Applicability of Correlations for Boiling/Condensing in Macrochannels to Minichannels

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Abstract

Channels with small flow passages, commonly known as mini channels, are being widely used in heat exchangers for boiling and condensation. Correlations for heat transfer validated with macro channel data have been reported to sometimes fail for small diameter channels. Hence it is important to know the limits of applicability of such correlations. Many criteria have been proposed for boundary between macro and mini channels. The suitability of these criteria for determining the limits of applicability was evaluated by comparing wide ranging data for heat transfer during condensation, saturated boiling, sub cooled boiling, film boiling, and with data for CHF (critical heat flux), with well-validated correlations for macro channels. The criteria based exclusively on diameter or Bond number and its equivalents were found inadequate. Satisfactory criteria for mini-macro boundary were identified for condensation and saturated boiling heat transfer. Macro channel correlations for sub cooled and film boiling, and for CHF, were found to be satisfactory even for very small diameter channels.

Keywords: *Channels; Mini/macro classification; boiling; condensation; heat transfer; correlations*

Nomenclature

Bd	Bond number $= g(\rho_L - \rho_G)D^2\sigma^{-1}$		N	Number of data points
Bo	Boiling number $= q\,(G\,h_{LG})^{-1}$		p_r	Reduced pressure
Co	Confinement number		Re_{LO}	Reynolds number of liquid phase
D	Inside diameter of tube, or hydraulic equivalent diameter of non-circular channel (m)			$= G \times D\,\mu_f^{-1}$
			We_{GT}	Weber number for all mass flowing as vapor
Eo	Eotvos number		x	Vapor quality
F	Factor in criterion for saturated boiling		**Greek**	
Fr_L	Froude number for all mass flowing as liquid $= G^2(gD\rho_f^2)^{-1}$		μ	Dynamic viscosity (kg m^{-1} s^{-1})
			ρ	Density (kg m^{-3})
G	Total mass flux (liquid + vapor) (kg m^{-2}s^{-1})		σ	Surface tension (N m^{-1})
g	Acceleration due to gravity (m s^{-2})		**Subscripts**	
h	Heat transfer coefficient (Wm^{-2}K^{-1})		f	Liquid
h_{LG}	Latent heat of vaporization (J kg^{-1})		g	Vapor
L_{cap}	Capillary length (m)			

1. Introduction

Channels with small flow passages, commonly known as mini channels, are being widely used in heat exchangers for boiling and condensation. There are several reasons for it. Use of mini

channels results in more compact and economical heat exchangers. For refrigeration systems, another advantage of mini channels is that they require smaller refrigerant charge which reduces the environmental impact and fire hazard in case of leakage. There are applications such as computer chip cooling in which mini channels are the only possible choice due to space limitations. For designing the heat exchangers with mini channels, methods to predict heat transfer coefficients during condensation, various modes of boiling (saturated, sub cooled, film), and to predict CHF (critical heat flux) are needed. Well-verified methods for predicting these for macro/conventional channels are available. It is needed to know the limits of their applicability to smaller channels.

Many criteria for the boundary between mini and macro channels have been proposed. These have been reviewed among others by Cheng and Mewes [1], Ghiaasiaan [2], Ong [3] and Ong and Thome [4]. Some are based entirely on physical dimensions of channels. Others are based on flow pattern transitions, comparison of pertinent forces, theoretical analyses, and comparison of macro channel correlations with data for small channels. The present author recently proposed criteria based on comparison of extensive databases for saturated boiling and condensation with well-validated correlations for macro channels, Shah [5, 6].

In the following, the ability of these criteria to predict the limit of applicability of predictive techniques for macro channels is examined by comparison with results of extensive analyses of data for heat transfer during condensation, saturated and subcooled boiling prior to CHF, occurrence of CHF, and heat transfer during dispersed flow film boiling.

2. Classification of Channels

2.1 Based on Physical Dimensions

According to Shah [7], the heat exchangers with area to volume ratio more than 700 m^2/m^3 are compact. This results in 6 mm diameter being the boundary between mini and macro channels. Mehendale et al. [8] proposed:

        D > 6 mm, macro channels
        D = 1 to 6 mm, compact channel
        D = 100 μm to 1 mm, meso channel
        D = 1 μm to 100 μm, micro channel

A widely used one is by Kandlikar [9] according to which:
Conventional Channels: D >3mm
Minichannels: 3 mm $\geq$ D>0.2 mm
Microchannels: 0.2 mm $\geq$ D > 0.01mm
This classification was based mainly on single phase flow of gases but for uniformity, he also recommended it for boiling and condensing flows. This is the most widely used classification.

