IMPROVED CRITICAL HEAT FLUX CORRELATION FOR REFRIGERANT FLOW IN CIRCULAR MICROTUBES

Saptarshi Basu,[1] Yoav Peles,[2] Michael Jensen[3]

[1]Illumina Inc., 5200 Illumina Way, San Diego, CA, 92122, USA
[2]University of Central Florida, 4000 Central Florida Blvd, Orlando, FL, 32816, USA
[3]Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY, 12180, USA

ABSTRACT

A new improved CHF correlation using critical quality and a modified measure of subcooling is developed for refrigerant flow in circular microtubes. The correlation showed a MAE of only 3% with R134a and 12% with R123 data, respectively. Nine different correlations were tested against the R134a data. Among the pre-existing correlations, the Shah and the Zhang correlation performed well for R134a with a MAE of 16% and 19%, respectively. In general, the conventional scale correlations performed better than the microchannel correlations. Compared to the microscale correlations, the accuracy of the conventional scale correlations were impacted by critical quality. The proposed new correlation and updated version of the Wojtan-Thome and Basu correlation were trained on the R134a dataset. All the correlations were compared against the independent R123 dataset and the new correlation fared better than the existing correlations in the literature.

KEY WORDS: CHF, flow boiling, microscale, correlation, prediction, refrigerants, R134a, R123

1. INTRODUCTION

Heat dissipation is a critical engineering challenge in a range of industries: electronics, semiconductor, aerospace, defense, HVAC, biomedical, etc. The objective of most thermal management system is to maximize heat transfer while reducing volume or weight of the cooling system. One way to achieve this target is by increasing the heat transfer coefficient. Two-phase heat transfer like flow boiling at microscale exhibits very high heat transfer coefficients as a result of the latent heat of vaporization and enhanced mixing due to bubble growth and motion [10]. There is thus considerable research interest in analyzing flow boiling at microscale. The interested reader is directed to a few selected publications related to flow boiling at microscale for reference ([1–8, 11–13, 15–20, 22]).

Any boiling system that is heat flux controlled, needs to be designed with the critical heat flux in consideration. The critical heat flux or CHF is the maximum heat flux that a thermal system can withstand before it transitions from a highly efficient heat transfer mechanism to a very poor heat transfer one. This is generally accompanied with a sharp temperature spike. The sudden increase in temperature is detrimental to system reliability and can often lead to burnout.

There are two main mechanisms of critical heat flux [10]. The first is Departure from Nucleate Boiling (DNB) which is driven by transition from nucleate boiling to film boiling . The second mechanism is observed at higher quality and annular flow and is driven by dryout of the liquid film. Vapor is a poor conductor of heat compared to the liquid. When the wall adjacent region becomes liquid deficient, heat transfer drops drastically,

---

resulting in very high surface temperatures [10].

Accurate determination or prediction of critical heat flux is of paramount importance in the design of any boiling based cooling system. Several analytical and empirical methods are available in the literature. The empirical methods have correlated the critical heat flux to a combination of different parameters such as $\frac{\rho_v}{\rho_l}$, $\frac{L}{D}$, We_l, x_{crit}, k_f, C_p, and some measurement of subcooling.The overall goal is to develop a correlation that can accurately predict the critical heat flux condition across a range of fluids and geometry.

In this work, nine different correlations (Bowring [9], Katto and Ohno [13], Shah [21], Bowers and Mudawar [8], Qu and Mudawar [18], Koşar et al. [14], Zhang et al. [23], Wojtan et al. [22], and Basu et al. [2]) are compared against the R134a CHF data obtained in microtubes by Basu et al. [2]. Some of the empirical correlations are then fitted against the R134a dataset. A new correlation is also developed using the same dataset. All the correlations are then tested against the R123 CHF data for flow boiling in circular microtubes (Roday and Jensen [19]), for an independent test of accuracy.

Details about the dataset and the correlations considered for comparison in this study are discussed below.

2. DESCRIPTION OF R134A AND R123 DATASET

A total of 113 CHF data points were measured in the Basu et al. [2] study. Details of the parametric trends and discussion of the same are provided in the paper [2]. The experiments were conducted across three tubes with internal diameters of 0.50 mm, 0.96 mm, and 1.60 mm. CHF was found to increase with increasing mass flux and decrease with decreasing tube diameters and increasing saturation pressures. CHF also displayed an increasing trend with increasing inlet subooling. The trend between exit quality and critical heat flux was complex and was dependent on the flow regime.

A total of 72 R123 CHF data points were obtained from the study by Roday and Jensen [19]. CHF showed an increase with increasing mass flux. However, the effect of subcooling and exit quality on CHF was impacted by the flow regime. CHF was also found to decrease with increase in heated length of the tubes. Over the limited pressure range in the R123 study, saturation pressure did not have a significant impact on CHF. In comparison to the Basu et al. [2] results, CHF was found to have an inverse relationship with tube diameter.

