Development, calibration and validation of a mathematical model for the low-pressure-vaporization of the water in porous media

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A B S T R A C T

This paper reports the development, calibration and validation of a mathematical model of the low-pressure-vaporization process in different types of porous media. This model aims to improve models developed by other authors in this area, namely by considering some aspects that have not been addressed, such as: the vapor pressure is not equal in the whole chamber; the interfacial vapor pressure is not equal to the saturation pressure; the surroundings have a significant influence on the vaporization phenomena in all zones of the porous media; and the first stage of the process is not characterized only by diffusion vaporization. For that purpose, an experimental calibration procedure was made involving the definition of several LPV parameters: vaporization coefficient of the porous medium ε_{PM}, vaporization coefficient at the liquid–vapor interface within the porous medium $\varepsilon_{i,PM}$, free surface vapor pressure $P_{v,FS}$, vapor pressure of the free layer $P_{v,FL}$, interfacial vapor pressure $P_{v,i}$, volume of the vaporization layer V_{VL} and volume of the free layer V_{FL}. These parameters were represented by a set of multivariable functions and determined from a series of experiments in different types of porous media, each one characterized by a different initial water temperature. Thus, in this work an enhanced physical model of the LPV in porous media is proposed, concerning two distinct stages. The experimental set-up comprises two main components: the vacuum chamber (VC) and the depressurization system (DS). Part of the VC volume is occupied by an open container for porous media, which is isolated from the VC walls.

The results obtained show that the multivariable functions determined through the vaporization coefficient have a good agreement with experimental results (e.g., R^2 varies within 0.9581–0.9903) and also that this parameter describes well all regimes of the second stage of the LPV process. The importance of the capillary effect and of the surface tension forces on the superheating degree and, consequently, on the LPV evolution was demonstrated, as well as the effect of the amount of water initially contained in the porous medium. From the validation based on the measured water temperature evolutions, deviations within ±5% are found, which confirm the good agreement between experimental and simulated values. Thus, it is possible to conclude that the calibrated mathematical model describes well the experimental results and it is a good model of reference to various studies and applications.

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1. Introduction

The enhanced heat transfer techniques are nowadays very required for industrial applications and scientific explorations such as nuclear power plants, solar energy concentration and conversion, high power cold production, temperature control and an all sorts of energy conversion systems [1,2]. As demonstrated in this paper, it is unequivocal that heat transfer enhancement benefits

from the combination of low-pressure-vaporization (LPV) and vaporization in porous media (PM). For this reason, significant experimental and theoretical efforts have been dedicated to understand the phenomena of both LPV and vaporization in porous media, and to assess their potential for practical applications. For example, Figueiredo and Costa [3] studied the use of porous media for thermal protection against high intensity heat fluxes (flames). Other authors [4–6] analyzed the application of porous media for the matter of temperature control in buildings. Zhao et al. [4] investigated the heat and mass transfer properties of several different types of porous media considering the potential application in air-conditioning systems of buildings. Meng and Hu [5] studied the possibilities of the application of humid structures

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Nomenclature

$c_{p,PM}$	mass-averaged initial specific heat of porous medium saturated with water
$C_{PM,0}$	initial heat capacity of the porous medium
$C^*_{PM,0}$	normalized initial heat capacity of the porous medium
h_{fg}	water latent heat of vaporization
$\dot{m}_v$	rate of change of the water vapor mass
$\dot{m}_{v,i}$	mass flow rate of vapor into CV2 (generated in CV1)
$\dot{m}_{v,o}$	mass flow rate of vapor out of CV2
$\dot{m}_{v,DS}$	mass flow rate of vapor extracted by the depressurization system
m_w	initial mass of water
m_t	initial total mass
M_v	molecular weight of water vapor, $=18.015$ (kg kmol^{-1})
P	total pressure
P_a	partial pressure of the air
P_{sat}	saturation pressure
P_v	partial pressure of the water vapor
$P_{v,FS}$	free surface partial pressure of the water vapor
$P_{v,FL}$	free layer partial pressure of the water vapor
$P_{i,v}$	partial pressure of the water vapor at the interface
R	universal ideal gas constant, $= 8314.5$ (J kmol^{-1} K^{-1})
r_p	pore radius
t	time
T_c	chamber temperature
T_w	liquid water temperature
$T_{w,0}$	initial liquid water temperature
T^*	normalized initial temperature
t_{FP}	time to the flash point
t_{RT}	time to the regime transition
V_w	volume of liquid water
$\dot{V}_e$	volume flow rate of the pump
V_f	free volume of the vaporization chamber
$V_{f,0}$	initial free volume of the vaporization chamber
V_{vc}	volume of the vaporization chamber
$V_{PM,0}$	initial volume occupied by the porous medium
$V_{w,0}$	initial water volume (water absorption capability of the PM)

