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ORIGINAL ARTICLE

Hypergravity to Explore the Role of Buoyancy in Boiling in Porous Media

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Abstract Boiling in porous media is an active topic of research since it is associated with various applications, e.g. microelectronics cooling, wetted porous media as thermal barriers, food frying. Theoretical expressions customary scale boiling heat and mass transfer rates with the value of gravitational acceleration. Information obtained at low gravity conditions show a deviation from the above scaling law but refers exclusively to non-porous substrates. In addition, the role of buoyancy in boiling at varying gravitational levels (i.e. from microgravity—important to satellites and future Lunar and Martial missions, to high-g body forces—associated with fast aerial maneuvers) is still unknown since most experiments were conducted over a limited range of g-value. The present work aims at providing evidence regarding boiling in porous media over a broad range of hypergravity values. For this, a special device has been constructed for studying boiling inside porous media in the Large Diameter Centrifuge (LDC at ESA/ESTEC). LDC offers the unique opportunity to cancel the shear stresses and study only the effect of increased normal forces on boiling in porous media. The device permits measurement of the temperature field beneath the surface of the porous material and video recordings of bubble activity over the free surface of the porous material. The preliminary results presented from experiments conducted at terrestrial and hypergravity conditions, reveal for the first time the influence of increased levels of gravity on boiling in porous media.

Keywords Porous media · Boiling · Buoyancy · Hypergravity

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1 Introduction

This work is motivated by the need to study a simplified frying process where the extra complication induced by the continuous changing of the material characteristics (i.e. material shrinkage and the pores collapse) has been excluded by using a non-deformable artificial porous material. It must be noted that the frying process, beyond the usual appliance met in food industry (Lioumbas and Karapantsios 2012; Lioumbas et al. 2012) the last years attracts dynamically the interest of other disciplines such as waste management (e.g. fry-drying of sewage sludge, Romdhana et al. 2011) and wood industry (i.e. Boulton process, Grenier et al. 2010) related applications. Frying takes place when a water saturated porous matrix is immersed in an immiscible fluid with temperature well above the water boiling point. The phenomena that characterize frying can be roughly categorized in the bellow listed two groups:

A. Evaporation and/or boiling **within** the saturated porous structure.

Transport processes with phase change **within** porous media, have gained extensive attention in the last decades since, saturated with water porous matrices are

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applied in the development of the "inverted meniscus" type evaporators (Liao and Zhao 2000), loop heat pipes (Prat 2010) and in the research of finding novel ways of thermal protection against high intensity heat fluxes (Sahota and Pagni 1979; Foreest et al. 2009). At the aforementioned applications the use of liquid instead of gas as a coolant has the advantage that the heat of vaporization can be used as an additional cooling mechanism.

B. Bubble dynamics over the heated porous surface.

Heat transfer coefficient values during boiling over porous media significantly depend on the bubble dynamics over porous surfaces. Boiling **over** porous media can be more efficient than boiling over plain surfaces since heat transfer is augmented due to nucleation from numerous sites, evaporation inside the pore structure, vapour ejection, and liquid suction from the top surface of the porous layer (Li and Peterson 2010). Boiling **over** the surface of porous coatings combines heat and mass transfer in porous media with phase change phenomena and removal of large energy amounts. Nevertheless, the increased flow resistance **inside** the porous layer (i.e. at a micro region below the porous surface) may cause the formation and extension of a vapour layer near the heated surface, which may result in the transition from nucleate to film boiling (Mori and Okuyama 2009; Snabre and Magnifotcham 1998; Liter and Kaviany 2001). Thus, boiling over porous media is controlled by flow, heat transfer and mass transfer phenomena **inside** the porous matrix which are not fully understood at present and which, if not properly tuned, can slow down boiling and cancel the advantages of using a porous substrate.

