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Falling-Film Evaporation on Vertical Tubes-a Critical Review

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Abstract: *A state of the art review of vertical tube, falling film evaporation is presented; the review is critical, in an attempt to uncover strengths and weaknesses in prior research, with the overall purpose of clearly identifying gaps in our understanding. The review cover the experimental parameters that affect the heat transfer performances on plain single, multiple and enhanced surfaces. In addition, this paper presents a comprehensive review on the empirical correlations for the heat transfer coefficient. Emphasis is placed on studies that are related to refrigeration, distillation and desalination applications.*

1. INTRODUCTION

The heat transfer in a vertical channel has been the subject of several studies in natural, free or mixed convection with symmetrical, asymmetrical heating of the plate or at imposed temperatures [27-30]. The combined heat and mass transfer through a film in evaporation [31-44] raises much interest because it finds applications in several industrial fields, in particular in desalination [31,32,39,40]. The work carried out by AitHammou [38] concerns the evaporation of the liquid stream on one of the plates of the channel maintained at an imposed temperature, with mixed convection of the humid air. Yan et al. [43, 44] treat evaporation during the cooling of an overheated liquid film falling on the walls of a channel whose walls are maintained at constant temperature. The studies treating the heat and mass transfer in channels, with the walls at imposed flux density are relatively rare [31,32,40,42]. To simplify the study, several authors neglect the liquid film and do not take account of its dynamics. The earliest theoretical research on falling film evaporation dated back to the work did by Nusselt[12] in 1916, in his study, the control equations, heat transfer coefficient and film thickness were derived by the assumption of the smooth laminar flow in the film. In later time, Chun and Seban [9] investigated the falling film evaporation of pure water on interior surface of vertical tubes, and Struve [13] carried out experiments on falling film process in vertical tube using the refrigerant R11. In Struve’s study, the local heat transfer coefficient was found to be determined by flow velocity, heat flux and film thickness. Fujita and Ueda [14] further investigated both laminar flow and turbulent flow when pure water falling film in vertical tube, their experimental results showed that increasing Re decreased heat transfer coefficient in laminar flow and it was just opposite to turbulent flow condition. The effects of mass transfer on local heat transfer coefficient in vertical tubes was discussed by Chen and Palen [5], they concluded that neither surface evaporation nor nuclear boiling induced such an effect. In fact, it was determined by the bubble point temperature of solution. Philipp Adomeit et al. [6] observed the velocity distribution, film thickness and surface wave characters by partial microscope system in water film. And these researches indicated that the heat transfer coefficient was very large when the heating flux was low. For the aim of energy conservation, the flue gas (its temperature is about 200°C) can be utilized as the heat resource in lithium bromide absorption refrigeration systems. In submerged generator, the heat transfer coefficient between flue gas and tube is very small, because it is hard to use annular fins to enhance heat transfer inside the generation tubes. As a result, the size of generator becomes rather huge. And in submerged generator, the pressure of solution column can cause the bubble point temperatures in different heights unequal, the whole heat transfer coefficient is not efficient in this case.

Nomenclature

d	tube diameter, mm
q_w	average wall heat flux, Wm^{-2}
Re	film Reynolds number
T_1	liquid temperature, K
T_w	average wall temperature, K
Ka	Kapitza number
h	heat transfer coefficient ($h= q_w/ \Delta T$), $Wm^{-2}K^{-1}$
Γ	falling film mass flow rate per unit length on one side of tube, $kgm^{-1}s^{-1}$
μ	dynamic viscosity, $kgm^{-2}s^{-1}$
Pr	Prandtl number
δ	film outside thickness, mm
	F_{wave}wave factor

2. CORRELATION BETWEEN SPRAY DENSITY AND ANNUAL GAP.

In Chao Luo et al.(2011)[1] experimental study for fluid hydrodynamic characteristics in thin water films falling down the outside of a vertical tube was performed with the analysis of several factors about the uniformity and stability of the film. . In this publication a novel falling-film distributor which is used annular gap and inlet tube rotated tangentially 270^o to guarantee the film uniformity is presented.

