EXPERIMENTAL STUDY OF HEAT TRANSFER AND HYDRODYNAMICS OF FALLING FILM ON A NOVEL DESIGN OF HELICAL FINNED TUBE EVAPORATORS

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Abstract

An improved evaporator with helical finned tube falling film is presented. Its technology of building is simple and it is a question of piling plates in two wings, identical and simple forms, by respecting a regular gap between them to get the densely populated double helical finned tube of walk of staircase. This new evaporator design introduces advantages to have two helical fins taken up in parallel allowing doubling its area of exchange, a helical geometry allowing influencing flow favorably for a good distribution of the film and a strong density of walk of staircase playing promoters turbulence role that can improve its heat transfer coefficient side film. Thermal study, in heating, evaporating and convective boiling regimes, allowed showing, on the basis of the criterion of the thermal height unit, HTU, a better performance compared with mono-finned evaporators and the smooth double helical finned tube without walk of staircase of the same density.

***Keywords** - helical evaporator, falling film, double fins, density of walk of staircase, HTU*

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I. INTRODUCTION

The technologies of the falling film are useful in various industries due to their specific advantages and remain potential candidates to be the seat of a better heat transfer. They knew a considerable development having allowed improving their performances. To enhance the density of evaporators with falling film new structures of promoters of turbulence were developed allowing to influence flow favorably, to raise the heat exchange area and to improve the convective heat transfer coefficients and to increase of the density of the heat flux. L.Cong et al. [1] carried out three independent experiments which correspond to the characteristic study on the performance of the horizontal-tube falling film evaporators. The simulation was conducted with the superficial evaporation temperature on the shell side of 60°C, the superficial overall temperature difference of 3.0°C, the inlet brine salinity of 30 g/kg, the inlet brine spray density of 0.06 kg/m s, and the maximum steam inlet velocity of 40 m/s. S. Shen et al. [2] performed an experimental platform for horizontal-tube falling-film evaporation to measure heat transfer capacity HTC. The results revealed that the HTC increased first and then decreased with growth of Reynolds number Re, and the HTC of seawater decreased with increasing saturation temperature. The results also showed that the HTC of rotated square pitch was higher than triangular pitch, rotated triangular pitch, and square pitch, but the heat transfer capacity per unit volume of triangular pitch was the highest. Chi et al. [3] studied the airside performance of finandtube heat exchangers having plain, louver, and semi-dimple vortex generator. A total of eighteen samples are made and tested with different fin pitch and the number of tube row. Test results indicate that the heat transfer coefficient for louver fin geometry with a smaller fin pitch is higher than that of semi-dimple and plain fin geometry. The cylindrical tubes with external and internal smooth helical fins constituted an attractive solution for evaporators with falling film [4-6].Indeed, the existence of the fin allowed to increasing the area of heat exchange, and its helical form influenced flow favorably and led to enhancing the fluid internal mixture within the falling film [7,8,9], but they introduce the disadvantage of a relatively expensive manufacture. To overcome this drawback and to intensify the heat transfer and increase the heat exchange area, an improved evaporator, characterized by a simple technology of building and by a competitive cost, for tubes with helical fins, is presented.

II. EXPERIMENTAL SETUP

2.1. Building Technology Principle

The principle of the technology consists of building the tube with helical fins by stacking up of a high number of identical plates, of simple forms to be manufactured in series. Every plate is an individual graphite disc, with a circular orifice in the centre, which one or several parts is removed away according to a given angle.

Fig.1 presents two versions of such plates. Fig.1-a shows the mono-wing plate [10] and Fig.1b gives the two wings plate.

Table 1 regroups their geometric parameters. The stacking up of plates, of same type, respects a regular step to give helical finned tube with walk of staircase, as the spiral staircase. The stacking up of plates mono-wing, gives the helical mono-finned tube with walk of staircase [9] and that of two wings plates to give the helical finned double tube with walk of staircase.

