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Correlations of Flow Boiling Heat Transfer of R-134a in Minichannels:

Comparative Study

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Abstract: R-134a is one of the most widely used refrigerants, and minichannel refrigeration systems with R-134a have rapidly developed in many fields, such as home, automobile and aircraft air conditioning systems, for high efficiency operations to save energy and space. A number of correlations for flow boiling hear transfer have been proposed. There is some literature to evaluate existing correlations for R-134a flow boiling heat transfer in minichannels. However, they were only based on the authors own experimental data. Therefore, results are often not consistent, even controversial. Our efforts are devoted to develop a better flow boiling heat transfer correlation for R-134a in minichannels, and this paper presents the first part of our efforts: A comparative study of existing correlations for flow boiling hear transfer of R-134a in minichannels. From 9 published papers, 1158 data points of flow boiling heat transfer of R-134a in minichannels are collected. Eighteen flow boiling heat transfer correlations, including almost all well-known ones, are reviewed and compared with the data collected. It is found that no correlation has satisfactory accuracy. The best one has a mean absolute relative deviation above 36%. It is interesting to note that among the six best correlations, one was developed for pool boiling and two were developed for conventional channels, and most of correlations developed specially for minichannels do not work quite well. More efforts should be made to better understand the mechanism of flow boiling heat transfer in minichannels for developing better correlations.

Key words: R-134a; Flow boiling; Heat transfer; Correlation; Minichannel

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Nomenclature

Bo	boiling number, $q/(h_{lg}G_{tp})$
C	Chisholm parameter
Co	convective number, $(1/x\text{-}1)^{0.8}(\rho_g/\rho_l)^{0.5}$
Co_f	confinement number, $\sqrt{\sigma/[g(\rho_l-\rho_g)D_h{}^2]}$
c_p	specific heat at constant pressure (J/kg·K)
$\overline{c_p}$	average specific heat at constant pressure (J/kg·K)
D	inner diameter (m)
D_h	hydraulic diameter (m)
F	Reynolds number factor
f	Moody friction factor
F_f	fluid-surface parameter
Fr	Froude number
G	mass flux (kg/m^2·s)
g	acceleration due to gravity (m/s^2)
Gr	Grashof number
h	specific enthalpy (J/kg); heat transfer coefficient (W/m^2·K)
h_{lg}	latent heat of vaporization (J/kg)
L	tube length (m)
M	molecular mass, kg/kmol
Nu	Nusselt number
p	pressure (Pa)
Δp_{sat}	difference in vapor pressure corresponding to ΔT_{sat}
P_R	reduced pressure, p/p_{crit}
Pr	Prandtl number
$\overline{Pr}$	average Prandtl number
q	heat flux from tube wall to fluid (W/m^2)
Re	Reynolds number
S	suppression factor
T	temperature (K)
T_R	reduced temperature, T/T_{crit}
ΔT_{sat}	superheat, T_w - T_{sat}
t	temperature (°C)
We	Weber number
X	Martinelli parameter
x	vapor quality

Greek Symbols

β	thermal expansion coefficient (1/K)
θ	aspect ratio: height to width of channel cross-section
λ	thermal conductivity (w/m·K)
Δ	increment
ε	channel surface roughness (μm)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ϕ^2	two-phase friction multiplier

Subscripts

$crit$	critical point
exp	experimental
g	saturated vapor
go	all flow taken as vapor
in	channel inlet
l	saturated liquid
lo	all flow taken as liquid
m	average
nb	nucleate boiling
out	channel outlet
$pred$	predicted
sat	saturated state
sp	single-phase
tp	two-phase
t	turbulent
w	at inner wall temperature

1. INTRODUCTION

HFC refrigerant R-134a is one of the most widely used refrigerant in many home, automobile and aircraft air conditioning systems. With the increasing demand for energy conservation and space saving, the design of more efficient and compact air conditioning systems is increasingly important, resulting in wide applications of minichannel evaporators not only in high-tech sects such as aeronautical and aerospace fields, but also in conventional industries. Consequently, flow boiling heat transfer in minichannels has received considerable investigations in the last 20 years and is still an intense research spot. A number of correlations for flow boiling hear transfer have been proposed, among which most are empirically formulated from data analysis. However, flow boiling heat transfer of R-134a in minichannels remains a problem unsolved and controversial opinions are not uncommon.

Unlike flow in conventional channels, the mechanism of R-134a flowing in minichannels is still not very clear. Kaew-On et al. (2011) presented the experimental results of flow boiling heat transfer characteristics of R-134a in the multi-port minichannel heat exchangers of the internal hydraulic diameter of 1.1 mm and 1.2 mm, respectively. The experimental ranges are the heat flux of 15 - 65 kW/m^2, mass flux of 300 - 800 kg/m^2, and saturation pressure of 4 - 6 bar. They found that the flow boiling regime corresponded to nucleate boiling, and thus the average heat transfer coefficients increase with increasing heat flux while being independent of the vapor quality and mass flux. Saisorn et al. (2010) investigated experimentally flow boiling heat transfer of R-134a in a circular mini-channel of 600 mm long and 1.75 mm inner diameter (ID) in the range of the mass flux of 200 - 1000 kg/m^{2}s, heat flux of 1 - 83 kW/m^2, and saturation pressures of 8, 10, and 13 bar. They obtained the similar findings with those of Kaew-On et al. (2011).

