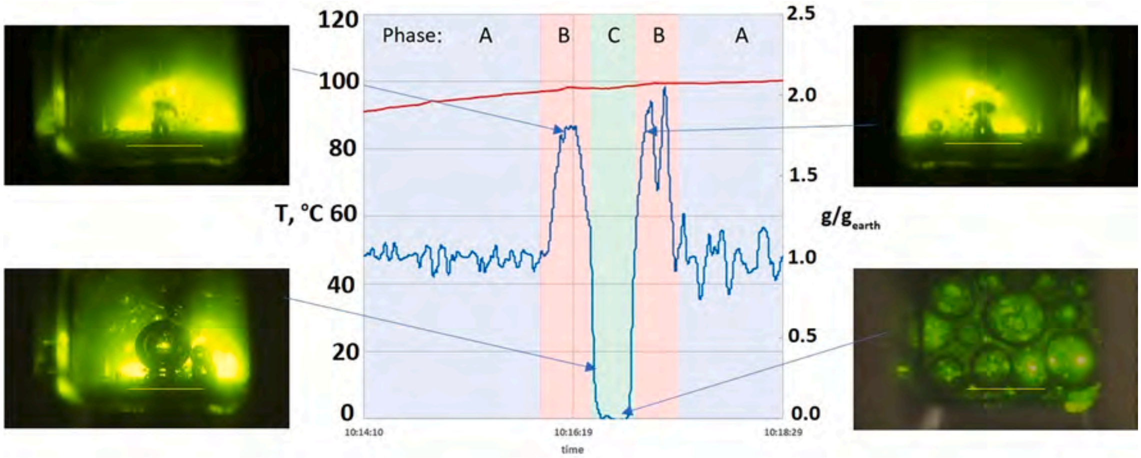

Fig. 4. Phases that designate the various gravitational acceleration conditions during frying in parabolic flight (the red line represents the oil temperature – left axis; the blue line stands for the gravitational acceleration profile-right axis), the potato slab is pointed out with the yellow line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

quantity of the generated bubbles, as frying evolves during successive parabolas.

3.2. Bubble dynamics analysis and vapor production estimation

Till now bubble behavior during frying for various gravity levels has been described qualitatively. At the forthcoming sections, the influence of gravitational acceleration on bubble behavior during frying is examined quantitatively. Ultimate aim of that analysis is to examine whether or/and under what conditions the frying process could be feasible under nearly zero gravitational acceleration value.

3.2.1. Bubbles population, size and volume from analysis of static images for a range of gravitational acceleration values

Fig. 5 presents the dependence of the number and size of the bubbles (i.e. number of bubbles in observational window versus their size; population density plots) on the various gravity conditions for three successive parabolas (i.e. Parabola 1, 2 and 3 corresponding to Fig. 5a, 5b and 5c, respectively). Fig. 5 presents the status of bubbles behavior above the potato surface at arbitrary time instants (but sufficient to describe the phenomena observed in each parabola, i.e. maximum time between the time instants <200 msec) within distinct gravitational acceleration range of values. The plots of Fig. 5, confirm what has been described in the previous section based on visual observations (i.e. as g/g_{earth} decreases, larger size bubbles appear). This observation is quantitatively similar among the three successive parabolas tested. However, as frying proceeds from one parabola to the next, the size of bubbles increases.

Fig. 6a presents the influence of gravitational acceleration on the average bubble radius, r_{ave}, for the three successive parabolas described in the previous paragraph; r_{ave} is calculated after employing the bubble size data, as follows:

$$r_{ave} = \frac{1}{N}\sum_{i=1}^{N} r_i \quad (1)$$

where r_i is the radius of the i-th bubble and N is the total number of bubbles.

Fig. 6a shows that r_{ave} values decrease as g/g_{earth} decreases, but increase as the frying process evolves among the successive parabolas. Interestingly, the relation between r_{ave} and gravitational acceleration values, seems similar to that arising in experiments examining the influence of gravity on bubble size during pool boiling (Di Marco & Grassi, 2009). However, in the case of frying the boiling process characteristics are closely related to the frying process efficiency and for the food quality (Bordin et al., 2013). A rough estimation of the influence of gravity on the produced vapor can be provided from the data presented in Fig. 6b. Specifically, the average bubble volume V_{ave} can be calculated from the volume of each bubble, ($V_i = 4/3\pi r_i^3$), assuming they have a spherical shape as follows:

$$V_{ave} = \frac{1}{N}\sum_{i=1}^{N} V_i \quad (2)$$

Fig. 6b presents the influence of gravitational acceleration on V_{ave} for the same as above three parabolas. It is found that the average volume of the generated bubbles decreases as g/g_{earth} increases and becomes larger as frying evolves through parabolas (the latter is more apparent moving to parabola #3 where a smaller number of bubbles are generated).

