EXPERIMENTAL STUDY ON FORCED CONVECTIVE BOILING OF AMMONIA WATER MIXTURES IN A VERTICAL SMOOTH TUBE

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ABSTRACT

As part of our work on the absorption solar refrigeration cycle and with the object to optimize the efficiency of flat plat collector in generation phase, an experimental study has been conducted on the boiling heat transfer of NH_3-H_2O mixtures flowing inside a 6 mm inner diameter vertical smooth tube. The used experimental device is presented. Using a water-heated double pipe type generator, the local heat transfer coefficients are measured inside the inner tube for a range of heat flux (8.211–18.521 kW/m^2), mass flux (707–2688 kg/m^2.s), mass flow rate (0.02 –0.076 kg/s), equilibrium mass quality (0–0.6) and ammonia mass concentration (25% - 61%). Three theoretical models are used to predict the boiling heat transfer coefficients. Experimental data were compared with the available correlations. The obtained results confirm the good performance of Bennett-Chen's correlation in predicting boiling heat transfer coefficient of ammonia water mixtures. This correlation is able to predict the boiling heat transfer data within an accuracy of ± 15 %.

Keywords: *Two phase flow, mixtures, convective boiling, heat transfer, ammonia-water*

الملخص

في إطـار بحوثنا حول دورات التبريد الشمسية و بغية تحقيق كفاءة أفضل للاقط شمسي مسطح ذو أنابيب متوازية، تم إنجاز دراسة تجريبية حول انتقال الحرارة أثناء غليان محاليل من الأمونيا و الماء داخل أنبوب عمودي ذو قطر داخلي يبلغ 6 مم. الوحدة التجريبية المستعملة تم وصفهـا. أستعمل أنبوب مزدوج كمولد للبخار، حيث يتم تسخين المحلول المنساب عبر الأنبوب الداخلي باستخدام الماء الساخن. وقع تحديد معامل انتقال الحرارة عمليا داخل الأنبوب بالنسبة للمجـالات التاليـة للمتغيـرات التجريبيـة: الفيـض الحـراري *(8.211 - 18.521 kW/m^2)*، كثافة سريان الكتلة *(700 - 2688 kg/m^2.s)*، معدل سريان الكتلة للمحلول *(0.02 - 0.076 kg/s)*، نسبة البخار *(0 - 0.6)*، و نسبة التركيز *(10 % - 61%)*. من ناحية أخرى تم اعتماد ثلاثة نماذج نظريه لتحديد معامل انتقال الحرارة. النتائج العملية أثبتت صلاحية نموذج بنيت و تشان لتحديد معامل انتقال الحرارة أثناء غليان محلول الأمونيا و المـاء. هذا النموذج يمكن من تحديد قيمة معامل انتقال الحرارة بانحراف أقصاه ± 15 % مقارنة بالنتائج العملية.

NOMENCLATURE

A: tube area	m^2
Bo: boiling number	
d: tube inside diameter	m
Cp: specific heat of fluid	$J.kg^{-1}.K^{-1}$
G: mass flux	$kg.s^{-1}.m^{-2}$
g: acceleration of gravity	$m.s^{-2}$
h: heat transfer coefficient	$W.m^{-2}.K^{-1}$
h_m: mass transfer coefficient	$m.s^{-1}$
Lv: latent heat of vaporisation	$J.kg^{-1}$
M: molecular weight	$kg.mole^{-1}$
$\dot{m}$: mass flow rate	$kg.s^{-1}$
P: pressure	Pa
Pr: Prandt number	
pr: reduced pressure	
q: heat flux	$W.m^{-2}$
Ra: surface roughness	$10^{-6}\ m$
Re: Reynolds number	
Sc: Schmidt number	
T: temperature	C, K
X: liquid mass fraction	kg_{AmL}/kg_{mel}
X_M: liquide mole fraction	
x: vapor quality	
Y: vapor mass fraction	kg_{Amg}/kg_{mel}
z: distance along tube	m

Greek symbols

δ_m: liquid mass diffusivity	$m^2.s^{-1}$
δ_{th}: thermal diffusivity	$m^2.s^{-1}$
Δ: variation	
λ: thermal conductivity	$W.m^{-1}.K^{-1}$
χ_{tt}: Lockhart-Martinelli parameter	
μ: dynamic viscosity	$kg.m^{-1}.s^{-1}$
ρ: density	$kg.m^{-3}$
η: thermal losses rate	
σ : surface tension	$N.m^{-1}$

Subscript

Am: ammonia	nb: nucleate boiling
c: critical state	npb: nucl. pool boiling
cv: convective	sat: saturation condition
g: gas (vapor)	SC: subcooled
L: liquid	tp: two-phase
M: molecular	W: water
mix: mixture	w: wall

1. INTRODUCTION

Ammonia and ammonia-water mixtures had been widely used in refrigeration and A/C cycles. However, the high pressure, the toxicity and the aggressiveness of ammonia on the copper alloy have reduced its use in refrigeration and A/C plants. The Chlorofluorocarbon refrigerants (CFC) have taken the place of ammonia. However, given the problems of global warming and potential ozone depletion that the use of these fluids provokes, the ammonia appears again, in our days, as one of the alternatives.