This paper presents a novel falling-film distributor which is used annular gap distance and inlet tube rotated tangentially 270^o to guarantee the film uniformity. The distributor in the vertical falling-film tube improves the heat transfer performance of falling film. Basic data for evaporator design can be drawn from the experiment, which will have a better prospect in energy conversion industry.

(1) The falling film has its characteristics such as simple structure, reliable performance and convenient machinability.
(2) Annular gap distance has a great influence to the film uniformity and wettability, optimum annular gap distance value is between 1.5 and 2.0 mm.
(3) Fig.1. shows the relationship of film spray density r and film outside thickness δ,the maximum thickness of liquid film is no more than 0.4mm
(4) The spray density should be controlled between 250 and 700 kg m^{-1} h^{-1} in order to prevent a dry wall and film splash phenomenon on the outside falling-film tube surface appeared. The formula definition of film spray density is given below

$$r = \frac{3600W}{\pi d}$$

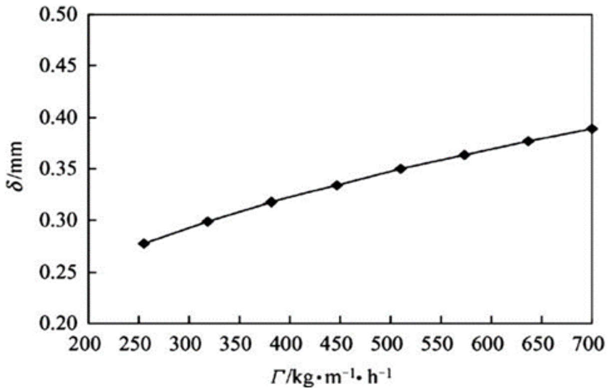

Fig. 1. The relationship between r and δ.

(5) The way of liquid flows into the falling-film tank has a significant effect on the film uniformity, tangential flow is significantly better than radial flow for single vertical falling film.

3. WAVE FACTOR VERSUS REYNOLDS NUMBER OVER WIDE RANGE OF HEAT TRANSFER AND THEIR RELATION

T. Storch et al.(2013)[2] local heat transfer coefficients for falling film evaporation of isopropanol were experimentally measured inside a vertical brass tube at near-zero shear stress. The measurements included film Re numbers up to 100, inner wall heat flux up to 12,500 Wm^{-2} without bubble formation in the super-heated liquid, and vapour temperatures ranging from 8.5^{o}C to 36^{o}C ($Pr_{liquid,\ freesurface}$=14.5-20.8). The heat transfer measurements were focused on Re number and heat flux effects on falling liquid film evaporation. Based on own visual investigations of vertically falling liquid films, as reported in Philipp et al. (2006)[3] and Gross et al. (2009)[4],five main characteristic

Renumber ranges are obtained in Fig. 2with the limits as indicated by bold vertical lines:

(a) Re <2.5: F_{wave} (=$Nu_{experimental}/Nu_{Nusselt\ (1916)}$) is nearly constant;
(b) 2.5 < Re < 4: The wave factor starts to rise moderately;
(c) 4 < Re < 25: The increase becomes stronger …
(d) 25 < Re < 70: and weaker again …
(e) Re > 70: …and finally a re-intensification is obtained with a significantly stronger slope of the middle trend line.

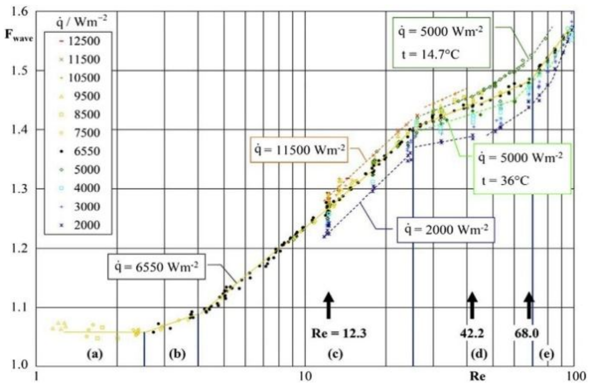

Fig. 2. Wave factor (=Nu $_{experimental}$/Nu$_{Nusselt\ (1916)}$) vs. Re number for a wide range of heat fluxes and several vapour temperatures (evaporation heat transfer data; liquid: isopropanol).

