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Review on the Liquid Film Evaporation and Condensation

Ahmed Nassif[1], Abdelaziz Nasr[1, 2]

[1]Mechanical Engineering Department, College of Engineering, Umm Al-Qura University, Makkah P.O. BOX 5555, Kingdom of Saudi Arabia

[2]Laboratory of Thermal and Energy Systems Studies, Monastir University, Ibn Eljazzar Street, 5019 Monastir, Tunisia
+ Corresponding author. Tel. +966 1252 700 70, Fax. +966 1252 700 27

Abstract: ***In many applications, including desalination and absorption, separation processes, cooling towers, air conditioning, cooling evaporators and liquid film evaporation and condensation occur. A pure, binary, or multicomponent liquid film and nanofilm is involved, along with complex and coupled heat and mass transfer processes under free, force and mixed convection. The falling film evaporation and condensation in various geometrical configurations, such as on horizontal tubes and inside inclined or vertical tubes or channels, are presented in this study along with significant fundamental characteristics that are intrinsic to those processes. The paper's first section reviews current studies on the heat and mass transfer associated with liquid film evaporation. The review of recent studies on heat and mass transfer with liquid film condensation is the focus of the paper's second section.***

Keywords: evaporation, condensation, heat and mass transfer, liquid film, mixed convection, forced convection, mixed convection, thermal desalination, absorption, horizontal tubes

1. Introduction

Film evaporation and condensation process is encountered in different industrial applications. The liquid film can be pure, binary, ternary and nanofilm and it can be flowing down on a vertical, horizontal and inclined plate or tube under free, force and mixed convection. An important challenge in the optimal design and manufacture of numerous evaporators and condensers used in diverse applications, is the evaluation of the heat and mass transfer coefficients and corresponding evaporation and condensation rates in various configurations. This paper covers a summary of the major current studies on falling film evaporation and condensation in the first phase and the related heat and mass transfer and fluid flow in the second phase.

2. Literature Review

This section presented an updated literature that includes significant works on the evaporation of single-component and multicomponent liquid films with associated transport phenomena and related applications.

2.1 Liquid film evaporation

Ali Cherif and Daif [1] presented a numerical study of the evaporation by mixed convection of binary liquid film flowing of one of the two parallel plates. They analysed the influence of the liquid composition in the mass and thermal transfers. For the ethanol-water liquid mixture, the results seem to be foreseeable while it is different for the second mixture (ethylene glycol–water). They showed, in particular, that the film thickness cannot be neglected and that the latent heat transfers are increasingly significant as the liquid film components become more volatile. Agunaoun et al. [2] studied numerically the evaporation of a binary liquid film flowing on an inclined plate. They showed that it is possible to evaporate more water when the liquid mass fraction of ethylene glycol is less than 40%. Debissi et al. [3] presented a numerical study of the evaporation of binary liquid film. The film is falling down on one plate of a vertical channel under mixed convection. The first plate of a vertical channel is externally submitted to a uniform heated flux while the second one is dry and isothermal. The liquid mixture consists of water (the more volatile component) and ethylene glycol while the gas mixture has three components: dry air, water vapour and ethylene-glycol vapour. They showed that from a definite distance and from a certain value of the inlet liquid mass fraction of ethylene glycol, it is possible to evaporate in the same conditions more water than if the film at the entry was pure water only. They showed that the existence and the value of the inversion distance essentially depend on the value of the heat flux density. Nasr et al. [4] studied numerically the evaporation of binary liquid film flowing on a vertical channel by mixed convection. They showed that, when the inlet liquid concentration of ethylene glycol is less than a particular value, it is possible to increase the accumulated evaporation rate of water and of the liquid mixture. This result has been justified by the fact that an increase of the inlet liquid concentration of ethylene glycol has two antagonistic effects on the accumulated evaporation rates of water and of liquid mixture. Hoke et al. [5] studied numerically the evaporation of a binary liquid film on a vertical plate. They analysed the evolution of Sherwood and Nusselt numbers. Wang [6] presented the evaporation of ternary liquid film. The author presented the simultaneous heat and mass transfer in evaporating multicomponent films. El Armouzi et al. [7] presented a numerical study of the evaporation of a binary liquid film flowing down the wall of two coaxial cylinders. They analysed the effect of the volatilities of the mixture liquid film on the heat and mass transfer during evaporation. Palen et al. [8] studied experimentally the evaporation of an ethylene glycol–water mixture liquid film. They determined, using an approximate film-theory formulation, the mass-transfer coefficients for the falling films from the experimental data and they presented the correlations in terms of Sherwood, Schmidt and Reynolds numbers. A numerical study of the heat and mass transfer in evaporating two-component liquid film flow has performed by Baumann and Thiele [9]. They analysed the influence of the phase equilibrium and its interaction with the local transport processes during evaporation of benzene-methanol mixtures into a hot tubular air stream. O'Hare et al. [10] presented an experimental study of the evaporation of water-ethanol binary liquid mixture on a horizontal plate. They studied the effect of the composition of binary liquid mixture on the total evaporating rate. Ziobrowski et al. [11] studied experimentally and theoretically the evaporation of water/isopropanol binary liquid film. They presented a comparison of experimental and calculated data of evaporation of water–isopropanol binary liquid film. Yan [12] studied the pure liquid film evaporation by mixed convection of a humid air in a vertical channel. By neglecting convective terms in the momentum and energy equation of the liquid, it is shown that the assumption of an extremely thin film thickness is valid only for a low mass flow rate. Yan and Lin [13] investigated laminar natural heat and mass transfer in a vertical plate channel with pure liquid film evaporation. They show that the influence of the liquid is substantial near the interface. Feddaoui et al. [14] reported a numerical study of the evaporative cooling of pure liquid film falling down along a vertical tube under mixed gas convection. Zheng Hongfei [15] presented an experimental study on an enhanced falling film evaporation–air flow absorption and closed circulation solar still. Bassam et al. [16] studied the water film cooling over the glass cover of a solar still including evaporation effects. They show that the presence of the cooling film neutralizes the effect of wind speed on still efficiency.