Although both studies were conducted with refrigerants in circular microtubes, there were considerable differences in the operating conditions for the two studies (Table 1). The R123 tests were conducted in smaller diameter tubes and the length-to-diameter ratio was kept constant by varying the tube length. Also, CHF occurred at lower quality compared to the R134a case.

Table 1 Operating conditions for the R134a and R123 dataset

Parameters	R134a [2]	R123 [19]
ID (mm)	0.500, 0.960, 1.600	0.286, 0.430, 0.700
G (kg/m^2-s)	300, 600, 1000, 1500	375, 530, 825
$P_{sat}(kPa)$	490, 670, 890, 1160	165, 225
L(mm)	≈ 120	17-90.84
x$_{crit}$	0.3-1.0	0.05-0.84
$\Delta T_{subcool}$ $(^{\circ}C)$	5 - 40	2 - 25

3. DESCRIPTION OF CORRELATIONS

A brief description of the correlations used for comparison in the study are provided in Table 2. The reader is directed to the references listed in the table for additional details on the correlation related to the derivation, application, and constants. The Katto and Ohno [13] correlation was developed for conventional channels but

it has been adapted in some form for microscale flows based on comparison with multiple datasets (Qu and Mudawar [18], Koşar et al. [14], Wojtan et al. [22], and Basu et al. [2]). The functional form of the Bowring [9], Shah [21], and the Zhang et al. [23] correlation are however different from the Katto and Ohno [13] correlation. It should be noted that the original Basu et al. [2] correlation was developed with the data from the work of Basu et al. [2] and Roday and Jensen [19].

Table 2 List of correlations used in the present study

Author(s)	Correlation Functional Form	Fluid, Geometry	Parameter Range
Bowring [9]	$q''_{crit} = \frac{A + 0.25GD(h_f - h_{in})}{C + z}$ where A and C are empirical constants	$2 \leq D \leq 45$ mm $0.15 \leq z \leq 3.7$ m	$136 \leq G \leq 18600$ kg/m^{2}s $2 \leq P_{sat} \leq 190$ bar
Katto and Ohno [13]	$q''_{crit} = q''_{co}\left(1 + K_k \frac{h_f - h_{in}}{h_{fg}}\right)$ $q''_{co} = f\left(Gh_{fg}, We_l, \frac{\rho_v}{\rho_l}, \frac{L}{d}\right)$	uniformly heated, vertical tubes $5 \leq (L/d) \leq 880$	$0.00003 \leq (\rho_v/\rho_l) \leq 0.41$ $3 \times 10^{-9} \leq \frac{1}{We_L} \leq 2 \times 10^{-2}$
Shah [21]	$q''_{crit} = 0.124 Gh_{lv}\left(\frac{d_h}{L}\right)^{0.89}\left(\frac{10^4}{Y}\right)^n (1 - x_i)$ $n = \left(\frac{d_h}{L}\right)^{0.54}$ $Y = \left(\frac{Gd_h C_{p,f}}{k_f}\right)\left(\frac{G^2}{\rho_f^2 gd_h}\right)^{0.4}\left(\frac{\mu_f}{\mu_g}\right)^{0.6}$	23 fluids, Circular vertical tubes $d_h = 0.315 - 37.5 mm$	G = 4 - 29051 $kg/m^2 - s$ $P_r = 0.0014 - 0.96$ $x_{in} = -0.4 - 0.85$
Bowers and Mudawar [8]	$q''_{crit} = 0.16 Gh_{lv} We^{-0.19}\left(\frac{L_h}{d}\right)^{-0.54}$	R113, square heat sink mini-channel (D = 2.54 mm) micro-channel (D = 0.510 mm)	$V_{l,max} = 95 ml min^{-1}$ $P_{inlet} = 1.38$ bar $\Delta T_{subcool} = 10 - 32^\circ C$
Qu and Mudawar [18]	$q''_{crit} = 33.43 Gh_{lv}\left(\frac{\rho_v}{\rho_l}\right)^{1.1} We^{-0.21}\left(\frac{L_h}{d}\right)^{-0.36}$	Water, Rectangular channels $d_h = 0.38 - 2.54 mm$	G = 86 - 368 kg/m^{2}s $P_{exit} = 1.13$ bar $T_{inlet} = 30$ and $60^\circ C$
Zhang et al. [23]	$\frac{q''_{crit}}{Gh_{lv}} = 0.0352\left[We_d + 0.0119\left(\frac{L_h}{d}\right)^{2.31}\left(\frac{\rho_v}{\rho_l}\right)^{0.361}\right]^{-0.295}$ $\left(\frac{L_h}{d}\right)^{-0.311}\left[2.05\left(\frac{\rho_v}{\rho_l}\right)^{0.170} - x_{in}\right]$	Water, small diameter tubes $D_h = 0.33-6.22$ mm	P_{sat} = 0.101-19.0 MPa G=5.33-$1.34 \times 10^5 kg/m^2$s x_{crit} = -1.75-1.00 x_{in} = -2.35-0
Koşar et al. [14]	$q''_{crit} = 0.0035 Gh_{lv} We^{-0.12}$	Water, Rectangular channels $d_h = 0.227 mm$	G = 41-302 kg/m^{2}s $P_{exit} = 101.3 kPa$
Wojtan et al. [22]	$q''_{crit} = 0.437\left(\frac{\rho_v}{\rho_l}\right)^{0.073} We^{-0.24}\left(\frac{L_h}{d}\right)^{-0.72} Gh_{lv}$	R134a, circular micro-tubes d = 0.50, 0.80 mm	G = 400-1600 kg/m^{2}s T_{sat} = 30, 35 $^\circ$C $x_{crit} = 0.35 - 0.95$
Basu et al. [2]	$q''_{crit} = 0.3784 Gh_{lv}\left(\frac{\rho_v}{\rho_l}\right)^{0.051}\left(\frac{L_h}{d}\right)^{-1.03} x_{crit}^{0.8}$	R134a, circular micro-tubes $d = 0.50, 0.96, 1.60 mm$	$G = 300 - 1500 kg/m^2 s$ $P_{sat} = 490 - 1160 kPa$ $x_{crit} = 0.3 - 1.0$ $\Delta T_{subcool} = 10 - 32^\circ C$

