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New cooling approach using successive evaporation and condensation of a liquid film inside a vertical mini-channel

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ABSTRACT

In this paper, the successive evaporation and condensation of water-ethanol and water-methanol liquid film mixtures for cooling purpose is investigated. The simulations are achieved using a finite difference model to describe the heat and mass transfer during this process. The studied process relies on the absorption of energy at the evaporator and then the release of this energy at the condenser. The evaporation and heat exchange abilities of the mixtures composition are analysed to identify the appropriate mixture for the new proposed cooling approach. The results indicate that more energy equilibrium occurs with high concentration of water in the mixture with the advantage of having low bulk and interface temperature.

1. Introduction

With the technological advancement of the electronics industry, electronic devices nowadays are characterised by the high power dissipation and heat flux densities. However, high rates of generated heat give rise to high operating temperatures of electronic devices, which considerably reduces their reliability. Therefore, the need for efficient thermal management of the heat load is now an emergency. In fact, the conventional heat sinks, air convection cooling, and liquid cooling technics have been widely used for decades. So far, those technics have many physical limitations in term of heat transfer capability and cannot respond to the required cooling performances. Recently, industrial and academic researchers have developed new devices to overcome the perceived limits of conventional devices. Solutions like nanofluids, microchannels, spraying jets and phase-change coolinghave been proposed. In this context, the evaporation and condensation of liquid films for cooling applications present many advantages owing to the low thermal resistance(due to the thin thickness of the liquid films) and the large heat flux transfer occurring when the phase change occurs. Relying on the phase change phenomenon, several techniques are able now to overcome the limit of natural or forced convection air-cooling.

Up to now, many researches have beencarried out about liquid film evaporation. Literature is full of both numerical and experimental studies. Classical works including heat and mass transfer and neglecting the thickness of the liquid film are largely described in the literature [1–4]. The effects of momentum and energy transport in the liquid film on the gaseous phase flow are therefore neglected in those studies. A more realistic investigation should nevertheless consider those effects. For this purpose, Yan [5] conducted a study on the heat and mass transfer during thin liquid film evaporation in a vertical channel. The study reveals that assuming an extremely thin film is suitable only for systems with small liquid flow rate. Results indicate that the exchange of heat by the latent mode is dominating the system. Shortly afterwards, many investigations have been made by Yan and Soong to describe deeply the heat and mass transfer mechanism and characteristics in multiple geometries and boundary conditions [6–9]. Palen et al. [10] have run experimental tests of a binary liquid mixture of ethylene and propylene glycol evaporation on a vertical surface. They showed that the mass transfer caused a decrease of the effective heat transfer coefficient and they proposed semiempirical correlations to predict the temperature elevation in binary films. Feddaoui et al. [11–14] extended many of the previous studies of Yan and his co-workers. They provided numerical results for tube and channel's flows. The authors reported the convenient conditions for a better cooling of the liquid film and for heat removal from the wall. They also mentioned the existence of two cooling mechanisms: convective cooling in the case of low liquid film

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Nomenclature

C_P	specific heat (J kg^{-1} K^{-1})
D	mass diffusivity (m^2 s^{-1})
d	half mini-channel width (m)
h_∞	convective heat transfer coefficient (W m^{-2} K^{-1})
h_{fg}	latent heat of vaporisation (J kg^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
$\dot{m}$	evaporating mass flux (kgm^{-2} s^{-1})
p	pressure (Pa)
q_L	latent heat flux (W m^{-2})
q_{conv}	flux imposed at condenser wall (Wm^{-2})
q_s	sensible heat flux (W m^{-2})
q_e	flux imposed at evaporator wall (W m^{-2})
q_{fc}	liquid film convective heat (W m^{-2})
Re	Reynolds number of the gas mixture stream
T	temperature (K)
u	velocity component in x direction (m s^{-1})
v	velocity component in y direction (m s^{-1})
$w_{G,i}$	vapour mass fraction of species i
$w_{L,i}$	liquid mass fraction of species i

Greek symbols

δ_x	local liquid film thickness at x coordinate (m)
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
Γ	liquid mass flow rate (kg s^{-1} m^{-1})
∞	at ambient air (W m^{-1} K^{-1})

