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Bubble dynamics and substrate thermalization during boiling in water saturated porous matrix

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Boiling over and just below the surface of a porous matrix is experimentally studied during the immersion of ceramic porous matrix saturated with water inside a bath of a hot immiscible liquid (i.e. oil with temperature well above the water boiling point). To simplify the geometry of the problem, the porous matrix has only one surface exposed to hot oil, the others being thermally insulated. Therefore, the hot oil triggers boiling solely over the exposed porous surface.

Continuous temperature measurements inside the oil bath, on the oil-porous interface and inside the porous matrix (i.e. 0.5, 1.0 and 1.5 mm below the surface) are acquired along with optical images of bubbles activity (based on fast-video recordings) over the exposed porous surface. Temperature profiles along with images are cross-examined aiming at identifying a possible relation between bubbles behavior and boiling heat transfer inside the porous matrix. The influence of the oil bath's temperature, T_{oil}, on the above phenomena is studied by testing various T_{oil} values (i.e. 150, 160, 170 and 180 °C). Increased levels of gravity in the range from 1 g to 9 g are used as a tool (experiments conducted in the Large Diameter Centrifuge at ESA/ESTEC) to modify bubble dynamics over the porous surface.

The results reveal the influence of T_{oil} on the evaporation front propagation beneath the porous surface. In addition, the analysis of the experimental results elucidates the relationship between the heat transfer coefficient and the gravitational acceleration parameter. Moreover, the data analysis indicates a strongly non-linear effect of increasing gravity on heat transfer coefficient over porous media.

1. Introduction

This work is motivated by the need to elucidate the complicated phenomena that take place when a saturated with liquid porous matrix is immersed in an immiscible fluid with temperature well above the water boiling point. The observed phenomena that take place during this process can be roughly categorized in two separate groups:

A. Temperature increase of the porous matrix (thermalization), which leads to water phase change and vapor formation inside the pores.
B. Vapor transportation from the formation spots inside the pores toward the porous matrix–oil interface.
C. Bubbles growth and detachment from porous matrix–oil interface.

When a saturated with liquid, porous matrix is immersed in a hot immiscible fluid the above phenomena take place simultaneously. The motivation to investigate these phenomena arose from the need to study a simplified process of frying where the extra complication induced by the continuous changing of the matrix characteristics (i.e. matrix shrinkage and pores collapse) has been excluded. Frying involves unsteady heat and mass transfer phenomena in porous media (the crust formatted at the matrix's surface can be considered as such), phase change of water, vapor bubble formation and growth on the matrix surface, and forced heat convection induced by the violent bubble departure from the matrix surface [1]. The problem becomes even more complex if one takes into account the dramatic changes in the properties of the matrix being fried (e.g. thermophysical properties, water concentration profiles and structural features such as porosity and pore sizes). It must be noted that the frying process, beyond the usual appliance met in food industry [2,3], the last years attracts dynamically the interest of other disciplines such as waste management (e.g. fry-drying of sewage sludge) and wood industry (i.e. Boulton process) related applications.

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Nomenclature

D_b	average bubble diameter (mm)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/(m^2 K))
q	heat flux (W/m^2)
T	temperature (°C)
U_y	rising velocity (mm/s)
Greek symbols	
α	thermal diffusivity (m^2/s)
δ_{ef}	evaporation front thickness (mm)
λ	thermal conductivity (W/m K)
ν	kinematic viscosity (m^2/s)
ρ	densities (kg/m^3)
Subscripts	
b	boiling
oil	extra virgin olive oil
sur	porous matrix surface
v	vapor

From the above it becomes apparent that in the present study we are dealing with "unconventional" boiling on the surface of a porous matrix and below it, since the bubbles are not formed solely because of the rapid vaporization of a liquid – heated to its boiling point – on the porous matrix surface, but are formed mainly due to the heat transfer from the hot oil (that surround the porous matrix) to the – entrapped within the porous structure – water (with temperature below the boiling point) in a region close to porous interface. Moreover, the employed 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 the suppression of the effect of natural convection in the surrounding liquid layers since the hot oil is above the cold porous matrix and a more uniform heating of the exposed porous surface (which is a significant source of unsteadiness with conventional heating methods) leading to smoother boiling operation.

