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Water falling film evaporation on a corrugated plate

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ABSTRACT

This paper presents experimental results on the study of falling water film evaporation on a single vertical corrugated plate. The corrugated plate module, made of stainless steel having a total heat transfer area of 0.267 m^2, was fabricated and tested in a pilot scale setup. The special geometry of the plate module allows the heat transfer between the liquid flowing in parallel channels inside de module and a film flowing on the two outer faces. Hydrodynamic and thermal tests were carried out. Results of heat transfer for evaporation from the surface of the water film are presented and compared to various correlations found in the literature. It is observed that when the surface is invaded by the film, decreasing film flow-rate provides higher ratio of wetted surface compared to increasing film flow-rate. The enhancement of heat transfer has been observed. Based on our own results, a new correlation has been proposed to predict the evaporative heat transfer by falling film.

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1. Introduction

During recent years, research aimed at the development of technologies that make more efficient use of renewable energy such as solar energy and waste heat from industry plants and power stations is attaining a fast growth. Based on absorption/desorption of water by aqueous solutions, absorption process is now widely considered for solar or waste heat driven refrigeration [1], heat or cooling transportation over long distance [2,3] and long-term solar heat storage [4–6]. In the operating cycle of the absorption system using saline solution ($LiBr/H_2O$; $CaCl_2/H_2O$, $LiCl/H_2O$, etc.), water is the working fluid and evaporates under vacuum condition. Used for the evaporation of fluids under vacuum in desalination [7] and chemical industry [8], falling film technique is well adapted for low pressure applications, due to its low pressure drop characteristic. Compared with flooded-type evaporators, falling film evaporators have the advantages of high evaporating-side heat transfer coefficient, low working fluid charge and small temperature difference between the working fluid and the wall [9]. Experimental researches on falling film evaporation were reviewed by Ribatski and Jacobi [10], by Thome [8] and by Gonzalez et al. [11]. Special emphasis was given on falling film evaporation on horizontal tubes and experimentally based correlations were presented to predict heat transfer coefficient in evaporating falling films for water, ammonia and alternative refrigerants. Experimental studies on falling film evaporation on a single vertical tube have also been reported in the literature and correlations were also proposed for water films [12,13] and for highly viscous liquid films [13–15].

Some of the correlations dealing with non-boiling falling water film evaporation are summarized in Table 1. Note that the Nusselt number (Nu) for falling film is usually defined as:

$$Nu = \frac{h_f}{k}\cdot\left(\frac{v^2}{g}\right)^{1/3} \tag{1}$$

Where h_f is the convective heat transfer coefficient in falling film (W/m^2 K), k the thermal conductivity of fluid (W/m K), v the kinematics viscosity of fluid (m^2/s) and g the gravitational acceleration (m/s^2).

The Reynolds number (Re) for characterizing the flow regime of falling film is expressed as:

$$Re = \frac{4\cdot\Gamma}{\mu} \tag{2}$$

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Nomenclature

a	constant defined in Eq. (7) (–)
A	module total heat transfer area (m^2)
A_1	parameter defined in Table 1
A_2	parameter defined in Table 1
A_3	parameter defined in Table 1
B	parameter defined in Table 1
C_1	parameter defined in Table 1
C_p	specific heat (J/kg K)
D_H	hydraulic diameter of channels (m)
e	plate wall thickness (m)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity of fluid (W/m K)
Ka	Kapitza number $\equiv (g \cdot \mu^4)/(\rho \cdot \sigma^3)$
Nu	Nusselt number defined in Eq. (1) (–)
Pr	Prandtl number $\equiv \mu \cdot Cp/k$ (–)
q	heat flux density (W/m^2)
Q	mass flow-rate of heating fluid (kg/s)
Re	Reynolds numbers defined in Eqs. (2) and (8) (–)
T	temperature (°C)
ΔT_{LMTD}	logarithmic mean temperature difference (°C)
U	overall heat transfer coefficient (W/m^2 K)
V	velocity of the heating fluid (m/s)
x	constant defined in Eq. (9) (–)
y	constant defined in Eq. (9) (–)

Greek symbols

α	constant defined in Eq. (7) (–)
Γ	specific mass flow-rate (g/s m)
δ^+	parameter defined in Table 1
θ	plate slope (°)
λ	thermal conductivity of plate wall (W/m K)
μ	dynamic viscosity (Pa s)
v	kinematics viscosity (m^2/s)
ρ	density (kg/m^3)
σ	surface tension (kg/s^2)

Subscripts

f	falling film side
h	heating fluid side
i	inlet
lam	laminar
o	outlet
s	saturation
tur	turbulent

where Γ is the mass flow-rate per width unit (g/m s) and μ the dynamic viscosity (Pa s).

