Experimental study of the low-pressure-vaporization of water in different porous media

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ABSTRACT

The present study aims to evaluate the benefits of using porous media (PM) to enhance the rate of the low-pressure-vaporization (LPV) of water. An experimental characterization of the process of low-pressure-vaporization (LPV) of water is presented considering four different types of porous media and different initial conditions. This characterization involves the measurement of the time evolution of the porous media temperature and of the total and the vapor pressure inside the vaporization chamber, as well as the indirect determination of the saturation pressure, the mass of water vaporized, its specific rate of vaporization and of the energy removed by this phenomenon. A direct comparison between the evolution of the LPV of water in porous media and the LPV of free water was also made for two selected situations. The results show that the evolution of the LPV parameters, namely the temperature decrease and the rate of energy removal, are strongly dependent on the volume of the water initially contained in the porous medium which in turn, depends essentially of the medium microstructure. The significant differences found between the evolution of the LPV parameters in free water and in porous media are related to different boiling onset mechanisms, which is strongly dependent on the surface tension of the liquid water in the whole LPV process in PM. The practical result of these effects is an increased vaporization rate and an enhanced surface heat transfer capability that justify the use of porous media in a wide variety of applications.

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1. Introduction

Nowadays high capacity heat transfer techniques are quite required for non traditional industrial applications and scientific research such as nuclear power plants, solar energy concentration and conversion, freezing and refrigeration, temperature control in aviation and spaceflight and all sorts of energy conversion systems [1–2]. Some of these techniques are based on the liquid to vapor phase-change phenomenon. The low-pressure-vaporization (LPV) analysed in [3] is a very fast phase-change process, enhanced by a sharp pressure decrease and presents all the important characteristics that lead to high heat transfer rates.

As described by Mutair and Ikegami [4], LPV is a combined heat and mass transfer phenomenon in which the liquid, initially in thermodynamic equilibrium, is exposed to a sudden pressure drop that brings it to a superheated state; i.e., with a temperature above the saturation value at that new pressure condition. In this situation the liquid is in a metastable stage and will begin to vaporize

throughout all its extension to increase the total pressure over its free surface so that the phase equilibrium is again established. In this phenomenon the energy necessary for the liquid vaporization is taken from the liquid phase itself. Since the specific energy of vaporization is usually very high, the vaporization rate, essentially determined by the superheating degree which depends on the difference between the actual pressure and the saturation pressure at the temperature of the liquid phase, can also be very high, even for small pressure drops. Thus, this phenomenon can lead to high heat removal rates for which a wide range of interesting practical applications are envisaged. In a previous work [3] the LPV process applied to free water systems (LPV-FW) was analysed, showing the LPV potential to enhance the water vaporization rate and consequently the rate of temperature decrease in the liquid water. The application of the LPV phenomenon to other situations beyond the simple temperature control of free liquid water was already envisaged as having even more potentially practical applications. As referred by Webb and Kim [2], the application of LPV to moister filled media applied over surfaces could be a way to overcome the problems associated with the low heat transfer coefficients in surface heat transfer processes and thus take advantage of the high heat removal rates related to the phase-change phenomenon. Webb and Kim [2] concluded that significant improvements of

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Nomenclature

c_p	mass-average specific heat of porous media with water
E_v	energy removed by vaporization
E_v^*	specific energy removed by vaporization ($=E_v/m_{w,0}$)
$\dot{E}_v$	rate of energy removal by vaporization
$\dot{E}_v^*$	specific rate of energy removal ($=\dot{E}_v/m_{w,0}$)
h_{fg}	latent heat of water vaporization
m_t	initial total mass
$m_{w,0}$	initial mass of liquid water
$m_{w,v}$	mass of water vaporized
$m_{w,v}^f$	final mass of water vaporized
$\dot{m}_{w,v}$	rate of water vaporization ($=dm_{w,v}/dt$)
$\dot{m}_{w,v}^*$	specific rate of water vaporization ($=\dot{m}_{w,v}/m_{w,0}$)
P	total pressure
P_{sat}	saturation pressure
P_v	partial pressure of the water vapor
$P_{v,p}$	partial pressure of the water vapor within pores
$P_{i,v}$	partial pressure of the water vapor at the interface
P_w	partial pressure of the liquid water
r_p	porous radius
t	time
T_w	liquid water temperature
$T_{w,0}$	initial temperature of the porous media
$T_{i,v}$	temperature of the water vapor at the interface
V_w	water volume
$V_{w,0}$	initial water volume (water absorption capability of the PM)

