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Status of prediction methods for critical heat fluxes in mini and microchannels

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ABSTRACT

Saturated critical heat flux (CHF) is an important issue during flow boiling in mini and microchannels. To determine the best prediction method available in the literature, 2996 data points from 19 different laboratories have been collected since 1958. The database includes nine different fluids (R-134a, R-245fa, R-236fa, R-123, R-32, R-113, nitrogen, CO_2 and water) for a wide range of experimental conditions. This database has been compared to 6 different correlations and 1 theoretically based model. For predicting the non-aqueous fluids, the theoretical model by Revellin and Thome [Revellin, R., Thome, J.R., 2008. A theoretical model for the prediction of the critical heat flux in heated microchannels. Int. J. Heat Mass Transfer 51, 1216–1225] is the best method. It predicts 86% of the CHF data for non-aqueous fluids within a 30% error band. The data for water are best predicted by the correlation by Zhang et al. [Zhang, W., Hibiki, T., Mishima, K., Mi, Y., 2006. Correlation of critical heat flux for flow boiling of water in minichannels. Int. J. Heat Mass Transfer 49, 1058–1072]. This method predicts 83% of the CHF data for water within a 30% error band. Some suggestions have also been proposed in this paper for the future studies.

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1. Introduction

Boiling heat transfer in so-called "microchannels" or "minichannels" holds great promise to replace air-cooling and water-cooling of microprocessor chips. The increasing demand for dissipating high heat fluxes from plasma-facing components in a nuclear fusion reactor, solid targets of a high power accelerator, etc. are also great challenges (Zhang et al., 2006). Flow boiling is a topic that has been increasingly investigated in the last decade but requires the development of reliable and accurate design tools based on extensive experimental investigations to reach its technological potential.

However, high heat flux flow boiling is limited by the critical heat flux (CHF) or burnout. When the liquid, in contact with the heated surface, is replaced with a vapor blanket, the surface heat transfer coefficient drops dramatically which results in a sudden increase of the surface temperature and possible failure of the cooled device. CHF may occur in subcooled as well as in saturated boiling conditions. In subcooled CHF, the bulk temperature at the channel outlet is subcooled and the thermodynamic equilibrium vapor quality is lower than zero, $x < 0$. These are the typical conditions for very high mass velocities, high inlet subcoolings and relative short channels compared to their hydraulic diameters. In saturated CHF, the thermodynamic equilibrium vapor quality at the channel outlet is greater or equal to zero, $x \geqslant 0$. This is typically encountered at low mass velocities, at low inlet subcoolings and in channels with a large length to diameter ratio. In this paper we will focus on the saturated CHF that are representative of computer chip cooling applications.

CHF prediction and analysis are complex. Physics explaining the phenomena is so far not well understood and most of the authors propose their own correlation. The question raised after studying the existing works is: What is the best CHF prediction method for saturated flow conditions? The aim of this paper is to answer this question. To begin with, we will present the database collected for this study. Thereafter, we will present the different prediction methods available in the literature. Finally, we will suggest some relevant issues for future CHF studies.

2. Presentation of the database

The ranges of experimental conditions for the entire database (2996 data points from 19 different laboratories) are presented in Table 1. Since the experimental parameters for water are much different from those for the non-aqueous fluids, the database is separated into two distinct groups: the non-aqueous fluids and water.

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Nomenclature

Bo	bond number (–)
Co	confinement number (–)
c_p	specific heat capacity at constant pressure (J/kg K)
CHF	critical heat flux (kW/m^2)
D	diameter (m)
Δh_{sub}	inlet enthalpy of subcooling (J/kg)
g	acceleration of gravity (m/s^2)
G	mass flux (kg/m^2 s)
H	height of the channel (m)
h_{lv}	latent heat of vaporization (J/kg)
k	thermal conductivity (W/m K)
K	empirical inlet subcooling parameter of Katto and Ohno (–)
K'	empirical inlet subcooling parameter of Qi et al. (–)
L	length (m)
$\dot{m}$	mass flow (kg/s)
MAE	mean absolute error = $\frac{1}{N}\sum_1^N \left\lvert\frac{\text{predicted value}-\text{experimental value}}{\text{experimental value}}\right\rvert \times 100\%$
MRE	mean relative error = $\frac{1}{N}\sum_1^N \left(\frac{\text{predicted value}-\text{experimental value}}{\text{experimental value}}\right) \times 100\%$
n	exponent of Y in Shah's correlation (–)
p	pressure (Pa)
p_r	reduced pressure (–)
q	heat flux (W/cm^2)
q_{co}	saturated CHF of Katto and Ohno (kW/m^2)
R	internal radius of the tube (m)
T	temperature (°C)
ΔT_{sub}	inlet subcooling temperature (K)
u	velocity (m/s)
W	width of the channel (m)
We_D	Weber number based on the diameter (–)
We_{lo}	Weber number for liquid only (–)
x	vapor quality (–)
Y_{shah}	Shah's correlating parameter (–)

Greek letters

δ	liquid film thickness (μm)
$\Delta\delta_i$	height of the interfacial waves (μm)
λ	percentage of data within ±30% error band (%)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	shear stress (N/m^2)

Subscripts

chf	critical heat flux
do	dryout
eq	equivalent
in	inlet
l	liquid
lv	liquid to vapor
sat	saturation
sub	subcooling
v	vapor

2.1. Database for non-aqueous fluids

Fig. 1a presents the repartition of the database as a function of the fluids. The database includes 8 different non-aqueous fluids. Almost 70% of this database concern the following synthetic refrigerants: R-134a, R-245fa and R-236fa. About 8% of the data are dedicated to CO_2 and 8% to R-113. Nitrogen, R-32 and R-123 complete this database which comprises 569 experimental data coming from 12 different papers and from 10 different laboratories.

The repartition of the database as a function of the reduced pressure is shown in Fig. 1b: $0.036 \leqslant p_r \leqslant 0.688$. Most of the data display a reduced pressure less than 0.3. As expected, all CO_2 data belong to a range of p_r comprised between 0.45 and 0.7. Usually, CO_2 is evaporated at much higher reduced pressures than other refrigerants. High vapor density, a surface tension lower by one order of magnitude and a low vapor viscosity drastically influence the hydrodynamic and heat transfer characteristics of CO_2 in comparison with synthetic refrigerants. The question emerging from this observation is: "Is CO_2 a maverick fluid for the critical heat flux?" It is of importance to note here that the data for carbon dioxide were given in the original articles as dryout vapor qualities. As a result, the CHF data used in this paper have been calculated using a heat balance between the fluid and the wall and assuming that dryout occurred at the outlet of the channel without any inlet subcooling. The heat balance is given as follows:

$$x_{do} = \frac{4q_{chf}L}{Gh_{lv}D} \quad (1)$$

Fig. 1c presents the distribution of the database as a function of the diameter: $0.29 \leqslant D \leqslant 3.15$ mm. In addition, Fig. 1d shows the number of data points versus the bond number $(\mathrm{Bo} = (\rho_l - \rho_v)gD^2/\sigma)$: $0.09 \leqslant \mathrm{Bo} \leqslant 13.99$. The vertical line corresponds to the transition between micro/minichannel proposed by Kew and Cornwell (1997). The latter uses the confinement number, Co, which is related to the bond number, Bo, by the following relation: $\mathrm{Bo} = \mathrm{Co}^{-2}$. As the Kew and Cornwell criterion identifies the microscale region when $\mathrm{Co} > 0.5$, this yields $\mathrm{Bo} < 4.0$. This transition reflects the balance between gravitational and surface tension forces (actually it is a measure of stratification). One can see that the database includes both micro and minichannels results.

