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Low-pressure-vaporization of free water – Characterization of the boiling regimes

C.M. Augusto*, J.B. Ribeiro, A.R. Gaspar, J.J. Costa

ADAI–LAETA, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal

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ABSTRACT

This paper reports an experimental study for the detailed characterization of the low-pressure-vaporization (LPV) process of free water. For that purpose, an integrated analysis of the influences of the initial temperature $T_{w,0}$ and volume $V_{w,0}$ of the liquid water on the LPV process is made. The time evolutions of the water temperature and of the total pressure within the LPV chamber, for different initial conditions, were experimentally measured. The two stages of the LPV process and the respective regimes were identified and characterized, enhancing the current knowledge of the phenomena.

The experimental set-up comprises two main components: the vaporization chamber (VC) and the depressurization system (DS). Part of the VC volume is occupied by an open container for the water, which is insulated from the VC walls. Two different containers were used having different surface areas and heights, both with a negligible heat capacity.

The results obtained show that the process parameters studied, $T_{w,0}$ and $V_{w,0}$, have great influence on the superheating degree, and consequently on the LPV evolution, as well as on the total mass of the water vaporized. The identification and characterization of distinct boiling regimes in the second LPV stage allow a physically based optimization of the processes, such as enhanced heat removal or water vaporization existing in several industrial areas.

1. Introduction

When a liquid initially in equilibrium is submitted to a sudden pressure drop that takes it below the saturation value, it becomes a metastable phase, and begins to vaporize both through its free surface and in the bulk volume in order to restore the initial equilibrium state, towards the new value of the saturation pressure (at the new temperature value) [1]. This set of associated phenomena (sudden pressure decrease and bulk vaporization) is known as low-pressure-vaporization (LPV). In a LPV process, the great amount of energy required by the vaporization – the latent heat of phase change – is taken from the liquid itself. Thus, the LPV process usually leads to vaporization rates much higher than in natural atmospheric vaporization.

This characteristic makes the LPV suitable for a wide variety of applications. Saury et al. [2] studied this process (calling it *flash evaporation*), and analysed the flashing time and the vaporized mass of a water film. They showed that the vaporization rate during the *flash evaporation* is an order of magnitude higher than during simple vaporization and evidenced the importance of this process for several applications. Mutair and Ikegami [1] proposed a model for heat transfer in water superheated drops resulting from flashing water jets, putting also in evidence the great interest of this process for several applications. Bouchama et al. [3] evidenced the importance of a detailed study of the different stages of the LPV process. They developed a model for the design and the optimization of a two-stage flash evaporator focussing on thermodynamic aspects.

The LPV process has been widely studied to be implemented in industries of the distinct areas. Several authors [4–8] refer to the LPV as a promising technique to enhance the water vaporization and the heat removal for several industrial process. For example, Muthunayagam et al. [4] used the low-pressure-vaporization of saline water for the production of potable water, and they achieved a significantly good yield. Gude and Nirmalakhandan [5] 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. In contrast to traditional phase-change processes, this can be operated in the range of 45–50 °C. Thus, it could be driven by low-grade thermal energy sources such as solar energy or process waste heat. On the other hand, Miyatake and co-authors developed a *spray flash evaporation technique* for which a fluid is injected directly into a low pressure vapour zone inside the

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* Corresponding author. Tel.: +351 239 790 700; fax: +351 239 790 701.
E-mail address: catia.augusto@dem.uc.pt (C.M. Augusto).

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Nomenclature

A	surface area (m^2)
A_1	surface area of container C1 (m^2)
A_2	surface area of container C2 (m^2)
C1	container 1
C2	container 2
c_p	specific heat (J kg^{-1} K^{-1})
DS	depressurization system
E_0	enthalpy of the initial mass of liquid water (kJ)
h_{fg}	latent heat of vaporization of water (J kg^{-1})
m_w	initial mass of water (kg) or (g)
$m_{w,v}$	water mass vaporized (g)
$m_{w,v}^f$	final mass of water vaporized (g)
P	total pressure (Pa)
P_0	initial pressure (Pa)
P_{sat}	saturation pressure (Pa)
P_v	partial pressure of the water vapour (Pa)
t	time (s)
T_w	liquid water temperature (K) or (°C)
$T_{w,0}$	initial water temperature (°C)
t_{FP}	flash point (instant) (s)
t_{RP}	reaction point (instant) (s)
VC	vaporization chamber
V_w	water volume (ml)
$V_{w,0}$	initial water volume (ml)