A major matter of concern in boiling on porous substrates is the heat propagation inside the porous matrix which, by conventional means, e.g. by electrical or radiation heating at the boundary, is often inadequate due to non-homogeneous conductive properties of the matrix. As a result, boiling occurs at **arbitrary** nucleation sites inside the matrix with characteristics (i.e. density and size) that are difficult to predict because of the non-stratified density gradients and gravitational instabilities (Ramesh and Torrance 1990). An interesting solution to this problem is to trigger boiling **inside** the porous matrix (saturated with the working liquid) by immersion into a hot immiscible liquid (e.g. oil) surrounding the matrix. The hot immiscible liquid heats up the matrix not only by conduction but also by convection as it can penetrate in the pores. This unconventional top-down heating approach by hot oil offers two distinct advantages compared to conventional approaches of heating porous substrates by electrical or radiation means from their bottom. These are:

- Suppression of the effect of **natural** convection in the surrounding liquid layers since the hot oil is above the cold porous medium.
- More uniform heating of the exposed porous surface (which is a significant source of unsteadiness with conventional heating methods) leading to smoother boiling operation.

However, the above approach, which involves vapor escape from the porous network and hot liquid penetration, brings about also some complications. For instance, mass transfer inside the porous media affects the heat diffusion properties and, eventually, thermalization of the matrix and vice versa heat transfer yields temperature gradients inside the porous media which influences mass diffusivity and, eventually, mass propagation. Nevertheless, phenomena related to bubble dynamics like:

- Bubbles growth, coalescence and detachment on the porous/heater surface.
- Bubbles rise, interaction and coalescence right above the porous/heater surface.
- Relative motion between the bubbles and the liquid (i.e. secondary and/or turbulent flow, wakes induced either by buoyancy and/or by natural heat convection).
- Liquid recirculation induced by the rising bubbles; which is expected to increase the heat transfer coefficient.

are common in both the unconventional boiling approach presented in this study and the classical pool boiling by conventional heating at the boundary.

The gradual scaling of gravitational acceleration has been proven to be a useful tool for the study the bubbles behavior during classical pool boiling. Besides, several experimental studies in the past (Straub 2005) have demonstrated that for conventional boiling over plain surfaces, microgravity is a priceless tool. For instance, in the absence of gravity, buoyancy related phenomena (i.e. natural convection) are eliminated and it becomes easier to study the role of inertia and surface tension on bubble dynamics (Qiu et al. 2002). Despite the fact that **increased** levels of gravity could also be a valuable tool to study the role of buoyancy on the bubble dynamics related phenomena, to the authors' best knowledge, surprisingly only few studies have considered the influence of **hypergravity** on pool boiling (Merte and Clark 1961; Costello and Tuthill 1961). The results of these early works are somewhat contradictory, resulting in no understanding of the effect of increased levels of gravity. To our best knowledge, there is no recent published work where bubbles' behavior in gravity levels greater than 1.8 g_{earth} (achieved during parabolic flights) is examined. Recently, Raj et al. (2010) performed a set of pool boiling experiments during a parabolic flight campaign trying to bridge the gap between low-g and high-g conditions. They recognize that despite the fact that many models and correlations include gravity as a parameter, most fail when they are extended beyond the range of gravity levels they were based on, namely, 1 g and low-g and admit the difficulty of providing a **unified correlation** that can predict the heat transfer coefficients both in increased and decreased gravity levels.

The ultimate scope of the present ESA funded project is to provide a **unified correlation** that can predict the heat transfer coefficients both in increased and decreased gravity levels during boiling over saturated porous media, which will be available after the analysis of the experiments described in the present work and the completion of future planed experiments in microgravity conditions. The experimental results obtained from this unconventional boiling approach will provide insight to the complicated phenomena that take place during the frying process but hopefully it could be also useful in fields related with the boiling inside porous structures or/and boiling above porous substrates. In particular, the scope of this article is to present:

- The mathematical equations that articulate the physics of the boiling approach presented in this study.
- In detail the novel experimental procedure which has been followed to provide experimental evidence for the influence of a broad range of **increased** gravity levels on the complicated phenomena that take place during boiling over porous media.
- Preliminary findings obtained from the hitherto analysis of our experiments conducted in **hypergravity**.

2 Problem Formulation

The physical problem of the boiling approach presented in this study can be described on the basis of two different but closely related scientific topics:

- The heat and mass transfer **inside** the porous material.
- The bubble dynamics **over** the porous surface.