Shiferaw et al. (2007, 2009) conducted R-134a flow boiling heat transfer experiments with stainless steel tubes of 4.26 mm, 2.01 mm, and 1.1 mm ID in the parameter ranges of the mass flux of 100 - 600 kg/m^{2}s, heat flux of 13 - 150 kW/m^2, pressure of 6 - 12 bar, and vapor quality up to 0.9, They found that the local heat transfer coefficient increased with the heat flux and system pressure, but was independent of vapor quality when this was less than about 40 - 50% in the 4.26 mm tube, 20 - 30% in the 2.01 mm tube, and about 50% in the 1.1 mm tube, which could be interpreted that at low quality the flow boiling is dominated by nucleate boiling. Local transient dryout was deduced when the quality was above these values. The effect of mass flux was observed to be insignificant.

In and Jeong (2009) investigated flow boiling heat transfer of R-134a in a single circular micro-channel of 0.19 mm ID under experimental conditions of the heat flux of 10 - 20 kW/m^2, mass flux of 314 - 470 kg/m^{2}s, saturation pressure of 9 - 11 bar, and vapor quality of 0.2 - 0.85. They found that nucleate boiling was dominant heat transfer mechanism until its suppression at high vapor quality and then two-phase forced convection heat transfer became dominant.

Bertsch et al. (2008, 2009a, 2009b) investigated flow boiling heat transfer with R-134a in multi-port rectangular microchannels of hydraulic diameter of 1.09 and 0.54 mm. The measured parameter ranges are the heat flux of 0 - 220 kW/m^2, mass flux of 20 - 350 kg/m^{2}s, saturation temperature of 8 - 30 °C and vapor quality of -0.2 - 0.9. They found that nucleate boiling dominated the heat transfer, and that heat transfer coefficients varied significantly with heat flux and vapor quality. Besides, they observed that for the 1.09 mm channels the heat transfer coefficient first rose steeply as vapor quality increased from a subcooled value, and then dropped sharply with further increases in vapor quality, with a peak at a vapor quality of 0.2. Findings about the effect of mass flux on heat transfer coefficient are not consistent. Bertsch et al. (2008) first reported that the heat transfer coefficient increased strongly with increasing mass flux, but later they (Bertsch et al., 2009b) found that the heat transfer coefficient varied only slightly with mass flux.

Saitoh et al. (2007) presented the experimental results of the heat transfer of R-134a flowing through channels with three different diameters of 0.51, 1.12, and 3.1 mm. They found that the heat transfer coefficient for the 3.1 mm channels depended upon both heat flux and mass flux, while the heat transfer coefficient for the 0.51 mm channels increased with increasing heat flux but was not significantly affected by mass flux. Moreover, for the small channels, the influence of surface tension became a more important parameter which resulted in the occurrence of dryout at lower quality.

Yan and Lin (1998) conducted experiments on flow boiling heat transfer coefficients and pressure drops of R-134a in a multi-port circular tube with an inner diameter of 2 mm and a length of 200 mm. They found that for a higher heat flux, the heat transfer coefficient was higher except in the high vapor quality region and was lower in the high vapor quality region for a high heat flux. At a low heat flux, the heat transfer significantly increased for a small rise in the mass flux, but at a higher heat flux the increase in the heat transfer could be slight and even reduced.

Agostini and Bontemps (2005) performed an experimental study of upflow boiling of R-134a in vertical mini-channels of a flat extruded multi-port tube composed of 11 parallel rectangular channels (3.28 mm × 1.47 mm) with a hydraulic diameter of 2.01mm in the range of the mass flux of 90 – 295 kg/m^{2}s, heat flux of 6.0 - 31.6kW/m^2, working pressure of 4 and 6 bar, and inlet subcooling from 1 to 17K. Nucleate boiling was found to be the dominant mechanism for q > 14kW/m^2 and ΔT_{sat} > 3K. The transition from nucleate boiling to supposed convective boiling occurred for $Bo(1- x) \approx 2.2 \times 10^{-4}$ regardless of the heat and mass fluxes.

All investigations above have one thing in common: Minichannels enhance heat transfer compared with conventional channels. Yan and Lin′s results indicate that the heat transfer coefficients in small tubes are higher than those of conventional tubes by around 30–80%. The effect of the saturated pressure on heat transfer is also less controversial: The heat transfer coefficient is either higher at a higher saturated pressure (Saisorn et al., 2010; Shiferaw et al., 2007, 2009; Yan & Lin, 1998) or slightly varies with the saturated pressure (Bertsch et al. 2008, 2009).