The repartition of the inlet subcooling is presented in Fig. 1e. The database display a variation of the inlet subcooling from 0 to 74.41 K, which is a large range. The highest subcooling has been measured for R-113. For very high subcoolings, we can suspect some CHF datapoints to be in the subcooled region, which is not the purpose of the present paper (saturation CHF). However, as we have no means to determine whether the datapoints are in the subcooled region or not, we will trust the results presented in the papers. For the interested readers, they should refer to the paper of Celata et al. (1992) who present data for small diameter channels in subcooled region. Fig. 1f shows the repartition of the data points as a function of the mass velocity. The range of G is comprised between 27.9 and 3736.1 kg/m^{2}s. The variation of all the experimental parameters is therefore important. In this database, different geometries may be encountered: single tube, multiple tubes and multi-rectangular microchannels. The equivalent diameter in the case of rectangular channels is given by the following relation:

$$D_{eq} = \frac{4 \cdot H \cdot W}{2 \cdot H + W} \quad (2)$$

with H the height of the rectangular channel and W its width. This equivalent diameter corresponds to the "heated" diameter of a multi-microchannel heat sink heated at the bottom. The mass velocities input into the various methods are the actual values based on the

Table 1
Experimental conditions of the entire database. ○: single round tube; ○○○: multi-round tubes; ⊔⊔⊔: multi-rectangular channels.

Author	Geometry	Fluids	D (mm)	L (mm)	$p_{sat,in}$ (bar)	$T_{sat,in}$ (°C)	G (kg/m²s)	ΔT_{sub} (K)	q (kW/m²)
Wojtan et al. (2006)	○	R-134a/R-245fa	0.500-0.800	20.15-70.70	2.42-9.49	30.41-41.72	354.1-1533.3	4.43-11.97	114.40-596.96
Lazarek and Black (1982)	○	R-113	3.150	126.00	1.23-4.25	53.71-98.91	232.0-740.0	2.16-74.41	189.00-336.00
Yun and Kim (2003)	○	CO_2	0.980-2.00	400.00-1200.00	34.81-44.97	0.00-10.00	500.0-2000.0	0.00	7.90-40.00
Pettersen (2004)	○	CO_2	0.810	540.00	34.81-44.97	0.00-10.00	280.0-570.0	0.00	10.00-20.00
Jeong and Park (2007)	○	CO_2	0.800	1100.00	39.65-44.97	5.00-10.00	400.0-800.0	0.00	15.00-18.00
Agostini et al. (2008)	⊔⊔⊔	R-236fa	0.383	20.00	2.32-3.68	20.31-34.28	275.8-992.2	0.42-15.25	219.02-521.55
Park and Thome (in press)	⊔⊔⊔	R-134a/R-245fa/R-236fa	0.351-0.883	20.00	1.44-7.71	10.08-50.66	84.0-3736.1	−1.13 to 23.96	151.03-931.32
Bowers and Mudawar (1994)	○○○	R-113	0.510-2.540	10.00	1.38	57.20	27.9-476.5	20.00	320.27-1054.52
Hihara and Tanaka (2000)	○	CO_2	1.000	357.50	50.81	15.00	360.0-1140.0	0.00	8.00-37.50
Qi et al. (2007)	○	Nitrogen	0.531-1.931	250.00	2.02-9.09	−189.43 to −170.86	421.7-2799.5	4.23-23.44	87.13-233.71
Kosar and Peles (2007)	○	R-123	0.290	10.00	2.25-5.20	51.83-82.43	291.0-1118.0	26.83-57.43	286.97-1060.30
Del Col et al. (2008)	○	R-134a/R-32	0.960	52.49-202.93	7.93	31.00	101.2-605.1	5.00	33.87-219.16
Becker et al. (1965)	○	Water	3.930-6.070	1000.00-1500.00	11.28-69.65	185.18-285.49	486.5-8209.5	108.90-230.73	1587.00-5660.00
Kureta (1997)	○	Water	1.000-6.000	4.00-679.80	1.02	100.00	1.0-4105.0	0.00-93.30	93.47-31440.00
Lezzi et al. (1994)	○	Water	1.000	239.00-975.00	19.00-72.00	209.80-287.74	776.0-2738.0	−19.99 to 241.17	285.00-2363.00
Lowdermilk et al. (1958)	○	Water	1.300-4.800	65.00-1000.00	1.02	100.00	27.1-34171.2	0.00-78.90	167.22-41646.00
Roach et al. (1999)	○	Water	1.131-1.448	160.00	3.36-10.47	137.43-181.88	240.5-1036.9	66.16-131.62	860.00-3698.00
Griffel (1965)	○	Water	6.223	914.40	68.90-103.35	284.76-313.43	1672.8-13872.0	18.65-262.76	2601.90-7812.00
Nariai et al. (1989)	○	Water	1.000-3.000	50.00-100.00	1.02	100.00	7000.0-11000.0	16.68-70.94	4800.00-17000.00
Thompson and Macbeth (1964)	○	Water	1.016-5.740	25.40-3119.12	1.0473.44	100.46-289.09	13.0-10441.2	0.01-246.84	113.27-19277.05
Vandervort et al. (1994)	○	Water	0.330-2.016	6.79-51.71	1.31-22.77	107.33-219.03	5027.0-40280.0	8.56-96.67	19000.00-88400.01
Qu and Mudawar (2004)	⊔⊔⊔	Water	0.380	44.73	1.21-1.40	105.00-109.20	85.9-368.4	45.16-77.10	264.20-542.00

cross-sectional area of the channel (that is, they are not calculated using a hydraulic diameter).