Subscripts

a	air
ad	adiabatic section
av	average
b	bulk quantity
c	condenser section
I	interface
i	species i
G	gas
L	liquid
w	wall
0	at inlet condition

temperature and phase change cooling. Nait Alla et al. [15] investigated the evaporation of ethanol liquid film in a partially heated wall of a vertical channel and found no influence of heated zones number on the evaporation rate. Armouzi et al. [16] studied the evaporation by mixed convection of binary liquid film inside two geometries for water-ethanol and water-ethylene glycol mixtures. It is found that the liquid film thickness cannot be neglected and that the heat transfer by latent mode becomes significant as the mixture volatility increases. Binary liquid films are also investigated numerically by Nasr et al. [17]. At first, the authors did not consider the liquid film thickness. The temperature distribution, velocities profiles and evaporation rate were analysed. A similar study was realised by Belhadj and Orfi [18] to analyse and describe the evaporation of water and ammonia mixture. Subsequently, Hfaiedh et al. [19] extended the last study by considering the thickness of an evaporating liquid film. They highlighted the effects of inlet parameters in the variation of interfacial temperature and evaporation rate. Very recently, Nasr et al. [20] analysed the evaporation by natural convection of water film flowing in a porous layer inside a vertical channel. They found that the decrease of porosity or porous layer thickness enhances the liquid film evaporation. Najim et al. [21] studied the effect of salinity on the heat and mass transfer during liquid film evaporation in a vertical tube. The authors investigated the variation of salinity along the tube and compared the effects of operating conditions on the efficiency of the desalination process. Wan et al. [22] have developed a combined 1-D and 2D model to calculate the average Nusselt and Sherwood numbers during the evaporation of falling liquid films. The authors considered two types of boundary conditions: uniform wall heat flux and uniform wall temperature.

Similarly to evaporation, a large and growing body of literature has investigated liquid film condensation. Nusselt [23] was the first to provide an in-depth analytical study of vapour condensation into a liquid film and suggested solutions to determine velocity, temperature, liquid flow rate and heat transfer coefficient profiles. Yang et al. [24] applied an analytic method in order to study the liquid film condensation on a horizontal wavy disk. They claim that the wavy form of the disk reduces the mean Nusselt number when compared to flat disk. In order to release a more realistic film condensation solutions, Srzick et al. [25] have conducted a detailed numerical study on mixed-convection condensation on isothermal plates by taking into account the existence of two phases. In recent years, there has been an increasing amount of literature on vapour condensation into liquid film since it plays an important role in the efficiency of the processes mentioned above. This motivates many authors to investigate intensively the condensation into liquid films [26–32]. Siow et al. [26] reported detailed investigations on laminar condensation of steam-air and R134a-air inside horizontal channels. The developed model permitted to simulate complete condensation cases. Later, the same authors [29] extended their work to simulate the steam-air condensation inside a tilted channel. Nubuloni and Thome [30] developed a numerical and theoretical model to predict the laminar film condensation inside various channel shapes. They showed that the channel shape stronglyaffects the overall thermal performance. Nubuloni and Thome [31] carried out another study to investigate the effects of oil on the condensation process inside minichannels for different shapes. The authors indicate that the oil presence increases the pressure drop, moreover, in case of laminar film flows, capillary- dominated condensation processes are slightly less affected by the variation in viscosity (due to the oil presence) than gravity driven processes. Recently, Charef et al. [32] investigated the condensation process of water vapour-air into liquid film inside a vertical tube under two different boundary conditions: imposed temperature and imposed heat flux. The results indicated a better condensation process under imposed heat flux. It was found that the presence of non-condensable gas affects negatively the system efficiency.

The idea of combining both, liquid film evaporation and condensation phenomenon in one device didn't get the appropriate attention until the invention of heat pipes for cooling devices and the implementation of vertical evaporating tube bundles in the food and desalination industries. For example, Park et al. [33] have investigated numerically the heat and mass transfer of conjugated processes of film evaporation and condensation inside and outside a vertical tube. The authors discussed the evaporation delay and temperature inflection near the inflow region. Merouani et al. [34] conducted a similar study, by considering an evaporating liquid film in the inner tube and a condensing film in the outer tube (annulus) of a tubular heat exchanger. Recently, the effects of inlet parameters on the heat and mass exchanges were reported. Successive evaporation and condensation of R134a and R404a fluids in a closed thermosiphon are analysed by Bandar et al. [35]. The