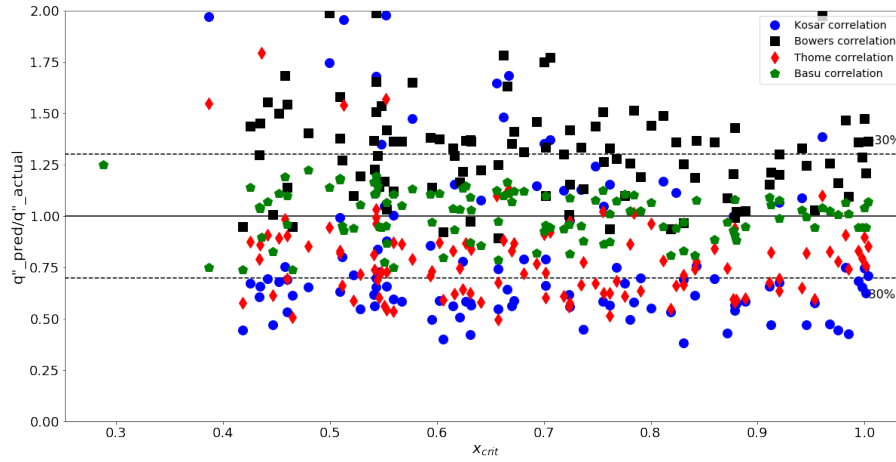## 4. COMPARISON OF DIFFERENT CORRELATIONS WITH R134A DATA

The nine correlations were compared against 113 CHF data points obtained for R134a flow in circular microtubes [2]. The performance results for the four conventional scale correlations against the data are plotted in Fig. 1. The ratio of the predicted heat flux to the actual heat flux variation is shown against the critical quality. Critical quality is the quality at which CHF occurs. Although the Katto and Ohno [13] and the Zhang et al. [23] have different functional form, they follow the same trend in predicting the R134a data. The correlations overpredict the data at lower quality and the accuracy improves at higher quality. The Shah [21] correlation also follows the same trend but is generally more accurate compared to the former two correlation. The Bowring [9] correlation performed similarly across all quality ranges.
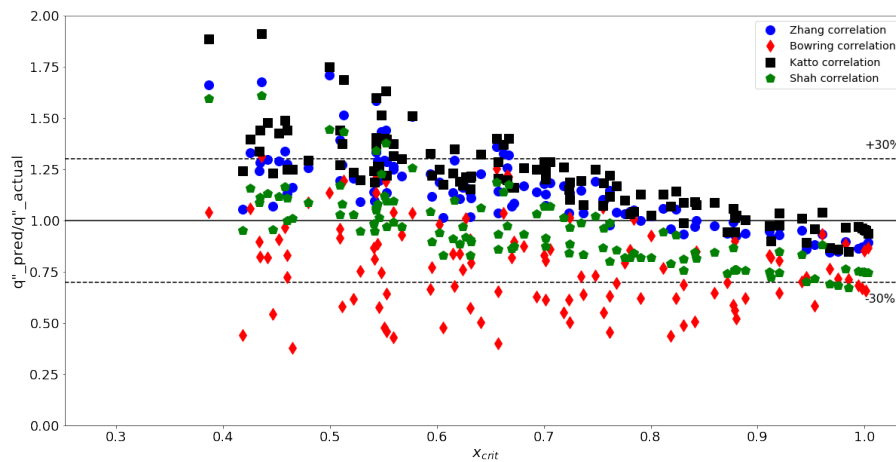
Fig. 1 Comparison of conventional scale correlations with R134a data [2]