Apparently, static images cannot describe the dynamics of the process, e.g. the effect of gravity level on bubbles generation frequency and bubble growth rate. Such information is essential for the complete comprehension of the influence of gravity on vapor production and eventually on the efficient progress of frying.

3.2.2. Bubble growth of individual large bubbles in low gravity conditions

The analysis continues by focusing on the study of bubble growth during near zero gravity levels. In contrast to Section 3.2.1 that analyzes static images at arbitrary time lapses (each image is separated by several seconds from its preceding one), here the size analysis refers to individual bubbles obtained from continuous time recordings by the 30fps camera. The analyzed recordings have been acquired from the same set of parabolas as in previous sections, to maintain the consistency between the presented data. For convenience, the analysis here focuses exclusively on bubbles growing at the location on the potato surface where the largest bubbles are generated.

Fig. 7 presents the time evolution of individual bubbles volume V from their first appearance on the potato surface till the time they detach from it, for near zero gravitational acceleration levels and during four successive parabolas (i.e. Fig. 7a, 7b, 7c and 7d respectively). In Fig. 7 the vertical axis represents the bubble volume as it is calculated considering spherical bubble shape; the time is shown on the horizontal axis; the level of g/g_{earth} is shown next to the dashed lines. From Fig. 7 it is shown that at every low gravity condition tested, the volume of bubbles increases almost linearly with time which implies that the radius varies with time according to a 1/3 power. This is in accordance with observations from literature concerning the bubbles size dependence on gravity during boiling in microgravity conditions (Urbano et al., 2019) Noticeably, the bubble volume growth rate R_v (=dV/dt) remains roughly constant during each parabola since the slope of the

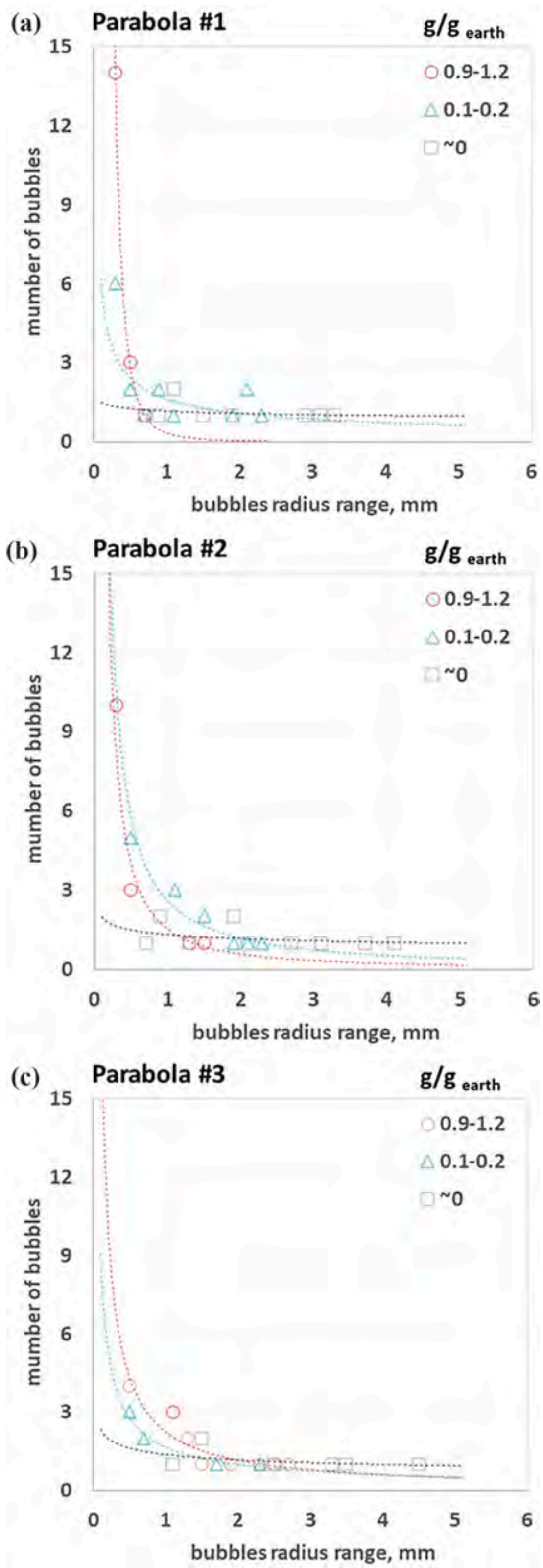

Fig. 5. Bubble population density distribution for three successive parabolas; power law fitting curves to the data also appear (details concerning the parameter values appear in supplementing material D).