Exhaustive research on forced convective boiling of ammonia water mixtures has not been conducted. In this paper, we have optimized the efficiency of a solar flat plate collector of an absorption solar system using NH_3-H_2O as working fluid. An experimental study has been performed on the forced convective boiling of ammonia water mixtures inside a vertical tube.

In this paper also a review of previous works is given with mainly heat transfer correlations. The experimental device is presented. Finally a comparison of experimental results with the available correlations is presented.

2. PREVIOUS RESEARCHS ON BINARY MIXTURES

Several research works have been done on the forced convective boiling on refrigerant binary mixtures. The first studies in this field have been conducted by [Bennett-Chen, 1980] on aqueous ethylene/glycol solutions. A correlation has been developed to predict the heat transfer coefficient, where the effects of diffusive resistance on nucleate boiling and on two phase forced convection, were taken into account separately. [Mishra et al., 1981] have performed an experimental study on forced convective boiling of the CFC refrigerant mixtures R22/R12 inside horizontal tubes. The experimental results showed a lower heat transfer coefficient of the binary mixture with respect to the simple linear interpolation between the values corresponding to the two pure components. [Hihara and Saito, 1990] have performed experiments on the CFC refrigerant mixtures R22/R114 in a horizontal tube. The experimental results have confirmed that heat transfer coefficients for mixtures are much lower than those for pure R22 and R114. A study on forced convective boiling inside horizontal tube was investigated experimentally by [Murata et al., 1993], using mixtures of the CFC refrigerants R123/R134a. The heat transfer coefficient for the mixture was found to be lower than that for an equivalent pure refrigerant with the same physical properties. The reduction in heat transfer coefficient for the mixture, is attributed to the mixture effect on nucleate boiling and to the heat transfer resistance in the vapor phase. An experimental study on binary mixtures of the CFC refrigerants R12/R114 in up-flow forced convective boiling has conducted by [Celata et al., 1993]. The degradation of heat transfer coefficients with the mixture composition appears to be depending on both saturation pressure and mass flux. Obtained results confirm the good performance of the Bennett-Chen correlation in predicting heat transfer coefficient in the case of refrigerant mixtures.

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3. CORRELATIONS

3.1. Pure Fluids

Two methods are used to express the heat transfer coefficient in forced convective boiling (h_{tp}). The first method is derived from the well-known Chen's correlation and can be expressed as the arithmetic summation of two-phase convection contribution (h_{cv}) and the nucleate boiling contribution (h_{nb}).

$$h_{tp} = h_{cv} + h_{nb} \tag{1}$$

$$h_{cv} = h_l F(1/\chi_{tt}) \tag{2}$$

$$h_{nb} = h_{npb} S \tag{3}$$

Where h_l is the single-phase heat transfer coefficient if the pure liquid was flowing through the tube.

$$h_l = 0.023 \frac{\lambda_l}{d_i} Re_l^{0.8} Pr_l^{0.4} \tag{4}$$

Re_l is the Reynolds number in liquid phase expressed as:

$$Re_l = G d_i (1 - x)/\mu_l \tag{5}$$

Where d, G, x and μ are the tube diameter, the mass flux, the vapor quality and the dynamic viscosity respectively.

The factor F represents the acceleration effect of liquid due to vapor shear stress. The pool boiling heat transfer coefficient (h_{npb}), is calculated for the same value of wall super-heat as for forced convective boiling. The factor S represents the suppression of nucleate boiling due to liquid flow.

The second method for the heat transfer calculation is based on the relationship:

$$h_{tp} = h_l f(\chi_{tt}, Bo) \tag{6}$$

Where χ_{tt} and Bo are respectively, the Lockhart-Martinelli parameter and the boiling number expressed by:

$$1/\chi_{tt} = (\rho_l/\rho_g)^{0.5} (\mu_g/\mu_l)^{0.1} \left(\frac{x}{1-x}\right)^{0.9} \tag{7}$$

where $Bo = q/(G L_v)$

ρ is the density and L_v the latent heat of vaporization.