Subscripts

0	initial condition
v	water vapour
w	liquid water

Greek symbols

ρ_w	water density (kg m^{-3})
ϕ	superheating degree (Pa)

flash chamber through a tubular nozzle where the fluid vaporizes to regain equilibrium and steam is formed [9]. The authors have explored this technology along the years [10–14] and they applied this technology to desalination processes in 2001 [15–17]. Miyatake et al. [16] studied the transient characteristics and the performance of a novel desalination system based on heat storage and spray flashing evaporation for the production of fresh water. The authors concluded that the hybrid system studied showed good results for steam generation and seawater desalination and that its evolution can be predicted with sufficient accuracy, facilitating the design of practical systems. Junjie et al. [18] and Zhang et al. [19] carried out an experimental activity of the static and circulatory flash evaporation of aqueous NaCl solution. The works show that higher initial water film concentration inhibited phase change, and decrease the rate of flash evaporation and the intensity of boiling heat transfer. The studies with static/circulatory experiment indicated that heat transfer coefficient is time dependent function with a peak formation in its evolution.

Other authors [20–25] found relevant roles for LPV, when used in combination with other technologies to dry and refrigerate fruits, vegetables and other agriculture products. For example, Nimmol et al. [21] combined the superheated steam and far-infrared radiation with LPV process for drying banana – a product that is rather sensitive to heat. The traditional technology – hot air drying – is a very energy-intensive operation with high drying temperature, and the presence of oxygen leads to often degradation of the product quality. This study showed a final product with more crispness, especially at higher temperatures.

In wine industry, the use of LPV allows the wine concentration to improve its quality, as several authors show in their works [3,26–29]. Paranjpe et al. [28] specifically compared the LPV and the enzymatic processing routes as means of increasing juice yield and quality, obtaining very good results with the LPV in two types of grapes.

Space shuttle industry is another area where the low-pressure-vaporization is studied. Aoki [30] performed a detailed analysis of water *flash evaporation* under low-pressure, by studying the maximum heat flux, and emphasizing their relevance to space shuttle technology.

In most of the previously referred applications, LPV has been used with the aim at increasing the rate of water vaporization. As stated before, the vaporization of the liquid water requires significant amounts of energy. That energy can be taken from both the water and its surroundings, when the rate of vaporization is small, or just from the water when the rate of vaporization is high. In the later case, a significant decrease in the liquid water temperature can be observed. The field of practical applications of such sudden temperature drop is very wide and the process deserves to be studied in more detail in order to identify the most relevant physical phenomena and process parameters. In fact, most researchers analysed the influence of several parameters, but considering just the two stages (pre and pos-flash point) [2,31–33].

The present work is a step forward in the understanding of the second stage of the LPV processes, which is the most relevant for the practical applications. Based on a series of experiments, the effects of both the initial volume $V_{w,0}$ and temperature $T_{w,0}$ of the liquid water were analysed in an integrated way. The identification and characterization of distinct boiling regimes in the second LPV stage will allow a physically based optimization of the processes (*e.g.*, enhanced heat removal or water vaporization existing in several industrial areas), namely the definition of the adequate stopping time.

2. Experimental modelling

2.1. Features of the low-pressure-vaporization processes

As referred above, the LPV is a complex physical phenomenon that results from a sharp pressure drop in a closed space where water (or any other liquid) is initially in equilibrium with its vapour at a pressure close to the atmospheric value. In these conditions, a sudden pressure drop will lead the system to a non-equilibrium situation from which it will tend to recover through a quick vaporization that will result into a very heterogeneous spatial distribution of the water temperature, with saturated, superheated and subcooled zones [2]. These distinct zones with rather different temperatures are then responsible for significant buoyancy forces and highly turbulent water movements that greatly justify the observed high vaporization rates. As typically, the experimental set-up used in the present study to analyse the LPV process comprises two major components: a vaporization chamber (VC) and a depressurization system (DS). The pressure decrease that is required in the vaporization chamber is achieved with the depressurization system that includes a single stage vacuum pump as the main component. The process is known to occur in two distinct stages. In the initial stage, while the total pressure in the