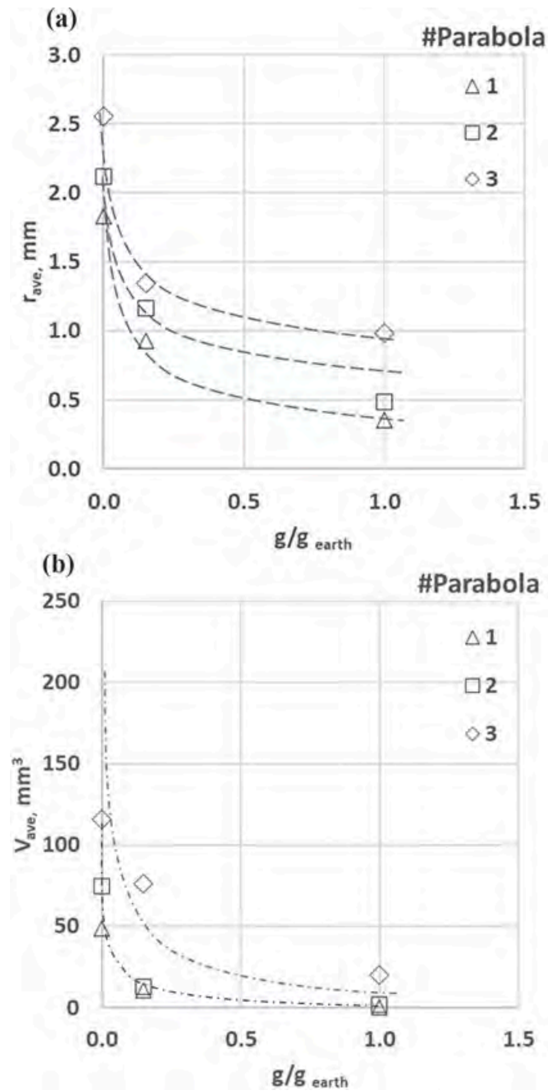

Fig. 6. Average values of (a) bubble radius r_{ave}, and (b) Bubble volume V_{ave}, during three successive parabolas.

data is almost similar for all the cases tested. Moreover, the value of bubble growth rate among the different parabolas, lies mostly between 240 and 270 mm^3/s with only exception the substantially higher value 420 mm^3/s in the second parabola. This increased value may be associated with the expected maximum vapor flux values soon after the onset of frying, which is a typical behavior during the frying process (Lioumbas, Kostoglou, & Karapantsios, 2012a; Fig. 11). During the 3rd and 4th parabola, where frying is at later stages and the vapor amount diminishes, the bubble growth rate value is similar to the one observed during the 1st parabola. The volume growth rates R_v corresponding to each parabola are averaged and the resulting $R_{v,ave}$ is plotted in Fig. 8. This parameter exhibits similar behavior during parabolas with the one observed during the evolution of frying in terrestrial experiments (Lioumbas, Kostoglou, & Karapantsios, 2012a).

3.2.3. Vapor production from individual large bubbles in low gravity conditions

From the analysis presented so far it has been shown that bubbles appearing during frying continue to generate even in low gravity conditions (Section 3.2.1) and the vapor production rate attains values that are within the range of values measured in terrestrial conditions (Section 3.2.2). Aim of the current section is to examine how the vapor production is affected by the various gravity levels.