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Several correlations have been proposed to calculate F, S and h_{npb}. In the following we present the selected correlations used in this study.

[Chen, 1966] have proposed the following correlations:

$$F = 1 \text{ for } 1/\chi_{tt} \le 0.1 \quad \text{and} \quad F = 2.35\left(1/\chi_{tt} + 0.213\right)^{0.736} \text{ for } 1/\chi_{tt} > 0.1 \tag{8}$$

$$S = \left(1 + 0.12\,\mathrm{Re}_{tp}^{1.14}\right)^{-1} \tag{9}$$

$$h_{nb} = 0.00122\left(\frac{\lambda_l^{0.79}\,Cp_l^{0.45}\,\rho_l^{0.49}}{\sigma^{0.5}\,\mu_l^{0.29}\,Lv^{0.24}\,\rho_g^{0.24}}\right)\Delta T_{sat}^{0.24}\,\Delta P_{sat}^{0.75} \tag{10}$$

where Re_{tp} is the two-phase Reynolds number expressed by:

$$\mathrm{Re}_{tp} = F^{1.25}\,10^{-4}\,G(1-x)d_i/\mu_l \tag{11}$$

σ is the surface tension

$$\Delta T_{sat} = T_w - T_{sat} \quad \text{and} \quad \Delta P_{sat} = P_{sat}(T_w) - P_{sat}(T_{sat})$$

[Jung et al., 1991] have proposed the following correlations to calculate, F, S and h_{npb}.

$$F = 2.37\left(0.29 + 1/\chi_{tt}\right)^{0.85} \tag{12}$$

$$S = 4048\chi_{tt}^{1.22}Bo^{1.13} \text{ for } \chi_{tt} < 1 \text{ and } S = 2 - 0.1\chi_{tt}^{-0.28}Bo^{-0.33} \text{ for } 1 < \chi_{tt} \le 5 \tag{13}$$

$$h_{npb} = 207\frac{\lambda_l}{d_b}\left(\frac{q d_b}{\lambda_l T_{sat}}\right)^{0.745}\left(\frac{\rho_g}{\rho_l}\right)^{0.581} Pr_l^{0.533} \tag{14}$$

where q is the heat flux and d_b the bubble diameter given by:

$$d_b = 0.146\beta\left[\frac{2\sigma}{g(\rho_l - \rho_g)}\right]^{0.5} \text{ with the angle } \beta = 35°$$

3.2. Mixtures

[Bennett and Chen, 1980] have proposed an extension of equation (1) to binary mixtures. The h_{cv} was calculated according to equation (2) and using F_{mix} factor, which takes into account the effective mass transfer on the thermal driving force. By the same method, the coefficient

h_{npb} was calculated using an expression proposed by [Forster and Zuber, 1955] for pool boiling taking into account the greater thermal gradient in the vapor generating zone near the wall due to the forced convection. A suppression factor S_{mix} was defined as a function of the two-phase Reynolds number. The final Bennett-Chen correlation is expressed as:

$$h_{tp} = h_{cvmix} + h_{nbmix} \tag{15}$$

where $h_{cvmix} = h_l F_{mix}$ and $h_{nbmix} = h_{npb} S_{mix}$

$$F_{mix} = F f(Pr_l)\left(\Delta T/\Delta T_{sat}\right)_{nb} \tag{16}$$

$$f(Pr_l) = \left[(Pr_l + 1)/2\right]^{0.444}$$

$$\left(\frac{\Delta T}{\Delta T_{sat}}\right)_{nb} = 1 - \frac{(1-Y)q}{\rho_l L v h_m \Delta T_{sat}} \left.\frac{dT_{sat}}{dX}\right|_{P_{bulk}}$$

h_m is the mass transfer coefficient given by:

$$h_m = 0.023 \frac{\delta_m}{d_i} Re_{tp}^{0.8} Sc^{0.4} \tag{17}$$

where Sc is the Shmidt number expressed as: $Sc = \mu/(\rho.\delta_m)$

$$S_{mix} = \frac{S}{1 - \frac{Cp_l (Y - X)}{Lv} \frac{dT_{sat}}{dX} \left(\delta_{th}/\delta_m\right)^{0.5}} \tag{18}$$

δ_{th} and δ_m are the thermal and the mass diffusivity.