The general Re number effect on F_{wave} is found to be superposed by a certain influence of the wall heat flux. This is clearly seen in Fig 2forRe>12 (in range (c)) showing some increase of$F_{wave}$when the heat flux is raised from 2000 Wm^{-2} to 11,500 Wm^{-2}. This influence seems to be even stronger in range (d), i.e. in presence of developing turbulence. Here an additional temperature effect be-comes visible showing a decrease of F_{wave} when the temperature is raised from 14.7 ^oC to 36 ^oC (as measured for 5000 Wm^{-2}) due to transition to the developed turbulence at last the conclusion is as the heat flux increases at constant vapour temperature brings proportionally increasing temperature difference evaporating liquid film.

The effects of mass transfer on local heat transfer coefficient in vertical tubes was discussed by Chen and Palen [5] they concluded that neither surface evaporation nor nuclear boiling induced such an effect. In fact, it was determined by the bubble point temperature of solution. Philipp Adomeit et al [6] observed the velocity distribution, film thickness and surface wave characters by partial microscope system in water film. And these researches indicated that the heat transfer coefficient was very large when the heating flux was low.

4. NUSSELT NUMBER VARIATION

4.1 Chengming Shi et al.(2009)[7]

Falling film generation process in lithium bromide absorption refrigeration generation system is researched in this paper. To describe the coupled heat and mass transfer of laminar falling film in vertical generation tube, a mathematical model is developed, in which the effect of mass transfer and heat transfer is carefully evaluated. Moreover, an equation related Re number with solution volume flow was also obtained in given conditions.

$$Re=95.238q\ (\pi\upsilon)^{-1}$$

Fig. 3 shows the dependence of the heat transfer coefficient on heat fluxes with different volume flow in our experiment. It is seen that increasing the heat flux results in an increase in heat transfer coefficient. It is also shown that the heat transfer coefficient decreases with increasing the volume flow when it is less than about 9ml/s; and it increases with increasing the volume flow larger than 9ml/s. is due to change of flow pattern.

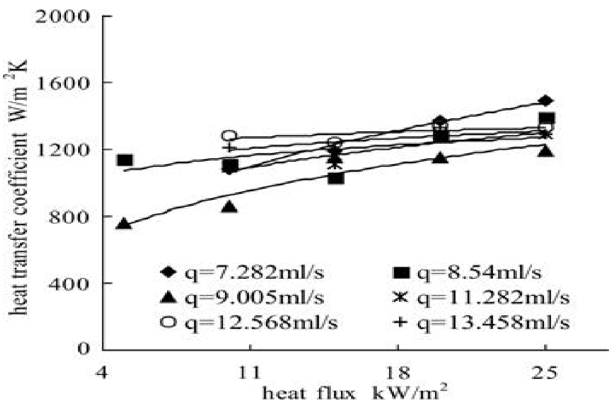

Fig. 3 Variation of heat transfer coefficient and heat flux

Fig. 4 represents the heat transfer coefficient obtained in experiment and numerical results when the heat flux is 25kW/m^2 and the volume flow is less than 10ml/s. The slope of experimental results is larger than that obtained by simulations, and the magnitude of each heat flux in experiment is bigger than simulation results. The main reason is due to the film becomes thinner in generation process. On the other words, the corresponding thermal resistance becomes smaller, and enhances the heat transfer.

Table 1 Correlation reported in the literature for the calculation of dimensionless heat transfer coefficient.