The microscale correlations are compared against the same dataset and the results against quality are shown in Fig. 2. The microscale correlations did not show any strong trend with quality. The Koşar et al. [14] correlation was less accurate but it did not systematically underpredict or overpredict the data. On the other hand, the Bowers and Mudawar [8] correlation overpredicted the data and the Wojtan et al. [22] correlation underpredicted the data by a moderate margin. The Basu et al. [2] correlation performed best but it was fitted to the same dataset. Due to the quality dependence observed in the conventional scale correlations, the Basu et al. [2] correlation included the critical quality as one of the parameter. The Qu and Mudawar [18] correlation overpredicted the data significantly and is not shown in the plot. Although, the functional form of the correlation is similar to many of the other Katto and Ohno [13] based correlations, it was developed on water data in a parallel microchannel configuration, and the flow characteristics are different from refrigerant flow in a single circular microtube. The first constant in the correlation is about 100 times larger in magnitude compared to the other correlations.

Mean Absolute Error is defined in Equation 1. The MAE is used to compare the performance of different correlations and is shown in Table 3. Overall, the Basu et al. [2] displayed the lowest MAE of 10%. Among the independently developed correlation, the Shah [21] and the Zhang et al. [23] correlation performed well with a MAE of 16% and 19%, respectively. Overall, the conventional scale correlations performed superior to the microscale correlations for the Basu et al. [2] dataset. These correlations were developed for circular tubes over a large dataset with multiple fluids. However, the conventional scale correlations overpredicted the data at lower quality and performed poorly at smaller diameters. Interestingly, aside from this quality dependence, the conventional scale correlations typically included an inlet subcooling parameter, which was not considered in most of the microscale correlations.

Fig. 2 Comparison of microscale correlations with R134a data [2]

$$MAE = \left(\frac{1}{M}\right) \sum_{1}^{M} \frac{\left|q''_{crit,pred} - q''_{crit,expt}\right|}{q''_{crit,expt}} \times 100\% \tag{1}$$

Table 3 MAE of different correlations with R134a dataset [2]

Correlations	Mean Absolute Error (%)			
	d = 0.50 mm	d = 0.96 mm	d = 1.60 mm	Average
Bowring [9]	34	33	19	28
Katto and Ohno [13]	41	15	22	25
Shah [21]	22	16	13	16
Bowers and Mudawar [8]	83	22	32	43
Qu and Mudawar [18]	2484	1215	1197	1556
Zhang et al. [23]	33	12	15	19
Koşar et al. [14]	45	30	44	40
Wojtan et al. [22]	38	32	17	28
Basu et al. [2]	10	9	10	10

5. DESCRIPTION OF NEW CORRELATIONS

Based on the results and discussion in Sec. 4, the Shah [21] and the Zhang et al. [23] correlation are not updated with the R134a dataset. However, a new correlation based on the Wojtan et al. [22] and Katto and Ohno [13] correlation is fitted to the R134a data. This correlation referred to as updated Thome correlation is given by Equation 2.

$$\frac{q''_{crit}}{Gh_{lv}} = 0.315 \left(\frac{\rho_v}{\rho_l}\right)^{0.096} \left(\frac{L_h}{d}\right)^{-0.85} We^{-0.096} \tag{2}$$

Similarly, the Basu et al. [2] correlation is updated only on the basis of the Basu et al. [2] data and not the Roday and Jensen [19] data. The fitted correlation keeps the same functional form but is updated with new coefficients. The correlation referred to as updated Basu et al. [2] correlation is given in Equation 3.

$$\frac{q''_{crit}}{Gh_{lv}} = 0.426 \left(\frac{\rho_v}{\rho_l}\right)^{0.167} \left(\frac{L_h}{d}\right)^{-0.971} x^{0.852} \tag{3}$$