A number of correlations are proposed for flow boiling heat transfer. Bertsch et al. (2009b) compared the measurements with predictions from several correlations (Bennett & Chen, 1980; Bennett et al., 1980; Cooper, 1984; Gorenflo, 1993; Haynes & Fletcher, 2003; Kandlikar & Balasubramanian, 2004; Lazarek & Black, 1982; Lee & Lee, 2001; Lee & Mudawar, 2005; Liu & Winterton, 1991; Saitoh et al., 2007; Shah, 1982; Sumith et al., 2003; Thome et al., 2004; Tran et al., 1996; Yun et al., 2006; Zhang et al., 2005; Warrier et al., 2002). They found that the correlations which delivered the lowest errors were that of Cooper (1984) developed for pool boiling and those of Liu-Winterton (1991) and Tran et al. (1996) developed for conventional channels, and that equations developed specifically for small channels did not predict the heat transfer coefficient better. Shiferaw et al. (2007, 2009) compared several existing correlations (Kandlikar & Balasubramanian, 2004; Thome et al. 2004; Zhang et al., 2004) with their experimental data. They concluded that the existing correlations did not predict their small-diameter data to a satisfactory degree, and that the three-zone evaporation model based on Thome et al. (2004) showed a better agreement, but it did not predict the effect of diameter and the partial dryout. Kaew-On et al. (2011) compared the experimental data with several existing correlations (Chen, 1963; Kaew-On & Wongwises, 2009; Kaew-On et al., 2010; Kenning & Cooper, 1984; Kew & Cornwell, 1997; Lazarek & Black, 1982; Malek & Colin, 1983; Tran et al., 1996; Warrier et al., 2002; Yu et al., 2002). They found that the correlations of Lazarek and Black, Malek and Colin, Kew and Cornwell, Yu et al., Kaew-On and Wongwises, and Kaew-On et al. showed better agreement with the experimental data, but none had a mean deviation lower than 20%. Saisorn et al. (2010) made a comparison of their data with correlations of Chen (1963), Trant et al. (1996), Kandlikar and Balasubramanian (2004), and Choi et al. (2007), and reported that none of them predicted well. Sun and Mishima (2009) compared correlations of Chen (1963), Liu-Winterton (1991), Zhang et al. (2004), Saitoh et al. (2005), Lazarek-Black (1982), Kew–Cornwell (1997), Kandlikar (1990), Tran et al. (1996), Yu et al. (2002), Warrier et al. (2002), Kenning-Cooper (1989), Pamitran et al. (2007), Cooper (1984), and Sun-Mishima (2009) with a database including 2505 data for 11 liquids covering diameter from 0.21 to 6.05 mm. The results show that the Chen method and the Chen-type correlations are not suitable for mini-channels very much, and that the correlations of Sun-Mishima, Lazarek-Black, and Kew-Cornwell are the best three methods, but none of them has the mean absolute error less than 30.8%.

From the brief review above, it is clearly seen that flow boiling heat transfer of R-134a in minichanels needs more research efforts, and that satisfactory correlations remain a problem. The existing examinations of the correlations for R-134a flow boiling heat transfer are only based on the author(s) own experimental data, and thus it is predictable that the evaluation results differ from one another, though none found a complete satisfactory correlation. Our effort is devoted to develop a better flow boiling heat transfer correlation for R-134a in minichannels. This paper presents the first part of the effort, which includes reviewing the existing correlations for flow boiling heat transfer, collecting flow boiling heat transfer experimental data of R-134a in minichannels, and conducting a comprehensive evaluation of the existing correlations against the data bank.

2. REVIEW OF FLOW BOILING HEAT TRANSFER COEFFICIENTS

2.1 Chen (1963) Correlation

By using the additive concept that suggests that the nucleate boiling and forced convection associated with flow boiling heat transfer could be added, Chen (1963) introduced two dimensionless factors, the suppression factor S that accounts for the smaller effective superheat due to forced convection as compared to that in a pool boiling case and the Reynolds number factor F that reflects the increase in convective turbulence due to the presence of vapor phase. He proposed the following correlation for flow boiling heat transfer coefficient of the turbulent regime (Zhang et al. 2004):

$$h_{tp} = S \cdot h_{nb} + F \cdot h_{sp} \tag{1a}$$

$$F = \begin{cases} 2.35(1/X_{tt} + 0.213)^{0.736} & \text{if } 1/X_{tt} > 0.1 \\ 1 & \text{if } 1/X_{tt} \le 0.1 \end{cases} \tag{1b}$$

$$S = 1/(1 + 2.53 \times 10^{-6} Re_l^{1.17}) \tag{1c}$$

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{0.1} \tag{2}$$

$$Re_l = \frac{(1-x) G_{tp} D_h}{\mu_l} \tag{3}$$

$$h_{nb} = 0.00122 \left(\frac{\lambda_l^{0.79} c_{p,l}^{0.45} \rho_l^{0.49}}{\sigma^{0.5} \mu_l^{0.29} h_{lg}^{0.24} \rho_g^{0.24}} \right) \Delta T_{sat}{}^{0.24} \Delta p_{sat}{}^{0.75} \tag{4}$$

$$h_{sp} = 0.023 Re_l^{0.8} Pr_l^{0.4} \lambda_l / D_h \tag{5}$$

The Chen equation was found to work well for low-pressure steam and some hydrocarbons and is taken as a benchmark in the literature. The applicable range of vapor quality of the Chen equation is 0-0.7.

2.2 Zhang et al. (2004) Correlation

In order to extend the Chen (1963) correlation to minichannels and laminar regime, Zhang et al. (2004) modified the Chen correlation with the h_{tp} and h_{nb} remaining the same forms as Eq. (1a) and Eq. (4), respectively, and S, F and h_{sp} listed in Tab. 1. Its applicable range of vapor quality is 0-0.7.