2.2. Database for water

The database for water includes 2427 data points from 10 different laboratories since 1958. This is the same database used in the study by Zhang et al. (2006) plus the data of Qu and Mudawar (2004). The reduced pressure varies from 0.005 to 0.47 as shown in Fig. 2a. Most of the data (64%) exhibit a reduced pressure less than 0.05. The range of inside diameters (Fig. 2b) varies from 0.33 to 6.22 mm which corresponds to the following variation of the bond number: $0.02 \leqslant Bo \leqslant 20.97$ as shown in Fig. 2c. The database for water includes micro and minichannels based on the criterion by Kew and Cornwell (1997) ($Bo = 4$).

The mass velocity is expressed in Mg/m^2 s in Fig. 2d because of its high value during flow boiling of water (from 10^{-3} to 40.28 Mg/m^{2}s). Almost 76% of the data are less than 2 Mg/m^{2}s. The inlet subcooling reaches a value up to 261.8 K as shown in Fig. 1e.

The database for water display a very large variation of all experimental parameters. In this database, two different geometries may be encountered: single tube and multi-rectangular microchannels. The equivalent diameter in case of rectangular channels is given by Eq. (2).

3. Prediction methods

In this section, the different prediction methods used in the comparison are presented. They are composed of one theoretical model and six different correlations and are described below:

3.1. Theoretical model by Revellin and Thome (2008)

For predicting CHF, Revellin and Thome, 2008 have recently developed a model to predict the critical heat flux under uniform or non-uniform heat fluxes in microchannels. Solving the continuity, momentum and energy equations for an annular flow without interfacial waves, the solution gives the variation in the liquid film thickness (δ) along the channel. The value of CHF is determined by matching the local liquid film thickness to the height of the interfacial waves ($\delta = \Delta\delta_i$). Based on the slip ratio and the Kelvin–Helmoltz critical wavelength (assuming the film thickness to be proportional to the critical wavelength of the interfacial waves), the height of the waves is predicted to as:

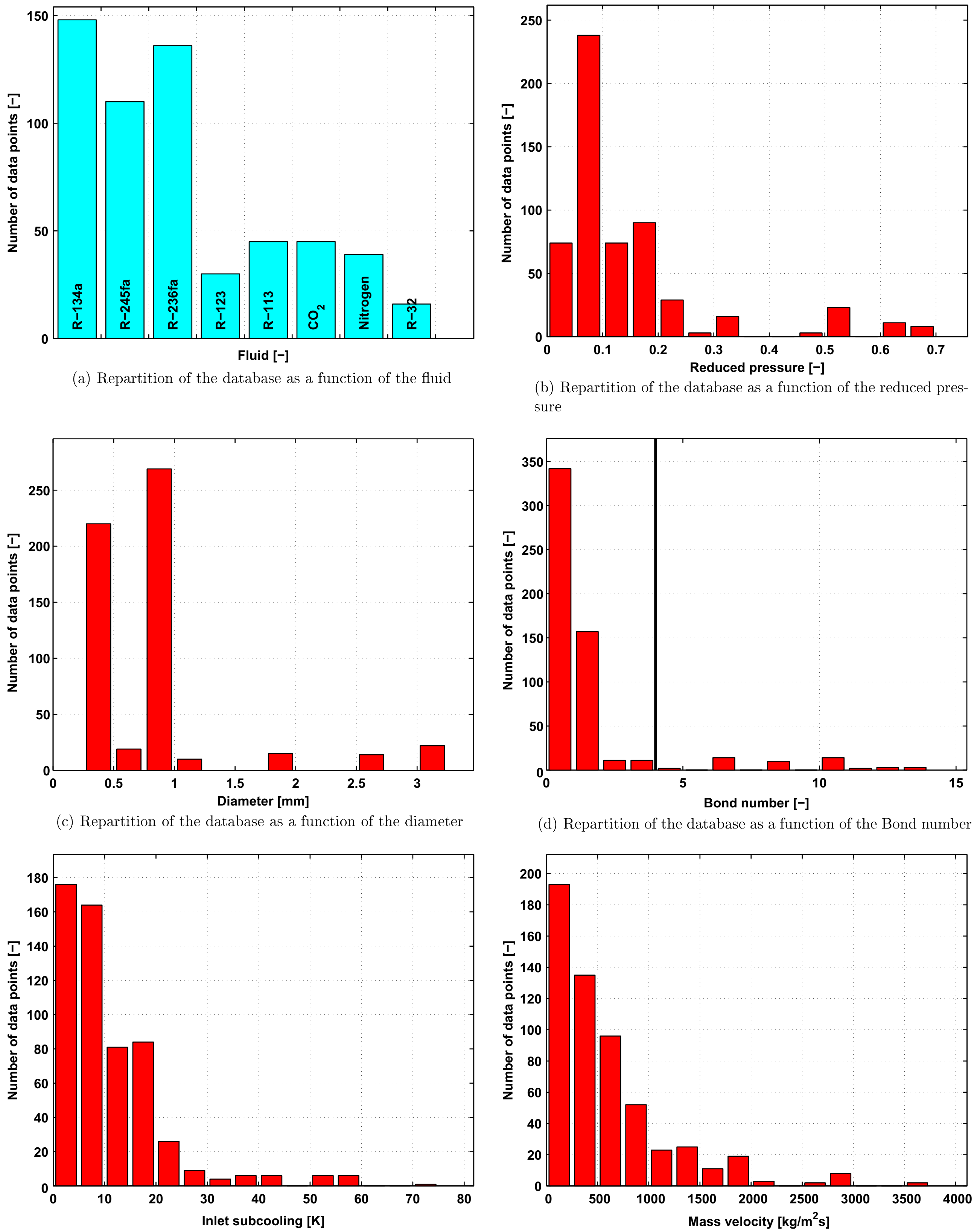
$$\Delta\delta_i = 0.15 \cdot R \left(\frac{u_v}{u_l}\right)^{-3/7} \left(\frac{(\rho_l - \rho_v) \cdot g \cdot R^2}{\sigma}\right)^{-1/7} \quad (3)$$

The three empirical constants were determined from the database of the studies by Wojtan et al. (2005) and Lazarek and Black (1982), predicting 96% of the data for three different refrigerants (R-113, R-134a and R-245fa) to within ±20%. It is of importance to say that the properties of the fluids were taken at the inlet of the channel.

When using this model, the number of discretization lengths should be set equal to 1000 and the initial radius should be set equal to 0.22R for all fluids.