Critical heat flux is mostly driven by either departure from nucleate boiling at lower quality or dryout at higher quality. Both of these mechanisms are impacted by the presence of vapor and hence, the quality at which critical heat flux occurs could have an influence on the magnitude of the heat flux. Similarly, if the fluid is subcooled, the fluid has to be heated to saturation temperature before boiling can occur. This would also impact the magnitude of the critical heat flux. The conventional scale correlations like Katto and Ohno [13] and Bowring [9] include the effect of subcooling but none of the microscale correlations consider inlet subcooling. The Shah [21] and the Zhang et al. [23] included the inlet quality as a proxy for inlet subcooling. Due to the superior performance of these four correlations, a new version of the Basu et al. [2] correlation is proposed that includes a form of non-dimensional subcooling defined as a pseudo-quality (Equation 4). The proposed new correlation is described by Equation 5. The correlation keeps the simple form of the Katto and Ohno [13] correlation but includes subcooling in the equation without the need of any iterative calculations. Compared to the conventional scale correlations, the proposed correlation use a power law formulation where the subcooling impact is additive when the natural log of the equation is taken.

$$x_{subcool} = \frac{h_l - h_{in}}{h_{lv}} \tag{4}$$

$$\frac{q''_{crit}}{Gh_{lv}} = 0.409 \left(\frac{\rho_v}{\rho_l}\right)^{0.0157} \left(\frac{L_h}{d}\right)^{-0.996} x^{0.834} x_{subcool}^{0.152} \tag{5}$$

The performance of the correlations are tabulated in Table 4. All three correlations showed an improvement when trained with the dataset. However, the low MAE of 3% by the proposed new correlation point to an improvement by the addition of the $x_{subcool}$ term in the correlation. The updated Wojtan et al. [22] correlation showed an improvement in MAE from 28% to 18%.

Table 4 MAE of new/updated correlations with R134a dataset [2]

| Correlations	Mean Absolute Error (%)			
	d = 0.50 mm	d = 0.96 mm	d = 1.60 mm	Average
Updated Wojtan et al. [22]	27	14	16	18
Updated Basu et al. [2]	10	8	8	9
Proposed new correlation	3	3	3	3

6. COMPARISON WITH R123 MICROTUBE DATA

All the correlations were compared and tested with the R123 microtube data [19]. The original Basu et al. [2] correlation was not considered for this comparison but the updated version of the correlation was used. The R123 dataset served as an independent verification as none of the correlations were developed using this dataset. The performance of the correlations in terms of MAE is shown in Table 5.

Almost all the pre-existing correlations performed poorly, specially at low quality dryout. Most of the correlations performed better at high quality and the smaller tubes. Among the correlations considered, the updated Basu et al. [2] and the proposed new correlation performed best due to the inclusion of the critical quality and subcooling term in the function. The proposed new correlation predicts the data best with an overall MAE of 14%. Compared to the other correlations, whose predictive accuracy was influenced by the critical quality, the proposed correlation only differed from the experimental data by a scaling factor (Fig. 3). Only the top four correlations in terms of MAE are plotted in the figure. Most of the pre-existing correlations grossly overpredicted the critical heat flux in the 0.70 mm ID tube (Table 5).

**Table 5** MAE of different correlations for R123 dataset [19]

Correlations	Mean Absolute Error (%)			
	d = 0.286 mm	d = 0.430 mm	d = 0.700 mm	Average
Bowring [9]	21	106	331	120
Katto and Ohno [13]	42	199	513	199
Shah [21]	19	119	349	126
Bowers and Mudawar [8]	130	367	815	361
Qu and Mudawar [18]	348	734	1504	734
Zhang et al. [23]	24	160	433	160
Koşar et al. [14]	51	88	274	116
Wojtan et al. [22]	40	189	457	182
Updated Wojtan et al. [22]	22	158	433	159
Updated Basu et al. [2]	24	17	24	23
Proposed new correlation	15	10	17	14
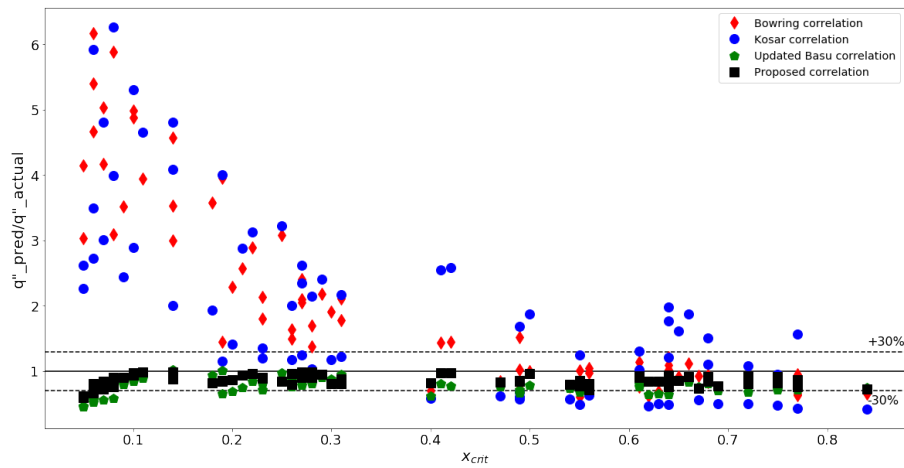
**Fig. 3** Comparison of the top four correlations with R123 data [19]