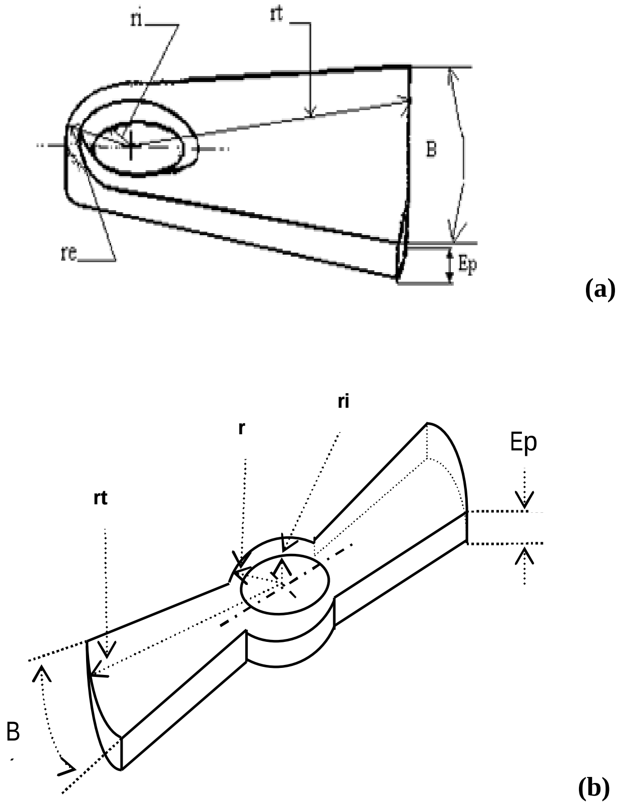

Fig.1: Mono wing plate (a), two wings plate (b)

Fig.2 sketches two schematic representations of the stacking up of plates and points out the cylindrical tube with 40 mm diameter allowed for the flow of the heat transfer fluid (HTF). Fig 2a shows the mono-finned tube of walk of staircase. The double finned tube of the same density is done by Fig.2b.

2.2. Geometrical Parameters of Helical Finned Tube With Walk Of Staircase

The main geometric characteristics of stacking up with walk of staircase are:

- Number of plates,n_p
- Density of walk of staircase (d) defined by the number of plates piled by one tour, d =n_{pt}
- Angle separating two successive walk of staircase, O
- Angle of the axial slope, θ
- Height of helical finned tube with walk of staircase, H

The tube with fins with walk of staircase gives more exchange area than that of the tube with fins without walk of staircase. The factor of increase of area F_a ($F_a > 1$) is defined by:

$$F_a = \frac{\text{finned tube with walk of staircase}}{\text{finned tube without walk of staircase}} \qquad (1)$$

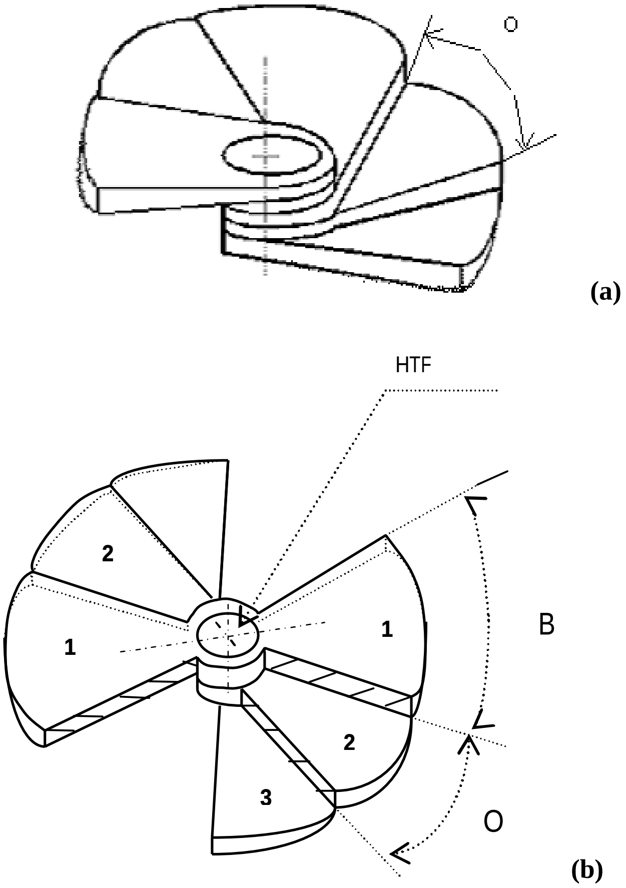

Fig.2- Stacking up of mono wing plates (a), two wing plates (b)

Table 1: Geometric parameters of plate

	B(°)	ri (mm)	re (mm)	rt(mm)	Ep (mm)
Mono wing	140	20	25	70	4
Two wings	140	20	25	70	4

Table 2 summarizes the geometric parameters of both stacking up of tubes: monofin and doubles fins.

