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Cooking in space: current situation, needs, and perspectives

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The current needs for food in space missions are restricted to the time limits of supplying the International Space Station (ISS) and it can be covered by preparation/processing/packaging of food on earth. However, future long-duration space missions (e.g. to Mars) will require to perform cooking under space conditions. The main aspect of these conditions is reduced gravity. In the present work, at first, the ways of achieving low-gravity conditions on earth are presented. It appears that there is little possibility to use these ways effectively to perform long-enough cooking tests in low gravity, with ISS being currently the only reliable alternative. The possible problems for conventional types of cooking in low gravity are discussed at a fundamental level and potential remedies are proposed.

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Why cooking in space?

The term 'space food' refers to the special type of food that is consumed in space conditions. In the present context, the term 'space conditions' refers exclusively to nearly zero gravity, that is, microgravity. Space food has to be different from common foods in composition, storage, nutritional value, and edible way. This is because it is necessary to assure a good health of astronauts by providing sufficient food and nutrition during the spaceflight. The advancement in science and technology during the last decades has led to a major improvement in the quantity and quality of space food. The astronaut's diet currently is almost the same with that on earth (apart from necessary morphological differences due to preprocessing and storage). The present needs for space food are restricted to the timescale of supplying the International Space Station (ISS). Space foods are prepared on earth and they are processed and packaged in a special way to ensure proper preservation for long time. Two very detailed reviews on space foods, including types of foods, processing techniques, packaging, and appropriate storage conditions can be found in [1] and [2]. It appears that cooking of precooked foods in space requires only simple heating. The shelf lifetime of space foods ranges from one month to 3 years. Although these shelf lifetime values are appropriate for the astronauts in the ISS, they are inappropriate for future manned deep space missions and especially for planned Mars colonization and for a permanent lunar base [3]. The findings of the Micro-Ecological Life Support System Alternative (MELISSA) and Digital Skills on Computational Biology (BIOS) projects suggest that extraterrestrial food production is cost-effective for missions of the timescale of few years [4]. The production of fresh foods in space exhibits several advantages for the health of the astronauts [5], whereas it allows the regeneration of water and oxygen and removal of carbon dioxide during the process [6]. However, the produced raw material must be cooked in order to become edible by humans.

Simulation of space conditions (i.e. low gravity) on earth

Let us start by examining what exactly cooking food in space means. The main feature making the conditions in space different from earth is the very small levels of gravity. Extensive experimental research is needed to exploit the requirements for cooking in low gravity. The obvious place to perform these experiments is the ISS. However, the experimentation there is too expensive, so alternative ways of simulated low gravity have to be exploited. There are several ways to simulate this lack of gravity on earth:

(i) Parabolic flights use airplanes to create low gravity for short periods of time. These airplanes achieve that by flying in a series of up-and-down parabolic trajectories. During each parabola, people and objects inside the airplane are in free fall for about 20–30 s. This approach is not very efficient in eliminating gravity leaving residual values of the order of 10^{-2} g (where g is the standard gravitational acceleration on earth). A strong advantage of parabolic flights is that scientists fly together with their experiments. So, they can make direct observations during low-gravity conditions and further can make adjustments in their experiment between parabolas, thus requiring a minimum degree of automation and no telemetry. In addition, experimental devices can be quite large in mass (max ~200 kg) and volume (max ~5 m^3) and they are usually cheap as they are built by the scientists themselves (safety requirements are strict but modest). On the contrary, the poor level of low-gravity conditions, the short duration of each parabola, and the waiting list to get onboard the few parabolic flight campaigns per year are major limitations.

