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Effect of increased gravitational acceleration in potato deep-fat frying

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ABSTRACT

This work extends our previous studies on crust thickness evolution and evaporation front propagation during deep fat frying of potato sticks (French fries) by incorporating the effect of increased gravitational acceleration. Scaling of gravitational acceleration allows scaling of buoyancy forces which control the heat transfer from hot oil to potato surface. For this, a special device is constructed which permits (a) temperature recording at specified positions below the potato surface (i.e. 0.5, 1.0 and 1.5 mm), (b) exposure of only one surface of a potato stick to hot oil, (c) rotation of the exposed surface at orientations 0° (horizontal, top), 90° (vertical, side) and 180° (horizontal, bottom), and (d) execution of deep fat frying experiments at increased gravity levels (i.e. 1.8, 3.0, 6.0 and 9.0 · g_{earth}). The latter is achieved by means of a large diameter centrifuge (European Space Agency). Temperature recordings and crust thickness evolution indicate that heat transfer during frying depends on gravity level but differently at different potato orientations. Most significant variations with gravity are found up to 3.0 · g_{earth} and for 0° orientation. Moreover, crust thickness evolution diverges from the evaporation front propagation in all times supporting the notion of a wide evaporation zone rather than a sharp evaporation front.

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1. Introduction

It is commonly accepted (i.e. Hubbard and Farkas, 1999; Moreira and co-workers, 1995) that during deep fat frying, heat is transferred from hot oil to food chiefly by means of (A) natural and (B) forced convection:

A. When a fryer full with oil comes in contact with a hot plate, natural convection oil-currents rise vertically from the hot bottom of the fryer towards the colder oil free surface. As a result, some weak horizontal convective currents appear owing to the small oil recirculation inside the fryer. As soon as a potato stick is immersed in hot oil these currents transfer heat to the food raising rapidly its temperature. In this context and since it is the hot bottom of the fryer that creates these currents they may be viewed as forced convection currents from the standpoint of the potato. However, for easy discrimination from other forced convection effects (see below) we shall keep calling them natural convection currents. Lioumbas and Karapantsios, (2012a, 2012c) have designated the initial thermalization period during which the exposed potato surface goes from room temperature to the water boiling point as the Heating Regime.
B. When boiling begins, vapor bubbles grow at the food surface and detach under the influence of (i) the momentum of the vapor ejected through the potato surface and of (ii) buoyancy. These bubbles create forced convection currents (macroscopic mixing of oil layers) as they rise towards the oil free surface and so enhance drastically heat transfer. Baik and Mittal (2002) performed small scale tofu frying experiments and argued that the convective heat transfer coefficient, *h*, is affected by the bubble flow direction, velocity, bubble frequency and magnitude of agitation. The period from the initial vapor bubble formation until the bubble end point is designated as the Boiling Regime (Hubbard & Farkas, 1999; Lioumbas & Karapantsios, 2012a, 2012c). During this period, a crust develops fast from the outside towards the inside of the potato following the propagation of an evaporation front which moves even faster. Evaporation inside the potato and transport at its surface (heat and mass transfer under blowing conditions) are coupled, making frying a conjugate problem (Halder & Datta, 2012). During the Boiling Regime, forced convection imposed by bubbles is the dominant heat transfer mechanism (Mir-Bel, Oria, & Salvador, 2012; Lioumbas & Karapantsios, 2012a).

We are not aware of any study that systematically investigates the effect of buoyancy in frying. This refers to both natural convection of oil currents and vapor bubble detachment from the food surface. Aiming to understand the role of buoyancy in frying, this work extends our previous studies (Lioumbas & Karapantsios, 2012a, 2012c) on crust thickness evolution and evaporation front propagation during deep fat frying of potato sticks (French fries) by incorporating the effect of increased gravitational acceleration. During the last 50 years, altered gravity conditions (i.e. microgravity and/or hypergravity) have been extensively used as a tool to study heat transfer phenomena in bubble dominated processes such as pool boiling (Straub, 2005). The absence of natural convection during microgravity conditions proved useful to study heat conduction and surface tension driven heat transfer

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(Marangoni convection) (van der Geld, Colin, Segers, Pereira da Rosa, & Yoshikawa, 2012). On the other hand, hypergravity conditions, e.g., achieved with the help of centrifuges, are excellent tools for scaling buoyancy effects in boiling (Merte & Clark, 1961). However, to the best of these authors' knowledge, altered gravity conditions have never been used in frying.

