ASSESSMENT OF THE TWO PHASE HEAT TRANSFER COEFFICIENTS IN THE VAPORIZER TUBES BY SEVERAL MODELS

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Abstract. Flowing fluids undergo boiling in many of case in which we transfer heat to fluids moving tubes. When we use the terms boiler, steam generator, or evaporator we usually refer to equipment that involves heat transfer within tubes .the prediction of heat transfer coefficients in these systems is often essential.

The object of this research is aimed to the assessment of the heat transfer coefficient in the vaporizer tubes in saturated regime by several models.

Two mechanisms appear in this regime: the nucleate boiling and the convection boiling; these two mechanisms can coexist or one can be dominant. Every model gives the interaction between the two mechanisms and precise their variations according to the different thermohydraulics parameters.

The finalized trial program concerns the prevision of the heat transfer coefficients; and the evaluation of the nature of two phase flow in the vaporizer tubes.

The application on the vaporizer tubes of the dynamic boiler of the thermal power station Sonelgaz – Annaba, Algeria and the comparison between the models gave us a very important databank.

Keywords: two phase flow, saturation, heat transfer coefficient, convective boiling, nucleate boiling

1. Introduction

The transfer phenomena putting in play the evaporation; ebullition is very answered in many domains of the energy [1]. He is sometimes of an important capital in industrial problems. In particular, the knowledge of the heat transfer coefficients in nucleate boiling, who depends on crucial manner of microscopic characteristics, these characteristics are sometimes difficult to determine experimentally and the direct numeric simulation appears then like an alternative permitting to have access to this information. The main interest of this research is to study the models of two phase flow liquid/vapour in saturated regime in the vaporiser tubes, which constitute the surrounding wall of the dynamic boiler. This last participates in the electric energy production process; providing dry steam to drag the group turboalternateur.

2. Nucleate boiling in the vaporiser tubes

Consider again a tube heated uniformly over its length with a low heat flux and fed subcooled liquid at its base at such a rate that the liquid is totally evaporated over the length of the tube, figure 1 shows, in diagrammatic form. The various flow patterns encountered over the length of the tube, together with the corresponding heat transfer regions [2]. While the liquid is being heated up to the saturation temperature and the wall temperature remains below that necessary for nucleation, the process of heat transfer is single phase convective heat transfer to liquid phase (Region A) at some point along the tube, the condition site can occur. Initially vapour formation takes place in the presence of subcooled liquid (Region B) and this heat transfer mechanism is known as subcooled nucleate boiling. In this region the wall temperature remains essentially constant a few degrees above the saturation temperature.

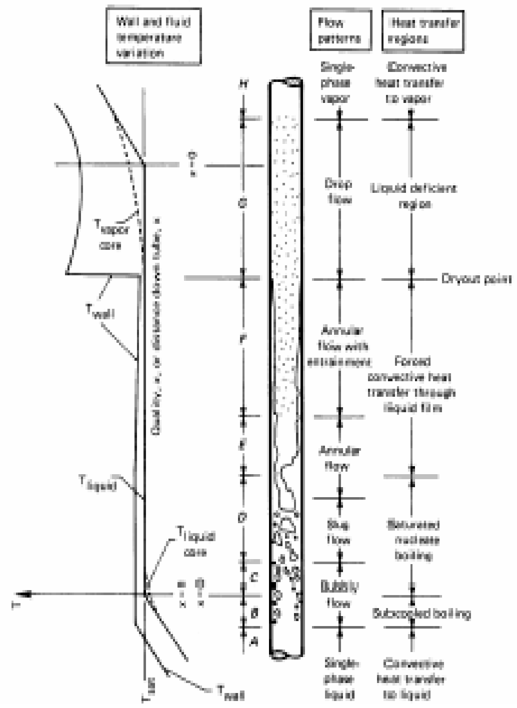

Figure 1. The development of a two phase flow in vertical tube with a uniform wall heat flux

But in the subsequent regimes of slug flow and annular flow (D, E, and F) the heat transfer mechanism changes substantially. Nucleation is increasingly suppressed, and vaporization takes place mainly at the free surface of the liquid film on the tube wall. Most efforts to model flow boiling differentiate between nucleate boiling–controlled heat transfer and convective boiling heat transfer. In those regimes where fully developed nucleate occurs (the later parts of C), the heat transfer coefficient is essentially unaffected by the mass flow rate and the flow quality. In convective boiling, vaporization occurs away from the wall, with a liquid –phase convection process dominating at the wall. In the annular regions E and F, heat is convected from the wall by liquid film and vaporization occurs at the interface of the film with the vapour in the core of the tube. Convective boiling can also dominate at low heat fluxes or high mass quality flow rates, where wall nucleate is again suppressed vaporization then mainly on entrained bubbles in the core of the tube. In convective boiling, the heat transfer coefficient is essentially independent of the heat flux, but it is strongly affected by the mass flow rate and quality. Building a model to capture these complicated and competing trends has presented a challenge to researchers for several decades [3, 4].

