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

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ABSTRACT

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.