This work is part of a project supported by ESA (European Space Agency) to examine (i) how gravity influences heat and mass transfer phenomena in natural and artificial porous media (fried food can be considered as a natural one) and (ii) whether frying is feasible in space. ESA interest stems from the need for earth-like food for crew members during future long-duration missions as this could have a positive psychological effect on crew morale (Morphew, 2001). The appeal for a highly acceptable and palatable fresh food (such as fried potatoes) during long-duration missions has been recently expressed directly by astronauts (Volkov, 2011). The present experiments conducted in hypergravity conditions provide experimental evidence on the influence of scaling the buoyancy forces on heat transfer during frying. Future tests conducted in microgravity conditions (in progress) will compliment the present work and will eventually allow estimating whether frying can be conducted in other than terrestrial gravitational conditions ($g/g_{earth} \neq 1$).

2. Materials and methods

Herein we perform single-potato frying experiments at terrestrial conditions, g_{earth}, and a wide range of hypergravity conditions, up to $9 \cdot g_{earth}$. Lioumbas and Karapantsios (2012a) have shown that different heating mechanisms are expected for different orientations of the exposed (to oil) potato surface, θ. Therefore, experiments are performed at $\theta = 0°$ (horizontal, top), 90° (vertical, side) and 180° (horizontal, bottom).

In order to conduct experiments at the increased gravity levels offered by the large diameter centrifuge (LDC, at ESA/ESTEC) we modified the experimental apparatus presented by Lioumbas and Karapantsios (2012a). Apart from satisfying geometrical and safety restrictions, the most serious modifications refer to making the apparatus amenable to automatic operation and remote control from the control room of LDC (Supplementary Material 1). A comprehensive description of the features of the LDC is given elsewhere (Krause, Dowson, & Zeugma, 2011). The apparatus (Fig. 1a) is housed in freely swinging gondolas (Fig. 1b) 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. This normal acceleration acting at a tilted direction is equivalent to gravitational acceleration acting at the vertical direction. That's why we shall keep speaking about increased "gravitational" acceleration in LDC although this is not rigorously correct. Experiments are performed at gravitational accelerations: $1.0 \cdot g_{earth}$, $1.8 \cdot g_{earth}$, $3.0 \cdot g_{earth}$, $6.0 \cdot g_{earth}$ and $9.0 \cdot g_{earth}$. The accuracy of achieving each one of these values is estimated at $\pm$ 0.5% of the multiplying factor (Krause et al., 2011).

As soon as the desired gravity level is achieved (after about 1 min of spinning), the head of an electro-hydraulic jack lifts a hot plate (625 W) supporting a rectangular vessel which contains 500 mL of hot oil. The rectangular vessel rises until a standing double Teflon unit holding a potato stick (see below) is immersed in the oil. Immersion stops when the oil free surface reaches 1 cm above the potato surface. A webcam is employed for optical observation of macroscopic bubbles behavior upon frying. A separate series of LDC experiments have been conducted using a high speed camera for registering the microscopic bubbles growth and detachment characteristics. These experiments will be reported in a subsequent study.