7. PREDICTION OF PARAMETRIC TRENDS BY DIFFERENT CORRELATIONS

Asides from MAE, the new correlation also accurately tracks the trend observed in the Basu et al. [2] and Roday and Jensen [19] dataset. In Fig. 4, the new correlation follows the trend versus mass flux and tube diameter. CHF is found to increase with increasing mass flux and tube diameter. Interestingly, the correlation also correctly tracks the inverse trend with respect to diameter that was observed in the R123 data (Fig. 5). The Basu et al. [2] study kept the heated length constant and the ratio of heated length to diameter varied with tube diameter changes. On the other hand, for the Roday and Jensen [19] data, the ratio was kept constant but the tube heated length varied in their experiments. As CHF decreased with increasing length, the diameter effect was impacted by the heated length of the tube.

The new correlation effectively tracked the CHF variation with critical quality at P_{sat} = 225 kPa for the R123 study (Fig. 6). Due to the limited number of data points, a clear trend could not be determined but the correlation closely followed the experimentally observed data. Generally, the critical quality is determined by the flow regime which depends on the applied heat flux, tube dimensions, inlet subcooling, and thermodynamic properties at the given saturation pressure. At small differences in critical quality, the variation in critical heat flux is not clearly understood.

461
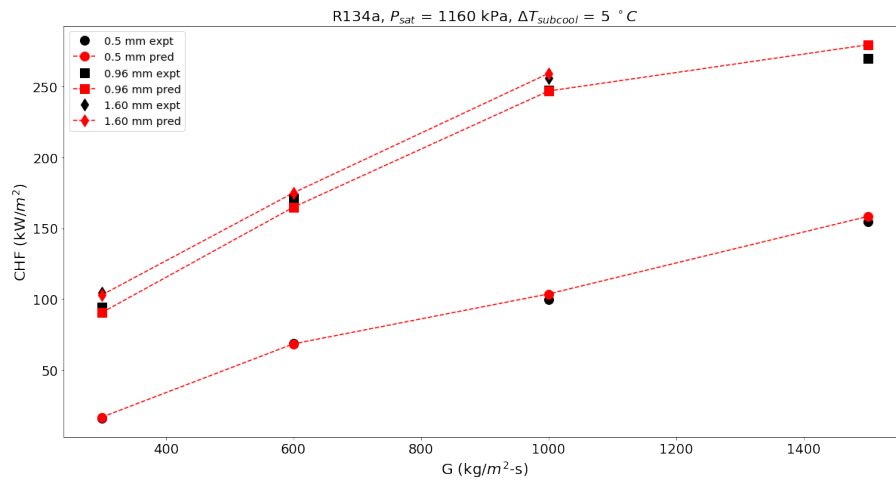
Fig. 4 Effect of diameter and mass flux on CHF: New correlation vs. Basu et al. [2] data
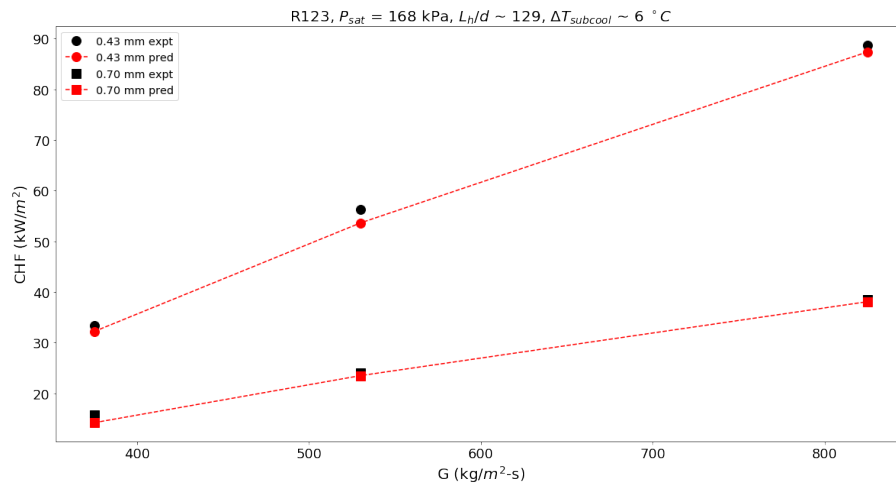
Fig. 5 Effect of diameter and mass flux on CHF: New correlation vs. Roday and Jensen [19] data
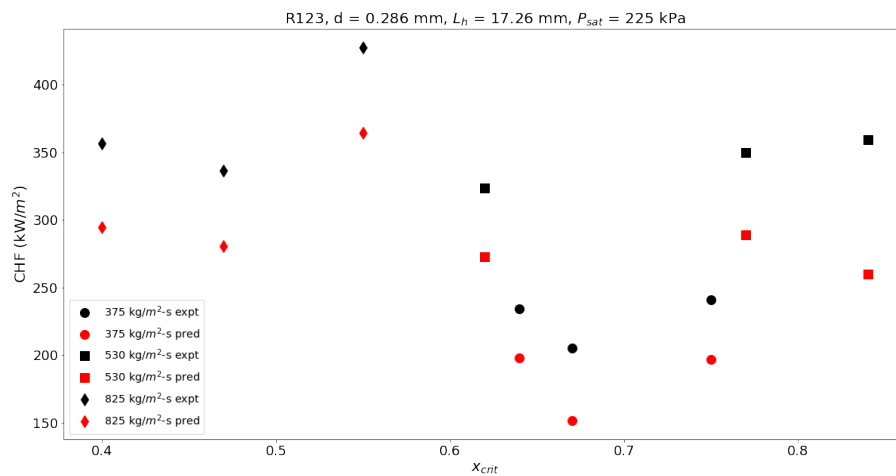
Fig. 6 Effect of critical quality on CHF at P_{sat} = 225 kPa: New correlation vs. Roday and Jensen [19] data