[Mishra et al., 1981] have correlated their experimental data, obtained using R12/R22 mixtures, by:

$$h_{tp} = h_l E\left(1/\chi_{tt}\right)^m Bo^n \tag{19}$$

where

(a) $\left.\begin{matrix} R12 : 23 - 27\% \\ R22 : 77 - 73\% \end{matrix}\right\} \Rightarrow$ E=5.64, m=0.23, n=0.05;

(b) $\left.\begin{matrix} R12 : 41 - 48\% \\ R22 : 59 - 52\% \end{matrix}\right\} \Rightarrow$ E=21.75, m=0.29, n=0.23.

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4. EXPERIMENTAL APPARATUS

The experimental loop is represented schematically in Fig.1. It mainly consists of a feed reservoir FR, of capacity of 50 liters, a boiler BL, a vapor generator G, a rectifier REC, an absorber ABS and a chilling unit CHL.

Ammonia-water mixture is introduced in the reservoir FR. A piston pump with variable speed drive PP, sends this mixture towards the adjustable power electrical pre-heater PH allowing to define the value of liquid sub-cooling. Afterward the mixture is sent towards the vapor generator G constituted by two stainless steel coaxial tubes (type 304) with a heated length of 1 m and the inside and outside diameters of 6 and 9 mm respectively. Ammonia-water mixture flows inside the inner tube and the heating water flows in the outer annulus. The inner and outer diameters of external tube are 28 and 32 mm respectively. The heating water temperature is controlled by a thermostat, which is connected to the boiler BL. At the generator outlet, the mixture is introduced in the phase separator PHS. Then the generated vapor is cleansed in the rectifier REC. The pure vapor stemming from the rectifier is condensed in CD and after that stored in the reservoir SRG. As for the poor solution, is cooled in the heat exchanger HEX and then stored in the reservoir SRL. The absorption phase is made later. Chilled water (CHL) is sent towards the condenser, the heat exchanger and the absorber by a centrifugal pump CP. All the elements in contact with the ammonia-water mixture are made from stainless steel. For the purpose of reducing the thermal losses towards surrounding, the generator elements are insolated by a wood glass layer of 5 cm of thickness.

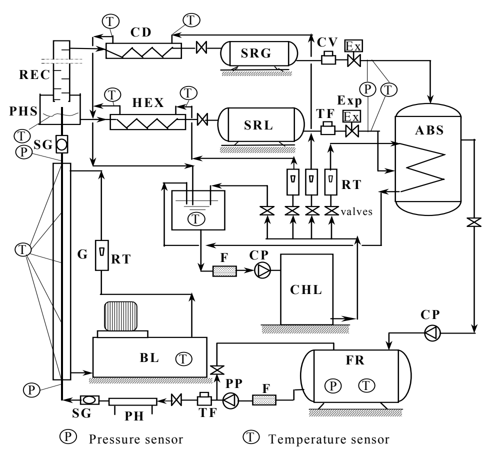

Fig. 1: Schematic of the experimental loop

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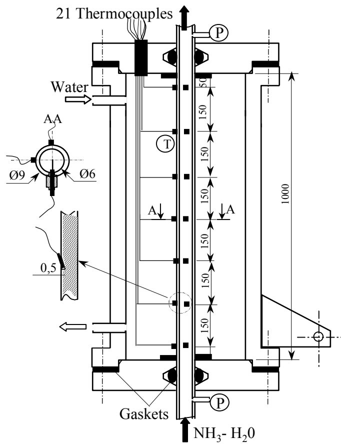

Fig. 2: The schematic of the generator tube

The test channel is shown in Fig. 2. The inlet and the outlet pressures are measured in (P) with two absolute pressure transducers type SEDEME and provided with integrated output regulators. The temperatures are measured with 0.5 mm K type insulated thermocouples. The temperature of the outside wall is measured at seven locations (T) along the tube length, with fifteen thermocouples oriented to measure the temperature at two sides of the tube perimeter as shown in Fig. 2. Seven thermocouples are used to measure fluid bulk temperatures. Two turbine flow meters TF are used to measure the volumetric flow rate of the ammonia-water mixture and the poor solution. Generated vapor flow rate is measured, at the condenser outlet, with the help of a volumetric technique provided by a precise stopwatch. Water volumetric flow rates in the various circuits are measured by rotameters RT. The errors on experimental parameters are indicated in Table (1).

All measurements were recorded with a Hewlett-Packard data acquisition/control unit connected to a micro-computer allowing to store all of the sensor outputs after conversion to engineering units.