Compared to shell-and-tubes configuration, vertical plate-type heat exchangers can be more compact, lighter and cheaper for falling film evaporation [16,17]. However, systematic experimental studies are lacking so that only very few correlations are available to predict the thermal performance on this geometry. The main technological barriers are [18]:

- It is difficult to obtain thin falling films reliably and reproducibly;
- Dry zones appear when the flow-rate becomes low or the heat flux becomes high;
- Distribution header which intends to spread the liquid in the form of a thin and uniform film has to be designed delicately.

Kafi et al. [7] developed one of the few correlations for a vertical plate-type evaporator for seawater desalination. In their study, horizontal wires were placed on the plate surface to improve film spreading and to promote turbulences. The hydrodynamics and thermal performances of falling film evaporation under vacuum condition were investigated. To the best of our knowledge, no other correlations are available for vertical plate under vacuum conditions.

In the present study, non-boiling falling water film evaporation on a corrugated plate (called “module” here after) is explored. We shall first investigate the hydrodynamic aspect to evaluate the wettability of the falling film on the plate. Then results of thermal test will also be discussed and compared with several correlations for approaching geometries. Finally, a new correlation based on our results and working conditions will be proposed to predict the heat transfer of water evaporating falling film on a corrugated plate, for

Table 1
Several experimental studies on falling film evaporation.

Authors	Material and geometry	Heating method	Pr range	Re range	Correlations for film side heat transfer
Kafi et al. [7]	Stainless steel plate with metallic grids to promote film turbulences; height: 1.8 m; width: 0.4 m.	Hot water	3.5	100–800	$Nu_{tur} = 0.0033 \cdot Re^{0.4} \cdot Pr^{0,65}$
Chun and Seban [12]	Outside of vertical stainless steel tube; diameter: 0.029 m; heated length: 0.292 m.	Electrical	1.77–5.7	320–21,000	$Nu_{lam} = 0.821 \cdot Re^{-0.22}$ $Nu_{tur} = 0.0038 \cdot Re^{0.4} \cdot Pr^{0.65}$ Transition: $Re = 5900/Pr^{1.06}$
Alhusseini et al. [13]	Outside of vertical stainless steel tube; diameter: 0.0381 m; length: 2.9 m.	Electrical	1.73–46.6	34–15,600	$Nu = (Nu_{lam}^5 + Nu_{tur}^5)^{1/5}$ $Nu_{lam} = 2.65 \cdot Re^{-0.158} \cdot Ka^{0.0563}$ $Nu_{tur} = \frac{Pr \cdot \delta^{+1/3}}{(A_1 \cdot Pr^{3/4} + A_2 \cdot Pr^{1/2} + A_3 \cdot Pr^{1/4} + C_1) + (B \cdot Ka^{1/2} \cdot Pr^{1/2})}$ where: $A_1 = 9.17$ $A_2 = 0.328 \cdot \pi \cdot (130 + \delta^+)/\delta^+$ $A_3 = 0.0289 \cdot (152100 + 2340 \cdot \delta^+ + 7 \cdot \delta^{+2})/\delta^{+2}$ $B = 2.51 \cdot 10^6 \cdot \delta^{+0,333} \cdot Ka^{-0.173}/Re^{(3.49 \cdot Ka^{0.0675})}$ $C_1 = 8.82 + 0.0003 \cdot Re$ $\delta^+ = 0.0946 \cdot Re^{0.8}$
Han and Fletcher [19]	Horizontal brass tube: smooth, circumferentially and axially grooved. Diameter: 0.0508 m; length: 0.254 m.	Electrical	1.3–3.6	770–7,000	$Nu_{tur} = 0.025 \cdot Re^{0.2} \cdot Pr^{0.53}$ (smooth-tube) $Nu_{tur} = 0.0028 \cdot Re^{0.5} \cdot Pr^{0.85}$ (grooved-tube)

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