Tab. 1: Summary of S, F and hsp in the Zhang et al. (2004) correlation

S	$S = 1/(1 + 2.53 \times 10^{-6} Re_l^{1.17})$
F	$F = \max\{F', 1\}, \quad F' = 0.64\phi_l, \quad \phi_l^2 = 1 + \frac{C}{X} + \frac{1}{X^2}$
	$C = \begin{cases} 5 & \text{If } Re_l < 1000 \text{ and } Re_g < 1000 \\ 10 & \text{If } Re_l > 2000 \text{ and } Re_g < 1000 \end{cases}$
	$C = \begin{cases} 12 & \text{if } Re_l < 1000 \text{ and } Re_g > 2000 \\ 20 & \text{if } Re_l > 2000 \text{ and } Re_g > 2000 \end{cases}$
	For other regions of Re_k, ($k = l$ or g), interpolate the above values of C.
	$X = \left(\frac{f_l}{f_g}\right)^{0.5} \left(\frac{1-x}{x}\right) \left(\frac{\rho_g}{\rho_l}\right)^{0.5}$

To be continued

Continued

Tab. 1: Summary of S, F and h_{sp} in the Zhang et al. (2004) correlation

With the subscript k denoting either l or g, the Moody friction factor is of the form

$$f_k = \begin{cases} 64/Re_k & \text{for circular channel and } Re < 1000 \\ 96B/Re_k & \text{for rectangular channel and } Re < 1000 \\ 0.184/Re_k^{\ 0.2} & \text{for } Re > 2000 \end{cases}$$

$$B = \left(1 - 1.3553\theta + 1.9467\theta^2 - 1.7012\theta^3 + 0.9564\theta^4 - 0.2537\theta^5\right)$$

For $1000 \le Re_k \le 2000$, interpolate the above values of f_k.

h_{sp}

$$h_{sp} = \begin{cases} \dfrac{\lambda_l}{D}\max\{Nu_{\text{sp,lam}}, Nu_{\text{Collier}}\} & \text{for } Re_l \le 2000 \text{ in vertical channel} \\ \dfrac{\lambda_l}{D}\max\{Nu_{\text{sp,lam}}, Nu_{\text{sp,t}}\} & \text{for } Re_l \le 2300 \text{ in horizaontal channel} \\ \dfrac{\lambda_l}{D} Nu_{\text{sp,t}} & \text{for } Re_l \ge 2300 \text{ both in vertical and horizontal channel} \end{cases}$$

For vertical flow at $2000 < Re_l < 2300$, interpolate the values of h_{sp} for vertical flow at $Re_l = 2000$ and $Re_l = 2300$.

$$Nu_{\text{Collier}} = 0.17 Re_l^{0.33} Pr_l^{0.43}\left(\frac{Pr_l}{Pr_w}\right)^{0.25}\left[\frac{g\beta\rho_l^2 (T_w - T_l) D^3}{\mu_l^2}\right]^{0.1}$$

$$Nu_{\text{sp,t}} = 0.023 Re_l^{0.8} Pr_l^{0.4}$$

$$Nu_{\text{sp,lam}} = 4.36 \quad \text{for circular channel}$$

$$Nu_{\text{sp,lam}} = 8.235\left(1 - 2.042\theta + 3.085\theta^2 - 2.4765\theta^3 + 1.058\theta^4 - 0.186\theta^5\right)$$

for rectangular channel

2.3 Gungor-Winterton (1987) Correlation

Compiled from a database of over 3600 data points, including data for R-11, R-12, R-22, R-113, R-114, and water, Gungor and Winterton (1987) proposed (ASHRAE 2009)

$$h_{tp} = (SS_2 + FF_2) h_{sp} \tag{6a}$$

where h_{sp} is calculated with Eq.(5),

$$S = 1 + 3000 Bo^{0.86} \tag{6b}$$

$$F = 1.12\left(\frac{x}{1-x}\right)^{0.75}\left(\frac{\rho_l}{\rho_g}\right)^{0.41} \tag{6c}$$

$$S_2 = \begin{cases} Fr_{lo}^{\ (0.1 - 2Fr_{lo})} & \text{if horizontal and } Fr_{lo} < 0.05 \\ 1 & \text{otherwise} \end{cases} \tag{6d}$$

$$F_2 = \begin{cases} Fr_{lo}^{\ 1/2)} & \text{if horizontal and } Fr_{lo} < 0.05 \\ 1 & \text{otherwise} \end{cases} \tag{6e}$$

$$Bo = q/(G_{tp} h_{lg}) \tag{7}$$

$$Fr_{lo} = \frac{G_{tp}^2}{gD\rho_l^{\ 2}} \tag{8}$$

The Gungor-Winterton correlation is applicable to both horizontal and vertical flows.

2.4 Cooper (1984) Correlation

Cooper proposed the following correlation for nucleate boiling heat transfer. Some literature suggested it apply to flow boiling.

$$h_{nb}=55P_R^{0.12-0.087\ln\varepsilon}(-0.4343\ln P_R)^{-0.55}M^{-0.5}q^{0.67} \tag{9}$$

2.5 Bertsch et al. Equation (2009)

Bertsch et al. (2009) developed a composite correlation for flow boiling heat transfer in minichannels from a database of 3899 data points covering 12 different wetting and non-wetting fluids, with hydraulic diameters ranging from 0.16 to 2.92 mm and confinement numbers from 0.3 to 4.0. The parameter ranges cover the mass flux of 20 - 3000 kg/m^{2}s, heat flux of 4 - 1150 kW/m^2, saturation temperature of -194 - 97°C, and vapor quality of 0 - 1. The Bertsch et al. correlation followed the basic form of the Chen (1963) correlation and is of the form

