Prediction of critical heat flux for water in uniformly heated vertical porous coated tubes at low pressure

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ملخص
يهدف هذا البحث أساسا للتنبؤ بالتدفق الحراري الحرج داخل أنابيب ساخنة مع استعمال ضغط من 0.1 إلى 0.7 ميغا باسكال(MPa) . في هذه الدراسة استعملنا 742 نقطة تجريبية للتدفق الحراري الحرج لأنابيب ذات طبقة مسامية. دقة المعادلات تم تقديرها بحساب الخطأ النسبي المتوسط و المتوسط الحسابي. كما تم اقتراح معادلة للتنبؤ بالتدفق الحراري الحرج للأنابيب ذات الطبقة المسامية.

الكلمات المفتاحية : التدفق *الحراري الحرج - النقل الحراري -بخار الماء - أنبوب ذو طبقة مسامية.*

Résumé
L'article étudie la prédiction du flux de chaleur critique (FCC) pour les tubes enrobés, poreux et verticaux uniformément chauffés à des pressions entre 0.1 et 0.7 MPa. Dans ce travail, un total de 742 points de données de FCC (flux de chaleur critique) a été utilisé. L'exactitude des corrélations a été estimée en calculant l'écart relatif et l'écart_ type avec des données expérimentales. Une nouvelle corrélation est présentée et elle prédit les conditions de FCC avec une erreur relative moyenne 0.07 % et un écart type 7.91 %.

Mots clé : *CHF - Transfert de la chaleur - Vapeur d'eau -Tube poreux enrobé.*

Abstract
This paper includes the prediction of critical heat flux (CHF) for uniformly heated vertical porous coated tubes at pressures between 0,1 to 0,7 MPa. In this study, we use a total of 742 data points of CHF for water in uniformly heated vertical porous coated tubes obtained from literature. Accuracy of correlations was estimated by calculating both the average and RMS error with available experimental data, and a new correlation is presented. The new correlation predicts the CHF data with average error 0.07% and RMS error 7.91 %

Keywords*: CHF - Heat transfer - Water vapor - Porous coated tubes.*

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1. INTRODUCTION

Critical heat flux (C.H.F), which is also known as burnout, dryout, or boiling crisis, represents an essential heat transfer phenomenon at which there is a sudden decrease in the value of heat transfer coefficient coupled with a high increase in the heating surface temperature. Estimating the CHF accurately is important for design and safety analysis of various industrial heat transfer equipment. The prediction of CHF under low pressures (P≤1 MPa) and low flow (G≤300 $\frac{kg}{m^2 s}$) conditions is further complicated by large specific volume of vapor as the effect of buoyancy becomes significant [1].

Critical heat flux has been studied extensively over the past several decades [2]. There are empirical correlations used since the early 60's [3]. The dimensional approach was pioneered by Katto and Ohno [4]. The phenomelogical approach was initiated in the 1970's [5] and fine tuned in 1990's [6]. The CHF lookup table method, initiated by the USSR Academy of sciences [7] and later, was adopted and extended by Groneveled *et al*. [8-11]. Experimental analyses of the influence of porous coatings on the critical heat flux in vertical round tubes are presented only in a few works [12-17]. In most cases, the examinations took place only at high pressure or high mass flow rates. Aoulmi *et al*. [18] presented the prediction of CHF for water at low pressure for uniformly heated vertical porous coated tubes using 1120 data points.

The objective of the present study is therefore to obtain CHF for water at low pressures (0.12-0.7 MPa) for uniformly heated vertical porous coated tubes. For this purpose, the work is aiming at providing an evaluation of existing CHF correlations with experimental databases for flow boiling CHF , and then developing a CHF correlation based on the databases. The newly obtained correlation will be verified with the collected database.