Table 2: Geometric parameters of different stacking up

Stacking up	$d = n_{PT}$	n_P	n_T	O(°)	θ(°)	F_a	H(mm)
Mono-wing	12	125	10,4	30	10	1,25	500
Two wings	12	125	10,4	30	10	2,18	500

2.3. Advantages of the Proposed Evaporator

The structure of the walk of staircase, for the falling film evaporator, introduces many advantages, the most important are:

- Mono-finned or double external helical finned tube, of the same axial slope is characterized by walk of staircase, as the spiral staircase. The walk of staircase acts as promoters of turbulence and allows good convective heat transfer, notably, in the weak liquid debit.

- The helical finned tube with walk of staircase is characterized by a density of walk of staircase which is fundamental because its variation influences the area of exchange, the hydrodynamics of the film and the heat transfer rate.
- The helical nature of the fin with the walk of staircase allows a good distribution of the film flowing on the area of exchange. As a result, this new design of tube works without particular distributors.
- The tube with helical fin with walk of staircase is characterized by a simple building and therefore by a low cost.

III. HYDRODYNAMICS OF THE FALLING FILM ON FINS

The hydrodynamics of the film streaming on the area of the helical internal and external fins, with and without walk of staircase, is complex and still little studied. Some authors, notably in papers [8,9], identified the different regimes of flow on helical fins with and without walk of staircase by pointing out the debit of transition. Besides, they gave simplistic models for flow in regime with and without overflow on the same fins with and without walk of staircase. The mono-fin of walk of staircase densely populated tube is assimilated with a perfect flow mixing [11]. Characterized by the same density of walk of staircase, the double tube fins is also qualified as perfect flow mixer. For the experimental determination of the regimes of flow for this last tube, the water, in the ambient temperature and under atmospheric pressure, is introduced by the top of the tube and flows by simple gravity. The progressive increase of its debit allowed identifying three regimes of flow:

- Regime without flood : Regime 1,
- Regime with flood : Regime 2,
- Regime with blocking: Regime 3.

Note that the range of the film debit to be exploited is wide for the double densely populated finned tube and his blocking regime occurs in a debit film (250 g/s), while for the tube densely populated monofin blocking appears early in a flow rate of 130 g/s which represents about 50 % debit relating to the double tube fins.

Table 3 sketch the different regimes of flow for the double densely populated finned tube compared with the mono-finned tube.

Table 3: Critical Debit of transition between different regimes

Experimental setup:	Critical Debit of transition ($g.s^{-1}$) (falling film : water at 298K)		
Mono wing (d=12)	0	5	130
Two wings (d=12)	0	12	250
Streaming regimes	without flood	with flood	blocking

IV. HEAT TRANSFER OF THE FALLING FILM

4.1 Heat Transfer Coefficient Film's Side

This coefficient quantifies the intensity of the heat transfer between the helical fin wall and the core of the falling film. It is determined by direct method [12,13] as:

$$h_f = \frac{Q_{moy}}{A_f . \Delta T_{(p-f)ml}} \tag{2}$$

- heating regime :

$$\Delta T_{(p-f)ml} = \frac{(T_{pe}-T_{fe})-(T_{ps}-T_{fs})}{Ln\frac{(T_{pe}-T_{fe})}{(T_{ps}-T_{fs})}} \tag{3}$$

- evaporating regime :

$$\Delta T_{(p-f)ml} = \frac{T_{pe}-T_{ps}}{Ln\frac{(T_{pe}-T_{sat})}{(T_{ps}-T_{sat})}} \tag{4}$$