3. Study on the saturated regime

Every regime of heat transfer possesses its proper physical mechanism and the nucleate boiling is the most practical. This zone being desirable in the nuclear reactor, the dynamic boiler, in the cooling technical, etc. the improvement of the heat transfer in this case is essentially due to a local effect of microconvection induced by the bubbles, this one by the frequency of their birth, the increase of their volume and their departure of the wall, play the role of agitators destroying the situated thermal boundary layer to the contact of the wall. This layer presents the main resistance to the passage of the heat of the wall to the liquid.

In the regions (C & D) exhibited appreciably on the figure 1 the mechanism of heat transfer changes. The nucleate boiling is presented more and more, and the vaporization takes place mainly on the surface of the liquid film on the tube wall. The two mechanisms can coexist or one can be predominant. The total heat transfer coefficient h can be decomposed then in one term of nucleate boiling h_{nb}; and a term of convective boiling h_{cb}. Webb & Guptes give the classification for the different models according to the manner of which the interactions between mechanisms of heat transfer are take in account and will fix the part of every mechanism according to the different physical parameters:

- Intensification model: $h = N \cdot h_{cb}$;
- Asymptotic model of n order: $h^n = h_{cb}^n + h_{nb}^n$;
- Superposition model: $h = h_{cb} + h_{nb}$.

We give here a correlation for every model, as well as the analysis to propose by every author.

3.1 Intensification model “Shah correlation”

Shah proposed a method to calculate the heat transfer coefficients, from the analysis of about 800 experimental data coming from 18 independent sources [5]. The numbers are used:

- Convection number

$$Co = (1 - x/x)^{0.8} \cdot (\rho_g / \rho_f)^{0.5}; \quad (1)$$

- Boiling number

$$B_0 = \frac{q}{G \cdot i_{fg}}; \quad (2)$$

- Froude number

$$Fr_f = \frac{G^2}{\rho_f \cdot g \cdot D_h}; \quad (3)$$

- The local liquid-phase forced convection coefficient:

$$h_f = 0.023 \cdot \left[\frac{G \cdot D_h \cdot (1-x)}{\mu_f} \right]^{0.8} \cdot \mathrm{Pr}_f^{0.4} \cdot \frac{\lambda_f}{D_h}; \quad (4)$$

He considered two distinct mechanisms: nucleate boiling and convective boiling characterized respectively by the coefficients of heat transfer h_{nb} and h_{cb}. But, it only considers the more important of the two coefficients, the method is as a follows:

Calculate the dimensionless parameter N:

- for the vertical tubes, and for the horizontal tubes as $Fr_f > 0.4$

$$N = C_v; \quad (5)$$

- for horizontal tubes when $Fr_f < 0.4$:

$$N = 0.38 \cdot Fr_f^{-0.3} \cdot C_v. \quad (6)$$

Then for $N > 1.0$:

$$B_0 > 0.003 \quad \Rightarrow \quad h_{nb} / h_f = 2.30 \cdot B_0^{0.5}; \quad (7)$$

$$B_0 < 0.003 \quad \Rightarrow \quad h_{nb} / h_f = 1 + 46 \cdot B_0^{0.5}; \quad (8)$$

$$h_{cb} / h_f = 1.8 / N^{0.8}; \quad (9)$$

$$h = \max(h_{cb}, h_{nb})$$

For $0.1 < N < 1.0$ calculate the value h_{cb} from equation (9) and h_{nb} in the bubble suppression regime as:

$$\frac{h_{nb}}{h_f} = F \cdot B_0^{0.5} \cdot \exp\left(2.74 \cdot N^{-0.1}\right) \qquad (10)$$

and choose the larger value of h.

For $N \leq 0.1$ calculate h_{cb} from equation (9) and h_{nb} in the bubble suppression regime as:

$$\frac{h_{nb}}{h_f} = F \cdot B_0 \cdot \exp\left(2.47 \cdot N^{-0.15}\right) \qquad (11)$$

and choose the larger value of h.

The constant F is determined as follows:

$B_0 > 0.0011$ F = 14.7;
$B_0 < 0.0011$ F = 1.