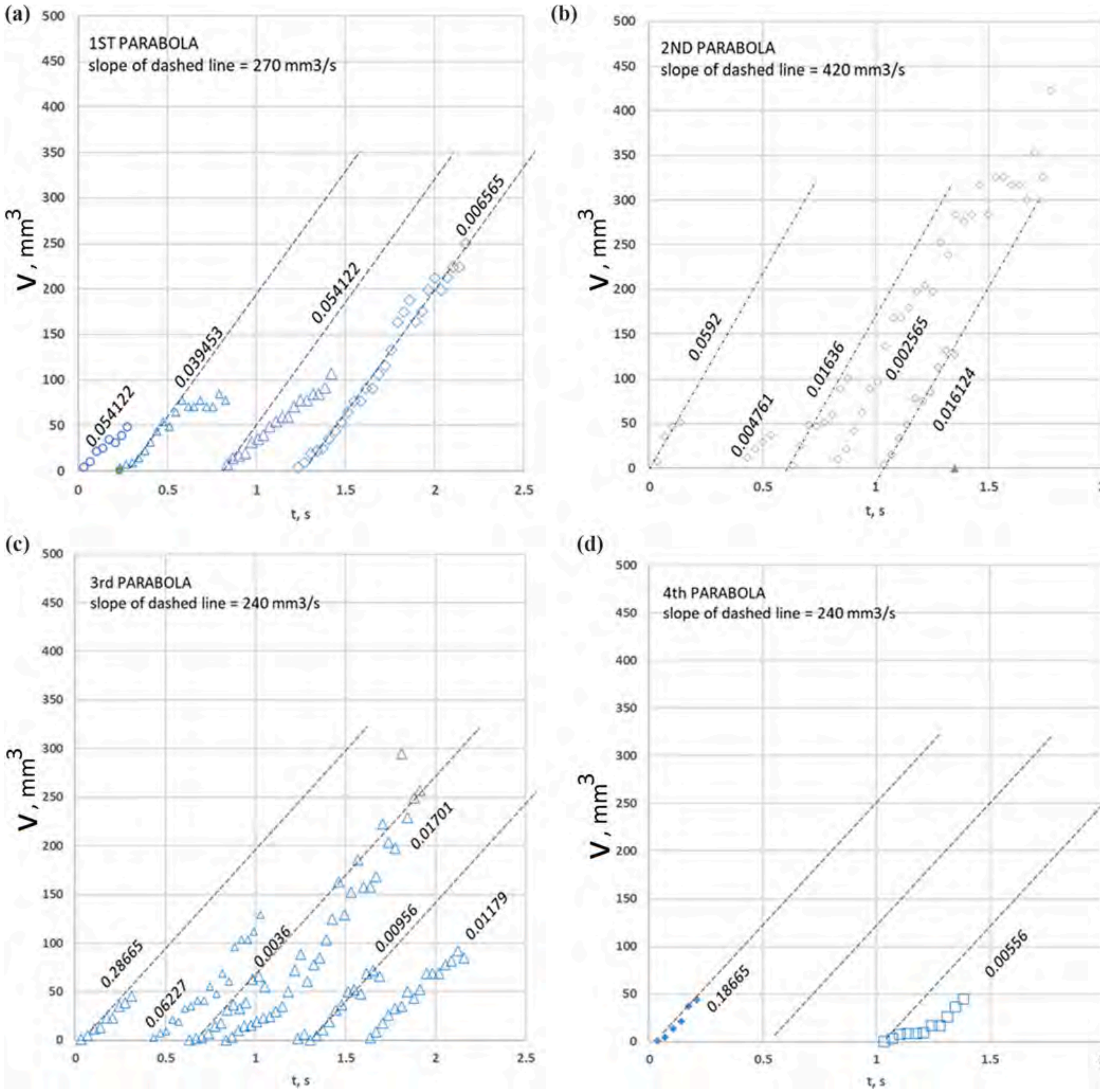

Fig. 7. Single bubble volume evolution for representative bubbles originating at the same site (pore) at near zero level of gravitational acceleration during four successive parabolas. The values of the gravitational acceleration appear next to the data (e.g. 0.0592, 0.054122 etc.) and the data of the volume growth rate R_v (mm^3/s) are shown at the top left of each plot (i.e. slope of the dashed lines).

The volume of vapor produced at a specific site (pore), can be calculated if the frequency and volume of the generated bubbles are both known. For this, specific sites (pores) are selected on the potato surface that lie at the front of the recorded images so as bubbles growing at these sites be not masked by other neighboring bubbles. The generation frequency for each one of the bubbles grown at these prescribed sites is calculated by measuring the time (frames) between the first bubble appearance and its detachment from the potato surface. Compared to this time, the time interval between two successive bubbles is not important (it is assumed that a bubble detaches right after its volume attains its maximum value). Fig. 9 presents the influence of the gravitational acceleration on the frequency of bubbles generation, f, for four sequential parabolas. That set of figures verifies what has been observed and described in Section 3.1, i.e. more bubbles are generated as gravity increases. In particular, for the first parabolas, where the frying process is expected to be in its early stages (with enough moisture maintained near the potato surface to produce bubbles), bubbles were recorded over a wide range of gravity acceleration values (i.e. from 0 to 1.2 g/g_{earth}). Of particular interest are the data in Fig. 9a and 9c, where the values of bubble generation frequency remain constant (~5Hz) over a wide range of gravity acceleration values (i.e. $0.2 < g/g_{earth} < 1.2$). As a transition to lower values takes place, the f values decrease significantly. In the case of the second parabola (Fig. 9b), there appears to be a larger spread on the f values both at x and y axis. This behavior could possibly be linked to the fact that the frying process has evolved, and in the second parabola a maximum vapor production would be expected. However, for the last parabola, where most of the moisture is expected to have been removed from the potato surface, bubbles are only recorded at very