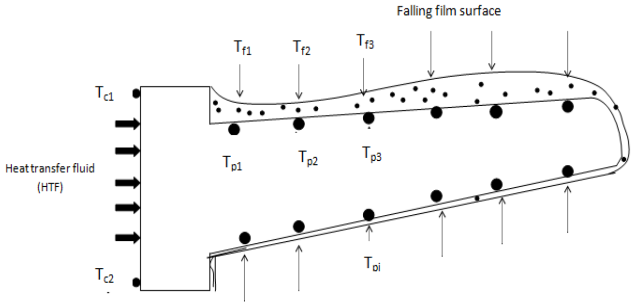

Fig. 3: Thermocouples localizations along fins area

Fig.3 shows a vertical cut of an edge of helical fin where six thermocouples are inserted on its upper wall and six others on its lower one capturing the temperatures T_{pi} of the wall. Different points of the registering temperature of falling filmT_{fi} and of heat transfer fluid/wall interface T_{ci} are also specified. Note that only the mean arithmetic temperatures T_{pi} and T_{fi}, measured at the wall of the fin and of the film at the inlet and outlet, are used in equations (3) and (4).

Tests of heating are driven under atmospheric pressure. To favor the convective boiling mechanism at the heating wall, we used a superheating ($T_p - T_{sat}$) level about 10°C under a partial space about 0.4 bar, while the evaporation in free area is favored by a weak superheating about 2°C under the same space. Note that, both mechanisms of evaporation co-exist but with different percentages according to applied setup conditions

Figures 4, 5 and 6 introduce, respectively, in regimes of heating, evaporating and convective boiling respectively, the variations of the partial convective heat transfer coefficient side film according to the film mass flow, for mono-finned and double densely populated finned tubes of walk of staircase (d=12). Their analyses show that:

- For all thermal regimes, heat transfer coefficient increases with falling film debit. Its growth diminishes and tends to become steady for high debit because of the import thicknesses of the falling film.
- The densely populated mono-finned tube gives greater heat transfer coefficient than the double tube fins of the

same density, the coefficient of heat transfer side film depends fundamentally on the film debit, and for the double finned tube, the total debit of feeding is practically divided in two equal fractions which stream on a sides of double helical fins.

- For the tube densely populated mono-fin of walk (d=12), in a debit of the streaming film $M_f = 100$ g/s the ratio h_f/M_f equals 82.12 W g / °C m^2s
- For the double densely populated finned tube of walk (d=1), the same film debit of $M_f = 100$ g/s, the ratio h_f/M_f is 89 W g / °C m^2s. So, in both cases, values are practically close.
- The double densely populated finned tube of walk of staircase allows greater debits of the film until 250 g/s.