(ii) Drop towers are tall tubes with their internal air evacuated, from the top of which a capsule containing experimental devices is made to fall. During their free fall, the capsule experiences very low-gravity levels. The tallest drop tower in Europe is at Center of Applied Space Technology and Microgravity (ZARM) in Bremen. It has a total height of 146 m with a clear free-fall length of 110 m. The duration of a single free fall is about 4.7 s, but a microgravity duration of 9.4 s can be achieved by employing a catapult that throws the capsule upward, doubling the free-fall flight path. Several drop tower facilities have communicated their theoretical residual acceleration. Zero Gravity Research Facility at NASA Glenn Research Center uses also a vacuum tube 143 m high to reach a residual acceleration below 10^{-5} g for about 5.2 s [7]. JAMIC drop tower in Japan, the biggest one in the world with a free-fall zone of 490 m, provides a microgravity environment of up to 10 s at 10^{-5} g [8]. The drop tower at Queensland University of Technology offers 10^{-4} g for 2.1 s during a 21.3-m free fall, while the one at Portland State University offers 2×10^{-4} g for 2.1 s during a 22.2-m free fall [9]. Among them, the Bremen drop tower at ZARM can provide the best microgravity condition, by using a double-capsule system, down to 10^{-6} g [10]. However, most of these results are theoretical predictions rather than experimental data. The actual values may be larger. A residual acceleration of $2{\cdot}10^{-4}$ g has been experimentally measured for the drop tower of Beijing [11]. The good level of microgravity conditions along with the low cost of experimental devices (usually built by the scientists themselves) and the easiness to refly many times within a few days are among the major advantages of drop towers. The short duration of microgravity, the small mass and volume (max ~1 m^3) of experimental devices, and the need for preprogrammed automatic operation are among the major disadvantages.

(iii) Sounding rockets. A rocket launched vertically, without reaching a stable orbit, can achieve for certain time microgravity conditions. The European sounding rocket project (MAXUS) system, for example, allows experiments that need up to 12 min of microgravity environments. The gravity levels are of the order of 10^{-5} g [12]. A major advantage of these rockets is the good microgravity conditions, but again, the few minutes duration of microgravity is still short, whereas experimental devices can be quite expensive as they have to be built by specialized firms to make them compact and lightweight with advanced automation and telemetry systems.

Further to the above, there are several other facilities and devices (e.g. clinostats and random positioning machines, rotating wall vessels, and magnetic levitation) designed to simulate microgravity on earth [13]. These devices actually simulate microgravity in contrast to the real microgravity achieved during free-fall processes (i)–(iii) [14]. However, these devices are designed mainly to perform biological experiments and their size and motion do not allow cooking experimentation. The summary of the ways to achieve microgravity on earth is presented in Figure 1.

Current status and opinion on cooking possibility

It appears that the timescale of microgravity conditions in cases (i)–(iii) is in general small compared with the timescale needed for conventional cooking, which is in general a slow process. It is important to notice that the

Figure 1

	Parabolic flights	Drop Towers	Sounding Rockets	Other (clinostats, magnetic levitation etc)
time	20-30 s	up to 10 s	up to 12 min	-
acceleration	10^{-2}g	10^{-5}g	10^{-5} g	-
microgravity	real	real	real	simulated

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Methods used to achieve microgravity on earth.

gravitational acceleration in ISS is at the order of 10^{-4} g. This reduced gravity is not due to the ISS distance from earth (the gravity field at about 400 km from earth is ~0.9 g) but because ISS is always in a free-fall situation. The appreciable residual gravity in ISS is mainly due to the systems operating on it. The above reference to so small values of the acceleration may seem useless (e.g. by considering them essentially as zero acceleration), but as it will be shown later in this communication, these values may be important. Regarding the current status, the only 'cooking' device used by astronauts is an espresso coffee machine [15], which is larger than a traditional coffee machine, it uses high pressure to overcome lack of gravity and it uses pre-encapsulated material. At a research level, there is also an oven designed from Zero G Kitchen [16] to hold and bake food samples in the ISS.

There are several nonconventional cooking approaches used on earth. Some of them do not depend extensively on gravity, so it appears that they can be effectively used in zero-gravity conditions. Among them, the most important ones are microwave cooking [17], extrusion cooking [18], and steam cooking [19]. However, the present work focuses on conventional types of cooking, leading to home-like food of superior quality that may have a strong impact on the psychological condition and well-being of astronauts. The physics behind these types of cooking and how it will be affected by the absence of gravity is the main interest in the present work.