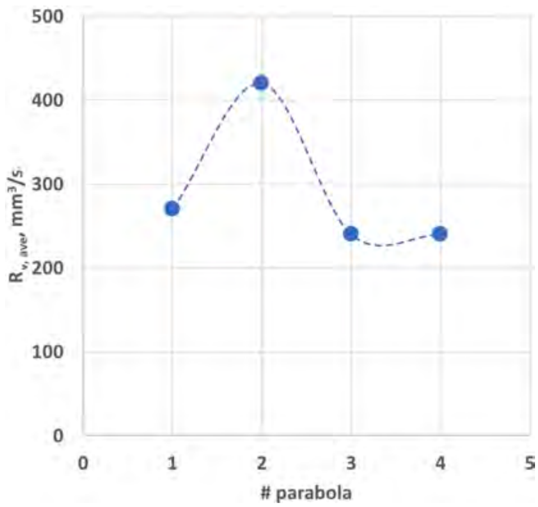

Fig. 8. Average bubble volume growth rate during the evolution of frying process and during parabolas sequences.

low values of gravity acceleration. Interestingly, high f values (i.e. 10–30hz) are recorded for the last parabola even for the lower g/g_{earth} values. A better understanding of what exactly happens with the vapor production in the different parabolas is expected to be obtained after the frequency data are studied in conjunction with the evolution of the bubble size during the parabolas. The radius of bubbles generated at these prescribed sites on the potato surface, is displayed with respect to gravitational acceleration values range in Fig. 10. The volume of the produced vapor (secondary y-axis, in Fig. 10) is calculated from the bubbles radii, considering them spherical. From Fig. 10, it becomes again apparent; as also described in Fig. 6, that the bubbles size increases as gravity levels decrease in a way like the one observed during pool boiling in reduced gravitational acceleration environments (Colin et al., 2016).

Having the above information at hand, the dependence of vapor production rate, R_v, on the g/g_{earth} is plotted in Fig. 11. Within experimental uncertainty, the vapor production rate attains roughly constant values across the different gravitational acceleration values of a parabola. This finding indicates that the frying process may not be seriously affected by the gravity level. If this is so, frying is possible during future long space missions where the gravitational acceleration may vary from a fraction of g_{earth} on Moon and Mars, to microgravity

