Physical and experimental calibration of a mathematical model of the low-pressure-vaporization of free water

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ABSTRACT

This paper reports the procedure used for the calibration of a mathematical model of the low-pressure-vaporization in free water previously developed by the authors. This calibration includes the determination of the time to the flash point, the time to the transition between the first and the second boiling regimes, the difference between the liquid–vapor interface pressure and the pressure experimentally measured in the free space of the vacuum chamber, which allows the definition of the vaporization coefficient ε, and the volume of the vaporization layer. The influence of the initial volume and temperature of the water on these parameters is also determined. For this purpose, a set of multivariable functions are determined from a series of experiments, with different initial water temperatures and volumes.

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 the water, which is isolated from the VC walls. Two different containers are used having different surface areas and heights, both with a negligible heat capacity.

The results obtained show that the functions determined for all the referred parameters are in a good agreement with the experimental results.

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1. Introduction

As described in a previous work by the authors (Augusto et al., 2012) and in several others (Bouchama et al., 2003; Mutair and Ikegami, 2012; Saury et al., 2005, 2002), the low-pressure-vaporization (LPV) is a fast phase-change process with characteristics suitable for a wide variety of applications that demand for enhanced heat transfer and water vaporization processes. For example, Muthunayagam et al. (2005) used the low-pressure-vaporization of saline water for the production of potable water achieving a significantly good yield. Gude and Nirmalakhandan (2009) focused their study on the development of a prototype for a new phase-change desalination process to produce potable water from impaired or saline waters and, in contrast with traditional phase-change processes they have found that this can be operated in the range of 45–50 °C. Other works put in evidence the applicability of the LPV in food and agriculture industry to dry and refrigerate different products (Bazyma et al., 2006; Kingcam et al., 2008; Kristiawan et al., 2011; Nimmol et al., 2007; Pimpaporn et al., 2007a,b). For example, the wine industry has been using the LPV

to concentrate the wine and improve its quality (Sebastian and Nadeau, 2002; Tiat et al., 2008). LPV is also used for the improvement of the juice yield and quality, as referred by Paranjpe et al. (2012).

The deepening and the enlargement of the potential practical applications of the LPV is, however, dependent on the understanding and ability to model the phenomena, which have been the object of significant efforts of experimental and theoretical research during the last 10 years. For example, Saury et al. (2002) and Mutair and Ikegami (2009) have developed an extensive experimental work to identify and characterize the behavior of the essential features of the LPV. Saury et al. (2002) measured the time to the flashing point and the amount of water vaporized from layers of water, for different LPV conditions, and compared the results with those obtained for simple vaporization. They showed that the vaporization rate during the *flash evaporation* phase of the LPV is an order of magnitude higher than in simple vaporization and emphasized the importance of this feature for several practical applications.

Other authors (Aoki, 2000; Augusto et al., 2012; Wang and Sun, 2002) developed mathematical models to study the LPV evolution. For example, Aoki (2000) developed a detailed model for the *flash evaporation* of the water under low-pressure and studied the

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Nomenclature

A	surface area (m^2)
c_p	constant pressure specific heat capacity (J kg^{-1} K^{-1})
D	diffusion coefficient (m^2 s^{-1})
h_{fg}	latent heat of vaporization of the water (J kg^{-1})
$\dot{m}_v$	rate of change of the water vapor mass (kg s^{-1})
$\dot{m}_{v,i}$	mass flow rate of vapor into CV2 (generated in CV1) (kg s^{-1})
$\dot{m}_{v,0}$	mass flow rate of vapor out of CV2 (kg s^{-1})
$\dot{m}_{v,DS}$	mass flow rate of vapor extracted by the depressurization system (kg s^{-1})
$m_{w,0}$	initial mass of water (kg)
M_v	molecular weight of water vapor = 18.015 (kg kmol^{-1})
P	total pressure (Pa)
P_a	partial pressure of the air (Pa)
P_{sat}	saturation pressure (Pa)
P_v	partial vapor pressure (Pa)
$P_{v,FS}$	c free surface partial vapor pressure (Pa)
$P_{v,FL}$	free layer partial vapor pressure (Pa)
R	universal ideal gas constant = 8314.5 (J kmol^{-1} K^{-1})
t	time (s)
T^*	normalized initial temperature (K) or (°C)
T_c	chamber temperature (K) or (°C)
t_{FP}	time to the flash point (s)
t_{RT}	time to the regime transition (s)
T_w	liquid water temperature (K) or (°C)
$T_{w,0}$	initial water temperature (K) or (°C)
V^*	normalized initial volume (m^3)
$\dot{V}_e$	volume flow rate of the vacuum pump (m^3 s^{-1})
V_f	initial free volume of the vaporization chamber (m^3)
V_{FL}	volume of the free layer (m^3)
V_{vc}	volume of the vaporization chamber (m^3)