3.2. Correlation by Wojtan et al. (2006)

Wojtan et al. (2006) proposed a simple correlation to predict their CHF data obtained for R-134a and R-245fa flowing in



(a) Repartition of the database as a function of the fluid

(b) Repartition of the database as a function of the reduced pressure

(c) Repartition of the database as a function of the diameter

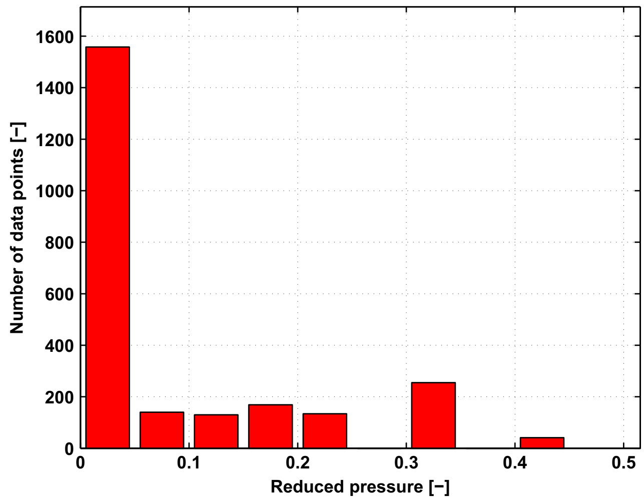
(d) Repartition of the database as a function of the Bond number

(e) Repartition as a function of the inlet subcooling.

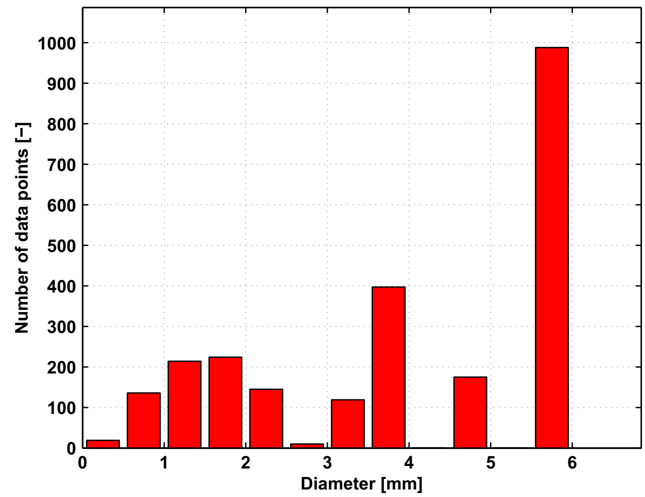
(f) Repartition as a function of the mass velocity.

Fig. 1. Repartition of the database for non-aqueous fluids.

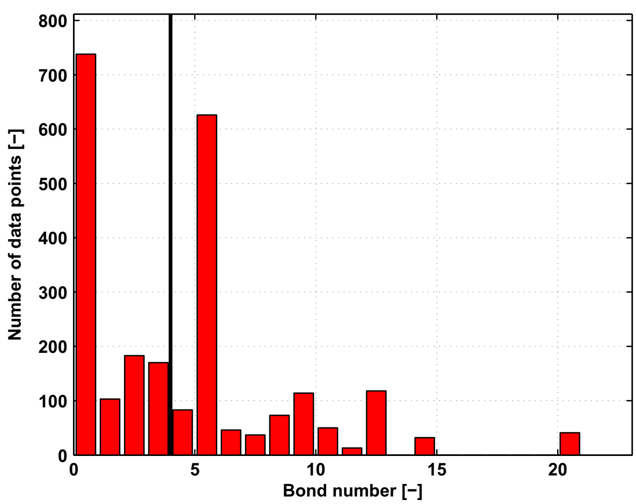
0.509 mm and 0.790 mm internal diameter microchannel tubes. The heated lengths of these microchannels were varied from 20 and 70 mm. The prediction of CHF during saturated boiling in microchannels was of the form:



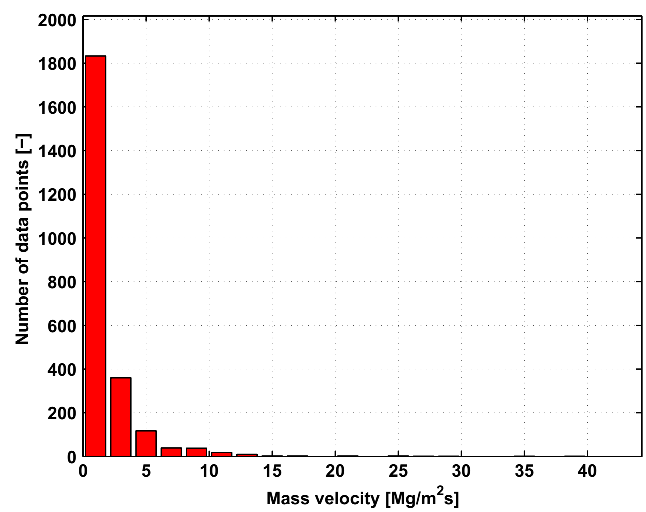
(a) Repartition of the database as a function of the reduced pressure



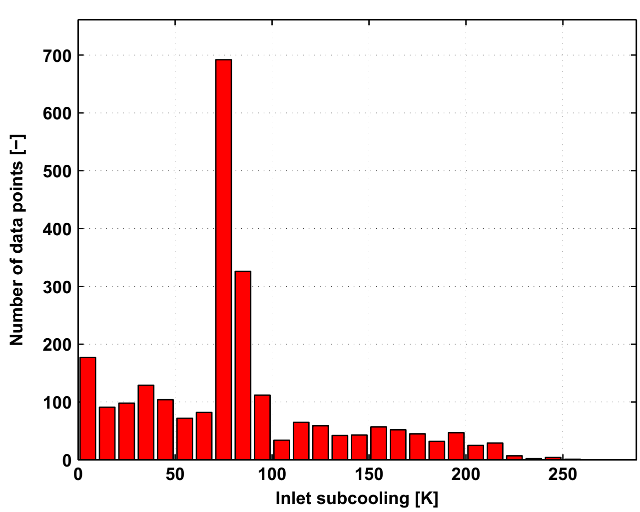
(b) Repartition of the database as a function of the diameter



(c) Repartition of the database as a function of the Bond number



(d) Repartition of the database as a function of the mass velocity



(e) Repartition as a function of the inlet subcooling

Fig. 2. Repartition of the database for water.

$$\frac{q_{chf}}{G \cdot h_{lv}} = 0.437 \left(\frac{\rho_v}{\rho_l}\right)^{0.073} We_{lo}^{-0.24} \left(\frac{L}{D}\right)^{-0.72} \quad (4)$$

with

$$We_{lo} = \frac{G^2 \cdot L}{\sigma \cdot \rho_l} \quad (5)$$

It is of importance to say that the properties of the fluids were taken at the inlet of the channel.