8. CONCLUSIONS

Nine different correlations were compared against the Basu et al. [2] data. Based on the comparison, three new correlations were developed and fitted to the same dataset. All the correlations were then tested on the 462

Roday and Jensen [19] dataset. The main findings of the study are listed as follows:

- Among the correlations available in the literature, the Shah [21] and Zhang et al. [23] conventional scale correlations performed well against the Basu et al. [2] data with a MAE of 16% and 19%, respectively. The conventional scale correlations overpredicted the data at lower quality and the error was generally higher at low qualities and at smaller diameters. The parallel microchannel correlations (Bowers and Mudawar [8] and Qu and Mudawar [18]) generally overpredicted the data. The Wojtan et al. [22] correlation which was developed for R134a flow in circular microtubes performed similar to the Bowring [9] and Katto and Ohno [13] but the accuracy was not impacted by critical quality unlike the conventional scale correlations.

- The original Basu et al. [2] correlation performed best with a MAE of only 10%. However, it must be noted that the correlation was developed with the Basu et al. [2] and Roday and Jensen [19] dataset.

- In order to ensure a direct comparison, two modified and one new correlation was developed. The modified correlations were updated version of the Wojtan et al. [22] and the Basu et al. [2] correlation that were fitted only against the Basu et al. [2] data and not the R123 data. The new correlation was developed from the Basu et al. [2] correlation with a modified non-dimensional subcooling term included in the function. The modified correlations performed better compared to the original correlations. The proposed new correlation performed significantly better with a MAE of only 3%.

- The test data to compare the different correlations were obtained from the Roday and Jensen [19] study. The proposed new correlation significantly outperformed the pre-existing correlations and the updated correlations. The MAE of the new correlation in predicting the R123 data is 14%. The new correlation also correctly tracked the CHF parametric trends.

The applicability of the correlation against different fluids and geometry will be tested further in future with additional datasets.

ACKNOWLEDGMENTS

NOMENCLATURE

C_p	Specific heat	(J/kg-K)
d	Diameter	(mm)
G	Mass Flux	$(kg/m^2 - s)$
h	Enthalpy	(J/kg)
k	Thermal Conductivity	(W/m-K)
L	Length	(mm)
P	Pressure	(kPa)
$q"$	Heat Flux	(kW/m^2)
T	Temperature	$(°C)$
We	Weber number	($G^2 L/\rho\sigma$)
x	Quality	$(-)$
Greek Letters		
Δ	Delta	$(-)$
μ	Viscosity	(Ns/m^2)
ρ	Density	(kg/m^3)
Subscripts		
$crit$	Critical	
$exit$	Exit	
$expt$	Experimental	
f	Fluid	
g	Gas	
h	Heated	
i	Inlet	
$inlet$	Inlet	
l	Liquid	
$pred$	Predicted	
sat	Saturated	
$subcool$	Subcool/Subcooling	
v	Vapor	

REFERENCES

[1] Basu, S., Ndao, S., Michna, G. J., Peles, Y., and Jensen, M. K., "Flow boiling of R134a in circular microtubes—Part I: Study of heat transfer characteristics," *Journal of Heat Transfer*, 133(5), pp. 051502, (2011).

[2] Basu, S., Ndao, S., Michna, G. J., Peles, Y., and Jensen, M. K., "Flow boiling of R134a in circular microtubes—Part II: Study of critical heat flux condition," *Journal of Heat Transfer*, 133(5), pp. 051503, (2011).