3.2. Asymptotic model "Chen correlation"

He considered two mechanisms: nucleate boiling and convective boiling and that the contributions made by the two mechanisms are additive. The two phenomena superpose themselves. Chen propose the use a nucleate boiling suppression factor S and a convective boiling intensification factor F [6, 7].

$$h = h_{cb} + h_{nb} = F \cdot h_f + S \cdot h_{npb}; \qquad (12)$$

To determine h_{cb}, the author part from the relation of Dattus-Bœlter:

$$h_{cb} = 0.023 \cdot \mathrm{Re}_{TP}^{0.8} \cdot \mathrm{Pr}_{tP}^{0.4} \cdot \frac{\lambda_{TP}}{D_h}, \qquad (13)$$

λ_{TP} - the thermal conductivity, and Re_{TP}, Pr_{TP} - the numbers of Reynolds and Prandtl are the effectives values associated with the two-phase fluid.

$$F = \left[\frac{\mathrm{Re}_{TP}}{\mathrm{Re}_f}\right]^{0.8} = \left\{\frac{\mathrm{Re}_{TP}}{G \cdot (1-x) \cdot \frac{D_h}{\mu_f}}\right\}^{0.8}. \qquad (14)$$

The equation (13) can write itself then:

$$h_{cb} = F \cdot 0.023 \cdot \mathrm{Re}_f^{0.8} \cdot \mathrm{Pr}_f^{0.4} \cdot \frac{\lambda_f}{D_h}. \qquad (15)$$

Writing the equation for h_{npb} using the Forester and Zuber analysis with the effective values of the superheat and the vapour pressure difference is resulting:

$$h_{nb} = 0.00122 \cdot \left[\frac{\lambda_f^{0.79} \cdot C_{p,f}^{0.45} \cdot \rho_f^{0.49}}{\sigma^{0.5} \cdot \mu_f^{0.29} \cdot i_{fg}^{0.24} \cdot \rho_g^{0.24}}\right] \times \\ \times \Delta T_{sat}^{0.24} \cdot \Delta p_{sat}^{0.75} \cdot S \qquad (16)$$

He then defines a suppression factor, S, the ratio of the mean superheat ΔT_e, to the wall superheat ΔT_{sat}

$$S = \left(\Delta T_e / \Delta T_{sat}\right)^{0.24} \cdot \left(\Delta P_e / \Delta T_{sat}\right)^{0.75}; \qquad (17)$$

$$\Delta P_{sat} = i_{fg} \cdot \Delta T_{sat} / T_{sat} \cdot \left(1/\rho_g - 1/\rho_f\right). \qquad (18)$$

3.3. Superposition model "Kandlikar correlation"

He has instead pursued correlation built from dimensional analysis and physical reasoning and proceed with a dimensional analysis:

- we first note that the liquid and vapour phases may have different velocities. Thus,
- we avoid introducing a flow speed and instead rely on the superficial mass flux, G, through the tube.

$$G = m / A_{tube} \quad [Kg / m^2 \cdot s]; \qquad (19)$$

- used Re_{f0} to calculate h_{f0}

$$\mathrm{Re}_{f_0} = G \cdot D / \mu_f; \qquad (20)$$

$$h_{f_0} = 0.023 \cdot (1-x)^{0.8} \cdot \mathrm{Re}_{f_0}^{0.8} \cdot \mathrm{Pr}_f^{0.4} \cdot \left(\lambda_f / D_h\right)$$

for a heat transfer coefficient, in vertical tubes h_{TP} takes the following form

$$h_{TP} / h_{f_0} = fn\left(B_0, Co\right); \qquad (21)$$

The first dimensionless group is the boiling number

$$B_0 = q / G \cdot i_{fg}; \qquad (22)$$

The other group is the convection number

$$Co = \left(1 - x / x\right)^{0.8} \cdot \left(\rho_g / \rho_f\right)^{0.5}. \qquad (23)$$

When a convection number is large $Co \geq 0.65$, as for low quality, nucleate boiling dominates; in this range h_{TP}/h_{f0} increases with the increase of B_0 and is approximately independent of Co. When the convection number is smaller, $Co \leq 0.65$, as at high quality, the effect of the boiling number declines and h_{TP}/h_{f0} increase with the decreasing Co.

His method is to calculate of h/h_{f0} from each of the two following correlation and choose the large value

$$\left.\frac{h}{h_{f0}}\right|_{nbd} = (1-x)^{0.8} \times \\ \times \left[0.6683 \cdot Co^{-0.2} \cdot f_0 + 1058 \cdot B_0^{0.7} \cdot F_{PL}\right]; \qquad (24a)$$

$$\left.\frac{h}{h_{f_0}}\right|_{cbd} = (1-x)^{0.8} \times \\ \times \left[1.136 \cdot Co^{-0.9} \cdot f_0 + 667.2 \cdot B_0^{0.7} \cdot F_{PL}\right]; \qquad (24b)$$

`nbd` means «nucleate boiling dominant»
`cbd` means «convective boiling dominant»

In these equations, the factor of orientation; f_0 is placed to the unit for the vertical tubes and F_{PL} is a fluid-surface parameter, were value is indicated in the table 1.