3.3. Correlation by Qi et al. (2007)

Qi et al. (2007) proposed a correlation based on 455 flow boiling nitrogen experimental data for 0.531, 0.834 and 1.042 mm microtubes. Their correlation is as follows:

$$\frac{q_{co}}{G \cdot h_{lv}} = (0.214 + 0.140\text{Co})\left(\frac{\rho_v}{\rho_l}\right)^{0.133} We_{lo}^{-1/3} \frac{1}{(1+0.03L/D)} \quad (6)$$

with

$$We_{lo} = \frac{G^2 \cdot L}{\sigma \cdot \rho_l} \quad (7)$$

and

$$\text{Co} = \left[\frac{\sigma}{(\rho_l - \rho_v)gD^2}\right]^{1/2} \quad (8)$$

Finally the expression of the critical heat flux is given by:

$$q_{chf} = q_{co}\left(1 + K' \frac{\Delta h_{sub}}{h_{lv}}\right) \quad (9)$$

If $1/We_{lo} < 3 \cdot 10^{-6}$, then

$$K' = 1.8\left(\frac{L}{130D}\right)^{(-5\rho_v/\rho_l)} \quad (10)$$

else

$$K' = 0.075\left(\frac{L}{130D}\right)^{(-5\rho_v/\rho_l)} We_{lo}^{0.25} \quad (11)$$

All the properties are taken at the outlet of the channel.

3.4. Correlation by Qu and Mudawar (2004)

The Katto–Ohno correlation was adapted by Qu and Mudawar (2004) for predicting their data for microchannel heat sinks containing 21 parallel 215 × 821 μm channels. According to the authors, due to flow instabilities, CHF was virtually independent of inlet subcooling. Their new empirical correlation based on their experimental CHF data for water and R-113 (Bowers and Mudawar (1994)) in mini/microchannel heat sinks is as follows:

$$\frac{q_{chf}}{G \cdot h_{lv}} = 33.43\left(\frac{\rho_v}{\rho_l}\right)^{1.11} We_{lo}^{-0.21}\left(\frac{L}{D_{eq}}\right)^{-0.36} \quad (12)$$

with

$$We_{lo} = \frac{G^2 \cdot L}{\sigma \cdot \rho_l} \quad (13)$$

This correlation predicted their experimental data with very low mean absolute error of 4%. All the properties should be taken at the outlet of the channel.

3.5. Correlation by Katto and Ohno (1984)

Katto and Ohno (1984) proposed one of the most widely used empirical methods developed for predicting saturated CHF in a single channel. For no liquid subcooling, they correlated CHF with q_{co} given as:

$$\frac{q_{co}}{G \cdot h_{lv}} = f\left[\frac{\rho_l}{\rho_v}, \frac{\sigma \cdot \rho_l}{G^2 \cdot L}, \frac{L}{D}\right] \quad (14)$$

For most regimes, they found a linear rise in CHF with increasing liquid subcooling. Therefore, subcooling was taken into account by the following equation:

$$\frac{q_{chf}}{G \cdot h_{lv}} = q_{co}\left(1 + K\frac{\Delta h_{sub}}{h_{lv}}\right) \quad (15)$$

To ascertain the applicability of the above correlation to fluids other than water, they conducted the following experiments:

- R-12 for $D = 3.0$ and 5.0 mm, $L/D = 200$ and 333, $\rho_v/\rho_l = 0.109–0.306$ and $G = 1100–8800$ kg/m² s in Katto and Yokoya (1982);
- R-12 for $D = 5.0$ mm, $L/D = 50$, $\rho_v/\rho_l = 0.109–0.306$ and $G = 700–7000$ kg/m² s in Katto and Ashida (1982);
- liquid helium for $D = 1.0$ mm, $L/D = 25–200$, $\rho_v/\rho_l = 0.409$ and $G = 10.5–108$ kg/m² s in Katto and Yokoya (1984).

Hence, for normal refrigerants this method is applicable only down to about 3.0 mm channels. The fluid properties are taken at the inlet of the channel.

3.6. Correlation by Zhang et al. (2006)

An extensive database including approximately 2500 saturated CHF data, from 10 different laboratories, for water flowing in small diameter tubes (0.33 < D < 6.22 mm) have been collected by Zhang et al. (2006). They proposed a new correlation based on the inlet conditions by doing parametric trend analysis of the collected database:

$$\frac{q_{chf}}{G \cdot h_{lv}} = 0.0352\left[We_D + 0.0119\left(\frac{L}{D}\right)^{2.31}\left(\frac{\rho_v}{\rho_l}\right)^{0.361}\right]^{-0.295} \cdot \left(\frac{L}{D}\right)^{-0.311} \times \left[2.05\left(\frac{\rho_v}{\rho_l}\right)^{0.170} - x_{in}\right] \quad (16)$$

with

$$We_D = \frac{G^2 \cdot D}{\sigma \cdot \rho_l} \quad (17)$$

All the fluid properties should be taken at the inlet of the channel.

3.7. Correlation by Shah (1987)

Shah (1987) proposed a correlation for CHF in uniformly heated vertical channels created from a database covering 23 fluids (water, cryogens, organics and liquid metals) for tube diameters varying from 0.315 mm to 37.5 mm and heated length to diameter ratios from 1.2 to 940, taking data from 62 independent sources. His correlation is given as follows:

$$\frac{q_{chf}}{G \cdot h_{lv}} = 0.124\left(\frac{L}{D}\right)^{-0.89}\left(\frac{10^4}{Y_{shah}}\right)^n (1 - x_{in}) \quad (18)$$

In this expression, the new parameter Y_{shah} is:

$$Y_{shah} = G^{1.8} \cdot D^{0.6}\left(\frac{c_p}{k_l \cdot \rho_l^{0.8} \cdot g^{0.4}}\right)\left(\frac{\mu_l}{\mu_v}\right)^{0.6} \quad (19)$$

When $Y_{shah} \leqslant 10^4$, $n = 0$. When $Y_{shah} > 10^4$, then n is calculated as follows:

$$Y_{shah} \leqslant 10^6, \quad n = \left(\frac{D}{L}\right)^{0.54} \quad (20)$$

$$Y_{shah} > 10^6, \quad n = \frac{0.12}{(1 - x_{in})^{0.5}}$$

The fluid properties are taken at the inlet of the channel.

4. Results

4.1. Non-aqueous fluids

Results of the comparison of the data for non-aqueous fluids with existing prediction methods are presented in Tables 2 and 3. The best predictions are highlighted in blue and underlined. It can be seen that the model by Revellin and Thome (2008) is by far the best prediction method for R-134a, R-245fa, R-236fa, R-113, R-32 and CO_2. It predicts nitrogen and R-123 data with less accuracy but it predicts 85.6% of the entire database for non-aqueous fluids within a ±30% error band. It is important to note that this database includes different geometries: single tube, multiple tubes and multi-rectangular microchannels coming from 10 different laboratories.

As expected, the correlation by Wojtan et al. (2006) predicts the refrigerant data well for R-134a, R-245fa, R-236fa and R-113 and the CO_2 data by Hihara and Tanaka (2000). However, the R-245fa experimental data by Park and Thome (in press) for multi-rectangular microchannels, the nitrogen, R-123 and CO_2 data are not well predicted.