Table (1): Errors on experimental parameters

Experimental parameters	Errors
Temperature	0.1 %
Pressure	0.2 %
Mixture flow rate	1.5 %
NH_3 vapor flow rate	2 %
Water flow rate	3 %

Table (2): Range of experimental parameters

Experimental parameters		Variation ranges
Heat flux	q kWm^{-2}	8.211 - 14.781 - 18.521
Mass flux	G $kgm^{-2}s^{-1}$	707 - 1590 - 2688
Pressure	P 10^5Pa	1.5 → 20
Boiling temper.	T °C	70 → 90
Sub-cooling	ΔT_{SC} °C	40
Mixture flow rate	$\dot{m}$ kg/s	0.02 – 0.045 – 0.076
Mass fraction	X %	10 – 25 – 42 – 55 - 61

5. EXPERIMENTAL RESULTS

5.1. Evaluation Of Thermal Losses

The thermal losses on the generator tube have been evaluated by proceeding to a series of measurements in single liquid phase. The thermal losses along the tube are defined as the relative error calculated by considering in one hand, the heat flux q received by the mixture inside the generator tube and in other hand, the heat flux q_{hw} supplied by the heating water as follows:

$$\eta = \frac{q_{hw} - q}{q_{hw}} \tag{20}$$

$$q = \frac{\dot{m}_{mix}.Cp_{mix}.(T_{omix} - T_{inmix})}{\pi.d_i.z} \tag{21}$$

$$q_{hw} = \frac{\dot{m}_{hw}.Cp_{hw}.(T_{ohw} - T_{inhw})}{\pi.d_i.z} \tag{22}$$

where: T_{inmix}, T_{omix}: The inlet and the outlet temperature of the mixture respectively,
T_{inhw}, T_{ohw}: The inlet and the outlet temperature of heating water respectively.

For a mixture flow rate varying from 0.02 to 0.06 kg/s and a heating water flow rate varying from 0.027 to 0.08 kg/s the thermal losses on the generator tube are lower than 8 %. The experimental parameter ranges are indicated in the Table (2).

5.2. Measurements On Ammonia-Water Mixtures

The useful heat flux in two phase-flow is given by:

$$q = \frac{\dot{m}_{mix}}{\pi d_i z}\left[Cp_{mix}(T_{sat} - T_{inmix}) + xLv\right] \tag{23}$$

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Considering the flow rate measurement errors and the calculation errors of T_{sat} and L_v, the accuracy of the heat flux q was evaluated within ± 5 % of error.

The boiling heat transfer coefficient h_{tp} is given by:

$$h_{tp} = q/(T_w - T_{sat}) \tag{24}$$

The tube inside wall temperature T_w, is calculated according to the value of its external wall temperature by using Fourrier's law related to the thermal conduction. Considering the precision of ±5 % on the heat flux q and the errors on T_w and T_{sat}, the error on the heat transfer coefficient h_{mix}, was evaluated within ± 7 %.

The vapor quality x_z in any tube level z is calculated by:

$$x_z = \pi d_i (z - z_{SC}) q/(AGL_v) \tag{25}$$

where z_{SC} is the sub-cooled liquid length given by:

$$z_{SC} = GACp_{mix}(T_{sat} - T_{in})/(\pi d_i q) \tag{26}$$

A test matrix was defined for which we have chosen three experience series related to three different values of heat and mass fluxes. For each measurement range, the ammonia mass fractions are 10, 25, 42, 55 and 61 %. For each mixture the boiling temperature vary between 70 and 90 °C except for a mass fraction of 61 % the maximum boiling temperature was taken equal to 80 °C. In order to avoid the vaporization downstream the generator, the mixture inlet temperature was taken as 40 °C.

In Fig. 3, the vapor quality x is plotted as a function of the length along the tube, for various heat and mass flux; x have a linear increase with z and its value depends on the ammonia mass concentration X_{NH3}. For the all performed tests the vapor quality is lower than 0.6.

According to studies performed on the flow patterns in small-diameter tubes [Collier, 1981 and Carey, 1992], the annular flow generally did not start until qualities of 0.6 to 0.8. Consequently, we assume that the two-phase flow is dominated by two regions. The first is the sub-cooled boiling region, which represents the end of single-phase liquid flow and the onset of two-phase flow. The second is the saturated boiling region for which the liquid reaches its saturation temperature with progressive forming of vapor bubbles. The annular flow appears at the generator outlet, only for high values of heat and mass fluxes.