The significant role of bubbles behavior above the porous matrix–oil interface on heat transfer rates inside the porous matrix, has been recognized by many researchers in the past working on frying [4,5], However, these works are limited only to **qualitative** descriptions of the observed phenomena mostly because of the varying properties (porosity, pore size, crust formation, etc.) of the food matrix. More specifically, a **quantitative** characterization of the bubble dynamics above the porous matrix–oil interface during frying is completely missing. The originality of this works refers to:

a. simplifying the porous matrix properties replacing natural food with a ceramic porous matrix and
b. collect and analyze systematically optical recordings of bubble dynamics. Here only preliminary results are presented.

Further analysis that will be presented in a subsequent work will allow understanding the interplay between the bubble dynamics above the porous surface (i.e. bubbles growth, coalescence and detachment on the porous/heater surface; bubbles rise, interaction and coalescence right above the porous/heater surface and 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), and heat transfer inside the porous matrix.

In order to study the bubbles behavior above the surface of a porous matrix, the gradual scaling of gravitational acceleration is a useful tool. Besides, several experimental studies in the past [6] 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 [7].

In line with the above, increased levels of gravity could also be a valuable tool to study the role of buoyancy on bubble dynamics. However, it seems that **only few studies** have considered the influence of hypergravity on pool boiling [8]. 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 (achieved during parabolic flights) is examined. Recently, Raj [9] performed a set of pool boiling experiments during a parabolic flight campaign trying to bridge the gap between low-g and high-g conditions. These authors recognize that although many models and correlations include gravity as a parameter, most of them fail when they are extended beyond the range of gravity levels they were based on, namely, equal or less than 1 g. They also admit the difficulty of providing a unified correlation that can predict the heat transfer coefficients both in increased and decreased gravity levels.

The scope of the present work is to experimentally study the influence of oil temperature and increased levels of gravity on the behavior of the thermal field below the porous surface and on the bubbles behavior above it.

2. Experimental test set-up

The interplay between the boiling mechanisms over and just below the surface of a porous matrix and the bubbles behavior above it is experimentally studied during the immersion of a ceramic porous matrix saturated with water inside a bath of a hot immiscible liquid. A prototype experimental apparatus is designed and built, that is capable of providing both temperature measurements at three locations (0.5, 1.0 and 1.5 mm, Fig. 1a) within a very thin substrate below the porous surface and video recordings of the bubble behavior above it. Details concerning the design parameters of the apparatus can be found [2,3]. The porous matrix consists of a cylindrical ceramic porous matrix (VitraPORTM, ROBU® porous size 10–16 μm and inner surface 1.75 m^2/g) which is saturated with water.

The bottom end of the porous matrix is fixed to a bended glass tube in the form of a reverse senile cane extending to a height above the top end of the porous matrix, Fig. 1a. The glass tube is filled with water and is used to saturate the porous matrix during experiments. After the porous matrix is saturated with water at room temperature (water is fed from the top of the reversed cane tube) the porous matrix is slotted into a specially designed double Teflon unit which insulates the side cylindrical wall of the porous matrix leaving only its top flat surface (mounted flush with the top of Teflon) exposed to hot oil, Fig. 1b. Then the porous matrix is immersed in hot oil. The above configuration simplifies the geometry of the problem since the porous matrix has only one surface exposed to hot oil, the others being thermally insulated.