2. EXPERIMENTAL CHF DATA

In this study, we collected a total of 742 data points of the CHF for water in uniformly heated round vertical tubes from published source [19]. The experiments were conducted in the low pressure test. Test sections were made of Inconel-600 round tube whose electrical and mechanical characteristics were well validated. Figure. 1 shows the schematic diagram of a test section. Sixteen thermocouples were attached onto the outer surface of test section by silver welding to detect a sudden temperature rise as the indication of CHF occurrence. A pair of movable clamp type copper electrodes connected to a direct current (DC) power supplier grabbed both ends of the test tube to provide electrical power and the test section was heated by Joule heating. The ranges of the collected experimental data were:

$$0.1 \le P \le 0.75 MPa \,,\, 10 \le \Delta T_{sub} \le 10 K \,,$$

$$D=0.009m,,\, 0.127 \le L \le 0.450 m \,,$$

$$20 \le G \le 400 \frac{kg}{m^2 s} \,,\, 24.02 \le q_{cr} \le 470.05 \frac{W}{cm^2} \,,$$

$$3.8 \le \frac{\delta}{d_p} \le 8.6 \,,\, 60 \le \varepsilon \le 70\% \,.$$

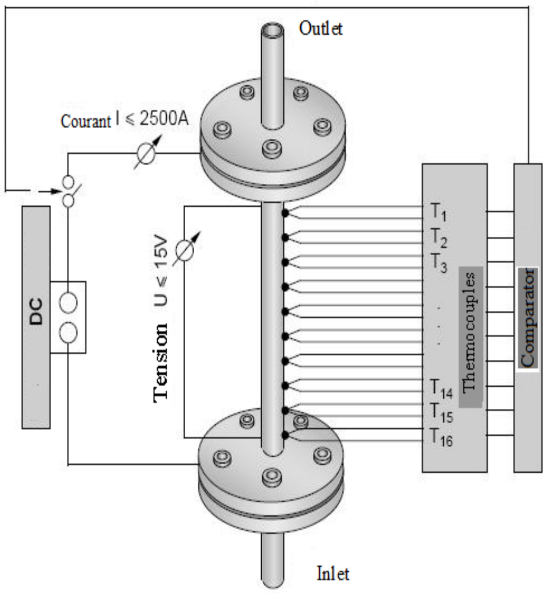

Figure 1. Schematic diagram of the test section [19]

3. COMPARISON OF CORRELATIONS

Presently, there exists a large number of empirical correlations that have been developed by correlating available CHF database obtained from particular flow channel geometries and parameter ranges. Compared to the mechanistic models or CHF lookup tables, the empirical CHF correlations are easy to use and have comparatively simple forms. They can be applied to fluids other than water and various geometries of heat transfer surface that includes non-uniform tubes. Thus, empirical correlations are widely used to predict the CHF in design and operation of the heat transfer equipments: nuclear reactors, steam boilers, and a variety of heat exchangers [2].

A use of the porous coated surfaces as a boiling enhancement method is to increase the number of small scale cavities on a surface [20].

Boiling on a porous surface differs essentially from boiling on a smooth surface. First, porous coatings set up a substantial hydraulic resistance to vapor filtration from the heating wall to the liquid bulk. Second, the vapor pressure at the heating wall differs from that in the liquid bulk [21].

Among the correlations available for uniformly heated vertical porous coated tubes at low pressure, two representative correlations are chosen in order to assess a comparative analysis reported here. The correlations considered in the present study are those reported by Stein [19] and Yildiz [22].

3.1 Stein correlation

Stein [19] derived the following correlation using 742 sets of experimental data.

$$q_{cr} = q_{c0}\left(1+0.7.\frac{\Delta h_{sub}}{\Delta h_{fg}}\right) \tag{1}$$

$$\frac{q_{c3}}{(GH_{fg})} = c_3.\frac{\left(\frac{\delta}{d_p}\right)^{0,315}\left(\frac{\rho_g}{\rho_l}\right)^{0,425}.\left(\frac{\sigma\rho_l}{(G^2.L)}\right)^{0,55}}{1+0.6\left(\frac{\rho_g}{\rho_l}\right)^{0,165}\left(\frac{\sigma\rho_l}{(G^2.L)}\right)^{0,499}\left(1+1.65.\frac{L}{D}\right)} \tag{1a}$$