$$h_{tp}=(1-x)h_{nb}+[1+80(x^2-x^6)e^{-0.6Co_f}]h_{sp} \tag{10a}$$

$$h_{sp}=xh_{sp,go}+(1-x)h_{sp,lo} \tag{10b}$$

$$h_{sp,ko}=\left[3.66+\frac{0.0668Re_{ko}Pr_k\,D_h/L}{1+0.04\left(Re_{ko}Pr_k\,D_h/L\right)^{2/3}}\right]\frac{\lambda_k}{D_h} \tag{10c}$$

where h_{nb} is calculated with the Cooper pool boiling equation (9), the subscript k denotes g or l, and the surface roughness ε (according to DIN 4762) should be set equal to 1 μm if unknown. The confinement number Co_f, the gas-only Reynolds number Re_{go}, and the liquid-only Reynolds number Re_{lo} are defined as, respectively

$$Co_f=\sqrt{\frac{\sigma}{g(\rho_l-\rho_g)D_h^{\,2}}} \tag{11}$$

$$Re_{go}=\frac{G_{tp}D_h}{\mu_g}\quad\text{and}\quad Re_{lo}=\frac{G_{tp}D_h}{\mu_l} \tag{12}$$

2.6 Kandlikar (1990) Correlation

Kandlikar (1990) utilized the single-phase, liquid-only heat transfer coefficient to predict the nucleate boiling and convective boiling components of turbulent regime as given by the following equation (ASHRAE 2009; Kandlikar and Balasubramanian, 2004):

$$h_{tp}=\text{larger of}\begin{cases}h_{tp,nb}\\h_{tp,cb}\end{cases} \tag{13a}$$

$$h_{tp,nb}=[0.6683Co^{-0.2}f(Fr_{lo})+1058.0Bo^{0.7}F_f](1\text{-}x)^{0.8}h_{lo} \tag{13b}$$

$$h_{tp,cb}=[1.136Co^{-0.9}f(Fr_{lo})+667.2Bo^{0.7}F_f](1\text{-}x)^{0.8}h_{lo} \tag{13c}$$

$$f(Fr_{lo})=\begin{cases}1 & \text{for } Fr_{lo}\ge 0.04\\(25Fr_{lo})^{0.3} & \text{for } Fr_{lo}<0.4\end{cases} \tag{13d}$$

$$Co=\left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{14}$$

$$h_{lo}=\frac{(f/8)Re_{lo}Pr_l(\lambda_l/D)}{1+12.7(f/8)^{1/2}(Pr_l^{2/3}-1)} \quad \text{for } 10^4\le Re_{lo}\le 5\times10^6 \tag{15}$$

$$h_{lo}=\frac{(f/8)(Re_{lo}-1000)Pr_l(\lambda_l/D)}{1+12.7(f/8)^{1/2}(Pr_l^{2/3}-1)} \quad \text{for } 3000\le Re_{lo}\le 10^4 \tag{16}$$

$$f=(0.79\ln Re_{lo}-1.64)^{-2} \tag{17}$$

The values of the fluid-surface parameter, F_f, are recommended in Tab. 2.

Tab. 2: Recommended F_f values in Kandlikar's flow boiling correlation

Fluid	F_f	Fluid	F_f
Water	1.00	R-134a	1.63
R-11	1.30	R-152a	1.10
R-12	1.50	R-31/R-132	3.30
R-13B1	1.31	R141b	1.80
R-22	2.20	R124	1.00
R-113	1.30	Kerosene	0.488
R-114	1.24		

$F_f = 1$ for stainless steel tubes for all fluids.

2.7 Kandlikar-Balasubramanian (2004) Correlation

Kandlikar and Balasubramanian (2004) extended the above Kandlikar correlation to laminar flow and mini- and micro-channels. The flow regions are classified as turbulent region ($Re_{LO}\ge 3000$), transition region ($1600 \le Re_{LO} < 3000$) and laminar region ($Re_{LO} < 1600$). They considered the effect of tube orientation for flow boiling in small diameter tubes negligible , and thus deleted the Froude number effect in the above correlation by setting $f(Fr_{lo}) = 1$. As a result, it follows that

$$h_{tp,nb}=[0.6683Co^{-0.2}+1058.0Bo^{0.7}F_f](1-x)^{0.8}h_{lo} \tag{18a}$$

$$h_{tp,cb}=[1.136Co^{-0.9}+667.2Bo^{0.7}F_f](1-x)^{0.8}h_{lo} \tag{18b}$$

where h_{lo} is constant for the laminar region, h_{lo} is calculated with Eq. (15) for the turbulent region and determined by linear interpolation in the transition region, and F_f values are listed in Tab. 2. The applicable vapor quality range is $x < 0.7\sim0.8$。

2.8 Yan-Lin (1998) Correlation

$$h_{tp}=(C_1Co^{C_2}+C_3Bo^{C_4}Fr_{lo})(1-x_m)^{0.8}h_l \tag{19a}$$

where h_l is assumed to be equal to $4.364\lambda_l/D_h$. The empirical constants C_1, C_2, C_3 and C_4 are assumed to be functions of the all liquid Reynolds number Re_{lo} and reduced temperature T_R. They can be expressed as

$$C_m=C_{m,1}Re_{lo}^{C_{m,2}}T_R^{C_{m,3}} \tag{19b}$$

where m = 1, 2, 3 and 4. The best fitting values for the constants $C_{m,1}$, $C_{m,2}$ and $C_{m,3}$ are listed in Tab. 3.