The correlation by Qi et al. (2007) predicts its underlying data and those by Hihara and Tanaka (2000). The method by Qu and Mudawar (2004) does not predict any data for non-aqueous fluids well except for their own data. One is reminded, however, that this method was initially developed for water. The correlations by Katto and Ohno (1984) and Zhang et al. (2006) give good statistics for the data of Lazarek and Black (1982), Agostini et al. (2008) and Kosar and Peles (2007). Note that the method by Zhang et al. was also developed for water. Finally, Shah, 1987 correlation predicts correctly the data by Lazarek and Black (1982), Hihara and Tanaka (2000) and Qi et al. (2007).

As a first conclusion, we can mention that none of the correlations are able to correctly predict the entire database. The only satisfactory method is the model by Revellin and Thome (2008) which has been plotted as a function of the experimental data in Fig. 3.

4.2. Water

Tables 4 and 5 show the results of the comparison between the water data and the different prediction methods. The best predictions are highlighted in blue and underlined. The Revellin and Thome, 2008 model, the Wojtan et al., 2005 and Qi et al., 2007 correlations do not predict the data very well which is not surprising since these methods were initially developed for synthetic refrigerants or nitrogen.

Table 2
Experimental non-aqueous database compared to the prediction methods.

Author	Fluid	Number of data points	Revellin and Thome			Wojtan et al.			Qi et al.			Qu and Mudawar		
			λ	MAE	MRE	λ	MAE	MRE	λ	MAE	MRE	λ	MAE	MRE
Wojtan et al. (2006)	R-134a	29	100.0	8.9	2.7	93.1	13.2	12.4	0.0	165.1	165.1	0.0	1602.2	1602.2
–	R-245fa	4	100.0	7.2	−5.5	100.0	4.7	4.0	0.0	224.9	224.9	0.0	239.3	239.3
Lazarek and Black (1982)	R-113	22	100.0	7.3	−1.6	100.0	9.6	−6.7	50.0	33.0	33.0	22.7	125.6	125.6
Yun and Kim (2003)	CO_2	23	47.8	31.8	17.4	73.9	23.1	−10.6	47.8	29.0	−10.0	0.0	10926.8	10926.8
Pettersen (2004)	CO_2	5	100.0	9.3	2.6	20.0	45.4	45.4	0.0	85.9	85.9	0.0	21605.9	21605.9
Jeong and Park (2007)	CO_2	9	100.0	13.9	−6.1	0.0	82.4	82.4	0.0	77.7	77.7	0.0	35465.7	35465.7
Agostini et al. (2008)	R-236fa	25	100.0	12.0	−10.8	100.0	8.9	−0.8	0.0	253.9	253.9	0.0	258.8	258.8
Park and Thome (in press)	R-134a	106	84.0	17.3	−15.4	91.5	12.2	8.4	0.0	203.0	203.0	0.0	526.4	526.4
–	R-236fa	111	96.4	14.8	−7.5	72.1	20.5	16.9	0.0	243.7	243.7	0.0	330.5	330.5
–	R-245fa	106	92.5	14.5	−1.9	45.3	34.4	34.4	0.0	315.4	315.4	4.7	198.3	198.3
Bowers and Mudawar (1994)	R-113	23	100.0	12.1	−12.1	30.4	43.3	43.3	26.1	125.3	125.3	60.9	18.6	16.4
Hihara and Tanaka (2000)	CO_2	8	75.0	26.9	−8.7	100.0	19.7	−19.7	100.0	11.3	−2.1	0.0	13014.7	13014.7
Qi et al. (2007)	Nitrogen	39	59.0	27.3	−19.8	20.5	35.6	−35.6	100.0	6.7	2.1	0.0	664.4	664.4
Kosar and Peles (2007)	R-123	30	40.0	32.4	−32.4	33.3	42.8	42.8	0.0	417.9	417.9	0.0	406.5	406.5
Del Col et al. (2008)	R-134a	13	69.2	22.3	20.8	30.8	42.3	42.3	0.0	207.5	207.5	0.0	1890.4	1890.4
–	R-32	16	93.8	13.1	−7.5	68.8	22.1	21.2	0.0	135.1	135.1	0.0	3499.7	3499.7
		569	85.6	17.0	−7.9	64.9	25.1	15.8	13.2	206.0	203.9	4.2	1883.9	1883.3

Table 3
Experimental non-aqueous database compared to the prediction methods.

Author	Fluid	Number of data points	Katto and Ohno			Zhang et al.			Shah		
			λ	MAE	MRE	λ	MAE	MRE	λ	MAE	MRE
Wojtan et al. (2006)	R-134a	29	48.3	36.4	34.4	51.7	36.7	33.7	75.9	20.5	6.2
–	R-245fa	4	100.0	6.0	−5.9	100.0	9.6	−9.6	50.0	28.7	−28.7
Lazarek and Black (1982)	R-113	22	100.0	13.4	−12.3	100.0	20.5	−20.1	90.9	13.8	3.8
Yun and Kim (2003)	CO_2	23	26.1	65.3	64.2	13.0	108.1	108.1	43.5	52.7	42.6
Pettersen (2004)	CO_2	5	0.0	69.2	69.2	0.0	94.7	94.7	0.0	84.0	84.0
Jeong and Park (2007)	CO_2	9	0.0	113.9	113.9	0.0	158.6	158.6	0.0	168.7	168.7
Agostini et al. (2008)	R-236fa	25	100.0	18.5	−18.1	100.0	16.4	−16.0	8.0	36.2	−36.2
Park and Thome (in press)	R-134a	106	71.7	22.2	−10.7	71.7	23.3	−16.1	29.2	35.7	−35.7
–	R-236fa	111	67.6	21.2	−13.4	76.6	20.2	−16.7	27.0	34.4	−34.4
–	R-245fa	106	78.3	22.5	−10.4	64.2	25.4	−15.1	30.2	33.4	−32.3
Bowers and Mudawar (1994)	R-113	23	30.4	36.2	−36.2	0.0	51.5	−51.5	39.1	34.7	−34.7
Hihara and Tanaka (2000)	CO_2	8	75.0	29.5	29.5	37.5	58.9	58.9	100.0	16.1	15.8
Qi et al. (2007)	Nitrogen	39	94.9	12.8	5.2	64.1	24.1	20.5	100.0	11.8	−2.7
Kosar and Peles (2007)	R-123	30	96.7	14.3	−0.1	93.3	15.2	8.0	63.3	22.8	18.7
Del Col et al. (2008)	R-134a	13	61.5	33.6	33.6	53.8	34.8	34.8	92.3	11.7	10.9
–	R-32	16	6.3	44.8	44.8	6.3	50.8	50.8	6.3	45.2	45.2
		569	69.1	26.3	0.2	63.6	31.7	1.6	41.7	33.7	−14.4