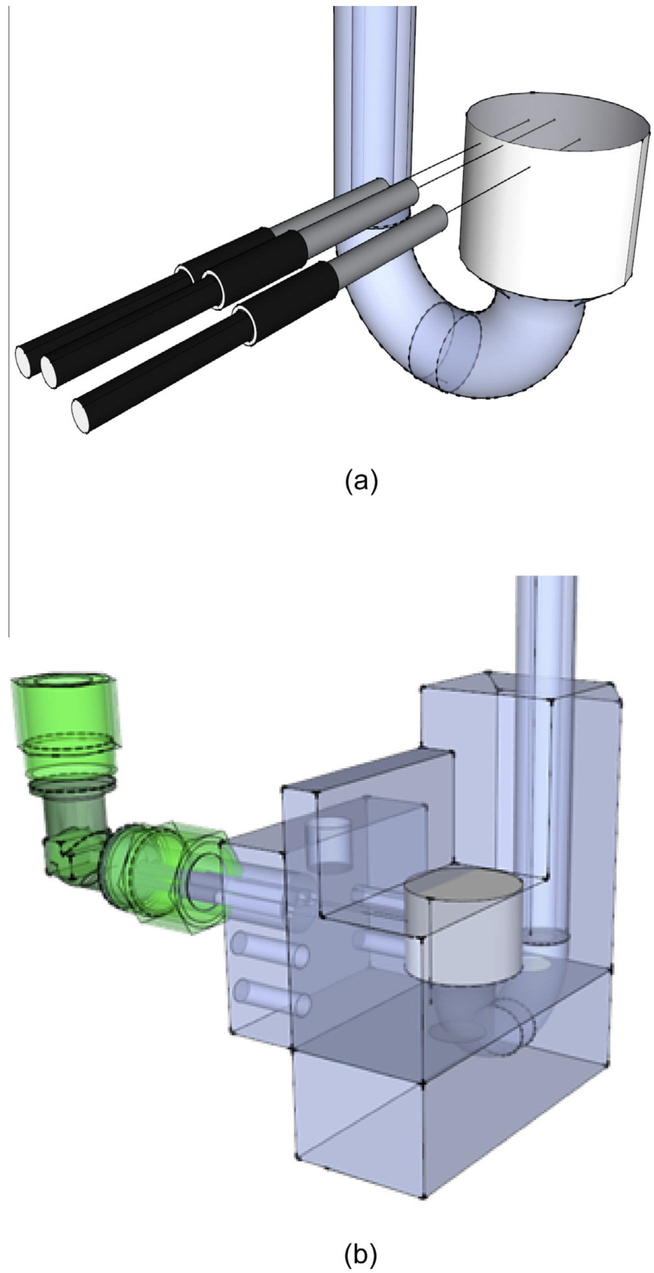

Fig. 1. Schematic description of: (a) porous material in the form of a reverse senile cane together with the three embedded thermocouples and (b) insulating double Teflon unit insulating the side wall of the porous material and leaving exposed to oil only its top flat surface.

Therefore, the hot oil triggers boiling solely over the exposed porous surface.

Olive oil is used as the heating matrix. Experiments at terrestrial conditions (1 g) were conducted at four different initial oil temperatures, T_{oil} (that is, 150, 160, 170, and 180 °C) while experiments at high gravity conditions (1.8–9 g) were conducted at T_{oil} = 150 °C. Experiments were repeated three times to check for reproducibility. To simplify the geometry of the problem, the porous matrix has only one surface exposed to hot oil, the others being thermally insulated. Therefore, the hot oil triggers boiling solely over the exposed porous surface.

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 [10]. 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 about 1 min of spinning), the head of an electro hydraulic jack, which is remotely controlled, lifts a hot plate supporting an optical cell containing 500 ml of hot oil. The optical cell rises until the, standing still, double Teflon unit holding the porous matrix is immersed in the oil. Immersion stops when the oil free surface reaches 1 cm above the exposed porous surface. Heat is transferred from the hot oil to the cold porous matrix and thus boiling is initiated over and below the surface of the porous matrix.

2.1. Temperature measurements

In order to acquire temperature measurements at positions very close below the exposed porous surface (i.e. 0.5, 1.0 and 1.5 mm) we used three miniature hypodermic probe thermocouples (HYPO, OMEGA), with a needle diameter of 0.2 mm. They are inserted in the aforementioned positions below the porous surface through holes at the side cylindrical wall of the porous matrix. These holes continue inside the Teflon insulating unit at a larger diameter (0.3 mm) which proved necessary to pass through the ∅0.2 mm thermocouples tip. A custom made metal fitting was constructed in order to hold the thermocouples tight enough and to ensure ±5% accuracy on the *x*–*y* thermocouples positioning.

2.2. Optical recordings

In order to reduce the number of bubbles and improve the images quality, we coated part of the exposed porous surface with a thermal- 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 known to us image analysis software are not capable of analyzing the extremely complex bubble behavior observed during boiling at several neighboring pores/spots. The bubbles population is calculated by hand utilizing commercial software (ImagePro®). In addition the rising velocity of each bubble is calculated also by hand using appropriate software (Redlake MotionScope®).

3. Results

3.1. Temperature measurements

Fig. 2 presents indicative temperature profiles, *T*, acquired at specific positions below the porous surface during the immersion of the saturated porous matrix in hot oil for various initial oil temperatures (Fig. 2a; 1.5 mm at 1 g) and for various gravity levels (Fig. 2b; 0.5 mm at T_{oil} = 150 °C). It is 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 due to inherent variability of samples. From Fig. 2 it becomes apparent that as T_{oil} and gravity levels increases, boiling begins sooner and the thermal profile attains larger values. These features indicate higher heat transfer rates both before and during boiling as T_{oil} and gravity level increases.