2.2 Based on Condensation Studies

Li and Wang [10] studied condensation in mini channels. They observed the transition of flow patterns from symmetrical to asymmetrical and noted that these depend on the capillary length L_{cap} (also known as Laplace constant) defined as:

$$L_{cap} = \left[\frac{\sigma}{g(\rho_f - \rho_g)}\right]^{0.5} \tag{1}$$

Their conclusions were:
- D < 0.224L_{cap}: Gravity forces are negligible compared to surface tension forces. Flow

regimes are symmetrical.

- $0.224L_{cap} < D < 1.75L_{cap}$: Gravity and surface tension forces are comparable. Flow distribution is slightly stratified.
- $1.75L_{cap} < D$: Gravity forces dominate surface tension forces and the flow regimes are similar to macro channels.

Cheng and Wu [11] re-arranged the above results of Li and Wang in terms of Bond number as below:

Microchannel, if Bd < 0.5 (negligible effect of gravity)

Minichannel, if 0.5 < Bd < 3.0 (both gravity and surface tension have significant effect)

Macrochannel, if Bd > 3.0 (surface tension has negligible effect)

Bond number is the ratio of surface tension and gravitational forces and is defined as:

$$Bd = \frac{gD^2(\rho_f - \rho_g)}{\sigma} \tag{2}$$

It is also the ratio of channel diameter to capillary length.

Based on the comparison of his general correlation for condensation in tubes [12, 13] with a wide ranging database, Shah [5] gave the following criterion. It is mini channel if:

$$We_{GT} < 100 \tag{3}$$

where

$$We_{GT} = \frac{G^2 D}{\rho_G \sigma} \tag{4}$$

2.3 Based on Boiling Flow Studies

The growth of bubbles during boiling in small channels may be restricted due to the limitation of tube diameter. This has led several authors to use the confinement number Co defined as:

$$Co = \frac{1}{D}\left[\frac{\sigma}{g(\rho_f - \rho_g)}\right]^{0.5} \tag{5}$$

Kew and Cornwell [14] compared the data from their tests on heat transfer during boiling in tubes of diameter 1.39, 2.87, and 3.69 mm, and a square channel 2 x 2 mm, to several correlations based on macro channel data. They found that these failed when the confinement number Co is less than 0.5. Accordingly, they gave the following classification.

Micro/mini channel: Co > 0.5

Macro channel: Co < 0.5

According to Ong and Thome [5], the lower threshold of macroscale flow is Co = 0.3–0.4 while the upper threshold of symmetric microscale flow is Co = 1 with a transition (or mesoscale) region in-between. This was based on the experimental two-phase flow pattern transition data together with a top/bottom liquid film thickness comparison for refrigerants R134a, R236fa and R245fa during flow boiling in channels of 1.03, 2.20, and 3.04 mm diameter.

Li and Wu [15] have given a transition criterion based on their analysis of data for boiling heat transfer in a variety of channels. According to it, it is mini channel if:

$$Bd. Re_{LO}^{0.5} \leq 200 \tag{6}$$

Shah [6] compared a very wide ranging database for saturated boiling prior to CHF with several correlations for macro channels including Shah [17]. He concluded that it is minichannel if:

$$F = (2.1 - 0.008\ We_{GT} - 110\ Bo) > 1 \tag{7}$$

For horizontal channels, F =1 if $Fr_L <$ 0.01. If F ≤ 1, it is macro channel. This is discussed in detail in Section 3.2.

2.4 Based on Two-Component Flow

Triplett et al. [16] studied gas-liquid flow in small diameter channels. They proposed that mini/micro channels are those with diameter less than capillary length Lcap. This is equivalent to Bd < 1.

Brauner and Ullman [18] studied flow pattern transitions in gas-liquid flow in channels and proposed that the transition between mini and macro channels depends on the Eotvos number Eo which is the ratio of buoyancy force to surface tension force. It is written as:

$$Eo = \frac{g(\rho_f - \rho_g)D^2}{8\sigma}$$ (8)

They proposed that mini channels are those with Eo < 0.2.