V_{VL}	volume of the vaporization layer (m^3)
$V_{w,0}$	initial volume of water (m^3)

Subscripts

0	initial condition
f	free volume
i	coming into
min	minimum value
max	maximum value
o	going out
v	water vapor
w	liquid water
z_0	free surface

Greek symbols

Δt	integration time step (s)
ε	vaporization coefficient (–)
ε_{z_0}	vaporization coefficient at the free surface (–)
ρ_v	water vapor density (kg m^{-3})
ϕ	superheating degree (Pa)

Acronyms

C1, C2	containers one and two, respectively; or lower and upper range of $V_{w,0}$, respectively
CV1, CV2	control volumes one and two, respectively
DS	depressurization system
FL	free layer
LPV	low-pressure-vaporization
VC	vaporization chamber
VL	vaporization layer

associated maximum heat flux, emphasizing its relevance to the aerospace technologies.

Despite of the relative success of the present models in the prediction of some characteristics of the LPV process, like the cooling capacity, most of them oversimplify its physical description due to the intrinsic complexity of the process. The consequences are normally an overestimation of the vaporization rates, which are then corrected with empirical coefficients that need to be calibrated. In most of the situations, the calibration process is done for a single coefficient and just for a certain initial condition (see Dostal and Petera, 2004; Sun and Wang, 2004), neglecting that the LPV is essentially a transient process and, for this reason, extremely affected by those initial conditions, which justifies the use of non-constant, time dependent, calibration coefficients. Given so, a detailed simulation of the LPV process with such models for situations other than those of the calibration is thus impossible.

One of the most common simplifications made when modeling the LPV process consists of ignoring the initial vaporization stage (before the flash point and of considering a single boiling regime for the second stage. The first stage, characterized by a diffusion vapor transport ruled the evaporative process, is often ignored because the consequences on the liquid water temperature are minimal. However, the consequences on the total time of the process are not negligible (Augusto et al., 2012). The duration of this first stage (i.e., the time to the flash point) is dependent on the characteristics of the depressurization system and of the vacuum chamber, but also on the initial volume and temperature of the water; and this dependence needs to be calibrated. It is also known that the second stage of the LPV is characterized by two different

boiling regimes: a first regime of exuberant boiling (just after the flash point), followed by a second, weaker one. The time of transition of the LPV process from the first to the second regime depends also on the initial volume and temperature of the water and likely needs to be calibrated.

Another very common simplification is to assume that the vapor pressure in the vaporization chamber is homogeneous and in equilibrium with the liquid water phase present in the chamber (Augusto et al., 2012). Nevertheless, it is known that there is a vapor pressure gradient in the chamber above the water free surface (Eames et al., 1997; Saury et al., 2002). It is the vapor pressure at the interface (free-surface vapor pressure) that is in equilibrium with the liquid phase and determines the rate of vaporization. This means that whenever this vapor pressure value, by the action of the depressurization system, decreases bellow the saturation pressure at the liquid water temperature, a certain part of that liquid water vaporizes to bring the free surface vapor pressure to equilibrium with the saturation value. This vapor pressure is known to decrease gradually along a layer (by us named *vaporization layer*) formed above the water free surface, down to a uniform value equal to the one experimentally measured. The thickness or volume of this layer and the magnitude of the difference between the free surface vapor pressure and the one effectively measured are thought to change with the process evolution and to be dependent on the initial conditions of the process; therefore they need to be calibrated.

The purpose of this work is to present the calibration procedure developed for the particular case of our model (described in Augusto et al. (2012) and experimental set-up, but easily adaptable