Table 1. Fluid-surface parameter F_{PL} for refrigerants in copper or brass tubes

Fluid	F_{PL}	Fluid	F_{PL}
Water	1.00	R-113	1.30
R-11	1.30	R-114	1.24
R-12	1.50	R-124	1.90

Equation (24) can be applicable for the nucleate boiling saturated regimes (C through F) with a mass quality in the range $0 < x < 0.8$ [8, 9, 10].

4. Application on the tubes vaporizer of the thermal power station Sonelgaz – Annaba, Algeria

The experimental characteristics of the vertical tubes of the dynamic boiler of the thermal power station Sonalgaz – Annaba, were used to study the comparison of the different models. The conditions are given in the table 2, and the mass quality in the tubes is 0.2. One had varied x of 0.1 to 0.9 and the heat flux q to see the variation of the thermohydraulics parameters of every model.

Table 2. The characteristics tube of the dynamic boiler of the thermal power station Sonalgaz – Annaba, Algeria

Length of tube: 20 m	Diameter: D = 65 mm; mass quality: x = 0.2	Inlet temperature: 340 °C; Inlet pressure: 145 bar	Flux = (13; 15; 70; 100) kW/m²

4. Results

4.1. Shah correlation

The figures 2, 3, 4, 5 show the variation the Shah correlation parameters. The figure 2 show that the convection number decrease with the increasing of mass quality x, while the Martinnelli number obtain an increasing pace with the large value of mass quality x, figure 3, this number represents the drop pressure in the two phase flows. The figure 4 present the pace of nucleate boiling coefficient h_{nb} according to dimensionless number N, h_{nb} growing with the increasing of N. The figure 5 shows that h_{cb} takes large values for small numbers of N and the small values for large N. The table 3 gives the value of nucleate boiling coefficient h_{nb} and the convective boiling coefficient h_{cb} of Shah correlation. For the variation of mass quality of 0.1 to 0.9 and for the value of follow heat flux q = (13; 15; 70) kW/m²; according to the gotten results one remark that: h_{nb} decrease slightly with the increase of mass quality x; and increase with the increasing of heat flux q, although h_{cb} remains constant some either the done variation.