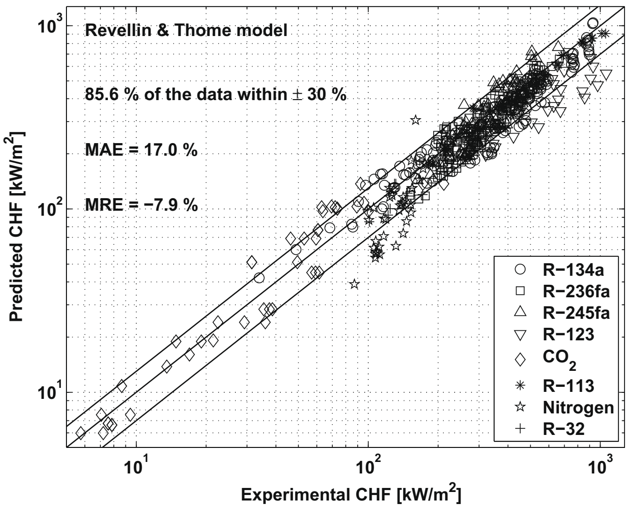


Fig. 3. Comparison between the Revellin and Thome (2008) model and the non-aqueous database.

The Qu and Mudawar, 2004 correlation predicts only its underlying database. This may be attributed to the presence of oscillations as mentioned by the authors.

The Shah's correlation and the Katto and Ohno's correlation predict the water data with a reasonable accuracy; however the best method is that by Zhang et al. (2006) which is not surprising since this correlation was specifically developed for this database (except for the data by Qu and Mudawar). The latter predicts almost 83% of the entire database within a ±30% error band as shown in Fig. 4. Note that this method does not predict the data by Qu and Mudawar (2004) which may be mainly attributed to the presence of oscillations during Qu and Mudawar's CHF tests. So far for water the Zhang et al. correlation predicts only single round tube data. We cannot go further in the conclusion since there is a lack of experimental data under stable conditions for multi-rectangular channel heat sinks with water. However, assuming the flow is well distributed and not subject to flow oscillations, their correlation can be expected to work.

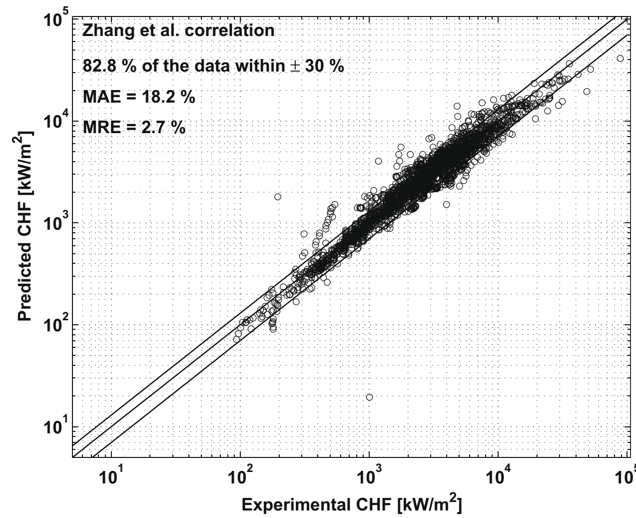


Fig. 4. Comparison between the Zhang et al. (2006) correlation and the database for water.

Table 4
Experimental database for water compared to the prediction methods.

Author	Fluid	Number of data points	Revellin and Thome			Wojtan et al.			Qi et al.			Qu and Mudawar		
			λ	MAE	MRE	λ	MAE	MRE	λ	MAE	MRE	λ	MAE	MRE
Becker et al. (1965)	Water	210	88.6	17.8	−2.8	3.8	44.4	−44.4	24.3	37.9	−37.9	0.0	475.7	475.7
Kureta (1997)	Water	745	51.1	43.6	16.5	9.9	210.2	209.6	2.8	281.9	281.8	0.1	74.0	−74.0
Lezzi et al. (1994)	Water	87	11.5	50.9	−50.9	21.8	34.9	−34.9	98.9	14.6	−6.4	0.0	1884.8	1884.8
Lowdermilk et al. (1958)	Water	551	17.6	50.6	−48.3	54.5	32.8	3.9	33.0	81.2	72.9	0.0	78.7	−78.4
Roach et al. (1999)	Water	72	8.3	49.4	−49.4	80.6	19.6	9.6	0.0	179.3	179.3	34.7	61.8	47.7
Griffel (1965)	Water	73	4.1	130.0	130.0	20.6	38.7	−38.7	6.9	40.3	−40.3	0.0	1910.6	1910.6
Nariai et al. (1989)	Water	40	87.5	15.6	−13.0	0.0	93.5	93.5	0.0	166.8	166.8	2.5	63.5	−63.5
Thompson and Macbeth (1964)	Water	613	43.6	46.8	11.0	32.1	45.6	0.7	30.0	101.8	60.7	0.0	824.3	806.9
Vandervort et al. (1994)	Water	18	50.0	33.7	15.6	11.1	83.9	80.3	5.6	243.0	243.0	5.6	65.3	29.3
Qu and Mudawar (2004)	Water	18	0.0	57.8	57.8	0.0	342.6	342.6	0.0	3234.9	3234.9	100.0	5.0	−0.4
		2427	41.0	46.4	−2.4	27.7	95.0	64.1	21.8	169.6	147.5	1.9	418.4	330.1

Table 5
Experimental database for water compared to the prediction methods.

Author	Fluid	Number of data points	Katto and Ohno			Zhang et al.			Shah		
			λ	MAE	MRE	λ	MAE	MRE	λ	MAE	MRE
Becker et al. (1965)	Water	210	47.1	28.6	−28.5	94.8	12.0	7.1	99.5	11.0	−6.5
Kureta (1997)	Water	745	62.4	35.9	32.6	72.6	21.1	−0.6	53.3	40.5	30.8
Lezzi et al. (1994)	Water	87	88.5	14.5	−12.0	97.7	9.1	7.5	96.6	14.5	13.3
Lowdermilk et al. (1958)	Water	551	82.4	20.6	−1.6	94.0	15.9	−4.3	90.0	17.1	−1.2
Roach et al. (1999)	Water	72	75.0	21.8	−1.8	79.2	21.2	−3.1	77.8	20.6	−8.6
Griffel (1965)	Water	73	21.9	38.4	−38.4	84.9	16.9	8.8	72.6	23.9	14.2
Nariai et al., 1989	Water	40	75.0	28.1	7.6	65.0	29.3	26.7	67.5	25.8	0.7
Thompson and Macbeth (1964)	Water	613	76.8	21.8	−13.4	82.5	16.7	6.9	86.3	16.7	5.9
Vandervort et al. (1994)	Water	18	55.6	33.0	−33.0	83.3	17.3	−13.8	5.6	48.3	−48.3
Qu and Mudawar (2004)	Water	18	0.0	157.7	157.7	5.6	102.9	102.9	0.0	121.9	121.9
		2427	69.1	27.9	3.2	82.8	18.2	2.7	76.3	25.0	11.3