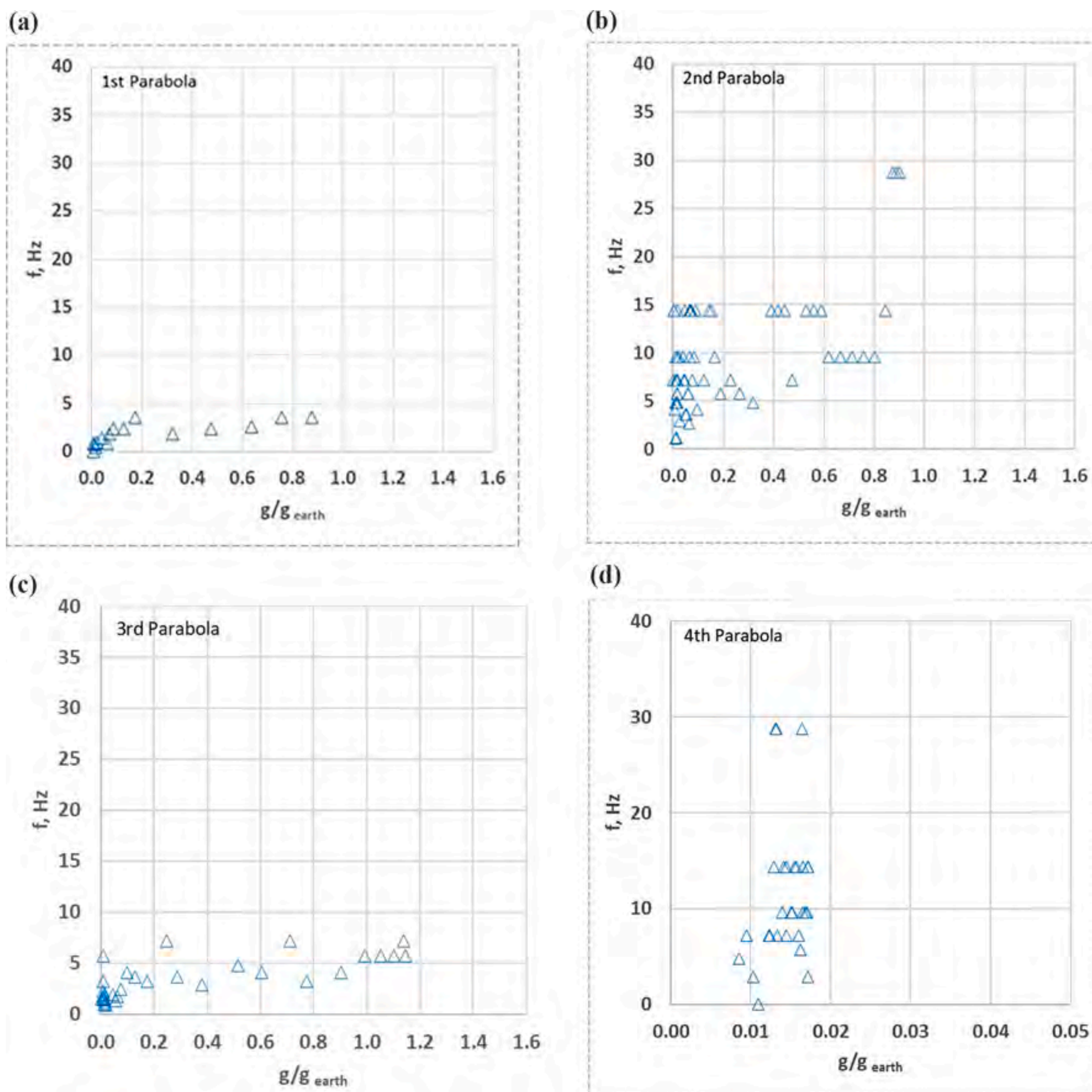

Fig. 9. Generation frequency f of bubbles originating at same site on the potato surface for various acceleration gravitational levels during four successive parabolas.