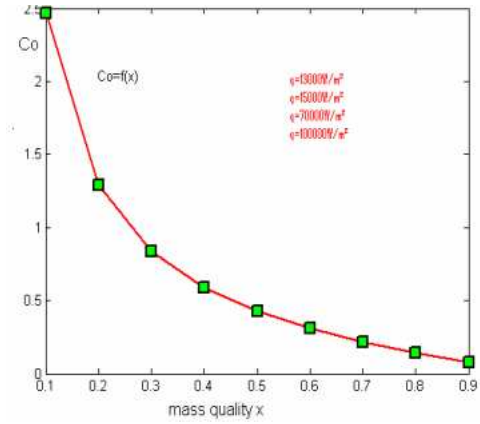

Figure 2. Co vs. mass quality x

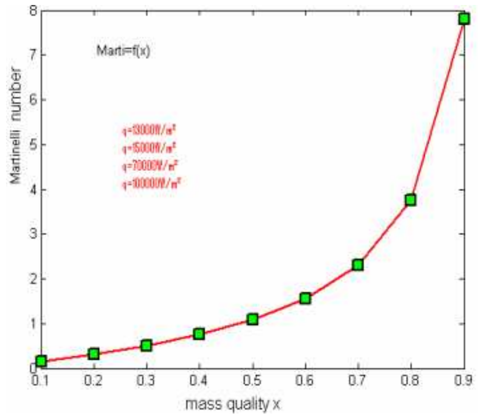

Figure 3. Martinnelli number vs. mass quality x

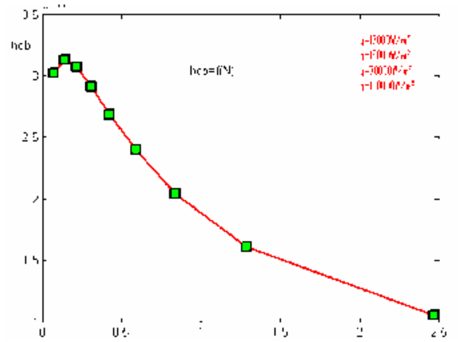

Figure 4. h_{nb} vs. dimensionless number N

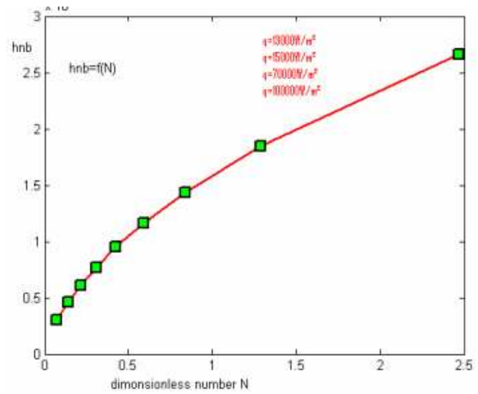

Figure 5. h_{cb} vs. dimensionless number N

Table 3. The value of the heat transfer coefficient of the Shah correlation

q = 13 kW/m² the Shah correlation									
x	x = 0.1	x = 0.2	x = 0.3	x = 0.4	x = 0.5	x = 0.6	x = 0.7	x = 0.8	x = 0.9
$h_{nb} \times 10^5$	2.1494	1.4877	1.1583	0.9360	0.7638	0.6192	0.4904	0.3695	0.2473
$h_{cb} \times 10^5$	1.0534	1.6109	2.0440	2.3973	2.6858	2.9124	3.0698	3.1336	3.0243
q = 15 kW/m² the Shah correlation									
$h_{nb} \times 10^5$	2.3088	1.5980	1.2442	1.0054	0.8205	0.6651	0.5268	0.3969	0.2656
$h_{cb} \times 10^5$	1.0534	1.6109	2.0440	2.3973	2.6858	2.9124	3.0698	3.1336	3.0243
q = 70 kW/m² the Shah correlation									
$h_{nb} \times 10^5$	8.0716	9.1575	9.6465	9.7901	9.6684	9.3030	8.6771	7.7214	6.2238
$h_{cb} \times 10^5$	1.0534	1.6109	2.0440	2.3973	2.6858	2.9124	3.0698	3.1336	3.0243
q = 100 kW/m² the Shah correlation									
$h_{nb} \times 10^6$	0.9647	1.0945	1.1530	1.1701	1.1556	1.1119	1.0371	0.9229	0.7439
$h_{cb} \times 10^5$	1.0534	1.6109	2.0440	2.3973	2.6858	2.9124	3.0698	3.1336	3.0243

4.2. Chen correlation

The figure 6, 7, 8, 9 shows the variation of the Chen correlation parameters. The figure 6 present the variation of the local two phase Reynolds number Re_{tp} according to liquid phase Reynolds number Re_f, Re_{tp} increase with the increasing of Re_f, as well as h_{cb} also increases with the increase of Re_f (see figure 7). The figure 8 shows that the coefficient h_{nb} increases with the increase of suppression factor S, itself factor decrease with the increase of Re_{tp} (figure 9).