Hoke et al. [17] presented a numerical study of the evaporation of a binary liquid film on a vertical plate. They presented the evolution of Sherwood and Nusselt numbers. Vijay et al. [18] studied the isotherm evaporation of a binary liquid film. They measured the diffusion coefficient during the evaporation of a binary liquid in a Stefan tube while observing the position of the liquid-gas interface. El Armouzi et al. [19] investigated numerically the evaporation by mixed convection of a binary liquid film flowing down of two coaxial cylinders. They showed that the volatilities of the mixture influence the heat transferred through the latent mode, which is more pronounced for a mixture composed of volatile components. They also showed that the heat and mass transfers are more important near the inlet of the channel and increase with the wall heat flux density. For the same inlet air velocity, the composition and the liquid film thickness are the critical parameters, which govern the transfer during its evaporation. O'Hare and Spedding [20] studied experimentally the evaporation of binary liquid mixture (water–ethanol) on a horizontal plate. They analysed the effect of inlet velocity on the evaporation processes. They showed that when we increase the inlet liquid concentration of ethanol, the total cumulate evaporating rate increases too. Wang [21] has analysed the evaporation of ternary liquid film. Ben Achour [22] presents a theoretical and experimental study of evaporation by mixed convection of binary liquid film flowing down the external wall of a vertical cylinder. Ziobrowski et al. [23] presented a theoretical and experimental study of evaporation of a binary liquid film (water–isopropanol mixture) in the presence of stagnant inert gas. They presented comparison of experimental and calculated data and show small effect of diffusion resistances in liquid phase on the total mass flux and on the selectivity.