2.1 Heat and Mass Transfer Inside the Porous Material

The theoretical analysis presented in this section is based on a sharp boundary evaporation approximation (crust-core model) proposed by Lioumbas et al. (2012) to describe the micro-scale phenomena in potato deep-fat frying. The porous material is assumed to have circular cross section of infinite length (Lioumbas et al. 2012). This assumption leads to an important reduction of the computational requirements of the mathematical problem rendering 1-D treatment possible. The governing set of equations used during the boiling period, where the porous surface temperature, $T(r = R)$, attains values larger than water boiling point, T_s is presented in Table 1. Where $T = T(r)$ is the temperature in the porous material, r is the radial coordinate, R is the porous radius, k_l, $\rho_l, c_{p,l}$ and k_v, $\rho_v, c_{p,v}$ are the thermal conductivity, density and specific heat capacity of the saturated porous region and the vapour respectively, V is the oil volume in the bath, ρ_{oil}, c_{poil} are the density and specific heat capacity of oil respectively and Q is the power supplied by the heater where h_f is the heat transfer coefficient that includes the effect of bubbling.

In most classical nucleate boiling experiments, power to the test surface is controlled. In that case the wall temperature will oscillate because of spatial and temporal variation in heat transfer on the fluid side. Thus, to determine the thermal response of the solid, one must solve a conjugate problem for heat conduction in the substrate. On the contrary, in our case we assume that there is no spatial and temporal variation on the fluid side. Moreover, the temperature measurements in various positions inside the porous material could be used in the future to estimate the temperature on the porous surface with the help of Eqs. 1–6.

2.2 Bubble Dynamics Over the Porous Surface

Pool boiling involves complicated nonlinear processes operating over a large range of length and time scales. The presence of more than one phase, poor understanding of the nucleation process and a strong dependence on the fluid properties have hindered researchers from developing a completely deterministic model for heat transfer in pool boiling. The mechanisms by which heat is removed from the surface and the effect of parameters such as gravity, subcooling, wall superheat, fluid properties, heater surface geometry, and structure are still unclear. Although many models and correlations include gravity as a parameter, most fail when extended beyond the range of gravity levels they were based on, namely, 1 g and low-g.

Table 1 Governing set of equations concerning the heat and mass transfer inside the porous material

Heat conduction inside the porous material:	(liquid region)	$\frac{\partial T}{\partial t} = \frac{1}{\rho_l c_{p,l}} \frac{1}{r} \frac{\partial}{\partial r} k_l r \frac{\partial T}{\partial r}$ in $0 \leq r \leq R_y$	(1)
	(vapor region)	$\frac{\partial T}{\partial t} = \frac{1}{\rho_v c_{p,v}} \frac{1}{r} \frac{\partial}{\partial r} k_v r \frac{\partial T}{\partial r}$ in $R_y \leq r \leq R$	(2)
Heat transfer from oil to porous surface		$-k_v \frac{dT}{dr} = h_f (T - T_{oil})$ at $r = R$	(3)
Oil bath heat balance (assumed perfectly mixed conditions)		$V \rho_{oil} c_{poil} \frac{dT_{oil}}{dt} = A h_f (T - T_{oil}) + Q$	(4)
Temperature continuity at vapour /liquid region interface		$T = T_s$ at $r = R_y$	(5a)
Symmetry boundary condition		$\frac{dT}{dr} = 0$ at $r = 0$	(5b)
Position of the edge between the liquid saturated and the vapour region		$\rho \varepsilon \Delta H_{vap} \frac{dY}{dt} = -k_l \left(\frac{\partial T}{\partial r}\right)_{r=R_y^-} + k_v \left(\frac{\partial T}{\partial r}\right)_{r=R_y^+}$	(6)

In order to have a credible predictive model of nucleate boiling, one must address four subprocesses and their interactions, which tend to be non-linear. These subprocesses are: (i) density of active nucleation sites, (ii) bubble dynamics that includes bubble growth, merger, and departure, (iii) several mechanisms of heat transfer, such as transient conduction into liquid replacing the volume originally occupied by a departing bubble, and (iv) evaporation at bubble base and bubble boundary. Convection (Marangoni convection) resulting from surface tension gradient along the interface and that induced by density difference must be included. The convective motion can be altered by the agitation created by vapour bubbles. The set of equations that has been extensively used for the prediction of the bubble and heat transfer characteristics in the case of classical saturated pool boiling and can be used also for the description of boiling over porous media is summarized in Table 2. Where q, λ_l, ν_l, α_l, σ are the heat flux, the thermal conductivity, the kinematic viscosity, the thermal diffusivity and the surface tension of saturated liquid, respectively; ρ_v and ρ_l are the densities of vapour and saturated liquid, respectively.