Where c_3 is expressed as:

$$c_3 = 1.224 + 0.0125\left(\frac{L}{D}\right) \tag{1b}$$

$$\frac{q_{c4}}{(GH_{fg})} = c_4.\frac{\left(\frac{\delta}{d_p}\right)^{0,095}\left(\frac{\rho_g}{\rho_l}\right)^{0,405}.\left(\frac{\sigma\rho_l}{(G^2.L)}\right)^{0,295}}{0.6+0.163.\left(\frac{\rho_g}{\rho_l}\right)^{0,255}\left(\frac{\sigma\rho_l}{(G^2.L)}\right)^{0,377}\left(1+1.65.\frac{L}{D}\right)} \tag{1c}$$

Where

$$c_4 = 0.315 + 0.463\left(\frac{\delta}{d_p}\right)^{-0.475} - \left[\left(0.0113+0.00925\left(\frac{\delta}{d_p}\right)^{-0.475}\right)\left(\frac{L}{D}\right)\right] + 0.000176\left(\frac{L}{D}\right)^2 \tag{1d}$$

$$\frac{q_{c2}}{(GH_{fg})} = c_2 . \frac{\left(\frac{\rho_g}{\rho_l}\right)^{0.199} . \left(\frac{\sigma\rho_l}{(G^2.L)}\right)^{0.291}}{0.96 + 0.163 . \left(\frac{\rho_g}{\rho_l}\right)^{0.065} \left(\frac{\sigma\rho_l}{(G^2.L)}\right)^{0,.377} \left(1 + 1.65 . \frac{L}{D}\right)} \qquad \text{(1e)}$$

Where

$$c_2 = 0.258 - 0.00565\left(\frac{L}{D}\right) + 0.00007\left(\frac{L}{D}\right)^2 \qquad \text{(1f)}$$

$$q_{c3} \leq q_{c4} \rightarrow q_{c0} = q_{c3} \quad \text{(DNB)} \qquad \text{(1g)}$$

$$q_{c3} \succ q_{c4} \rightarrow q_{c0} = q_{c4} . \qquad \text{(1h)}$$

$$q_{c3} \succ q_{c4} \text{ and } G < 30\frac{kg}{m^2 s} \rightarrow q_{c0} = q_{c2} \text{ (microfilm-Dry out)} \qquad \text{(1i)}$$

Data used for the correlation development cover the following ranges parameters**:**

$0.1 \leq P \leq 0.75 MPa$, $10 \leq \Delta T_{sub} \leq 10K$, D=0.009 m,, $0.127 \leq L \leq 0.450m$,

$20 \leq G \leq 400\frac{kg}{m^2 s}$, $24.02 \leq q_{cr} \leq 470.05\ \frac{W}{cm^2}$, $3.8 \leq \frac{\delta}{d_p} \leq 8.6$, $60 \leq \varepsilon \leq 70\%$.

3.2 Yildiz correlation

Yildiz [22] performed experiments with round coated tubes having diameters of 0.006 m and 0.008 m and the range of following parameters:

$0.18 \leq P \leq 0.76$ MPa, $D = 0.006$ m,

$3 \leq \Delta T_{sub} \leq 70K$, $\frac{L}{D} = 28.33$,

$20 \leq G \leq 400\frac{kg}{m^2 s}$, $60 \leq \varepsilon \leq 70\%$,

$3.5 \leq \frac{\delta}{d_p} \leq 4.37$

A general form of the correlation is presented as follows:

$$\frac{q_{cr}}{G.H_{fg}} = 0,04 . \left(\frac{\rho_g}{\rho_l}\right)^{0,269} . \left(\frac{\sigma\rho_l}{(G^2.L)}\right)^{0,191} \qquad \text{(2)}$$

The results from a comparison of CHF predictions from the correlations mentioned are presented in table 1 in terms of calculated average and Root-Mean Square Error (RMS) based on the experimental values. The result is also shown in table 1 and illustrated in figures 2 and 3, The Stein's correlation can predict all 742 CHF data with average and RMS errors of 5.40 % and 10.18 % respectively. The average error and the RMS error are defined as:

$$\text{average error} = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(q_{exp.} - q_{cal.}\right)}{q_{exp.}} 100\%. \qquad (3)$$

and

$$\text{RMS error} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{\left(q_{exp.} - q_{cal.}\right)^2}{q_{exp.}}} 100\% \qquad (4)$$

where N is the number of CHF data points.