V_{FL}	volume of the free layer
V_{VL}	volume of the vaporization layer

Subscripts

0	initial condition
i	into; interface
max	maximum value of the range
min	minimum value of the range
o	out
v	water vapor
w	liquid water
f	free volume
t	total

Greek symbols

ρ_v	water vapor density
ϕ	superheating degree
γ	surface tension
θ	contact angle
Δt	time step
ε_{PM}	vaporization coefficient of the porous medium
$\varepsilon_{0,PM}$	vaporization coefficient of the porous medium at the surface
$\varepsilon_{i,PM}$	vaporization coefficient at the liquid–vapor interface in the porous medium

Acronyms

DS	depressurization system
FP	flash point
LPV	low-pressure-vaporization
VC	vaporization chamber
VL	vaporization layer
FL	free layer
C	container
CV	control volume
CV1, CV2	control volumes one and two, respectively

for the temperature control of roofs, in a process designated as passive water evaporation. Webb and Kim [2] demonstrated that significant improvements of the heat transfer coefficients for specific surfaces have been achieved due to the promoted high performance nucleation of the boiling process and providing, by this way, an enhanced heat transfer rate.

Other authors [7–12] have focused their works to identify the main characteristic parameters and the different stages of the vaporization process within porous media. Wang and Peng [9] and Yortsos and Stubos [10] described the boiling vaporization heat transfer mechanism in porous media as an enhanced heat transfer technology, with a wide range of important practical applications. They emphasized the influences of the physical structure of the pores in the phase-change process and in the enhanced surface boiling nucleation.

By the reason appointed above, which is also demonstrated in [13], details of the physical phenomenon associated with the water vaporization in porous media at sub-atmospheric pressures are being widely studied and modeled for a deeper and more detailed knowledge, as it is reflected by the significant number of works [14–20]. For example Elustondo et al. [19] developed a model for moisture evaporation during foodstuffs drying under sub-atmospheric pressures in which internal water is pushed by the movement of the solid structures of the porous media, making the vapor to flow towards the outer surface. Sun and

Hu [17] developed a CFD model to simulate the heat and mass transfer within foods at low pressures, evidencing the complexity and importance of the boiling vaporization in pores. Wang and Sun [15] developed a complete three-dimensional and transient model of the coupled mass and heat transfer of the cooked meat during low pressure and temperature. The model includes a sub-model describing the mass transfer in the inner vapor generation and another with heat transfer in the inner generation. However, these authors consider that the surface vapor pressure of the PM is only affected by a constant parameter that relates its pressure with the pressure in the chamber. As already demonstrated in our works, this can be a limitation of the model because the LPV process is sharply transient and the relation between all pressure changes as the stages and regimes change.

Despite the relative success of the recent models in the prediction of some characteristics of the low-pressure-vaporization process, most of them oversimplify the physical description of the process due to its intrinsic complexity, as already referred in [12]. All of these works [15–18] focused their study mainly in the phase change within pores and the vapor movement up to surface, despising the effect that the surroundings have on the surface vapor pressure of the pores and consequently, its effects in the vaporization phenomena within porous media. One of the most common simplifications made when modeling the LPV process is to assume that the vapor pressure in the vacuum chamber is