No	Equation	Comments	Author
1	$h= 0.01(Re\ Pr)^{0.33}$	Turbulent flow of falling water inside copper tubes for Re between 1600 and 50000, and a mean water film temperature of 88 ^{o}C	20
2	$h= 0.02007Re^{\cdot 33}\ (sec\theta)^{0.334}$	Turbulent flow of a liquid falling over a flat plat 1 m long with varying slope and Re between 2900 and 12800 , and a mean liquid film temperature of 34 ^{o}C	21
3	$h= 8.7 \times 10^{-3}\ Re^{0.4}Pr^{0.344}$	Turbulent flow for heating of a falling film of water, and water – ethyleneglycol mixtures over the outside of a metallic rod 2.4 m long and diameter of 4.2 cm internally heated by mean of hot water.	22
4	$h= 6.92 \times 10^{-3}\ Re^{0.345}Pr^{0.4}$	Flow of Falling water and aqueous solution of glycerol in the inner surface of a copper tube of 3.015 cm I.D. with Re between 3 and 10250 and Pr between 3.6 and 950	23
5	$h= 8.54 \times 10^{-4}\ Re^{0.65}$	Water flowing inside a copper tube of 2.408 cm ID ,and Re, ranging from 3000 and 20000, with a mean film temperature of $71^{0}C$	24
6	$h= 3.8 \times 10^{-3}\ Re^{0.4}\ Pr^{0.65}$	Water evaporating as a falling film over an electrically heated vertical tube. Re 320 and 21000 , and saturation temperature between 28 and 100 ^{o}C	25

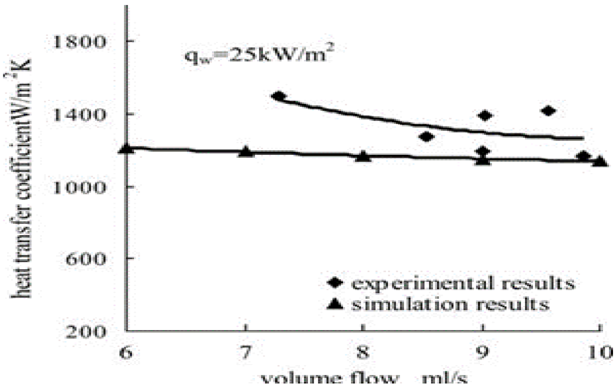

Fig. 4 Comparison of experimental and simulation results

4.2 Alhusseiniet. al.[8]

Evaporation data were obtained over a Prandtl number range of 1.73-46.6 using water and propylene glycol as test fluids. The Chun and Seban correlation [9] was found to be inadequate for fluids with Prandtl number larger than five. The experimental Nusselt number h*, exhibited a parametric behaviour in the wavy laminar region which had not been observed, suggesting that h* depends on at least one more dimensionless parameter besides Reynolds number. A correlation for h* in terms of both Reynolds and Kapitza numbers is proposed, for wavy laminar films. A semi-empirical correlation for h* is proposed for turbulent films. The correlation was found to be in very good agreement with the new evaporation data as well as with well-known correlations for heat transfer coefficient of sensible heating and mass transfer coefficients of absorption and liquid to wall solute transfer. The following dimensionless correlation is proposed for the evaporative heat transfer Nusselt number [8] in the wavy laminar region:

$$h^*=2.65Re^{-0.158}ka^{0.0568}$$

Chun and Seban[2] correlated their data in the wavy laminar region by,

$$h^*=h(v^2/g)^{1/3}/k\ =0.821Re^{-0.22}$$

And in fully turbulent region:

$$h^*=0.0038Re^{0.4}Pr^{0.65}$$

5. EFFECT OF DISTANCE BETWEEN THE PLATES

M. El Haj Assad [10]shows that increasing the liquid mass flow results in a decrease in the cooling rate between the plate. However, the cooling rate increases monotonically with distance between the plates. They also shows that the interfacial shear stress has significant negative effect on the cooling rate. They shows that the volumetric cooling rate has an optimum value. This optimum occurs at distance between the plate between 3.5 and 4 mm depending on the liquid mass flow. This is due to the fact that the cooling rate is sharply increasing for distance between the plates < 4 mm and is slightly increasing for distance between the plates > 4 mm. The variation of vapour exit velocity with distance between the plates is presented. As is expected, the interfacial shear stress decreases the vapour velocity. The variation of pressure drop of vapour is presented. The vapour pressure decreases in the vapour flow direction. The pressure drop is monotonically decreasing with distance between the plates. For higher liquid mass flow, this decrease in pressure drop is more significant.