[3] Basu, S., Ndao, S., Michna, G. J., Peles, Y., and Jensen, M. K., "Heat transfer characteristics of flow boiling of R134a in uniformly heated horizontal circular microtubes," *2010 14th International Heat Transfer Conference*, pp. 385–396, (2011).

[4] Basu, S., Ndao, S., Michna, G. J., Peles, Y., and Jensen, M. K., "Study of CHF condition for flow boiling of R134a in circular microchannels," *2010 14th International Heat Transfer Conference*, pp. 415–425, (2011).

[5] Basu, S., Werneke, B., Peles, Y., and Jensen, M. K., "Thermal behavior of a microdevice under transient heat loads," *International Journal of Heat and Mass Transfer*, 91, pp. 1078–1087, (2015).

[6] Basu, S., Werneke, B., Peles, Y., and Jensen, M. K., "Transient microscale flow boiling heat transfer characteristics of HFE-7000," *International Journal of Heat and Mass Transfer*, 90, pp. 396–405, (2015).

[7] Bergles, A. and Kandlikar, S., "On the nature of critical heat flux in microchannels," *Journal of Heat Transfer*, 127(1), pp. 101–107, (2005).

[8] Bowers, M. and Mudawar, I., "High flux boiling in low flow rate, low pressure drop mini-channel and micro-channel heat sinks," *International Journal of Heat and Mass Transfer*, 37(2), pp. 321–332, (1994).

[9] Bowring, R., "A simple but accurate round tube, uniform heat flux, dryout correlation over the pressure range 0.7-17 MN/m^2 (100-2500 psia)," , Tech. rep., UKAEA Reactor Group, (1972).

[10] Carey, V. P., *Liquid vapor phase change phenomena: an introduction to the thermophysics of vaporization and condensation processes in heat transfer equipment*, Taylor Francis Group, (2008).

[11] Hall, D. D. and Mudawar, I., "Critical heat flux (CHF) for water flow in tubes—i. compilation and assessment of world CHF data," *International Journal of Heat and Mass Transfer*, 43(14), pp. 2573–2604, (2000).

[12] Hall, D. D. and Mudawar, I., "Critical heat flux (chf) for water flow in tubes—ii.: Subcooled CHF correlations," *International Journal of Heat and Mass Transfer*, 43(14), pp. 2605–2640, (2000).

[13] Katto, Y. and Ohno, H., "An improved version of the generalized correlation of critical heat flux for the forced convective boiling in uniformly heated vertical tubes," *International journal of heat and mass transfer*, 27(9), pp. 1641–1648, (1984).

[14] Koşar, A., Kuo, C.-J., and Peles, Y., "Boiling heat transfer in rectangular microchannels with reentrant cavities," *International Journal of Heat and Mass Transfer*, 48(23-24), pp. 4867–4886, (2005).

[15] Lee, P.-S., Garimella, S. V., and Liu, D., "Investigation of heat transfer in rectangular microchannels," *International Journal of Heat and Mass Transfer*, 48(9), pp. 1688–1704, (2005).

[16] Obot, N., "Toward a better understanding of friction and heat/mass transfer in microchannels–a literature review," *Microscale Thermophysical Engineering*, 6(3), pp. 155–173, (2002).

[17] Palm, B., "Heat transfer in microchannels," *Microscale Thermophysical Engineering*, 5(3), pp. 155–175, (2001).

[18] Qu, W. and Mudawar, I., "Measurement and correlation of critical heat flux in two-phase micro-channel heat sinks," *International Journal of Heat and Mass Transfer*, 47(10-11), pp. 2045–2059, (2004).

[19] Roday, A. and Jensen, M., "Study of the critical heat flux condition with water and R-123 during flow boiling in microtubes. Part I: Experimental results and discussion of parametric effects," *International Journal of Heat and Mass Transfer*, 52(13-14), pp. 3235–3249, (2009).

[20] Roday, A. and Jensen, M., "Study of the critical heat flux condition with water and R-123 during flow boiling in microtubes. part ii–comparison of data with correlations and establishment of a new subcooled CHF correlation," *International Journal of Heat and Mass Transfer*, 52(13-14), pp. 3250–3256, (2009).

[21] Shah, M. M., "Improved general correlation for critical heat flux during upflow in uniformly heated vertical tubes," *International Journal of Heat and Fluid Flow*, 8(4), pp. 326–335, (1987).

[22] Wojtan, L., Revellin, R., and Thome, J. R., "Investigation of saturated critical heat flux in a single, uniformly heated microchannel," *Experimental Thermal and Fluid Science*, 30(8), pp. 765–774, (2006).

[23] Zhang, W., Hibiki, T., Mishima, K., and Mi, Y., "Correlation of critical heat flux for flow boiling of water in mini-channels," *International Journal of Heat and Mass Transfer*, 49(5-6), pp. 1058–1072, (2006).