3 Material and Methods

3.1 Description of the Experimental Apparatus

The interplay between the boiling mechanisms below the surface of a porous matrix and the bubbles behavior above it, is experimentally studied during the immersion of a ceramic porous medium saturated with water inside a bath of a hot immiscible liquid. A prototype experimental apparatus is designed and built up, that is capable of providing both temperature measurements at three locations within a very thin substrate below the porous surface (max. thickness: 1.5 mm) and video recordings of the bubble behavior above it (Fig. 1). The porous matrix consists of a cylindrical (diameter 10 mm, height 10 mm) ceramic porous material (VitraPOR™, ROBU®) which is saturated with water. The porous material applied has a porosity of 42 % a porous size of 10–16 μm and an inner surface area of 0.50 m^2/gr. The bottom of the porous material is fixed within a curved glass tube which is filled with water and it is used to saturate the porous matrix during experiments. After the porous material is fully saturated with water,

Table 2 Set of equations used for the prediction of the bubble and heat transfer characteristics in the case of classical saturated pool boiling

Heat transfer coefficient, h_f	$h_f = 207 \frac{\Delta H_{vap}}{D_b} \left(\frac{q D_b}{\Delta H_{vap} T_s}\right)^{0.745} \left(\frac{\rho_v}{\rho_l}\right)^{0.581} \left(\frac{\gamma_l}{a_l}\right)^{0.533}$ Stephan and Abdelsalam (1980)	(7)
Bubble diameter at departure, D_d	$D_b = 2.64^* 10^{-5} \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \left(\frac{\rho_l - \rho_v}{\rho_v}\right)^{0.9}$ Kocamustafaogullari (1983)	(8)
Bubble Release Frequency, f	$f D_b = 0.59 \left(\frac{\sigma g (\rho_l - \rho_v)}{\rho_l^2}\right)^{0.25}$ Malenkov (1971)	(9)