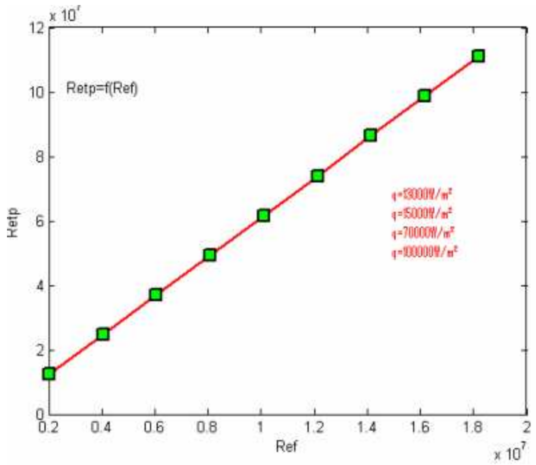

Figure 6. R_{etp} vs. R_{ef}

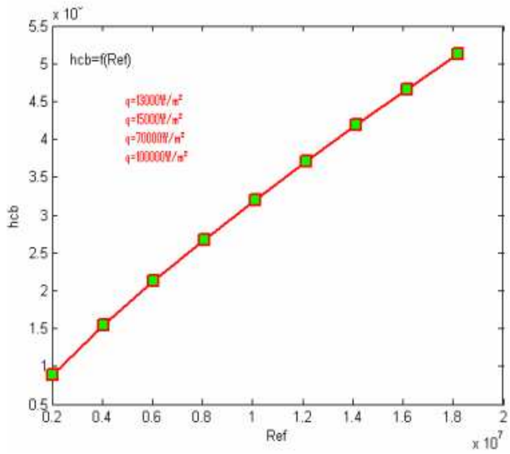

Figure 7. h_{cb} vs. $\mathrm{R_{ef}}$

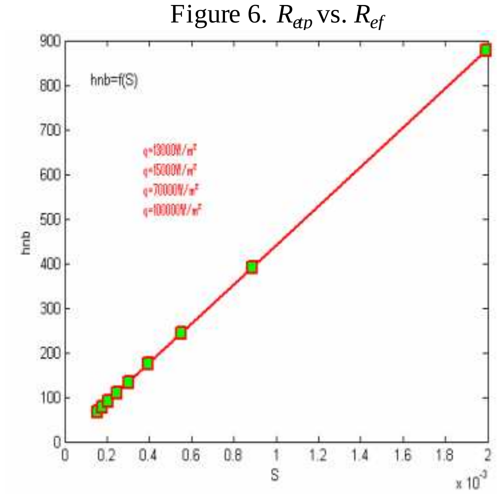

Figure 8. h_{nb} vs. S

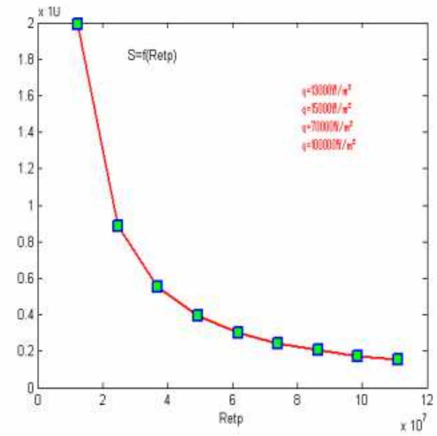

Figure 9. Suppression factor S

The table 4 present the value of nucleate boiling coefficient h_{nb} and the convective boiling coefficient h_{cb} of the Chen correlation for the variation of mass quality of 0.1 to 0.9 and for the value of following heat flux: q = (13; 15; 70; 100) kW/m²; according to the gotten results one remark that: h_{nb} takes the small values and constants some either the variation of q and x, and h_{cb} remains nearly constant and takes the large values.

Table 4. The value of the heat transfer coefficient of the Chen correlation

q = 13 kW/m² the Chen correlation									
x	x = 0.1	x = 0.2	x = 0.3	x = 0.4	x = 0.5	x = 0.6	x = 0.7	x = 0.8	x = 0.9
h_{nb}	67.3121	77.2559	90.317	108.1632	133.874	173.7968	243.3053	390.8705	878.5307
$h_{cb} \times 10^5$	5.1246	4.6639	4.1916	3.7056	3.2031	2.6800	2.1301	1.5422	0.8923
q = 15 kW/m² the Chen correlation									
h_{nb}	67.3121	77.2559	90.317	108.1632	133.874	173.7968	243.3053	390.8705	878.5307
$h_{cb} \times 10^5$	5.1239	4.6631	4.1907	3.7045	3.2017	2.6783	2.1277	1.5383	0.8835
q = 70 kW/m² the Chen correlation									
h_{nb}	67.3121	77.2559	90.317	108.1632	133.874	173.7968	243.3053	390.8705	878.5307
$h_{cb} \times 10^5$	5.1246	4.6639	4.1916	3.7056	3.2031	2.6800	2.1301	1.5422	0.8923
q = 100 kW/m² the Chen correlation									
$h_{nb} \times 10^6$	67.3121	77.2559	90.317	108.1632	133.874	173.7968	243.3053	390.8705	878.5307
$h_{cb} \times 10^5$	5.1246	4.6639	4.1916	3.7056	3.2031	2.6800	2.1301	1.5422	0.8923

4.3. Kandlikar correlation

The figure 10, 11, 12, 13, 14, 15 shows the variation of the Kandlikar correlation parameters. The figure 10 presents the variation of h_{nb} according to mass quality x for the aforementioned conditions; for x between 0.1 and 0.2 the coefficient h_{nb} increases quickly, this result justifies the speed birth of the bubbles in the regions (C and D) in the figure 1, beyond x = 0.2, h_{nb} decreases with the increase of x. Result to justify as bus in the regions superior of the D region, the nucleate boiling depart and the vaporization take place. The figure 11 shows that the coefficient h_{cb} takes small values for small mass quality x, and it increases with the increase of x; for small convection numbers the coefficient h_{cb} is large (figure 12) what justifies the good quality and the dominant of the convective boiling for (Co < 0.65); and nucleate boiling dominant for (Co > 0.65) as observe in figure 13 and the figure 14. The figure 15 presents that the convection number decrease with the increase of mass quality x. The table 5 shows the value of nucleate boiling coefficient h_{nb} and the coefficient of convective boiling h_{cb} of the Kandlikar correlation for the variation of mass quality x. Of 0.1 to 0.9 and for the value of follow heat flux q = (13; 15; 70; 100) kW/m², according to the gotten results one notices that: the nucleate boiling coefficient h_{nb} takes high value for small mass quality x and increase with the increase of q in this range "small value of mass quality x); with the increase of x (beyond x = 0.2) h_{nb} commence to decrease even though the heat flux increases. The convective boiling coefficient h_{cb} increase with the increase of x and with the increase of heat flux; these results confront with the physical reasoning and the existing literatures on an international scale.