Tab. 3: Values of the constants in Yan-Lin correlation

m	Co >0.5			0.5 < Co ≤ 0.5			Co ≤ 0.15		
	$C_{m,1}$	$C_{m,2}$	$C_{m,3}$	$C_{m,1}$	$C_{m,2}$	$C_{m,3}$	$C_{m,1}$	$C_{m,2}$	$C_{m,3}$
1	933.6	0.07575	26.19	47.3	0.3784	14.67	356600	-0.6043	18.59
2	-0.2	0	0	2612.8	0	37.27	1409.1	-0.5506	16.303
3	21700	0.5731	34.98	100150	0	24.371	12.651	0.3257	10.118
4	14.84	-0.0224	13.22	3.99	-0.1937	4.794	0.15	0	0

2.9 Shah (1982) Correlation

Shah (1982) proposed that the boiling heat transfer coefficient h is the largest of that given by the following equations:

$$h=230Bo^{0.5}h_{lo} \tag{20a}$$

$$h=1.8[Co(0.38Fr_{lo}{}^{-0.3})^{n}]^{-0.8}h_{lo} \tag{20b}$$

$$h=F\exp\{2.47[Co(0.38Fr_{lo}{}^{-0.3})^{n}]^{-0.15}\}h_{lo} \tag{20c}$$

$$h=F\exp\{2.74[Co(0.38Fr_{lo}{}^{-0.3})^{n}]^{-0.1}\}h_{lo} \tag{20d}$$

where h_{lo} is calculated as for the Kandlikar (1990) correlation, and

$$F=\begin{cases}14.7Bo^{0.5} & \text{if } Bo\ge 0.0011\\ 15.4Bo^{0.5} & \text{if } Bo<0.0011\end{cases} \tag{20e}$$

$$n=\begin{cases}0 & \text{if horizontal with } Fr_{lo}\ge 0.04 \text{ or vertical}\\ 1 & \text{if horizontal with } Fr_{lo}<0.04\end{cases} \tag{20f}$$

2.10 Lazarek-Black (1982) Correlation

Lazarek and Black (1992) proposed a simple flow boiling heat transfer correlation based upon 738 experimental data of R113 in a 3.15 mm ID tube

$$h_{tp}=30Re_{lo}^{0.857}Bo^{0.714}\frac{\lambda_l}{D_h} \tag{21}$$

2.11 Sun-Mishima (2009) Correlation

Based on the Lazarek–Black correlation and by introducing Weber number, Sun and Mishima (2009) proposed

$$h_{tp}=\frac{6Re_{lo}^{1.05}Bo^{0.54}}{We_l^{0.191}(\rho_l/\rho_g)^{0.142}}\frac{\lambda_l}{D_h} \tag{22}$$

where the Weber number for liquid phase is defined as:

$$We_l=\frac{G_{tp}^2D_h}{\sigma\rho_l} \tag{23}$$

2.12 Kew-Cornwell (1997) Correlation

Kew and Cornwell modified the Lazarek–Black equation to allow for an observed increase in the heat transfer coefficient with the vapor quality in larger tubes.

$$h_{tp}=30Re_{lo}^{0.857}Bo^{0.714}\left(\frac{1}{1-x}\right)^{0.143}\frac{\lambda_l}{D_h} \tag{24}$$

2.13 Tran et al. (1996) Correlation

Tran et al. (1996) conducted flow boiling heat transfer experiments for R12 in small channels and proposed

$$h_{tp}=840{,}000Bo^{0.6}We_l^{0.3}(\rho_l/\rho_g)^{-0.4} \tag{25}$$

2.14 Yu et al. (2002)

Yu et al. (2002) modified the Tran et al. correlation. The correlation proposed in the paper is

$$h_{tp}=6{,}400{,}000Bo^{0.54}We_l^{0.27}(\rho_l/\rho_g)^{-0.2}$$

However, our assessment shows that the above Yu form has far large predictions. It might be of the form

$$h_{tp}=640{,}000Bo^{0.54}We_l^{0.27}(\rho_l/\rho_g)^{-0.2} \tag{26}$$

The Eq. (26) is used for the comparative study of this paper.

2.15 Warrier et al. (2002) Correlation

Warrier et al. conducted experiments of both single-phase forced convection and subcooled and saturated nucleate boiling in small rectangular channels using FC-84 and developed the following saturated flow boiling heat transfer correlation:

$$h_{tp}=[1+6Bo^{1/16}-5.3(1-855Bo)x^{0.65}]h_{sp} \tag{27}$$

where h_{sp} is calculated with Eq. (5).

2.16 Kaew-On et al. (2011)

Kaew-On et al. modified the Kaew-On and Wongwises (2009) correlation and proposed

$$h_{tp}=SBo^{0.185}We_l^{0.0013}h_{sp} \tag{28a}$$

$$S=1.737+0.97(\theta\phi_l^2)^{0.523} \tag{28b}$$

$$\phi_l^2=1+\frac{C}{X}+\frac{1}{X^2} \tag{28c}$$

$$C=-3.356+41.836e^A+B \tag{28d}$$

$$A=-17.369\theta f_l D_h \tag{28e}$$

$$B=124.5\theta f_l D_h \tag{28f}$$

$$X=\left(\frac{f_l}{f_g}\right)^{0.5}\left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{29}$$

where the Moody friction factor, f, is calculated with the Haaland (1983) correlation (Fang et al., 2011)

$$1/\sqrt{f_k}=-1.8\log[((\varepsilon/D_h)/3.7)^{1.11}+6.9/Re_k] \tag{30}$$

where k denotes either l or g, h_{sp} is calculated with Eq. (5).