The heating medium is extra virgin olive oil (ELAIS S.A.; density 0.895 g/cm^3 and viscosity 83 mPa s, at 20 °C). A potato stick (Spunta variety, average moisture content 80% w.b.) with dimensions 9.8 × 9.8 × 20.0 mm (prepared by the authors) is placed inside an

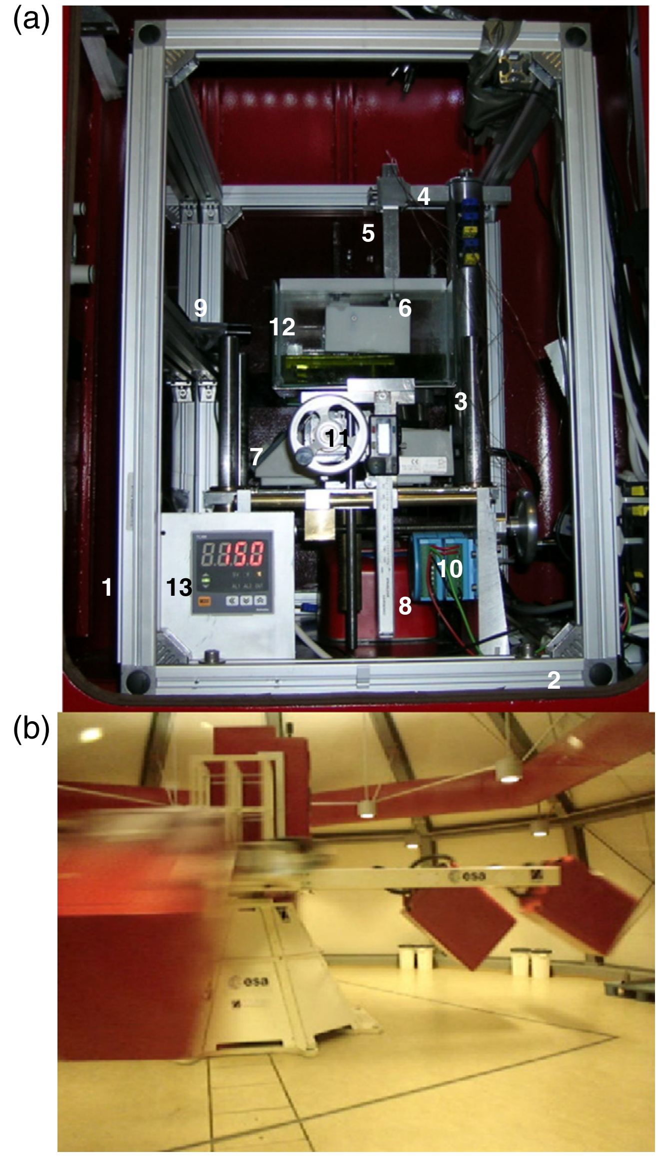

Fig. 1. (a) Photographic description of the experimental apparatus located inside the gondola of LDC: 1. protective frame, 2. base plate, 3. first arm, 4. second arm, 5. metal block, 6. position adjustment equipment for T_{oil} recordings and T_{oil} thermocouples, 7. hot plate, 8. hydraulic jack, 9. webcam, 10. data acquisition unit, 11. fast video recording camera position adjustment, 12. optical cell, 13. temperature controller. (b) Spinning the LDC.

insulating double Teflon trough unit (i.e. Teflon thermal conductivity 0.25 W/mK). The potato sample is placed inside the inner Teflon unit flush with the top of the trough leaving only one surface exposed to the oil. The side surfaces of the potato are prevented from contacting the oil by fixing tightly the potato inside the Teflon trough. The wall thickness of the troughs (>10 mm) ensures an efficient thermal insulation of the unexposed to the hot oil sides of the potato. The initial temperature of both the potato stick and the Teflon trough units is 25 °C. Three different double Teflon trough units are built to accommodate single potato sticks at different orientations. The trough units allowed putting the potato at angles: $\theta = 0°$ (exposed horizontal top surface), $\theta = 90°$ (exposed vertical side surface) and $\theta = 180°$ (exposed horizontal bottom surface). By squeezing the non-exposed sides of the potato tightly inside the Teflon trough, shrinkage has become marginal (Supplementary Material 2). Experiments are conducted at only one initial oil temperature, T_{in} (i.e. 150 °C) because higher temperatures were not allowed for safety reasons in the LDC. Runs are repeated five times to check for reproducibility.

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