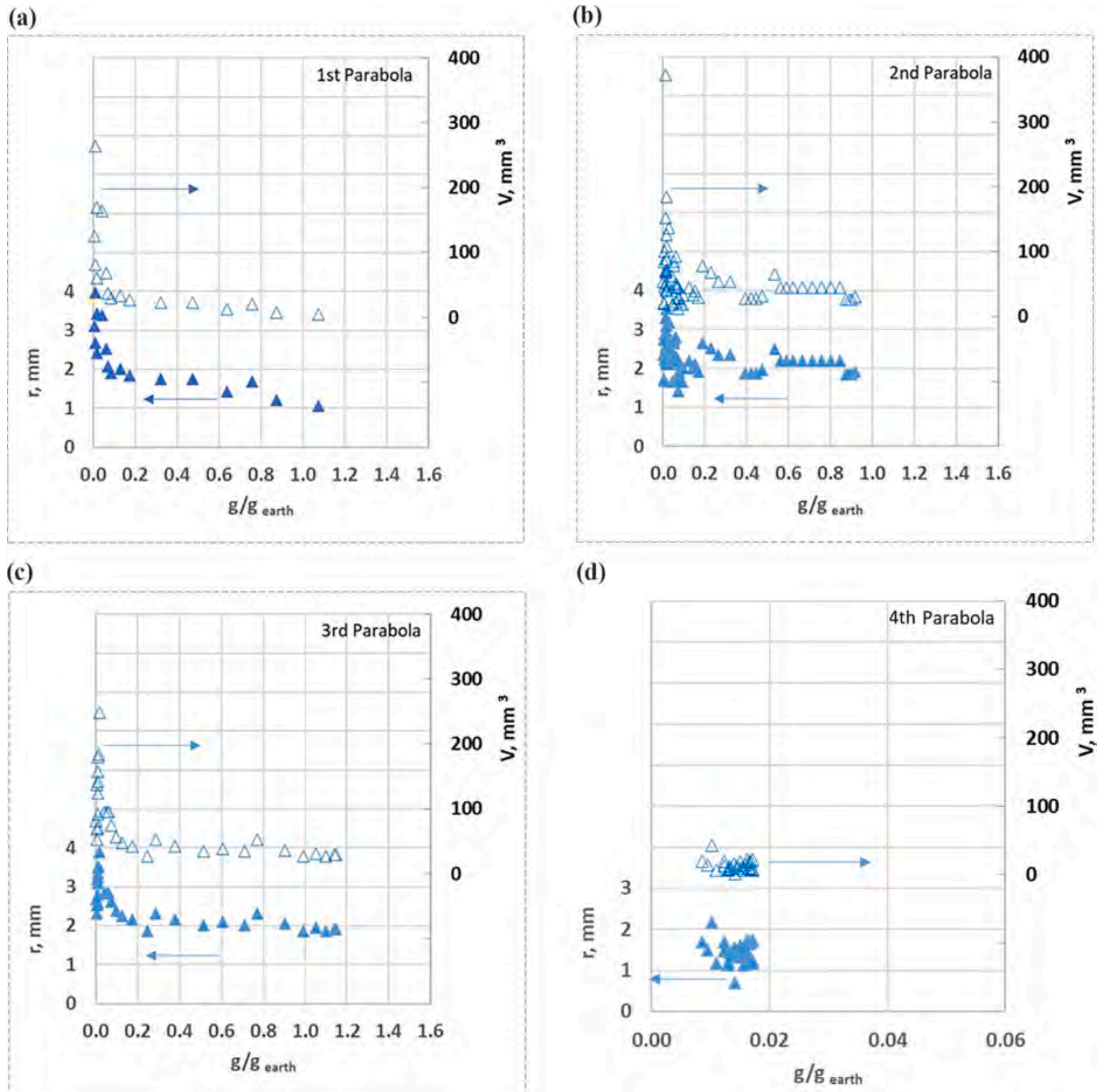

Fig. 10. Evolution of the bubbles radius r originating at the same site on potato surface for various acceleration gravitational levels during four successive parabolas.

during space traveling. Apparently, frying data over longer periods (e.g. 5–10 min) and at different levels of low gravity conditions (~0–0.5 g_{earth}) should be obtained before conclusive statements can be made.

4. Conclusions

The results of this study constitute a preliminary but strong evidence suggesting that vapor production during frying may not depend on gravitational acceleration levels. This finding supports the notion that the process of frying is feasible in space. During parabolas the temperature at three locations beneath the exposed (to hot oil) potato surface is recorded along with the vapour bubbles activity over the potato surface. Measured temperatures are alike those recorded in similar experiments on earth, manifesting that heat transfer is not seriously affected by the employed range of gravitational acceleration values (~0–1.8 g_{earth}), most likely because of the thermal inertia of the potato. In addition, bubbles detachment and departure from the potato surface is observed in all the examined levels of gravitational acceleration, including the periods of low gravity during parabolas. This implies that instantaneous overpressure inside potato pores upon boiling of potato water may be enough to remove bubbles even in the absence of buoyancy. Moreover, as the gravity levels decrease, the volume of the produced bubbles decreases and their frequency increases. Interestingly, the volume of the produced vapor attains values like the ones observed in terrestrial conditions after they are calculated as a product of the volume and the bubbles frequency. This is attributed once more to the thermal inertia of the potato which delivers similar amounts of energy for phase change (boiling) at the different gravity levels. Thermal inertia would have been even stronger if a realistic range of frying temperatures between 160 °C and 180 °C had been employed (instead of the 120 °C employed now for safety reasons). All the above strongly imply that the vapor production during frying in microgravity conditions attains very similar characteristics with the one observed in terrestrial conditions. Since previous studies have explicitly shown that the vapor production characteristics is a crucial parameter that defines the heat and mass transfer phenomena during frying and the produced food characteristics, the present study provides a first documented evidence that frying in space could not necessary be hindered by the absence of gravity. Clearly, future experiments should exclude the present study's limitations (e.g. short-living periodic appearance of microgravity),examine longer duration