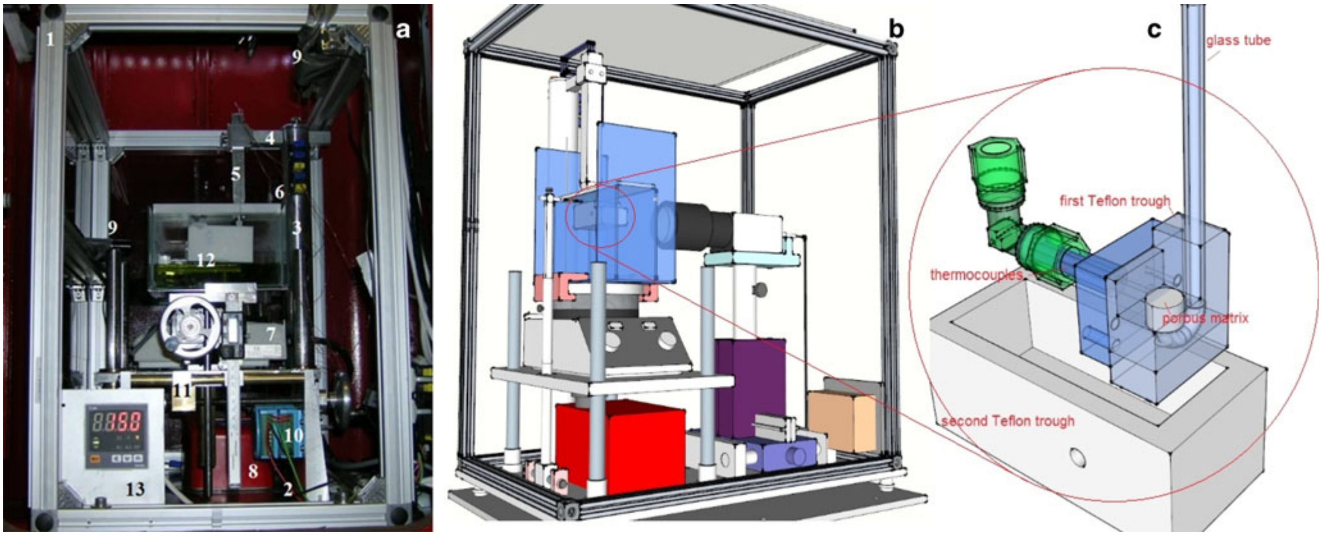

Fig. 1 **a** Photographic description of the experimental apparatus located inside the gondola of LDC: 1. Protective Frame, 2. Base plate, 3. First arm, 4. Second arm, 5. Metal Block, 6. Position adjustment equipment for T_{oil} recordings and T_{oil} Thermocouples, 7. Hot plate, 8. Hydraulic jack, 9. Webcam, 10. Data acquisition Unit, 11. Fast Video Recording camera position adjustment, 12. Optical cell, 13. Temperature controller; **b** Schematic description of the experimental apparatus; **c** Schematic description of the porous material and the insulating Teflon troughs

(water is inserted from the top of the curved tube) the porous material is slotted into a special designed Teflon equipment which insulates the porous material in such a way that its only surface exposed to the oil is flushed with the top of the trough. The porous material and the Teflon equipment are both inserted in a second Teflon insulating trough. Olive oil is used as the heating medium.

Various levels of increased levels of gravity are provided by the Large Diameter Centrifuge (LDC) located at ESA/ESTEC premises. A comprehensive description of the features of the LDC is given elsewhere (Krause et al. 2011). Experiments are housed in freely swinging gondolas which tilt more the higher the rotation speed in order to cancel tangential acceleration components and leave only normal acceleration components acting on the spinning specimens. As soon as the desired gravity level is achieved (after 1 min of spinning), the head of an electro hydraulic jack, which is remotely controlled, lifts a hot plate supporting an optical cell which contains the hot oil. The optical cell (which contains 500 ml of olive oil at 150 °C) rises until the standing still double Teflon unit holding the porous medium is immersed in the oil. Immersion stops when the oil free surface reaches 1 cm above the porous surface. The system is heated through the oil bath and boiling is initiated solely over and below the exposed surface of the porous sample. Experiments were repeated three times.

3.2 Temperature Recordings

In order to acquire temperature measurements at positions very close to the porous surface (i.e. 0.5, 1.0 and 1.5 mm below the porous surface) and since we do not want to disturb the surrounding insertion area, we used three miniature hypodermic probe thermocouples, HYP0, with a needle diameter of only 0.2 mm (OMEGA) that provides a fast time response. Holes with a diameter 0.3 mm are made on the Teflon insulating system to pass through the Ø0.2 mm thermocouples tip. A custom made metal fitting was constructed in order to hold the thermocouples tight and to ensure ±5 % accuracy on the x-y thermocouples positioning.

3.3 Video Recordings

In order to reduce the instantaneous concentration of bubbles and so improve the image quality, we partially coated the porous surface with a thermo and oil resistant silicone glue. Thus, bubble generation is allowed only from the uncoated porous surface region which permits unhindered bubble optical monitoring. A high-speed digital video camera (Redlake, MotionScope® PCI Model) is employed for bubble recording during boiling (1000 fps at image resolution 241 × 210, shutter speed 1/5000). The recorded images are used to calculate the trajectory, the volume, the velocity and the frequency of appearance of bubbles and to obtain an insight of the coalescence/breakage mechanisms. The camera is fixed on a stand very close to the area of observation in such a way that the test section is located between the camera and an appropriate lighting system (white light, 100W, 12DC). A light diffuser is placed between the light source and the object. Video recording starts as soon as the first bubble appears and lasts 100 msec, the time that it takes for the camera's video card to store the file is 4 sec. Just after the recording has been accomplished and the file's storage process has been completed, the recording of the next event begins. This procedure is automated by the help of macro recording software (JitBit), and allows us to have intermittent video streams that cover the total boiling process with duration of several minutes (0.7 Gbyte file). It must be noted that the optical system offers a very narrow depth of field (few hundreds μm). The calibration of the measuring system, to ensure the accurate measurement of bubbles size, is accomplished by measuring the known diameter of a reference cylindrical metal rod (Ø0.2 mm) placed at the focusing plane. Common image analysis software is not capable of analyzing automatically the chaotic and extreme complex patterns that are observed during boiling from several pores/spots. Consequently, we calculate the volume and the rising velocity of each bubble by hand using appropriate software (Redlake MotionScope®).