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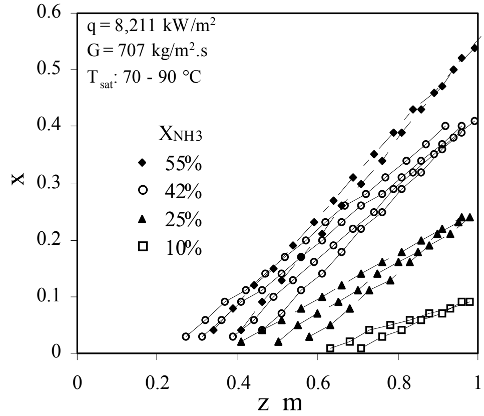

Fig. 3: Variation of the vapor quality vs the tube length

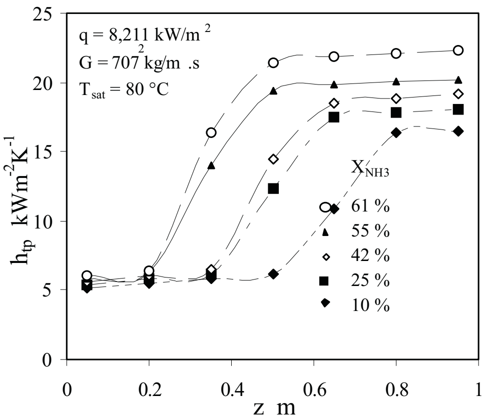

Fig. 4: Heat transfer coefficient as a function of the tube length

The heat transfer coefficient is plotted in Fig. 4 according to the length along the tube, for various ammonia mass fractions. The onset of sub-cooled boiling is marked by a fast increase of heat transfer coefficient h_{tp}. The length of sub-cooled liquid region z_{SC} is conversely proportional in the ammonia mass fraction, which does not influence on the heat transfer coefficient. In the two-phase region the heat transfer coefficient is almost constant.

The heat and mass flux influence on the heat transfer coefficient is shown in Fig. 5; the values of h_{tp} are even greater when q and G are improved.

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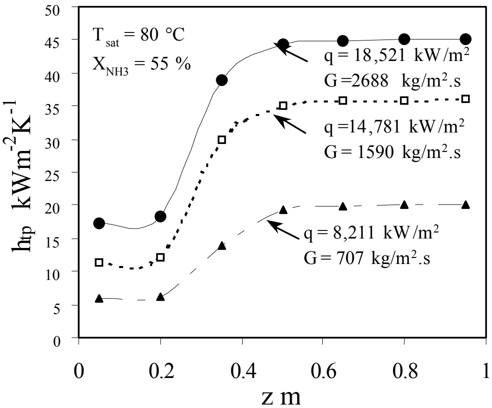

Fig. 5: Influence of the heat and mass fluxes on the heat transfer coefficient

6. DATA ANALYSIS

6.1. Calculation Procedure

Three models are used to predict the heat transfer coefficient. The first two models are both based on the Bennett-Chen's method defined by equation (15). Different correlations are used to calculate the nucleate pool boiling coefficient h_{npb}, the convective boiling factor F and the suppression factor S as follow:

Bennett-Chen: F, S and h_{npb} are calculated by eq. (8), (9) and (10) respectively, (**model I**).

Jung et al.: F, S and h_{npb} are calculated by eq. (12), (13) and (14) respectively. This model is called Jung-Bennett-Chen (**model II**),

The third model is based on the [Mishra et al. 1980] method; two correlations are used according to the values of E, m and n in the equation (19) as follows:

E = 5.64 ; m = 0.23 et n = 0.05. This model is called Mishra 1 (**moded III-1**),

E = 21.75 ; m = 0.29 et n = 0.23. This model is called Mishra 2 (**moded III-2**).

On the other hand, in order to determine the heat transfer coefficient variations along the generator tube, the wall superheat ΔT_{sat} along the tube has been calculated using correlations reported by [Collier, 1981].

The physical properties of ammonia-water mixtures are defined for the saturation temperature using correlations which are experimental validated by various research works [Ashrae, 1989], [Touloukian et al., 1970], [Reid et al., 1977], [Perry and Green, 1984] and [Jain and Gabel, 1979].

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The heat transfer coefficient h_{tp} is obtained by using the following procedure:

1- For a given T_{sat}, q, G and X_{NH3}, calculate z_{SC} from eq. (26).

2- From z_{SC} and according to a chosen step (5 cm), calculate x from eq. (25).

3- Calculate χ_{tt} and from eq. (7).

4- Calculate h_l from eq. (4).

5- Calculate F and S according to the models I and II; then calculate F_{mix} and S_{mix} from eq. (16) and (18) respectively.

6- Calculate h_{npb} for the models I and II from eq. (10) and (14) respectively.