Table1. Calculated errors of the correlations

			Correlations	
	Data source	**Data points**	**STEIN**	**YILDIZ**
	Stein (L/D=50) (a)*	244	2.56	-40.71
Average error (%)	Stein (L/D=50) (b)**	251	3.42	81.58
	Stein (L/D=14,1) (a)	106	10.04	-43.45
	Stein (L/D=14,1) (b)	141	10.34	-40.71
	Total	**742**	**5.40**	**36.40**
RMS error (%)	Stein (L/D=50) (a)	244	8.45	42.14
	Stein (L/D=50) (b)	251	7.7	88.09
	Stein (L/D=14,1) (a)	106	13.33	44.06
	Stein (L/D=14,1) (b)	141	13.52	42.14
	Total	**742**	**10.18**	**72.37**

* *Case (a):* $\delta = 300\,\mu m, d_p = 30 - 40\,\mu m, \varepsilon = 60 - 70\%$

** *Case (b):* $\delta = 300\,\mu m, d_p = 60 - 80\,\mu m, \varepsilon = 60 - 70\%$

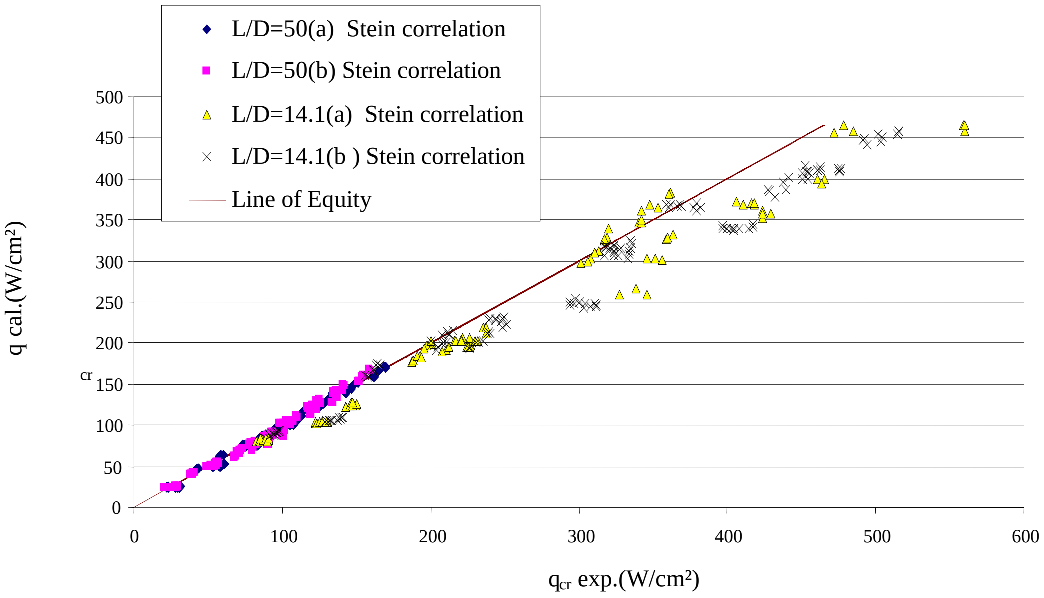

Figure 2. Performance of Stein correlation with experimental CHF of Stein

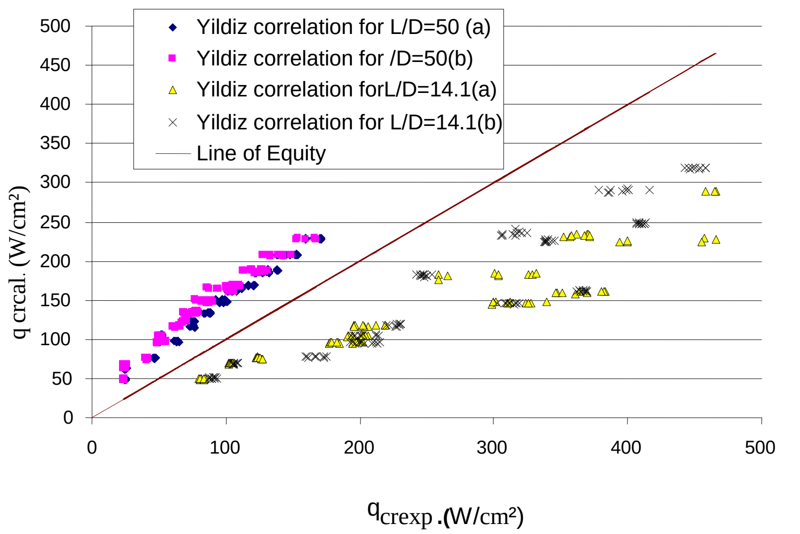

Figure 3. Performance of Yildiz correlation with experimental CHF of Stein

4. NEW CORRELATION

In this study, we propose a new correlation using 742 sets of experimental data. The final form of this correlation after performing the multiple regression is expressed as:

$$\frac{q_{cr}}{G.H_{fg}} = \exp(a).\left(\frac{\rho_g}{\rho_l}\right)^b.\left(\frac{\sigma\rho_l}{(G^2.L)}\right)^c\left(\frac{L}{D}\right)^d \quad (5)$$