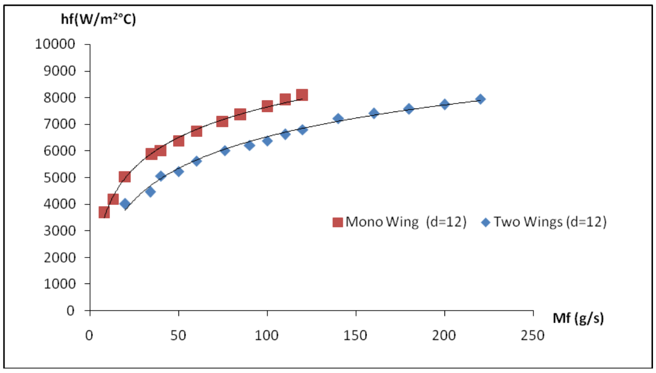

Fig. 4: Heating regime, h_f

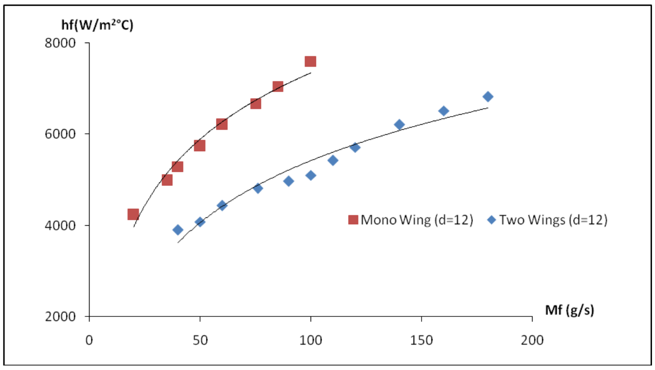

Fig. 5: Evaporating regime, h_f

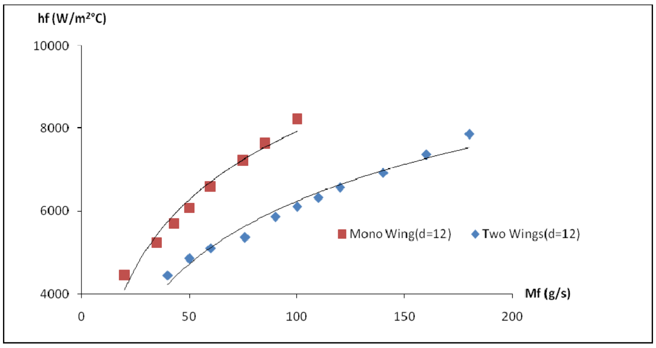

Fig. 6: Convective boiling regime, h_f

4.2 Heat Transfer Unit Height Side Film, HUT_f

HUT_f evaluates the complexity of the partial heat transfers in the half heat exchanger side film since it is necessary to accomplish a height of HUT_f meters of heat exchanger to transfer one unit of energy to the film. It is given by [14]:

$$HUT_f = \frac{H M_f C_p}{h_f A_f} \tag{5}$$

Figures 7, 8 and 9 give the variations of HUT_f as a function of the falling film mass debit, for both mono-finned and double finned tubes of the same density of walk of staircase, respectively, in heating, evaporating and convective boiling regimes, respectively. The double finned tube without walk of staircase and of axial slope θ_a = 6,5 ° is also introduced for comparison [11].

According to Fig 7, and, by considering HUT_f as criterion of performance, we can deduct that, under the heating regime, the double densely populated finned tube of walk of staircase (d=12) is classified in the first rank facing both tubes: mono-finned tube of high density of walk of staircase and doubles smooth finned tube without walk of staircase.

Figures 8 and 9 shows that:

- In the weak debits of the film until 60 g/s, the densely populated mono-finned tube of walk of staircase is more competitive, according to the criterion of HUT_f, than the tube doubles smooth fins without walk of staircase. It seems, in this range of debit, that the effect of high density of walk of staircase, as promoters of turbulence, is more important due to rise of the heat exchange area.
- For higher film debits until 150 g/s1, the double smooth finned tube without walk of staircase is more preferment than the densely populated mono-finned tube of walk of staircase, since their curves are reversed. It seems that for the high debits of the film, the effect of the splitting in two of the area of exchange is better than the unique effect of the densely populated walk staircase.
- For all debits of the film and during the three thermal regimes, the tube with double densely populated fins of walk of staircase (d=12), which associate at the same time, the advantages of the walk of staircase as promoters of turbulence and of the splitting in two of the surfaces is qualified as more competitive according to the criterion of comparison HUT_f since he shows lower values of HUT_f.in fact:
- In the low debits, values of HUT_f are weak, on average, of 14.3 %, in evaporating regime and of 12.21 %, in convective boiling regime in comparison with those of the densely populated mono-fin case.
- In the higher debits, values of HUT_f are lesser, on average, of 1245 %, in regime of evaporation and of 12.8 % , in regime of convective boiling in comparison with the double smooth finned tube without walk of staircase.
- The double densely populated finned tube of walk of staircase also exploits a wide range of debit until 220 g/s, for the heating regime, and 200 g/s for evaporating and convective boiling regimes. So, it is clearly possible to improve the industry production capacity using the

evaporators with the proposed new structure in their heat exchangers.