Given that the maximum pressure at the crust–core interface during frying is estimated to be very close to 1 atm [2] (approximately 800 Pa), we designate as evaporation front, δ_{ef}, the location inside the potato where the temperature is 100 ± 0.5 °C.

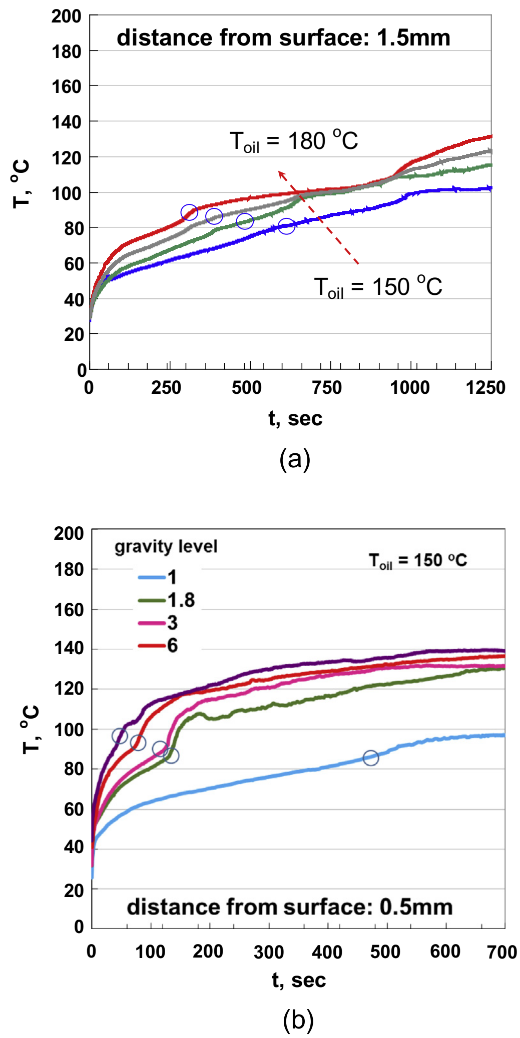

Fig. 2. (a) Comparison of temperature profiles measured at the same distances below the porous surface (1.5 mm) for T_{oil} = 150, 160, 170, and 180 °C. (b) Influence of gravity level on temperature profiles, T, 0.5 mm below the porous surface. The blue dots on the curves designate the beginning of the boiling regime. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

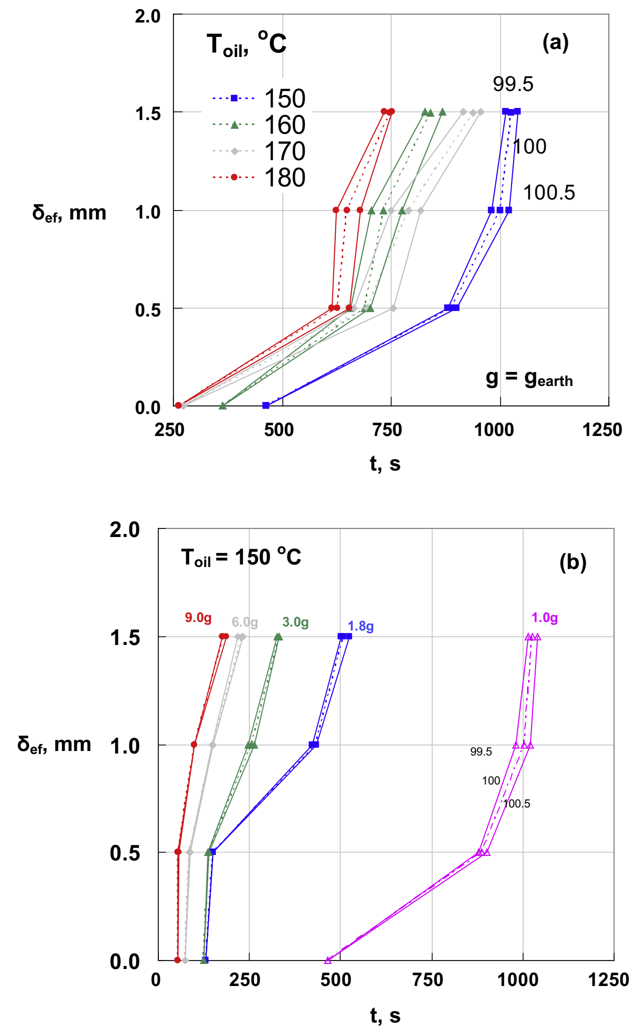

Fig. 3. Propagation of the evaporation front, δ_{ef}, (designated as the $T_p = 100 \pm 0.5$ °C zone) for various: (a) initial oil temperatures and (b) gravity levels.