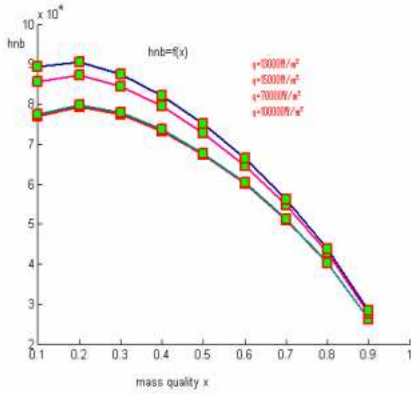

Figure 10. h_{nb} vs. Mass quality x

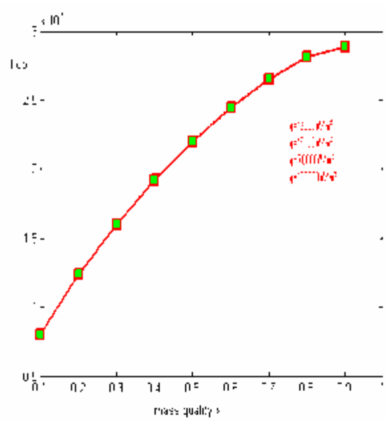
Figure 11. h_{cb} vs. mass quality x

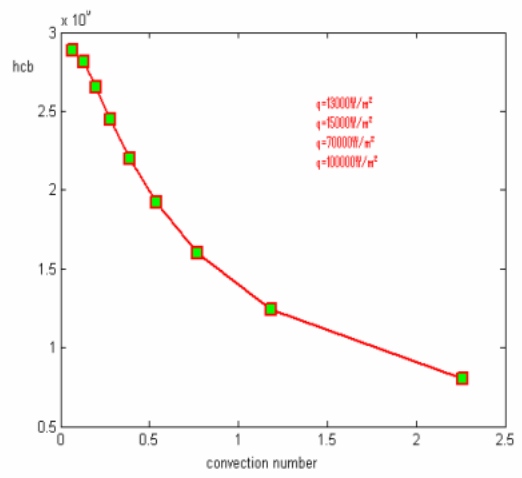

Figure 12. h_{cb} vs. Co

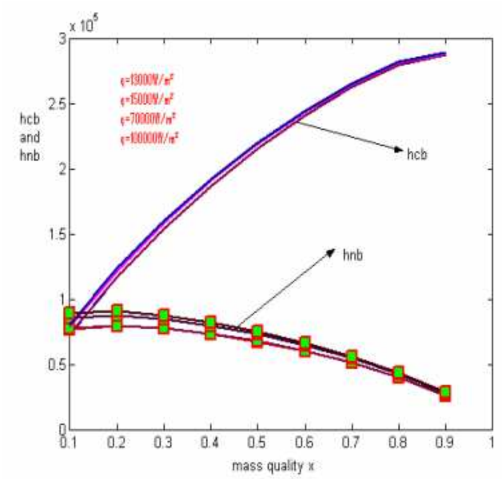

Figure 13. h_{cb} and h_{nb} vs. x

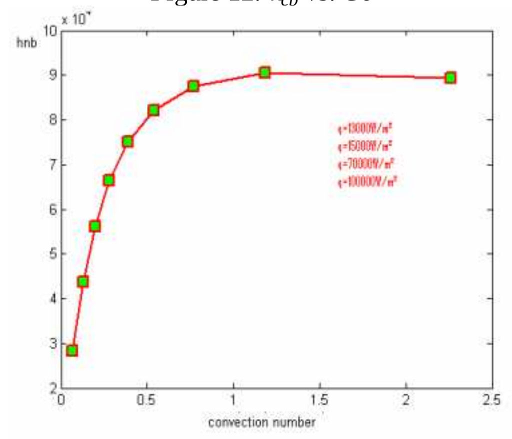

Figure 14. h_{nb} vs. Co

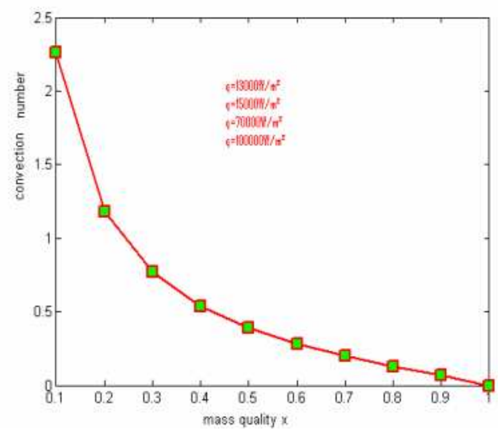

Figure 15. Co vs. mass quality x

Table 5. The value of the heat transfer coefficient of the Kandlikar correlation

q = 13 kW/m² the Kandlikar correlation									
x	x = 0.1	x = 0.2	x = 0.3	x = 0.4	x = 0.5	x = 0.6	x = 0.7	x = 0.8	x = 0.9
$h_{nb} \times 10^4$	7.7050	7.9351	7.7451	7.3277	6.7416	6.0039	5.1073	4.0147	2.6161
$h_{cb} \times 10^5$	0.7274	1.1694	1.5398	1.8644	2.1525	2.4067	2.6242	2.7934	2.8733
q = 15 kW/m² the Kandlikar correlation									
$h_{nb} \times 10^4$	7.7455	7.9720	7.7783	7.3570	6.7669	6.0251	5.1241	4.0268	2.6231
$h_{cb} \times 10^5$	0.7299	1.1717	1.5419	1.8662	2.1540	2.4080	2.6253	2.7941	2.8737
q = 70 kW/m² the Kandlikar correlation									
$h_{nb} \times 10^4$	8.5699	8.7222	8.4525	7.9530	7.2820	6.4560	5.4664	4.2743	2.7652
$h_{cb} \times 10^5$	0.7819	1.2190	1.5844	1.9038	2.1865	2.4352	2.6469	2.8098	2.8827
q = 100 kW/m² the Kandlikar correlation									
$h_{nb} \times 10^4$	8.9242	9.0447	8.7423	8.2092	7.5034	6.6412	5.6136	4.3807	2.8263
$h_{cb} \times 10^5$	0.8043	1.2393	1.6026	1.9199	2.2005	2.4469	2.6561	2.8165	2.8865

5. Conclusion

According to the results gotten by the comparison of several correlation in the two phase flow; one distinguishes that:

1. The two existing phenomena in the saturated regime "the nucleate boiling and the convective boiling" develop themselves in an inverse manner; the increase of one of the two generates the decrease of the other.
2. The Kandlikar correlation present the more logical results, because the coefficient of heat transfer reassemble the two numbers (boiling number and convection number); as it gives the nature flow regime in the tube. For (Co < 0.65)