There are mainly three conventional ways of transforming a raw material to edible food (cooking): in an oven pot, in a casserole, and in a frying pan. In all cases, the main feature of the process is the heat transferred first from an energy source (e.g. an electric heater) to the surrounding fluid and then from that fluid to the solid food. Energy is used to heat up the food to the boiling temperature of water or above (depending on the type of cooking). In all types of cooking, water of the food is partially removed either by boiling (at the external surface of food) or by evaporation (inside the pores of food), absorbing excessive heat and gradually allowing solid ingredients to thermalize and transform physicochemically and biochemically to edible food. In this later stage, the transformation processes take place inside the food that is a hygroscopic porous material [20]. The interfacial and capillary forces in the pores are by far larger than the gravitational force. This implies that elimination of gravity does not affect the phenomena occurring inside the food.

Let us examine one by one the effect of gravity on the heat transfer for the three types of cooking, respectively.

In case of an oven pot, the heat transfer mechanism is by infrared irradiation and forced convection of hot air outside the pot, whereas boiling convection (driven by expanding steam bubbles) and some limited natural convection (driven by residual gravity) dominate inside the pot. Thus, no considerable effect of gravity appears on how heat reaches the food. However, the detachment and departure of steam bubbles from the surface of the food during boiling to maintain the progress of cooking are a matter of concern in the absence of buoyancy (gravity). Moreover, in the absence of gravity, holding the food (liquid and solid parts) stable inside the pot in an appropriate manner (avoiding wiggling and sloshing) is equally important to cooking itself.

In cooking casseroles, the main mechanism of heat transfer is the conductive heating of the outside wall of the casserole, whereas boiling and evaporation of water (externally and internally to the food) govern heat transfer inside the casserole being followed by the extraction of ingredients from the food to the liquid phase. Like in an oven pot, boiling plays again a crucial role not only in terms of the amount of transferred heat but also in terms of steam bubble detachment and departure from the food.

The effect of gravity on boiling is an active scientific field [21]. In case of microgravity, not only the bubble buoyant motion but also the natural convection in the fluid phase is suppressed. Most of the studies on boiling in low-gravity conditions have been performed in parabolic flights. However, recent experiments in ISS focus on the study of isolated bubble growth in the absence of gravity [22]. It appears that the lack of gravity does not prevent the detachment of bubbles. The detachment diameter scales inversely to the gravity level with an exponent that can take values as small as 0.24 [23]. Such an exponent implies that even an acceleration of 10^{-4} g can give results quite different than zero g. Surface tension [24] (for single or for coalescing bubbles [25]) and fluid inertia [26] have been proposed as detaching mechanisms. Nevertheless, even right after its detachment from the surface, bubble departure is slowing down significantly and bubbles appear to accumulate near the surface. This is the main problem for pool boiling in microgravity conditions, leading to the argument that casserole cooking is not possible in the absence of gravity without an external means to remove bubbles, for example, by an agitator, electric field, and so on.

The mechanism of frying is a bit different than the previous one. At the outside of a frying pan, heat is transferred again by conduction from an external energy source. At the inside of the pan, heat is transferred first from the pan walls to the oil and then from the oil to the food by forced convection (driven by expanding boiling bubbles) and by some limited natural convection (driven by residual gravity). After an initial short boiling period of the water at the food surface, the temperature of the surface of the food increases to values above the boiling temperature, leading to formation of a completely dry layer, for example, crust in the case of potato frying, which gets thicker with frying time. In parallel, heat gradually penetrates the food beyond the position of the dry layer. At the moment, the temperature of the interior of the food reaches the saturation value, evaporation of the moisture at the internal pores of the food occurs, creating significant amounts of vapor that violently eject through the surface of the food in the form of bubbles that detach from the food inducing agitation to the oil and increasing the heat transfer coefficient from the oil to the food [27,28]. Potato frying in the low-gravity conditions occurring during parabolic flights has been recently studied [29]. It is found that the thermal profiles inside the potato and the oil are not different than the corresponding ones in terrestrial gravity. As the gravitational acceleration drops rapidly at the beginning of a parabola, bubbles increase their size progressively while still in contact with the potato surface but they eventually detach. The combination of the vapor ejection momentum and the volume displacement of the exiting steam has been suggested as the reason for bubble detachment from the surface. Owing to the limited time duration of each parabola, experiments do not span the whole course of the frying process but only a part of it. Although the results reveal that frying may be possible in microgravity, further experimentation is needed. There is the possibility that the thermal inertia of the food drives the process during the absence of gravity. The evaporation in the pores creates overpressure that leads to the detachment of the bubbles from the pore surfaces. However, bubbles after detachment accumulate close to the potato surface, and with no means of external agitation, the heat transfer coefficient is reduced. This reduction, however, cannot be observed in the short duration of low gravity during parabolas.