The ±0.5 °C band incorporates experimental uncertainty as well as deviations due to local phenomena. Knowing the exact location of the 3 thermocouples inside the porous matrix, it is possible to estimate the propagation of δ_{ef}, by plotting the distance of every thermocouple from the surface of the potato against the time that temperature stays at 100 ± 0.5 °C for every location. In Fig. 3, the propagation of the evaporation front, δ_{ef}, is presented for all the examined initial T_{oil} at 1 g (Fig. 3a) and every tested gravity level at T_{oil} = 150 °C (Fig. 3b). As T_{oil} increases the onset time of boiling decreases, i.e. time for $\delta_{ef} = 0$, which means that heating (substrate thermalization) lasts shorter. Once boiling has started and during the early stages of boiling (that is, $\delta_{ef} < 0.5$ mm), the evaporation front moves at roughly the same rate (approximately 1.15–1.30 × 10^{-3} mm/s) regardless T_{oil}. The same holds for the subsequent stages of boiling (0.5 mm < δ_{ef} < 1.5 mm), where the front propagates (approximately 3.5–4.5 × 10^{-3} mm/s) also regardless T_{oil}. On the other hand, as gravity level increases δ_{ef} propagates faster inside the porous matrix (Fig. 3b). Apparently, gravity level has a profound effect on both the initial heating period (time for $\delta_{ef} = 0$) and boiling period (rates for $\delta_{ef} > 0$). On the contrary, T_{oil} appears to affect heat transfer drastically only primarily during the initial heating period before the onset of boiling.

3.2. Optical recordings

Fig. 4a presents the bubble size distribution corresponding to the summation of all the bubbles generated during a single experiment for T_{oil} = 150 °C. It must be noted that the y-axis stands for the real number of bubbles counted. The bubble size distribution roughly follows a normal distribution. The average bubble diameter, D_b, is approximately 0.5 mm. Fig. 4b presents the average bubble diameter, D_b plotted against the boiling time for all the gravity levels tested. Average values at different time instants are computed from optical recordings lasting 1 s.

It is apparent that:

- The size of the bubbles practically does not change as boiling proceeds. This might be expected because the size of the pores of the ceramic porous matrix does not change during boiling.
- As gravity level increases, bubbles diameter, D_b, non-linearly decrease (inset plot in Fig. 4b). This is attributed to the increased buoyancy forces which force bubbles to detach from the porous surface at smaller sizes.