4 Results and Discussion

4.1 Temperature Recordings

Figure 2 presents temperature profiles, $T_{0.5}$, acquired at an indicative position below the porous surface (i.e. 0.5 mm), during the immersion of the saturated porous matrix in hot oil at 150 °C, at various gravity levels. It was decided to present indicative temperature profiles from individual runs instead of average profiles computed from repeatability runs. Apart from being strict, this avoids smoothing of local features.

As soon as the double trough unit is immersed in the hot oil the *Heating Regime* begins (designated as the light blue area in Fig. 2). This is the period that the porous matrix heats up from ambient to water boiling temperature. During this period, $T_{0.5}$ gradually increases with time and the duration of the *Heating Regime* decreases as gravity-level increases. Moreover, the fact that the values of the $T_{0.5}$ profiles increase during this regime with gravity level, designates that the natural convective heat transfer coefficient which is responsible for the heat transfer from the oil to the porous surface also increases with gravity.

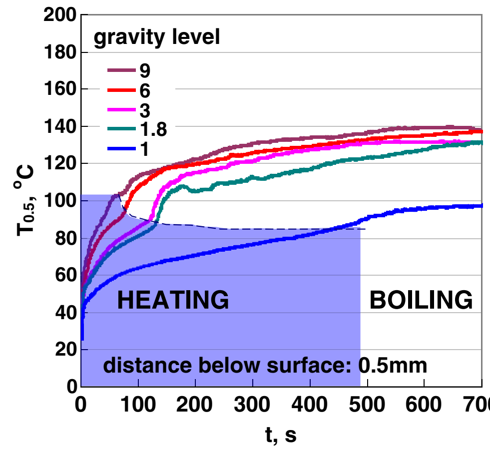

Fig. 2 Influence of gravity level on temperature profiles 0.5 mm below the porous surface for various gravity levels tested. The blue area designates the Heating Regime

The *Boiling Regime* begins the moment that the first vapour bubble (generated at a micro region beneath the porous surface) emerges from the porous surface. This regime initiates sooner as gravity level increases. As a matter of fact it seems that the initiation of the*Boiling Regime* depends with gravity by a non-linear way. Boiling creates intense agitation of the oil layers over the porous surface and leads to increased boiling convective heat transfer from the oil to the porous material. This enhances the boiling of water close to the porous surface. The increased boiling convective heat transfer caused by surface boiling is felt also inside the porous matrix by conductive heat transfer as a steep increase in $T_{0.5}$ values; observed for any given gravity level. The fact that the values of $T_{0.5}$ profiles increase with

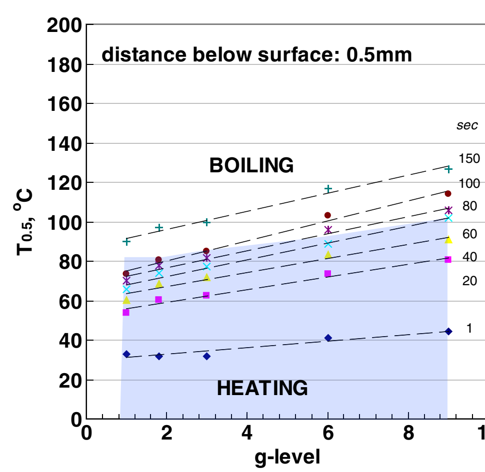

Fig. 3 Influence of gravity on temperature distribution under the porous material at various times (sec) during the heating and early stages of Boiling period at 0.5 mm below the porous surface