7- Calculate h_{tp} from eq. (15) for the models I, and II; and eq. (19) for the models III-1 and III-2.

A software elaborate in Turbo-Pascal language allows to performed the previously calculus into all the details.

6.2. Discussion

The evolution of the boiling heat transfer coefficient h_{tp} according to the vapor quality x is shown in Fig. 6a and 6b. For an ammoniac mass fraction of 25 %, the model III-1 of Mishra et al. allows to predict the heat transfer coefficient h_{tp} with an error of 6 %; contrary to the model III-2, which shows a great error (Fig. 6a).

Although the models I and II showed an error less than 25 % in predicting the heat transfer coefficient, the obtained values of h_{tp} have a linear increasing evolution versus the quality x, while the experimental values of h_{tp} are almost constants for x more than 0.1. These remarks are also observed for the other values of q and G.

For an ammonia mass fraction of 55 % the models I and II present the same evolution shape as that observed first (for X_{NH3} = 25 %) but with more divergence with regard to the experimental results, especially for x more than 0.3 as shown in Fig. 6b. Model III-1 presents a good result for the prediction of heat transfer coefficient. An error of ± 10 % is obtained by this model.

For greater values of q and G, and for the same ammonia mass fraction (55 %), the models I and II present more divergences as shown in Fig. 6c. Also the values of the heat transfer coefficient h_{tp}, are sharply greater.

For a vapor quality more than 0.25, a saturated nucleate boiling zone develops gradually along the tube. In this zone the values of the heat transfer coefficient h_{tp} depends essentially on the dominant contribution of nucleate boiling, characterized by the coefficient h_{ncmix}. The contribution of the forced convective boiling, characterized by the coefficient h_{cvmix} is consequently, less important. It seems that [Chen, 1966] and [Jung et al., 1991], over predict the coefficient h_{cvmix} in their correlations. In fact the correlations related to the calculation of the convective boiling factor F are modified in the aim to decrease the contribution of the forced convective boiling.

The factor F depends on the Lockhart-Martinelli parameter $1/\chi_{tt}$ and, as a result, on the vapor quality x. For the models I and II, F is calculated from the equations (6) and (11) respectively. These can be expressed as follows:

$$F = r\left(1/\chi_{tt} + s\right)^{t} \tag{27}$$

where r, s and t are defined in equations (8) and (12).

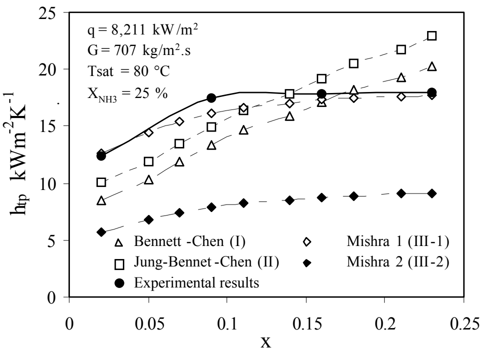

Fig. 6a

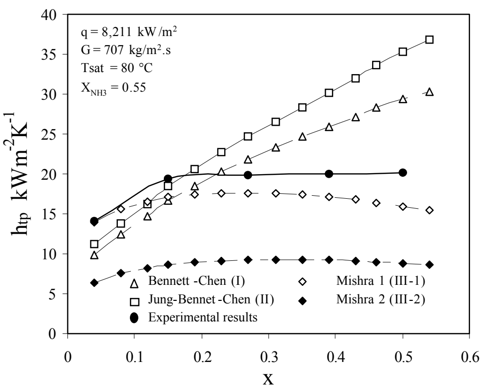

Fig. 6b

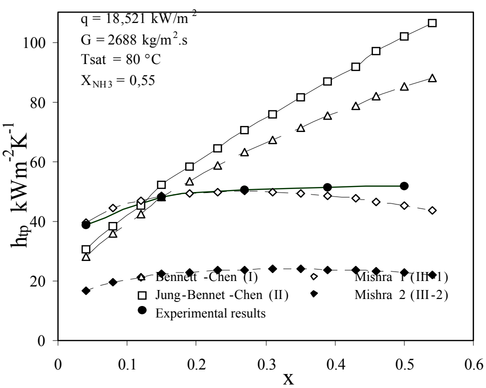

Fig. 6c

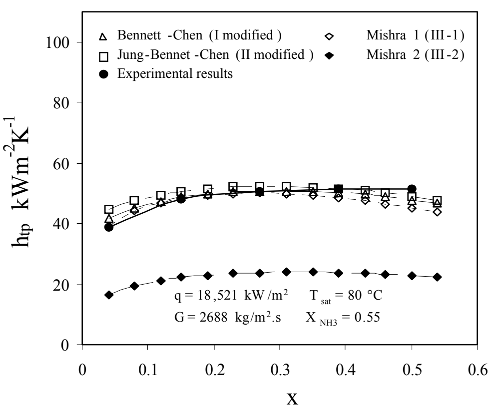

Fig. 6d

Fig. 6: Boiling Heat transfer coefficients as a function of the vapor quality

Top

Modifications of the exponent t (eq. 27) have been presented in this paper to converge the huge differences between the theoretical and the experimental results. The retained values of t are:

[Chen, 1966]	$t = 0.736$
[Jung et al., 1991]	$t = 0.5$
This work	$t = 0.45$ for $8.5 \le q$ 15 kW/m^2 and $800 \le G \le 1600$ kg/m^2.s
	$t = 0.3$ for $15 < q \le 18{,}5$ kW/m^2 and $1600 < G \le 2688$ kg/m^2.s

The results obtained after these modifications are shown in the Fig. 6d for the same conditions of temperature, mass fraction and heat and mass fluxes that those already considered in Fig. 6c.

The modified models I and II present a good result to predict the heat transfer coefficient. The maximum error, with regard to the experimental results of h_{tp}, is less than ± 12 %.

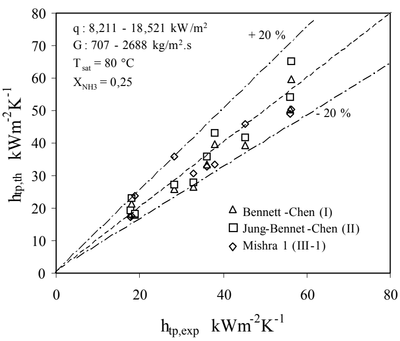

Fig. 7a

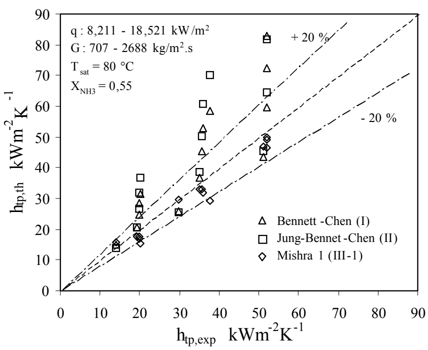

Fig. 7b

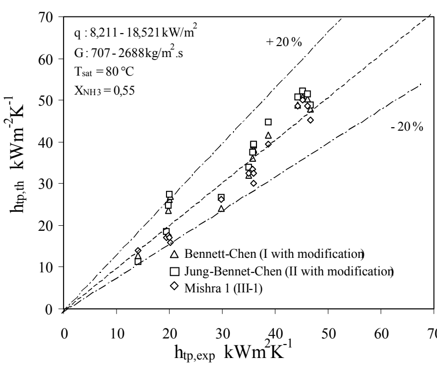

Fig. 7c

Fig. 7: Comparison between the predicted and the experimental heat transfer coefficients

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A comparison between the experimental and the predicted values of heat transfer coefficient is shown in Fig. 7a, 7b and 7c. For an ammonia mass fraction of 25 %, the models I, II and III-1 predicted data within ± 20 % (Fig. 7a). Whilst for X_{NH3} = 55 %, the data predicted by the models I and II (without modification) showed deviations more than 40 % as shown in Fig. 7b. After the modifications brought to the models I and II the predicted heat transfer coefficients agree with the experimental results within
±15 % (Fig. 7c).

7. CONCLUSION

The heat and mass fluxes have a significant influence on the values of the forced convective boiling heat transfer coefficients of ammonia-water mixtures; contrary to the ammonia mass fraction and the boiling temperature, which have a less influence on the values of h_{tp}.

The investigated variation ranges in this study concerning X_{NH3}, T_{sat}, q and G, have confirmed the validity of Bennett-Chen's method to predict the forced convective boiling heat transfer coefficient of ammonia-water mixtures in a vertical smooth tube. However, for an ammonia mass fraction more than 25 %, the correlation concerning to the convective boiling factor F calculation must be modified. The modified Bennett-Chen model's predicts data with an accuracy of ± 12 %.

In the same way, the adaptation of the Jung-Radermacher correlations to Bennett-Chen's method seems to give satisfactory results in predicting heat transfer coefficient of ammonia-water mixtures. The mean deviation, obtained according to this method, is lower than ± 20% .

Somewhere else, Mishra's correlation predicts boiling heat transfer coefficient within 15 % of error.

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