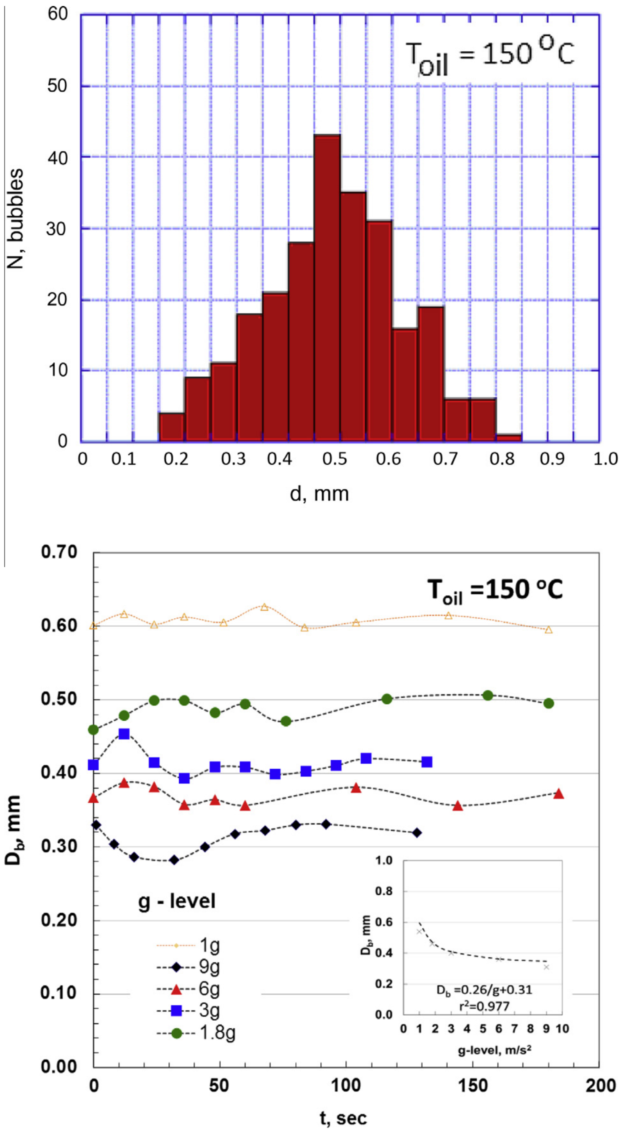

Fig. 4. (a) Bubble diameter and population distribution observed during boiling over a saturated porous medium for T_{oil} = 150 °C and (b) time evolution of average diameter of bubbles for all the gravity levels tested (1.8, 3.0, 6.0 and 9.0 g).

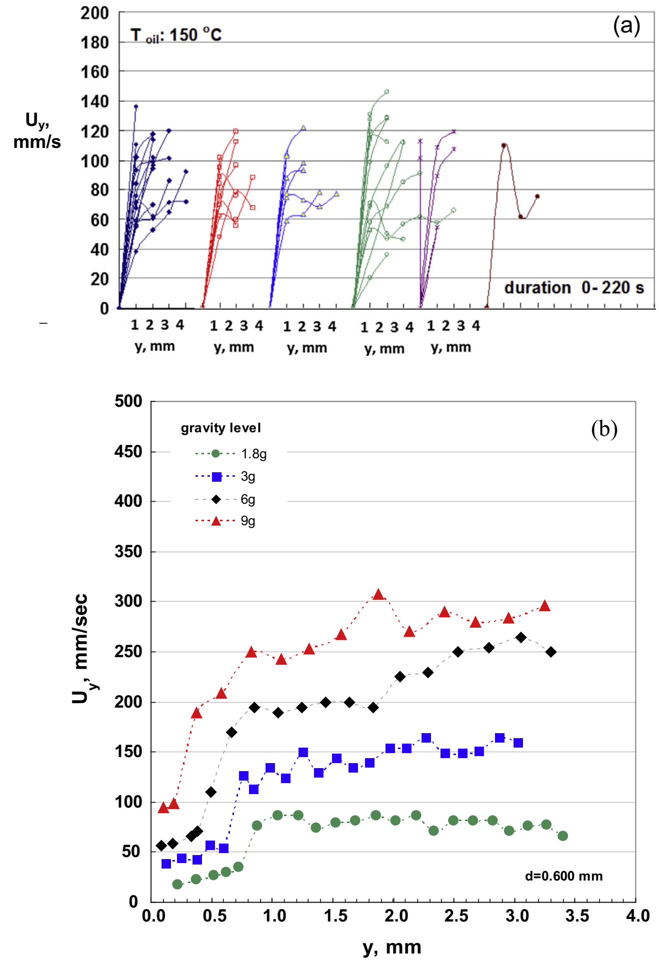

Fig. 5. Rising velocities of the bubbles recorded at T_{oil} = 150 °C for (a) earth gravitational conditions (different colors stand for distinguished pores) and (b) for different gravity levels.

In Fig. 5a the rising velocity profiles, U_y, are plotted versus the distance from the exposed porous surface, y, for initial oil temperature 150 °C (Fig. 5a). The distance y is calculated from the apex of the bubbles which at such small size are almost spherical. Profiles are shown for bubbles originating from the same pore (same color) and from different pores (different colors). All bubbles have approximately similar velocity profiles since bubble sizes are similar, most likely because of the constant pores size during boiling and the narrow pores size distribution of the ceramic porous matrix (10–16 μm). The above also implies either that bubbles interaction and coalescence over the porous surface do not change during boiling or that such phenomena are of limited extent in our experiments.

In Fig. 5b the rising velocity profiles, U_y, are plotted versus the distance from the exposed porous surface, y, for all examined gravity levels. The diameter of bubbles selected to shown in Fig. 5b is 0.6 mm. This is a size large enough to allow good accuracy in optical recordings but small enough to include an adequate number of bubbles. It is seen that U_y values of 0.6 mm diameter bubbles increase with gravity due to the higher buoyancy force as g increases. Quantitative analysis of specific features of this plot is beyond the scope of this work but, qualitatively speaking, U_y increases with g in a non-linear fashion contrary to what one might expect for small isolated bubbles with rigid interfaces (usually they are assumed so when their diameter is less than 0.5 mm in water) [11].