Subscripts and superscripts

0	initial condition
v	water vapor
w	liquid water
*	specific quantity (per unit mass of initial water)

Greek symbols

ρ_w	water density
ϕ	superheating degree
γ	surface tension
θ	contact angle
Δt	integration time step

Acronyms

DS	depressurization system
FW	free water
FP	flash point
LPV	low-pressure-vaporization
LPV-FW	low-pressure-vaporization of free water
LPV-PM	low-pressure-vaporization of water in porous media
PM	porous media
RP	reaction point
VC	vaporization chamber

the heat transfer coefficients have been achieved for specific surfaces, due to the promoted high performance nucleation of the boiling process providing this way, an enhanced heat transfer coefficient. Porous media are a sort of material capable of promoting this enhanced boiling process. Several authors have studied the use of porous media (PM) as a way to increase the heat removal rate in several situations. For example, Figueiredo and Costa [5] studied the use of porous media for thermal protection against high intensity heat fluxes (flames). Other authors [6–7] analysed the application of porous media to temperature control in buildings. Zhao et al. [6] investigated the heat and mass transfer properties of several different types of porous media considering its potential application in air-conditioning systems of buildings. Meng and Hu [7] studied the possibilities of applying humid structures for the temperature control of roofs, in a process designated by passive water evaporation. For some naturally porous media, such as foodstuff (meat, vegetables and fruits) and fabrics, a few industrial applications have already been developed taking advantage from the improved heat removal rate associated with the enhanced surface boiling nucleation. The refrigeration of fruits (strawberries and melons), vegetables (lettuce, broccoli and mushrooms) and meat (ham and cooked beefs) or the quick drying of fabrics are probably the most typical examples of the technological application of this phenomenon [8–11].

For this reason, details of the physical phenomenon associated with the water evaporation in porous media at sub-atmospheric pressures are being widely studied. For example, Elustondo [10] developed a model for moisture evaporation during drying under sub-atmospheric pressures, in which internal water is removed pushed by the movement of the solid structures of the porous media, making the vapor to flow towards the outer surface. On the other hand, Bakhshi and Mobasher [11] conducted an experimental study of early-age drying of Portland cement paste in low pressure conditions to promote quick water evaporation. They consider that the majority of moisture transfer in porous media occurs by diffusion up to the free surface, where evaporation occurs.

However, in other published works [12–16] the mechanisms behind the mass transfer are differently described: it is considered that the vaporization takes place within the pores and that the hydrodynamic movement of the water vapor within them is ruled by the pressure differences. Sun and Hu [17] developed a computational fluid dynamics (CFD) model to simulate the heat and mass transfer within foods at low pressures, demonstrating the complexity and importance of the boiling vaporization in pores. The studies of [18–20] also focus on the importance of the dynamic of vaporization within the pores for the global process of the heat removal.

From the exposed above, the importance of the vaporization phenomena within porous media under sub-atmospheric conditions seems clear. This importance is reflected on the significant number of works trying to identifying the main characteristic parameters and the different stages of the vaporization process within porous media [13–15,21,22]. Specifically, Wang and Peng [15] presented the boiling vaporization heat transfer mode in porous media as an enhanced heat transfer technology, with a wide range of important practical applications. They referred that boiling is affected by the pore structure (pore scale and bead size), bubble growth and coalescence, pore variation and vibration. Furthermore, they highlighted the importance of surface tension on bubble shape and on the interface formation, as well as on the bubble growth. The surface tension affects the boiling phenomena and bubble growth parameters; when boiling is fully established, the number of nucleation points increases due to the decrease of surface tension. Since the rate of bubble formation is higher, the amount of water vaporized is also increased and thus the rate of heat removal [23]. Yortsos and Stubos [13] showed that the phase-change process in porous media occurs mainly within pores but is constrained by the solid boundaries of the porous media. The phase-change process is described as being affected by properties of the solid boundaries, like the roughness, and it is dependent on the equilibrium established between the confined fluid (liquid and vapor), the solid structure of the micropores and the capillary