The study of cooking in hypergravity is related to that in microgravity since in both cases gravity is the factor affecting the process compared to the standard one (in 1 g) [14]. Hypergravity can be achieved employing large centrifugal devices. Potato [30] and egg plant frying experiments [31] have been performed in hypergravity showing heat transfer enhancement (faster frying) with increase of acceleration. There are several theoretical frying models in literature validated using terrestrial data. A naive suggestion is to set the gravity term equal to zero and run these models to find what the situation is in microgravity. However, this does not work. Experience shows that even for single-phase heat transfer, experiments in microgravity reveal a very different behavior compared with theoretical models [32,33].

In all types of cooking, keeping the food (liquid and solid parts) stable in a pot is a very important issue. Using rotating devices that create small acceleration values can achieve this task while at the same time can also provide some buoyancy and natural convection to help bubble detachment and departure from the solid surface. Alternatively, one may use pots with floating lids to avoid free space for the liquid to slosh.

In addition, in all cases, cooking devices must provide means to remove steam from inside the pot, otherwise, the pressure inside the pot will rapidly increase above the saturation point and boiling will stop. Furthermore, collection of steam during cooking is important also for drinking water regeneration by condensation since the water recycling in long space missions should be as close to 100% as possible.

Needs and perspectives

From the above, it is apparent that cooking experiments of full timescale in microgravity are needed. In case of failure, the most probable reason appears to be the accumulation of bubbles close to the surface of the solid food. Remedies to overcome this problem must be proposed and tested. Two examples are (a) the use of centrifugal devices to restore the gravity (or even achieve hypergravity) in the liquid and (b) the recirculation of liquid combined to a gas/liquid separator in order to remove the bubbles. The energy requirements of the above processes must be carefully measured. The final decision for their implementation must be taken based on their energy requirements, the energy availability (different for a permanent base compared with a spaceship), and the necessity of cooking procedure (e.g. potato frying is not nutritionally necessary, but it is important for the well-being of the astronauts). It is noticed that innovative 3D printing might be a promising technique for food production in space [34]. Also, microbial production of proteins is an interesting alternative [35]. However, the present work is restricted to traditional cooking approaches, so it does not cover these modern techniques. The essential outcome of the present work appears in Figure 2.

Figure 2

	Main mechanisms of heat transfer	Main effects of absence of gravity	Expected reduction of cooking performance	Existing experimental study	Possible Remedies
Oven pot	Radiation, forced convection (gas), boiling, natural convection	Lack of natural convection	Small	No	-
Casserole	Conduction (solid), boiling, bubble induced convection in liquid, natural convection	Lack of natural convection, bubbles accumulation	Very large	No	Agitation, restoring gravity, liquid recirculation/gas separation
Frying pan	Conduction (solid), bubble induced convection in oil, water evaporation in the food	Bubbles accumulation	Large	Periodic for time periods of 20-30 s [26]	

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Possible conventional types of cooking in space, main mechanisms, expected performance, and proposed actions to improve it.

Conclusions

The current nutritional needs of astronauts are covered by foods processed on earth and only a simple treatment (i.e. heating) is required to be performed on-site. However, future space missions will require food preservation in such timescale that fresh material production and cooking on-site become necessary. Based on fundamental arguments, it is thought that cooking may not be possible in space conditions (i.e. low gravity). However, there are recent controversial results for frying in parabolic flights. The short duration of low-gravity conditions during parabolas does not permit conclusive arguments. It is necessary to perform cooking tests in microgravity for realistic timescales (i.e. in ISS) in order to identify the problems of the process in the absence of gravity and suggest ways to fix them with as little as possible additional consumption of energy.

Data Availability

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

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.

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