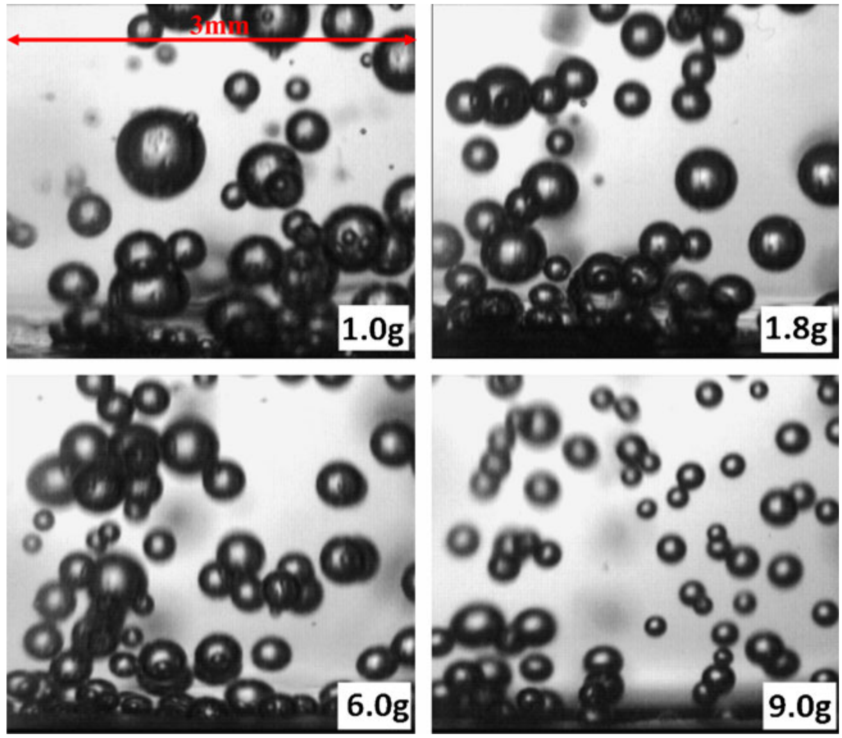

Fig. 4 Images of bubbles distribution above the porous medium surface at terrestrial & increased gravity levels

gravity, designates that the values of boiling convective heat transfer coefficient should probably increase with gravity.

In order to better understand, in a quantitative manner, how heat and mass transfer mechanisms are affected by the increased levels of gravity (during *Heating* and early stages of *Boiling Regime*), we combine the data presented in Fig. 2 and we create Fig. 3 where the temperature profiles are plotted versus the gravity-level for specific time and at specific location beneath the porous surface (i.e. 0.5 mm). From Fig. 3,it is very interesting to notice that the temperature linearly increases with gravity independently of the depth beneath the porous surface. The relation between the temperature values at any time (during *Heating Regime*) should have the following form:

$$T(t, g\_level) = a * g\_level + b \tag{1}$$

Where a, b are functions of time.

4.2 Video Recordings

In Fig. 4, images sequences that correspond to specific time from boiling initiation (i.e. 60 sec) are presented for typical level of gravity tested in the present study (i.e. 1.0, 1.8, 6.0 and 9.0 g). From Fig. 4 it is evident that:

- Bubbles are spherical as they are always pretty small (less than 1 mm).
- The diameter of the bubbles is smaller as the gravity level increase.
- This probably designates that fewer pores are activated as the gravity level increases.

Figure 5a presents the average bubble diameter, d_{ave}, plotted against the boiling time for all the gravity levels tested. It is apparent that:

- At constant gravity level, the size of the bubbles does not change as boiling proceeds. This might be expected because the size of the pores of the porous material does not change during boiling.
- As gravity levels increase, bubbles size decrease. This is attributed to the increased buoyancy forces which force the bubbles to detach from the porous surface at smaller sizes.

In Fig. 5b the rising velocity profiles, U_y, are plotted versus the distance from the porous surface, y, for all the gravity levels examined for a specific bubble diameter (i.e. 0.8 mm). From Fig. 5b it is obvious that the rising velocity of the bubbles formed on the porous surface during boiling, increases with gravity despite the smaller bubbles size.