Where :

If $G \le 30 kg/(m^2 s)$: a= -0.24 ;b = 0.0112;

c = -0.457; d= -1.05.

If $30 \le G \le 105 kg/(m^2 s)$: a= 0.090

9; b=0.269; c=0.105; d = -0.987

If $G \succ 105 kg/(m^2 s)$: a= -0.393; b=0.348;

c= 0.223, d = -0.693

Data used for the correlation development

cover the following ranges of parameters:

$0.1 \le P \le 0.75 MPa$, $10 \le \Delta T_{sub} \le 10K$,

D=0.009 m,, $0.127 \le L \le 0.450m$,

$20 \le G \le 400 \frac{kg}{m^2 s}$,

$24.02 \le q_{cr} \le 470.05 \frac{W}{cm^2}$, $3.8 \le \frac{\delta}{d_p} \le 8.6$,

$60 \le \varepsilon \le 70\%$.

The results from a comparison of CHF predictions from the new correlation are presented in table 2 in terms of calculated average and RMS error based on the experimental values. Graphic representations of the results of the comparison are presented in figure 4. It can be seen that the correlation predicts the data reasonably well, with RMS error of 7.91 %.

Table 2. Calculated errors of the new correlation

Data source	**Data points**	**Average error (%)**	**RMS (%)**
Stein (L/D=50) (a)*	244	-3.75	7.09
Stein (L/D=50) (b)**	251	3.67	7.03
Stein (L/D=14,1) (a)	106	0.11	11.07
Stein (L/D=14,1) (b)	141	0.24	7.90
Total	**742**	**0.07**	**7.91**