2.17 Liu-Winterton (1991) Correlation

Liu and Winterton proposed the following equation for subcooled and saturated flow boiling:

$$h_{tp}^{2}=(Sh_{nb})^{2}+(Fh_{sp})^{2} \tag{31a}$$

$$F=0.35\left[1+xPr_{l}\left(\frac{\rho_{l}}{\rho_{g}}-1\right)\right] \tag{31b}$$

$$S=1\Big/(1+0.055F^{0.1}Re^{0.16}) \tag{31c}$$

where h_{sp} is given by the Dittus-Boelter correlation, Eq. (5), h_{nb} is calculated with the Cooper (1984) pool boiling correlation Eq. (9).

2.18 Kenning-Cooper (1989) Correlation

Kenning and Cooper pointed out that the saturated flow boiling heat transfer coefficient depends primarily on local parameters in the annular flow regime and can be of the form

$$h_{tp}=(1+1.8X_{tt}^{-0.87})h_{sp} \tag{32}$$

where X_{tt} is given by Eq. (2) and h_{sp} is given by Eq. (5).

2.19 Thome et al (2004)

Thome et al. proposed a three-zone flow boiling model to describe evaporation of elongated bubbles in microchannels, which describes the transient variation in local heat transfer coefficient during the sequential and cyclic passage of (a) a liquid slug, (b) an evaporating elongated bubble and (c) a vapor slug. However, this model needs estimation of flow parameters, which makes it difficult to be used. Besides, it does not predict the effect of diameter and the partial dryout (Shiferaw et al., 2007, 2009). Hence, this paper will not introduce it in detail.

3. THE AVAILABLE EXPERIMENTAL DATA FOR FLOW BOILING HEAT TRANSFER OF R-134A IN MINICHANNELS

The 1158 experimental data of flow boiling heat transfer of R-134a in minichannels from 9 papers (Tab. 4) are collected. All data were presented graphically in the source papers.

Tab. 4: Experimental data sources of flow boiling heat transfer of R-134a in minichannels

Reference	Parameter range: T_{sat}(°C)/p_{sat}(bar)/G(kg/m^{2}s)/ q(kW/m^2)/x	Geometry range: D(mm)/L(mm)/ε(μm)/Height(mm)/ Width(mm)/Orientation and tube type	Number of data points
Agostini and Bontemps (2005)	*/4-6/90-295/6-31.6/0.01-0.85	2.01/1100※/<1/3.28/1.47/Vertical upflow, multi-port rectangular aluminium tube	54
Bertsch et al. (2009a, 2009b)	8.7-29/4-7.5/42-334/2.6-19.6/0-0.9	0.54/9.53/<0.5/0.953/0.381/Horizontal multi-port rectangular copper tube.	96
In and Jeong (2009)	*/11/314-370/10-20/ 0.2-0.85	0.19/31/*/*/*/Horizontal single circular stainless steel tube	104
Kaew-On et al. (2011)	*/4-6/300-800/ 15-65/From 0.05.	①1.1/220※/*/1.25/1/; ②1.2/220※/*/0.9/1.8/ All horizontal multi-port rectangular aluminium tube.	114
Saisorn et al. (2010)	*/8-13/200-1000/ 8-13/0.02-0.75	1.75/600/*/*/*/Horizontal single circular stainless steel tube	50
Shiferaw et al. (2007, 2009)	22-46.5/6-12/ 100-600/13-150/Up to 0.9	①4.26/600/1.75/*/*/; ②2.01/600/1.82/*/*/; ③1.1/600/1.28/*/*/ All are horizontal single circular stainless steel tubes	627
Yan and Lin (1998)	5-31/*/50-100/5-20/ 0.05-0.95	2/200※/*/*/*/Horizontal multi-port circular stainless steel tube	113

* Not available or not applicable.

※ The effect of the tube length on the heat transfer of entrance section should be considered.

4. COMPARATIVE STUDY OF THE EXISTING CORRELATIONS AGAINST THE EXPERIMENTAL DATA

The 1158 experimental data as indicated in Tab. 4 are used for the comparative study of the 18 heat transfer correlations as described above, and the results are listed in Tab. 5, where the MRD is the mean relative deviation and the MARD is the mean absolute relative deviation.

$$\mathrm{MRD} = \frac{1}{N}\sum_{i=1}^{N}\frac{y(i)_{cal} - y(i)_{exp}}{y(i)_{exp}} \tag{33}$$

$$\mathrm{MARD} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{y(i)_{cal} - y(i)_{exp}}{y(i)_{exp}}\right| \tag{34}$$

Where ycal is the calculated value, yexp is the experimental value, and N is the number of the data points.