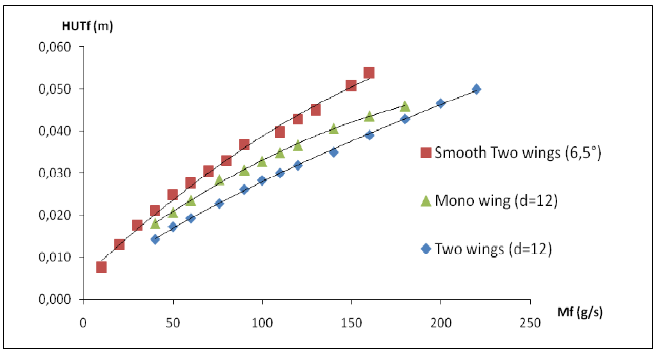

Fig. 7: HUT_f for different finned tubes in Heating regime

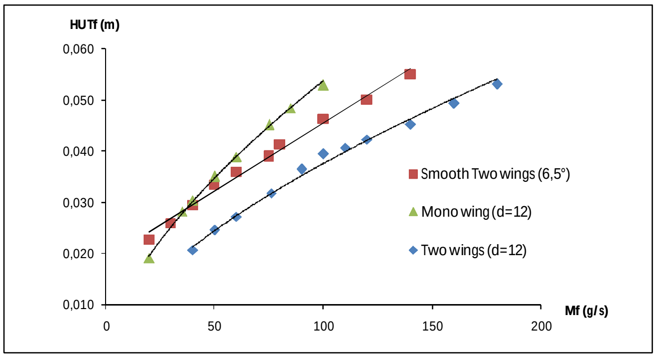

Fig. 8: HUT_f for different finned tubes in evaporating regime

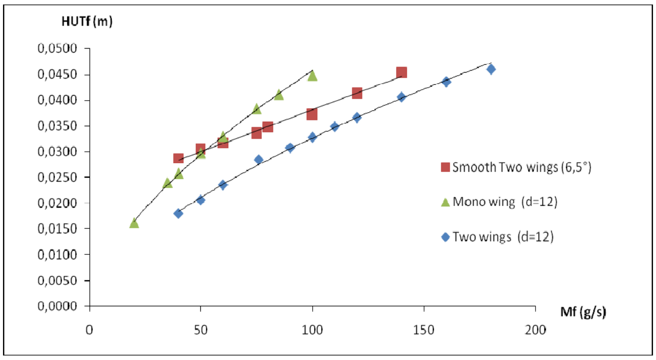

Fig. 9: HUT_f for different finned tubes in boiling regime

5. CONCLUSION

The high density of walk of staircase on a tube as promoter of turbulence improves the heat transfer and allows a better performance particularly at the weak debits, while the rise of the heat exchange area of smooth fins with high axial sloop seems to be efficient, particularly, in the higher debits. The regrouping of these favorable conditions and to achieve them, in a simple way, on unique tube, gave the densely populated double finned tube of walk of staircase. This new configuration allowed acquiring, on all range from weak to high debits of the film and during different thermal regimes a better thermal performance according to very low HUT_f coefficient, compared with those of two other tubes.

Nomenclature

A_f	area of the tube with fin wet by the film (m^2)
d	density of walk of staircase
E_p	thickness of the helical fin(mm)
F_a	factor of increase of area
H	height of the tube (m)
h_f	coefficient of partial heat transfer side film
HUT_f	($W/m^2°C$)
Q_{moy}	height of unit of partial heat transfer side film (m)
M_f	medium flux of heat (W)
n_p	mass flow rate of the falling film (g/s)
n_{pt}	number of plates
O	number of plates by turn
r_e , r_i, r_t	angle separating two successive walks (°)
T_{fe}, T_{fs}	radiusexternal, internal and of head of the bar
T_{pe}, T_{ps}	(mm)
T_{ce}, T_{cs}	temperatures of the film at the entrance and in the
Grecs	exit (°C)
θ_a	temperatures of the fin at the entrance and in the
β	exit (°C)
$\Delta T_{(p-f)ml}$	temperatures of the HTF at the entrance and in the
ΔT_{sat}	exit (°C)
	angle of axial slope of the helical fin (°)
	angle of area of the plate (°)
	means logarithmic difference of temperatures
	(°C)
	superheating defined by: (T_p-T_{sat}) (°C)

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