* *Case (a):* $\delta = 300\mu m, d_p = 30 - 40\mu m, \varepsilon = 60 - 70\%$

** *Case (b):* $\delta = 300\mu m, d_p = 60 - 80\mu m, \varepsilon = 60 - 70\%$

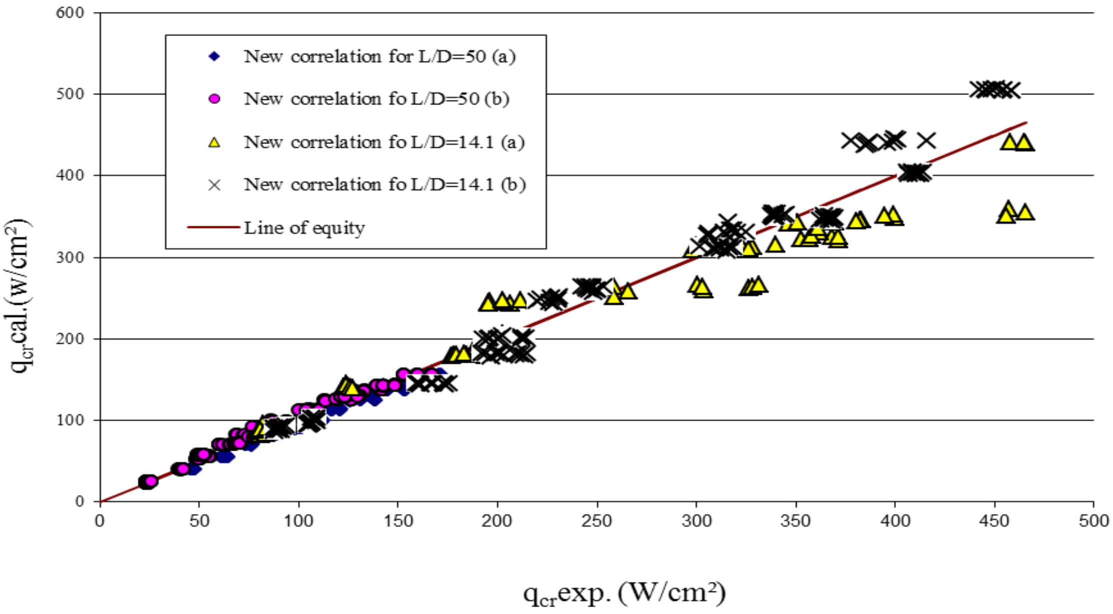

Figure 4. Performance of new correlation with experimental CHF of Stein

5. CONCLUSION

Two representative CHF correlations were compared with the newly developed CHF correlation for uniformly heated vertical porous coated tubes at low pressure and low mass flow. For this study, 742 points were selected from published work. The tested ranges for water in uniformly heated vertical porous coated round tubes were as follows:

$0.1 \le P \le 0.75 MPa$, $10 \le \Delta T_{sub} \le 10K$,

D=0.009 m,, $0.127 \le L \le 0.450 m$,

$20 \le G \le 400 \dfrac{kg}{m^2 s}$, $24.02 \le q_{cr} \le 470.05 \dfrac{W}{cm^2}$,

$3.8 \le \dfrac{\delta}{d_p} \le 8.6$, $60 \le \varepsilon \le 70\%$.

Average and RMS have been calculated for the new correlation as well as the correlations of Stein [19] and Yildiz [22]. The prediction of critical heat flux (CHF) using the new correlation resulted in the average error of 0.07 % and RMS error of 7.91 %. We hope that our work can be used to predict the critical heat flux (CHF).

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Nomenclature

a, b, c, d	Parameters of new correlation
L	Heated length (m)
d_p	Particle-diameters
D	Tube diameter (m)
G	Mass velocity $\left(kg.m^{-2}; s^{-1}\right)$
q_{cr}	Critical heat flux ($\frac{kW}{m^2}$)
P	System pressure (MPa)
H_{fg}	Latent heat of vaporization ($kJ.kg^{-1}$)
ΔT_{sub}	Inlet subcooling (K)
Δh_{sub}	Inlet subcooling ($kJ.kg^{-1}$)
ρ	Density $(kg.m^{-3})$
σ	Surface tension ($N.m^{-1}$)
g	Gravitational acceleration (9.807 $m.s^{-2}$)
δ	Thickness of the porous coating, (µm)
ε	Porosity of the porous coating, (%)
λ	Wave length scale of Taylor instability (m)
A	Flow area (m²)
A_h	Heat area (m²)

Subscripts

l	Saturated liquid
g	Saturated vapor
Exp.	Experimental
Cal.	Calculated

Abbreviations

CHF	Critical Heat Flux
RMS	Root Mean Square