What is of greater significance is to estimate the overall convective velocity induced by the entire population of rising bubbles – not just the 0.6 mm bubbles – per gravity level. As shown in Fig. 4b, when g level increases the average bubble size decreases and this counteracts the increasing effect of buoyancy as regards the induced convective velocity. On the other hand, we have shown (Fig. 2b) that when gravity level increases higher heat transfer rates are encountered (faster substrate thermalization). The latter implies that overall a higher convective velocity is created as g level increases. But this may be also influenced by the population of the generated bubbles and not only their size and magnitude of buoyancy force. Rigorous quantitative estimations of heat transfer rates at different gravity levels and different oil temperatures are underway and will be presented in a subsequent publication.

3.3. Heat transfer coefficient

The present experiments refer to a porous solid heated by immersion to hot oil. To our knowledge, there are no generally accepted expressions in literature to describe the convective heat transfer coefficient applicable to configurations similar to those

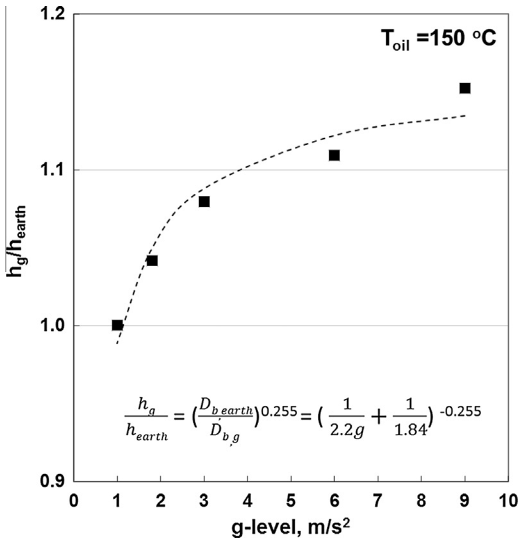

Fig. 6. Influence of gravitational acceleration on h_g/h_{earth} values.

used in this study. Nevertheless, as an order approximation, the h_g/h_{earth} ratio can been calculated from a known correlation that correlates the bubble behavior during conventional pool boiling (hot solid flat surface heated by heaters embedded in the solid) with the heat transfer coefficient, such as Stephan–Abdelsalam correlation [12]:

$$h = 207\frac{\lambda_{oil}}{D_b}\left(\frac{qD_b}{\lambda_{oil}T_b}\right)^{0.745}\left(\frac{\rho_v}{\rho_{oil}}\right)^{0.581}\left(\frac{\nu_{oil}}{\alpha_{oil}}\right)^{0.533} \quad (1)$$

where q is the heat flux supplied to the system, λ_{oil}, ν_{oil} and α_{oil} are the thermal conductivity the kinematic viscosity, and the thermal diffusivity of oil; ρ_v and ρ_{oil} are the vapor and liquid densities of oil; T_b is the boiling temperature of water. Assuming that from all the above parameters and properties only the average bubble diameter, D_b, depends on the level of gravitational acceleration, h_g/h_{earth} can be easily derived:

$$\frac{h_g}{h_{earth}} = \left(\frac{D_{b,earth}}{D_{b,g}}\right)^{0.255} \quad (2)$$

Moreover, if we take into account the D_b dependence on gravity (embedded plot in Fig. 3), the dependence of h_g/h_{earth} on gravity level becomes:

$$\frac{h_g}{h_{earth}} = \left(\frac{1}{2.2g} + \frac{1}{1.84}\right)^{-0.255} \quad (3)$$

Fig. 6 presents the gravity effect on the heat transfer coefficient for various gravity levels over the terrestrial heat transfer coefficient, h_g/h_{earth}. Preliminary results indicate that h_g/h_{earth} increases by as much as 17% when gravity climbs from 1 to 9 g (Fig. 6). Inasmuch as heat transfer coefficient depends chiefly on bubble dynamics over porous media, our results indicate a strongly non-linear effect of increasing gravity on bubble dynamics. However, more detailed analysis of our data is needed before conclusive statements can be made.

Acknowledgments

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