5. Discussion

When using the prediction methods, one must pay attention to the temperature (or pressure) at which the properties are taken. This aspect is hardly ever specified in the publications which can lead to a wrong use of the correlation or model. As an example, the data by Qi et al. (2007) are well predicted by the author's correlation (100% of the data within a ±30% error band, MAE = 6.7%) when taking the properties at the outlet of the channel. On the contrary, when the properties are taken at the inlet, only 97.4% of the data are predicted within a ±30% error band, with a MAE = 9.2%. Actually, along a mini or microchannel, the pressure drop is significant and can lead to an important variation of the properties from the inlet to the outlet of the channel. Del Col et al. (2008) mentioned in their paper that the mean saturation temperature for their CHF tests was nearly constant all along the channel and equal to 31 °C for a 0.96 mm diameter, which is not necessarily correct for smaller channels. This type of information should be better mentioned in future articles on CHF.

Another important point has been raised during this study: the definition of the non-dimensional numbers. In some articles, the non-dimensional groups are not well defined and this could lead to a wrong use of the prediction methods. A simple example could be the Weber number. This group may be defined by two different expressions: Eq. (13) or Eq. (17). The replacement of one definition by the other could be disastrous for the calculation. It is thus important to clearly define such non-dimensional groups.

Qu and Mudawar (2004) performed tests on CHF with the presence of oscillations. Their data obtained under oscillations are unique and cannot be compared with any other data. They mentioned in their paper that as CHF was approached, flow instabilities induced vapor backflow into the heat sink's upstream plenum, which significantly altered the coolant temperature at the channel inlets. According to them, the backflow negated the advantages of inlet subcooling, resulting in a CHF virtually independent of inlet temperature but which increases with increasing mass velocity. To avoid such problems, Park and Thome, in press and Agostini et al., 2008 both used small orifices at the inlet of each channel in order to reduce flow oscillations and backflow. Wojtan et al. (2005) installed a micro-valve at the inlet of their test section (single round tube) to avoid any backflow. It is important to suppress oscillations during CHF tests in order to get unbiased results.

For circular channels, the wall heat flux is easy to determine. It corresponds to the total heat rate $\dot{Q}$ divided by the internal surface of the tube: πDL. However, for multi-rectangular channels, the heat flux is measured at the base of the heat sink which is different from the wall heat flux determined by the correlations. As a result, it is important to accurately calculate the wall heat flux from the base heat flux. A first approximation would be to calculate the wall heat flux using a simple area ratio between the base surface of the heat sink and the wall surface of the channels, as performed by Qu and Mudawar (2004). However, this approach does not take into account the fin efficiency, in other words the conduction effect. Indeed, it assumes an infinite conduction in the heat sink which is not correct. On the contrary, Agostini et al., 2008 and Park and Thome, in press both calculated the wall heat flux using the fin efficiency. This approach is better and we see that their data can be predicted by the conventional models initially developed for a single round tube. As an example, Agostini et al., 2008 measured under certain conditions a base heat flux of 214 W/cm^2 and calculated a wall heat flux of 44.4 W/cm^2 using a fin efficiency of 0.9. If they had used a simple area ratio between the base surface of the heat sink and the wall surface of the channels, which means a fin efficiency of 1.0, they would have calculated a wall heat flux of 40.8 W/cm^2. The error would have been around 8% which is not negligible. Furthermore, the aspect ratio could play an important role. If the height of the channel is much longer than the width, then the flow configuration will be different than for a square channel (aspect ratio equal to 1) and CHF will probably be affected. Besides, the thin liquid film will likely behave differently in a round tube than in a channel with sharp angled corners. Finally, even if the Revellin and Thome, 2008 model correctly predicts the data for multi-rectangular channels, the physics of CHF in these geometries should be investigated to better understand the effects of the geometry on the evaporating liquid film.

In general, whatever is the fluid, saturated CHF shows the following behavior, maintaining the other properties constant:

- When G increases, CHF increases.
- When D increases, CHF increases. Note that in forced convection subcooled boiling, some authors (Kureta, 1997 and Nariai et al., 1989) pointed out the opposite behavior.
- When L increases, CHF decreases.
- When ΔT_{sub} increases, CHF increases.
- When P_{sat} increases, CHF increases.

Finally, it is possible to answer the following question: Is CO_2 a "maverick" fluid? As it was shown in the results, it is possible to predict all the data for carbon dioxide and non-aqueous fluids using a unique model (Revellin and Thome, 2008). However, it is also shown that CHF for water is difficult to predict with non-aqueous fluid models or correlations and inversely. This could be due to the high surface tension (multiplied by 6 for a given pressure compared to R-134a) and the low vapor density (divided by 10 for a given pressure compared to R-134a). As a consequence, the idea for the future is to complete the Revellin and Thome, 2008 model in order to take into account other phenomena (e.g. droplet redeposition) to improve the reliability of the method.

6. Conclusion

Saturated critical heat flux (CHF) is an important issue during flow boiling in micro and mini minichannels. It determines the upper limitation of a two-phase cooling system. CHF prediction and analysis are complex. Physics explaining the phenomena is so far not well understood and most of the authors propose their own correlation to fit newly obtained data. The question raised after studying the existing works is: What is the best CHF prediction method?

To answer this question, 2996 data points from 19 different laboratories have been collected since 1958. The database includes nine different fluids (R-134a, R-245fa, R-236fa, R-123, R-32, R-113, nitrogen, CO_2 and water) for a wide range of experimental conditions. This database has been compared to six different correlations and one theoretical model.

For predicting the non-aqueous fluids, the theoretical model by Revellin and Thome (2008) is the best method. It predicts almost 86% of the CHF data for non-aqueous fluids within a 30% error band. The data for water are well predicted by the correlation by Zhang et al. (2006). This method predicts almost 83% of the CHF data for water within a 30% error band.

In general, future studies should pay attention to:

- Explicitly mention the temperature (inlet or outlet) at which the properties should be taken for the use of the correlations or models. In small channels, pressure drop becomes significant from the inlet to the outlet of the channel and properties vary.
- Explicitly define the non-dimensional groups used in the prediction methods.
- Avoid oscillations in the two-phase system in order to get reliable results.

– Take into account the conduction effect in the multi-rectangular heat sinks (fin efficiency) in the determination of the value of CHF.
– Study the effect of the aspect ratio of rectangular channels on CHF.
– Advance the existing models to better account for the flow characteristics and perhaps flow pattern effects.

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