high quality, and for (Co > 0.65) it is the low quality); as well as the coefficient of heat transfer increases with the increase of heat flux, itself that is just

3. the two coefficients (h_{nb} and h_{cb}) of the Kandlikar correlation includes the same dimensionless groups and to choose one of the two truths value of transfer coefficient h don't suppress the parameters of basis used in the comprehension of the phenomenon mechanisms.
4. The Chen correlation and the Shah correlation show that the heat flux is independent of heat transfer coefficient, although the studies and the experiences made since the antique show that the increase of heat flux provokes the increase of heat transfer coefficient.
5. To choose $h = \max(h_{nb}, h_{cb})$ in the correlation of Chen or Shah, made lose quite a lot of information and parameters used in the process of the beginning.

Nomenclatures

Co: convection number
C_v: the Shah correlation convection number
p_c: specific heat, J/kg K
D: diameter, m, f_0 orientation factor
F: intensification facture of the convective
Fr_f: Froude number
g: gravitational acceleration, m/s²
G: specific mass, Kg/m²s
h: heat transfer coefficient,W/m² °C
h_f: heat transfer coefficient liquid phase
M: molecular weight, kg/kmol
q: heat flux, W/m²
i: latent heat, J/Kg
S: suppression facture of the nucleate boiling
Nu: Nusselt number
P: pressure, bar
Pr: Prandtl number
Re: Reynolds number
T: temperature, °C
ΔT: temperature difference, °C
Δp: pressure difference, bar

Greek symbols

ρ: density, kg/m^3
λ: thermal conductivity, W/m^2·°C
μ: dynamic viscosity, N·s/m^2
σ: surface tension, N/m
Ψ: Intensification facture
χ: Martinnelli number

$$\chi = [1 - x/x]^{0.9} \cdot (\rho_g/\rho_f)^{0.5} \cdot (\mu_g/\mu_f)^{0.5}$$

Indices

cb: convective boiling
f: fluid
g: gas
fg: fluid/gas
nb: nucleate boiling
TP: two phase (liquid phase/vapor phase)

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