Nanofilm's evaporation provides high thermal transfer rates because of its small thickness. This phenomenon is seen in heat pumps, heat exchangers, drying technology and nanotechnology applications. Do and Jang [24] showed that the heat transfer during liquid film evaporation is enhanced by the dispersion of nanoparticles into film. Zhao et al. [25] illustrated the impact of the dispersion of nanoparticles into a liquid film on its evaporation. They showed that the enhancement of the heat transfer during film evaporation is mainly due to the thermal conductivity enhancement of the liquid film. Numerical analyses of steady heat transfer and the forced turbulent flow of different nanofluids flowing inside a circular tube were presented by Namburu et al. [26]. The authors showed that an increase in the volume concentration of nanofluids induces pressure loss. Sefiane and Bennacer [27] experimentally analysed the effect of nanoparticle concentration on nanofluid viscosity. They showed that the dispersion of nanoparticles caused an increase in the nanofluid viscosity and then deterred drop evaporation. Gorjaei et al. [28] presented an analysis of the effect of adding Al_2O_3 nanoparticles in the heat transfer inside a three-dimensional annulus. A study of convective heat transfer of water containing C_uO nanoparticles has been presented by Lazarus et al. [29]. They showed that the convective heat transfer coefficient of the nanofluid can be enhanced for a lower volume concentration of CuO nanoparticles. Chen et al. [30] presented the effects of nanoparticles on nanofluid droplet evaporation. They showed an enhancement of nanofluid evaporation in the case of packing of nanoparticles in the fluid. They showed that these nanoparticles (Laponite, Fe(2)O(3) and Ag-water) droplets evaporate at different rates from the base fluid (water). Siddiqa et al. [31] investigated of heat transfer by natural convection of nanofluid flow along a vertical surface by natural convection. It was shown that the dispersion of the nanoparticles ameliorates heat exchange. Sheremet et al. [32] numerically studied the free fluid flow of the convective heat transfer inside a porous wavy cavity in the presence of a nanofluid. They showed that the local heat source influenced the nanofluid flow and heat transfer rate. The effects of Brownian motion of nanoparticles and thermophoresis on the heat transfer during liquid film boiling have been analysed by Malvandi et al. [33]. Orejon et al. [34] presented a study of evaporation of water droplets containing titanium dioxide nanoparticles (TiO_2) under direct current conditions. They showed that the TiO_2 nanofluids' receding contact was continuous and smooth when they applied direct current. Orejon et al. [35] treated the evaporation of water droplets containing different quantities of titanium oxide nanoparticles. Askounis et al. [36] studied the evaporation of water droplets containing a low concentration of Al_2O_3 nanoparticles. They concluded that the dispersion of Al_2O_3 nanoparticles in the water droplets at low concentrations did not affect the evaporation kinetics of droplets. Perrin et al. [37] analysed the evaporation of liquid drops containing a low nanoparticle concentration. A comparison between experimental and theoretical results of the evaporation of nanofluid liquid drops has also been presented. Abu-Hamdeh et al. [38] presented heat transfer and entropy formation of steady Prandtl–Eyring nanofluids. A numerical study of the first-grade viscoelastic nanofluid boundary layer flow with the transmission of entropy and heat was performed by Mashhour et al. [39]. Kam et al. [40] presented the removal of Tl(I) onto synthesised γ-alumina nanoparticles (γANPs) with a crystallite size of 4.1 nm. Yan [41] presented a numerical analysis of falling liquid film evaporation by mixed convection. Huang et al. [42] experimentally analysed liquid film evaporation. They showed that the increase of the inlet air flow rate and the inlet temperature enhanced the evaporation rate.