Tab. 5: Comparison between experimental data and correlation predictions

Data sources	Errors %	Correlations								
		Chen	Zhang et al.	Gungor-Winterton	Cooper	Bertsch et al	Kand-liker	Kandlikar-Balasub-ramanian	Yan-Lin	Shah
Agostini and Bontemps	MRD	-70.1	117.0	-5.1	19.3	8.8		-60.1	-34.8	-24.1
	MARD	70.1	158.7	58.8	61.4	52.4		60.1	37.4	72.8
Bertsch et al. (2009)	MRD	0.0	5.0	38.9	23.9	86.4		60.3	244.7	201.4
	MARD		23.9	41.3	29.1	86.9		62.9	282.1	206.6
In and Jeong	MRD	-36.8	-34.3	-40.8	-59.3	-37.7	-77.2	-81.3		-56.8
	MARD	39.0	38.7	40.8	59.3	37.7	77.2	81.3		66.5
Kaew-On et al.	MRD	-25.3	-27.0	-14.0	-49.4	-44.0	-51.2	-53.4	602.9	-57.3
	MARD	27.1	29.5	17.1	49.4	44.0	53.6	55.5	602.9	57.3
Saisorn et al.	MRD	80.3	69.2	17.5	-11.7	-7.9	-23.2	-23.2		1.4
	MARD	95.7	84.6	39.8	44.6	40.7	53.7	53.7		68.4
Shiferawa, et al.	MRD	-40.6	-36.7	-26.6	-18.6	-36.7	-45.1	-60.6	44.9	-28.9
	MARD	62.1	63.5	37.8	43.3	42.6	51.1	62.8	105.1	71.8
Yan and Lin	MRD	0.0	-0.8	-20.3	-25.6	2.8	0.0	-70.8	-65.2	-30.0
	MARD		25.4	24.3	35.7	25.7		70.8	65.2	56.5
Average	MRD	-27.5	-17.1	-15.4	-20.4	-20.1	-56.6	-51.4	86.3	-13.7
	MARD	58.6	57.0	36.6	44.3	44.7	61.7	63.7	154.0	79.5

* Data out of the applicable conditions of the correlation.

Tab. 5: Comparison between experimental data and correlation predictions

Data sources	Errors %	Correlations								
		Lazarek-Black	Sun-Mishima	Kew-Cornwell	Tran et al.	Yu et al.	Warrier et al.	Kaew-On	Liu-Winterton	Kenning-Cooper
Agostini and Bontemps	MRD	33.1	49.3	51.3	6.7	169.3	-62.8	-29.7	337.1	11.7
	MARD	67.6	75.9	82.9	57.7	169.8	62.8	50.5	351.4	82.5
Bertsch et al. (2009)	MRD	68.3	59.0	94.1	-23.6	77.9	-50.8	-70.7	66.2	-55.7
	MARD	71.1	60.0	96.4	34.5	77.9	50.8	70.7	69.2	58.9
In and Jeong	MRD	-52.4	-34.8	-46.3	-55.8	-5.5	-81.3	-76.9	-6.3	-46.8
	MARD	52.4	34.8	46.3	55.8	9.4	81.3	76.9	20.4	46.8
Kaew-On et al.	MRD	-28.7	-22.4	-26.1	-59.1	-1.4	-52.7	-65.0	82.0	-50.9
	MARD	28.7	23.7	26.2	59.1	22.0	52.7	65.0	82.0	50.9
Saisorn et al.	MRD	1.8	32.6	6.4	5.5	124.1	-18.0	-54.9	62.2	-24.9
	MARD	42.3	45.5	43.1	47.1	124.1	39.8	55.2	76.3	40.2
Shiferawa, et al.	MRD	-8.7	-5.2	0.5	-5.9	86.2	-70.0	-82.9	-12.6	-74.5
	MARD	42.7	38.3	46.9	41.7	87.5	70.5	83.4	45.6	77.2
Yan and Lin	MRD	-29.2	0.1	-19.7	-14.9	103.5	-74.9	-75.8	69.7	-39.3
	MARD	37.1	24.8	37.3	32.6	103.5	74.9	75.8	78.1	46.0
Average	MRD	-7.8	0.5	2.1	-16.9	75.9	-65.6	-75.2	31.4	-58.5
	MARD	45.1	39.1	49.5	44.2	80.2	66.8	76.4	67.6	66.0

From Tab. 5, the following can be seen:

(1) None of the described correlations predicts well. The smallest MARD is greater than 36%. Therefore, more work should be done to generate better correlations for flow boiling heat transfer of R-134a in minichannels.

(2) The Gungor-Winterton (1987) correlation performs best, with a MRD of -25.4% and a MARD of 36.6%. The correlations of Sun & Mishima (2009), Tran et al. (1996), Cooper (1984), Bertsch et al (2009), and Lazarek and Black (1982) are the next five best ones, with the MARD of 39.1%, 44.2%, 44.3%, 44.7, and 45.1%, respectively.

(3) The Chen-type correlations, which adopted the additive concept, generally do not work well, and the best correlations generally have simple forms, except for the Bertsch et al (2009) correlation.

5. CONCLUSIONS

(1) The 18 correlations for flow boiling heat transfer are reviewed, and 1158 data points of flow boiling heat transfer of R-134a in minichannels are collected from 9 published papers. The correlations are evaluated against the collected data.

(2) Among the 18 evaluated correlations, the smallest MARD is greater than 36%, which means that they can not predict experimental data well, and thus the flow boiling heat transfer of R-134a in minichannels still remains a problem. More research efforts need to be made to better understand the mechanism of flow boiling heat transfer in minichannels to develop better correlations.

(3) The Gungor-Winterton (1987) correlation is the best among the 18 evaluated correlations, and those of Sun and Mishima (2009), Tran et al. (1996), Cooper (1984), Bertsch et al (2009), and Lazarek and Black (1982) are the next five best ones.

(4) It is interesting to note that among the six best correlations, the Cooper (1984) correlation was developed for pool boiling and the Gungor-Winterton (1987) and the Lazarek-Black correlations were developed for conventional channels, and that five in six of the best correlations are in simple non-additive forms.

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