6. BUOYANCY EFFECT

The influence of buoyancy on heat transfer under conditions of turbulent forced flow in vertical tubes has received considerable attention over the years - see for instance Jackson and Hall et al. [16] and Jackson et al. [17] and M. Feddaoui et al. [19]. In the buoyancy- aided situation (upward flow in a heated tube), the shear force exerted on the flow by the wall can be partly, or even wholly, overcome by the buoyancy of the fluid adjacent to it. As a result, the local shear stress falls steeply with distance from the wall, turbulence production is affected and heat transfer by turbulent discussion is impaired. The experimental study by Li et al. [18] of heat transfer to air which was induced naturally through a heated vertical tube has demonstrated that buoyancy-induced impairment of heat transfer can also happen under such condition.

7. ENERGY EFFECT

[11] Energy analysis has been adopted to examine the behaviour of wavy interface for thin evaporating falling liquid film in a vertical tube. For falling film in vertical tube, there may be two converse effects of capillary force on film instability at different interface status. As capillary force, is the factor to restrain the interfacial waves. Otherwise, capillary force can also enhance film instability. Increasing perturbation wavelength (decrease of wave number) will increase the radius of curvature at wave crest, and hence, the centripetal part of capillary force becomes dominating, the instability of film increases gradually.Surface tension increases with decrease of interface temperature in wave crest and decreases with increase of interface temperature in wave trough.Higher tube wall temperature, more energy may be involved in improving interface wavy. It can be thus deduced that, increasing tube wall heat flux continuously to some extent, the system energy of promoting film waving at non-dimensional distance between wave crest and initial interface position, may become positive, that is to say, liquid film breakup takes place.

8. CONCLUSIONS

From this review, the following conclusions can be drawn:
In general, enhanced surfaces provide higher heat transfer performance than plain surfaces; however, confidence in the enhancement is underminedby complexity in the heat transfer which dependence ongeometry, tube layout, and operating conditions. Specialattention must be directed not only to the optimization ofenhanced tube geometry but also to the definition of theconditions in which enhancements can be clearly identified.Several models focusing on the prediction of h have beenproposed. However, in general, they do not include vapor-shear effects, interfacial waviness,or nucleate boiling effects.The falling-film evaporator meets many of the needs ofthe air-conditioning and refrigeration industry. Thethermal performance of falling-film heat exchangers isexcellent—it is thermally superior to flooded evaporatorsand competitive with plate heat exchangers.