2.2. Liquid film condensation

The liquid film condensation in a porous medium has received considerable attention in many theoretical and experimental investigations [43-63]. Chaynane et al. [43] presented a numerical and analytical study of the film condensation on the wall of an inclined porous plate. They presented a comparison between the Darcy-Brinkman-Forchheimer (DBF) model and the Darcy-Brinkman (DB). They also presented the effects of the effective viscosity, permeability and dimensionless thickness of porous coating on the flow and the heat transfer enhancement. Kibboua and Azzi [44] studied numerically the laminar film condensation of saturated vapor flowing over an isothermal elliptical tube embedded in a porous medium. They showed that the local film thickness and the local Nusselt number depend on practical dimensionless parameters such as Reynolds number, Darcy number, Bond number and eccentricity. Ebinuma and Nakayama [45] analysed the problem of non-Darcy and transient film condensation over a vertical surface in a porous medium. They showed that the time required for the steady state increases, while the surface heat transfer rate decreases, as the non-Darcy porous inertia effects become significant. Masoud et al. [46] introduced a mathematical model of the transient film condensation on a vertical plate imbedded in a porous medium. They presented the effect of the permeability of the porous material on several issues including the velocity profiles, the film thickness and the time required to reach steady state conditions. Merouani et al. [47] presented a numerical investigation of the laminar film condensation on an inclined channel with an insulated upper wall and an isothermal lower wall coated with a thin porous material. They presented the axial evolution of the condensate flow rate and the wall heat flux for different operating conditions. They showed that the inclination angle, the inlet values of relative humidity and the Reynolds number exert an influence on the condensation process much more significant than that coming from a change in the porous layer properties. Renken et al. [48] conducted a theoretical investigation of laminar film condensation along a solid impermeable surface coated with a porous material. They found that a conductive coating may yield a considerable heat transfer enhancement. Renken et al. [49] presented an experimental analysis of the film condensation on vertical isothermal porous metallic coated plates. They presented a comparison of the experiments with a theoretical model based on porous fluid composite condensation. Renken and Raich [50] presented a numerical analysis of the film condensation enhancement by a porous/fluid composite system. They compared the numerical results with Nusselt's theory and preliminary experimental data. Xue-Hu Ma et al. [51] performed an investigation of the influence of the porous layer characteristic parameters on filmwise condensation heat transfer enhancement. The results revealed that the enhancement ratio increased with the increase of the porous layer thickness and permeability. Ma and Wang [52] reported a numerical investigation of the film condensation on a vertical porous coated. They illustrate the effects of the porous coating thickness, the effective thermal conductivity and the permeability on condensate film thickness and local Nusselt number. They showed that the predicted average Nusselt number has similar tendencies to experimental results reported in literature. Chiou and Chang [53] investigated the steady-state film condensation on an isothermal horizontal disk with suction at the porous wall. The dimensionless film thickness along the disk is found to be a function of parameter Ja/Pr (Jakob number/Prandtl number) and the suction parameter Sw. They showed that the dimensionless heat transfer coefficient increases as suction parameter Sw increases. Char et al. [54] studied numerically the laminar mixed-convection film condensation along a vertical plate within a saturated vapor porous medium. They showed that the local heat transfer rate increases with a decrease in the Jakob number, the Peclet number, and the inertial parameter or an increase in the conjugate heat transfer parameter. Ping Cheng [55] studied the problems of steady film condensation outside a wedge or a cone embedded in a porous medium filled with a dry saturated vapor. El Hammami et al. [56] presented an analysis of the condensation of steam-gas mixture within a porous layer for different conditions. They examined the effects of porosity, porous layer thickness and non-condensable gas of the heat and mass transfer in condensed liquid film. White and Tien [57] presented a study of the laminar film condensation inside a porous medium. They showed that a simple rescaling of the Nusselt number calculated in each of these cases reduces to a simple function of the rescaled distance from the top of the condenser. Chang [58] reported a study of the laminar film condensation on a horizontal wavy plate embedded in a porous medium. They showed that the inclusion of capillary effects in the liquid film analysis has a significant effect on the computed results for the heat transfer coefficient. They showed also that the wave number and the wave amplitude of the wavy plate both have a significant effect on the mean Nusselt number. Kibboua and Azzi [59] presented a study of the laminar film condensation on an elliptical tube embedded in porous media. They analysed the effect of vapor shear on the condensation. They showed a dependence of the local film thickness and local Nusselt number on practical dimensionless parameters such as Reynolds number, Darcy number, Bond number and eccentricity. Kumari et al. [60] presented an analysis of the steady film condensation along a frustum of a cone in a porous medium. Al-Nimr and AlKam [61] conducted a study of the film condensation on a vertical plate imbedded in a porous medium. They presented closed-form expressions for the condensate's film thickness and flow rate and for the convective heat transfer coefficient. They showed that the liquid film thickness is proportional to $x^{1/4}$ in a thin porous domain and to $x^{1/2}$ in a thick porous domain. Renken et al. [62] analyzed the film condensation of a saturated vapor in forced flow on an inclined plate embedded in a porous medium. They analysed the effect of vapor velocity on the film condensation along a surface embedded in a porous medium.

One of the important studies on condensation of pure vapours on plates is that of Minkowycz and Sparrow [63]. In fact, they presented a theoretical study of falling film condensation by free convection on an isothermal vertical plate. They showed the importance of the effect of non-condensable gas at lower pressure levels. Yang [64] studied the condensation characteristics by free convection inside a vertical tube. Siow et al. [65] conducted a numerical study of the laminar film condensation of vapour–gas mixtures in horizontal channels. They analysed the effects of gas concentration, Reynolds number, pressure and the inlet-to-wall temperature difference on the film thickness and on the heat and mass transfers. Agrawal et al. [66] presented a study of the heat transfer augmentation by coiled wire inserts during forced convection condensation of R22 inside horizontal wetted tubes. Panday [67] numerically treated the film condensation of vapour flowing in a vertical tube and between parallel plates. They take into account the turbulence in the vapour and in the condensate film. They presented the heat flow rate for the condensation of R123 and the mean heat transfer coefficients for the condensation of vapour mixture R123/R134a. Chung et al. [68] presented the experimental results comparing film and drop condensations. They showed that in the pure steam cases, the heat transfer rates of drop condensations are much higher than of film condensations. Yan and Lin [69] studied the evaporation and condensation by natural convection along the wetted walls in vertical annuli. In this study, the walls are wetted by an extremely thin liquid film. They examined the effects of the wetted wall temperature, inlet relative humidity and radii ratio on coupled heat and mass transfers. Zheng Hongfei [70] experimentally studied the falling film evaporation and condensation in the closed circulation solar still. Their findings show that the thermal performance of the solar still is greatly improved because of the technology of the forced thin layer evaporation and film condensation used.

3. Conclusion

The combined heat and mass transfer during liquid film evaporation and condensation encountered in various industrial applications. The important investigations on falling film evaporation and condensation are reviewed in this paper, particularly those that involve numerical simulation. In addition, a framework for simulating fluid flow with heat and mass transfer while evaporation and condensation is present has been constructed and discussed.

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