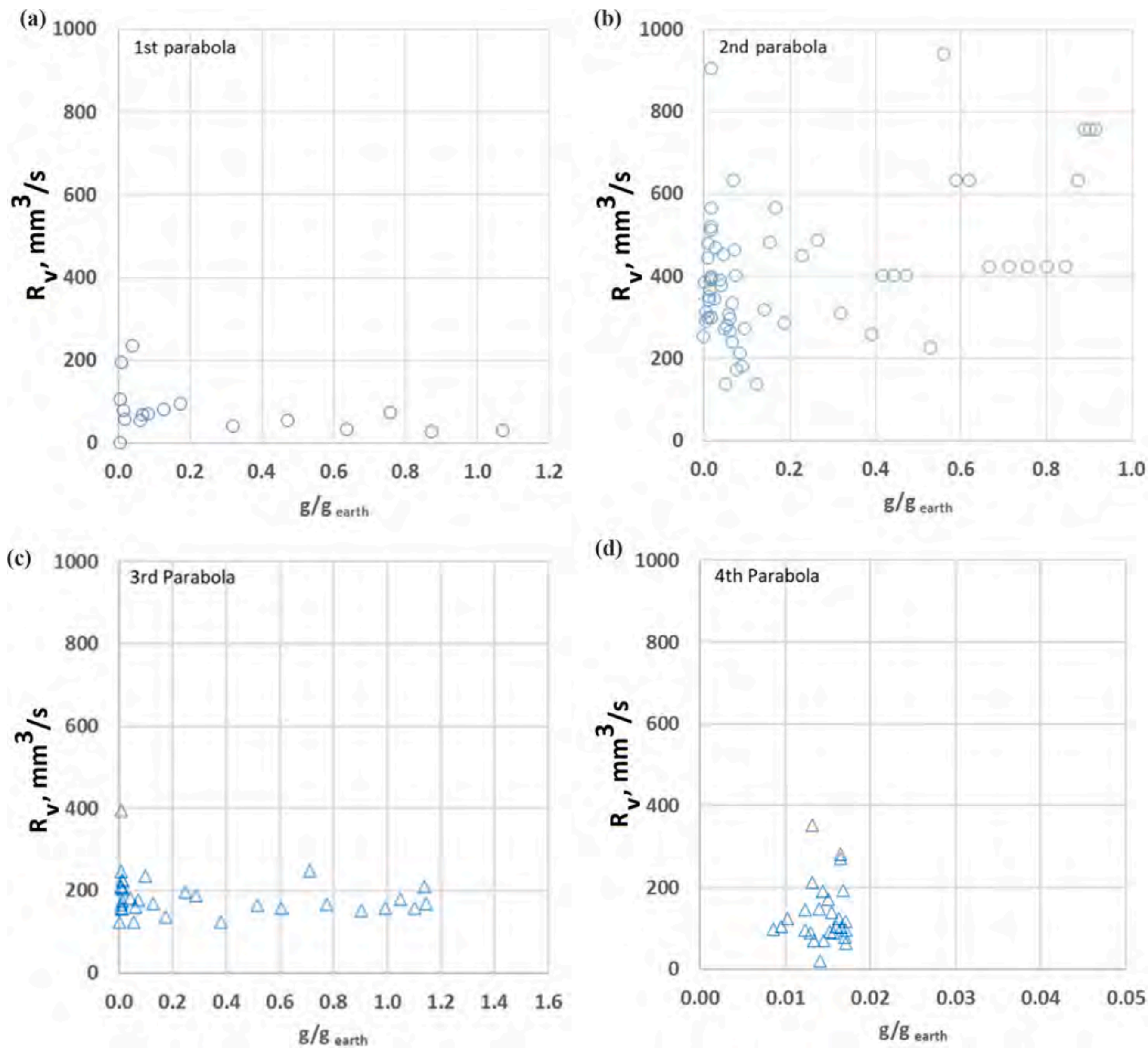

Fig. 11. Vapor generation rate, R_v, for various gravitational acceleration levels during four successive parabolas.

of low gravity i.e., several minutes, so that frying can be performed at steady conditions and consider additional examined parameters that include the qualitative characteristics of the produced food (e.g. structure of the food such as porosity). In addition, the application of different fractional values of gravitational acceleration (using a small centrifuge to examine conditions prevailing on planets) and of a realistic range of hot oil temperatures is also of significance. Frying experiments onboard sounding rockets, or better yet, in the International Space Station, would provide a definite answer on the question whether frying is feasible in space.

CRediT authorship contribution statement

John S. Lioumbas: Conceptualization, Validation, Resources, Visualization, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Sotiris Evgenidis:** Validation. **Margaritis Kostoglou:** Formal analysis, Investigation, Validation, Writing - review & editing. **Tsilipiras Triantafyllos:** Investigation, Validation. **Thodoris Karapantsios:** Conceptualization, Supervision, Funding acquisition, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2022.112249.

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