REFERENCE

[1] Luo, C., W. Ma, and Y. Gong, Design of single vertical tube falling-film evaporation basing on experiment. Journal of Loss Prevention in the Process Industries, 2011. **24**(5): p. 695-698.
[2] Storch, T., et al., Near-zero shear stress experiments with heat flux effects on falling film evaporation inside a vertical tube. International Journal of Thermal Sciences, 2014. **76**: p. 137-146.
[3] Philipp, C., et al. WAVE CHARACTERISTICS OF LIQUID FILMS-CORRELATION OF HEAT TRANSFER DATA WITH VISUAL OBSERVATIONS. in International Heat Transfer Conference 13. 2006. Begel House Inc.
[4] Gross, U., et al., Wave frequency of falling liquid films and the effect on reflux condensation in vertical tubes. International Journal of Multiphase Flow, 2009. **35**(4): p. 398-409.
[5] J. W. Palen, Qi Wang, J. C. Chen. Falling film evapora-tion of binary mixture, AICHE Journal, 1994, 40(2): 207−214.
[6] 6. Philipp Adomeit, Ulrich Renz. Hydrodynamics of three-dimensional waves in laminar falling films [J], Int. J. Multiphase Flow, 2000, 26: 1183−1208.
[7] Shi, C., et al., Study on falling film generation heat transfer of lithium bromide solution in vertical tubes. Journal of Thermal Science, 2009. **18**(3): p. 241-245.
[8] Alhusseini, A.A., K. Tuzla, and J.C. Chen, Falling film evaporation of single component liquids. International journal of heat and mass transfer, 1998. **41**(12): p. 1623-1632.
[9] Chun, K. and R. Seban, Heat transfer to evaporating liquid films. Journal of Heat Transfer, 1971. **93**(4): p. 391-396.
[10] Assad, M. and M.J. Lampinen, Mathematical modeling of falling liquid film evaporation process. International journal of refrigeration, 2002. **25**(7): p. 985-991.
[11] Du, X.-Z., et al., Energy analysis of evaporating thin falling film instability in vertical tube. International journal of heat and mass transfer, 2002. **45**(9): p. 1889-1893.
[12] Nusselt, W. Die. Oberflachenkondensation des Wasser-dampfes. ZeitschriftVereinDeutscheringenieure, 1916.60: 541−546 and pp.569−575.
[13] H Struve, Heat Transfer to an Evaporating falling Refrig- erant Film. 12th Congress of the International Institute of Refrigeration. Madrid. 1967.