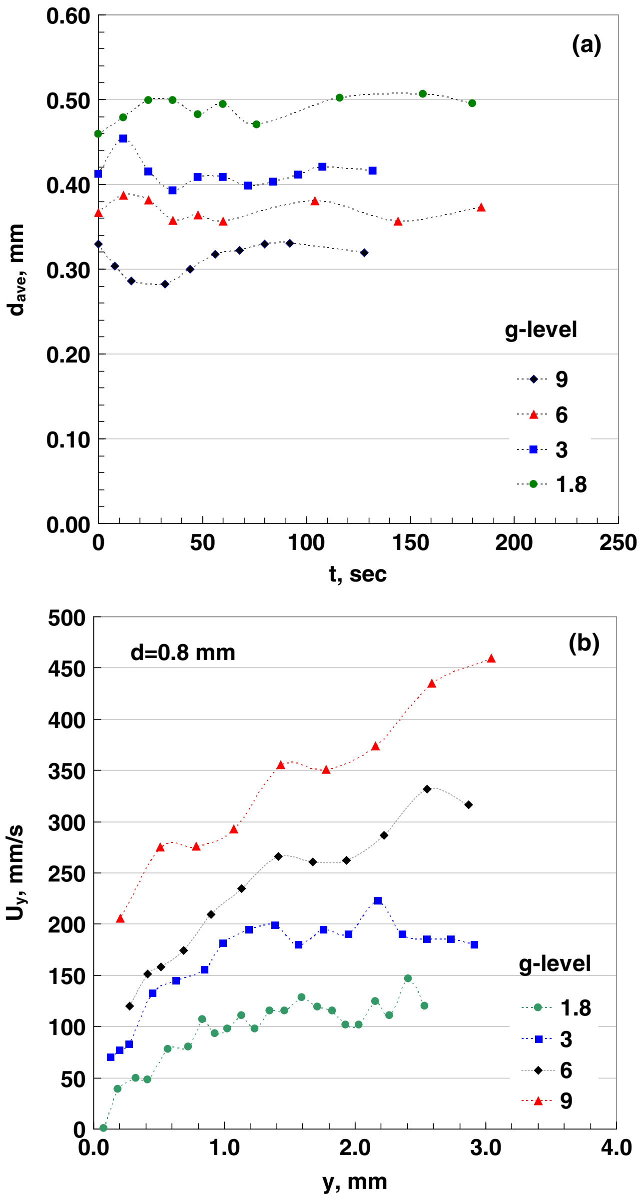

Fig. 5 **a** Time evolution of bubbles average diameter and (**b**) rising velocities of bubbles with specific diameter (d = 0.8 mm) during boiling over the porous medium surface for all the gravity levels tested (1.8, 3.0, 6.0 and 9.0 g)

Preliminary analysis of these results provide experimental evidence for the influence of a broad range of increased gravity levels on the complicated phenomena that take place during the immersion of a saturated porous medium in hot oil. Specifically, there are strong indications that gravity level plays a major role in the process. We suggest that it is not only the natural convective heat transfer between the bath and the porous material that is affected by gravity, but more importantly, the bubble formation (growth rate, population density) and bubble detachment (size, mode) as well. A hitherto analysis of our results indicates that as the gravity levels increase the:

- temperature profiles attain larger values during the entire *Heating* and *Boiling Regime*. However, this is more evident during the *Heating Regime* where boiling bubbles are absent at the surface of the porous medium. More specifically, the temperature values below the porous surface increase with gravity. This indicates that the natural convective heat transfer coefficient which is responsible for the heat transfer from the oil to the porous surface also increases with gravity. Thus, at higher gravity levels the cooling efficiency of the saturated porous material is faster but lasts shorter time because the evaporated water from the pores is not replenished
- boiling Regime initiates sooner
- duration of boiling decreases
- values of the rising velocity profiles increase.

Further analysis of the present experimental results is in progress aiming to provide new insight on the influence of gravity not only to frying related process but also to heat and mass transfer phenomena within porous media and bubble dynamics over porous surfaces.

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5 Conclusions

The results of the present work are quite unique, since to the best author’s knowledge there are no studies that employ:

- an artificial porous material saturated with water to examine the frying process
- hypergravity to scale the role of gravity on the bubble characteristics observed during boiling above porous media.

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