[14] T. Fujita, T. Ueda. Heat transfer to falling liquid films and film breakdown [J]. Int. J. Heat Mass Transfer. 1978. 21: 109–118.
[15] P. An, J. Li, J.D. Jackson. Study of the cooling of a uniformly heated vertical tube by an ascending ¯ow of air and a falling water film. International Journal of Heat and Fluid Flow 20 (1999) 268- 279.
[16] Jackson, J.D., Hall, W.B., 1979. Influences of buoyancy on heat transfer to fluids flowing the vertical tube under turbulent conditions. In: Turbulent Forced Convection in Channels and Bundles, vol. 2, Advanced Study Institute Book, (Hemisphere, Washington DC, pp. 613-640.
[17] Jackson, J.D., Cotton, M.A., Axcell, B.P., 1989. Review: Studies of mixed convection in vertical tubes. International Journal of Heat and Fluid Flow 10, 2-15.
[18] Li, J. 1994. Studies of buoyancy-influenced convective heat transfer to air in a vertical tube, Ph.D. Thesis, Manch.University
[19] M. Feddaoui, A. Mir, E. Belahmidi. concurrent turbulent mixed convection heat and mass transfer in falling film of water inside a vertical heated tube. International journal of heat and mass transfer, 46 (2003), 3497-3509
[20] Mc Adams, W. H., Drew, T. B., & Bays, G. S. (1940). Transactions of ASME, 62, 627.
[21] Garwin, L., & Kelly, E. W. (1955). Indian Journal Engineering and Chemical Fundamentals, 47, 392.
[22] Wilke, W. (1962). Ver. Deut. Ingr. Forschungsh, 490
[23] Ahmed, S. Y., &Kaparthi, R. (1963). Heat transfer studies of falling film heat exchangers. Indian Journal of Technology, 1, 377–381.
[24] Herbert, L. S., & Stern, U. J. (1968). Canadian Journal of Chemical Engineering, 46, 401.
[25] Chung &Seban (1971). Transactions of ASME, Journal of Heat Transfer, Section C, 93, 391
[26] Narayana Murthy, V., &Sarma, P. K. (1977). Falling film evaporators: A desing equation for heat transfer rates. Canadian Journal of Chemical Engineering, 55, 732–735.
[27] W. Aung, L.S. Fletcher,V. Sernas, Developing laminar free convection between vertical flat plates with asymmetric heating, International Journal of Heat and Mass Transfer 15 (1972) 2293–2308.
[28] R.A. Writz, R.J. Stutzman, Experiments on free convection between vertical plateswith symmetric heating, Journal of Heat Transfer 104 (1982) 501–507.
[29] T.F. Ayinde, S.A.M. Said, M.A. Habib, Experimental investigation of turbulentnatural convection flow in a channel, Heat Mass Transfer 42 (2006) 169–177.
[30] H.M. Badr, M.A. Habib, S. Anwar, R. Ben Mansour, S.A.M. Said, Turbulent naturalconvection in vertical parallel plate channels, Heat Mass Transfer 43 (2006)73–84.
[31] S. Ben Jabrallah, A.S. Cherif, B. Dhifaoui, A. Belghith, J.P. Corriou, Experimental study of the evaporation of a falling film in a closed cavity, Desalination 180 (2005)197–206.
[32] S. Ben Jabrallah, A. Belghith, J.P. Corriou, Etude des transfertscouplés de matière etde chaleurdansunecavitérectangulaire :application à une cellule de distillation,International Journal of Heat and Mass Transfer 45 pp. 891–904.
[33] B. Gebhart, L. Pera, The nature of vertical natural convection flows resulting from the combined buoyancy effect of thermal and mass diffusion, International Journalof Heat and Mass Transfer 14 (1971) 2025–2050.
[34] A. Agunaoun, A. Daif, R. Bariol, M. Daguenet, Evaporation en convection forcée d'un film mince s'écoulant en régime permanent, laminaire et sans ondes, surunesurface plane inclinée, International Journal of Heat and Mass Transfer 37 (1994)2947–2956.
[35] M. Mammou, M. Daguenet, G. Le Palec, Numerical study of heat and mass transfer from an inclined plate with wet and dry zones, International Journal of Heat andMass Transfer 35 (9) (1992) 2277–2287.
[36] A. Baquadir, L. Pietri, M. Grisenti, B. Zeghmati, Evaporation en convection forcéturbulente d'un film liquideruisselantsur la paroi interne d'un cylindre vertical,10ème JouméesInternationales de Thermique (JITH, TUNISIE, 2001).
[37] C. Debbissi, J. Orfi, S. Ben Nasrallah, Evaporation of water free convection in avertical channel including effects of wall radiative properties, InternationalJournal of Heat and Mass Transfer 44 (2001) 811–826.
[38] Z. Ait Hammou, B. Benhammou, N. Glalanis, J. Orfi, Laminar mixed convection ofhumid air in a vertical channel with evaporation or condensation at the wall,International Journal of Thermal Sciences 43 (2004) 531–539.
[39] B. Bouchekima, B. Gros, R. Ouahes, M. Diboun, Etude théoriqueet applicationpratique du distillateursolaire à film capillaire, International Journal of ThermalSciences 39 (2000) 442–459.
[40] K. Fahem, S. Ben Jabrallah, A. Belghith, J.P. Corriou, Numerical simulation of the behavior of a distillation cell with influence of the characteristics of the heating wall, Desalination 201 (2006) 185–197.
[41] A. Cherif, A. Daif, Etude numérique du transfert de chaleuret de masse entre deux plaques planes verticales en présence d'un film liquidebinaireruisselantsurl'une des plaques chauffée, International Journal of Thermal Sciences 42 (1999)2399–2418.
[42] M.M. Salah El-Din, Effect of thermal and buoyancy forces on the development oflaminar mixed convection between vertical parallel plates with uniform wall heatand mass fluxes, International Journal of Thermal Sciences 42 (2003) 447–453.
[43] W.M. Yan, T.F. Lin, Combined heat and mass transfer in natural convectionbetween vertical parallel plates with film evaporation, International Journal of Heat and Mass Transfer 33 (1990) 529–541.
[44] W.M. Yan, T.F. Lin, Y.L. Tsay, Evaporative cooling of liquid film through interfacial heat and mass transfer in avertical channel-I. Experimental study, InternationalJournal of Heat and Mass Transfer 34 (1991) 1105–1111.