2.5 Summary

A number of criteria have been proposed for the boundary between mini and macro channels. These are summarized in Table 1.

Table 1. Criteria for macro to mini transition by various authors.

Author	Criterion for Minichannel	Basis
Shah [7]	D < 6 mm	Surface area to volume ratio > 700 m^2/m^3
Mehendale et al. [8]	D < 6 mm	Same as above
Kandlikar [9]	D ≤ 3mm	Based on mean free path of common gases
Kew & Cornwell [14]	Bd < 4	Bubble growth confinement during boiling in channels
Triplett et al. [16]	Bd < 1	Flow pattern transitions in gas-liquid flows
Brauner & Ullman [18]	Bd < 1.6	Flow pattern transitions in adiabatic gas-liquid flows
Cheng and Wu [11]	Bd < 3	Flow pattern transitions during condensation in tubes.
Ong and Thome [4]	Bd < 1	Flow pattern transitions and top-bottom liquid film thickness during boiling in channels
Li and Wu [15]	Bd $Re_{LO}^{0.5}$ ≤ 200	Correlation of heat transfer coefficients during saturated boiling in channels.
Shah [5]	$We_{GT} <$ 100	Comparison of test data with correlation for condensation heat transfer in macro channels
Shah [6]	F = (2.1- 0.008We_{GT}-110Bo) > 1	Comparison of test data with correlation for saturated boiling heat transfer in macro channels

To make comparison easy, the criteria using Eo and Co have been given in terms of Bond number as they are related by the following equation:

$$Eo = \frac{Bd}{8} = \frac{1}{8Co^2}$$ (9)

It is seen that the value of the transition Bond number in various criteria varies from 1 to 4.

3. Data Analyses by the Author

The present author analyzed wide ranging databases for developing correlations for the following:
1. Heat transfer during condensation.
2. Heat transfer during saturated boiling prior to CHF.
3. Heat transfer during subcooled boiling prior to CHF
4. Heat transfer during dispersed flow film boiling.
5. Critical heat flux in channels.

in Section 2. The other three studies resulted in correlations which agreed with a very wide range of data that included diameters from very small to very large and a very wide range of parameters. These correlations did not include any factor for the effect of surface tension. Hence The first two also resulted in correlations for boundary between mini and macro channels given the threshold of mini channel was not reached in these studies. These therefore provide the range of parameters in which macro channel predictive techniques remain applicable. This is useful information for designers of heat exchangers.

Table 2 provides the range of parameters in these studies. Detail of these studies are discussed in the following. Mean absolute deviation (MAD) and average deviation mentioned in these discussions are defined as

$$\text{MAD} = \frac{1}{N}\Sigma_1^N \text{ABS}\{(h_{predicted} - h_{measured})/h_{measured}\} \tag{10}$$

$$\text{Average Deviation} = \frac{1}{N}\Sigma_1^N\{(h_{predicted} - h_{measured})/h_{measured}\} \tag{11}$$

Table 2. Range of parameters for mini and macro channels in various studies by the present author.

Heat Transfer Mode, Study	Geometry	Fluids	Channel Macro or Mini	Range of Parameter Minimum/Maximum					Remarks
				p_r	G (kg m^{-2}s^{-1})	D (mm)	Bd	We_{GT}	
Saturatedboiling, Shah [6]	Tubes, single & multi-channels (round, rectangular, triangular), full or partly heated, H, V.	30 (water, refrigerants, organics, cryogens,NH$_3$, CO$_2$)	Mini (F > 1)	0.0046 0.6103	23 300	0.51 6.4	0.31 13.7	22 124	Includes D and Bd>all criteria for minichannels
			Macro (F≤ 1)	0.0046 0.7857	22 1370	0.38 27.1	0.15 600	14 2.5E6	Includes D and Bd< all criteria for macro chan.
Condensation, Shah [5]	Tubes, single & multi-channels (round, rectangular, triangular), full or partly heated, H, V.	33 (water, refrigerants, organics, CO$_2$)	Mini (We$_{GT}$< 100)	0.0008 0.6542	3 300	0.494 47.5	0.43 417	2 97	Includes D and Bd> all criteria for minichannels
			Macro (We$_{GT}$> 100)	0.0023 0.9491	12 1400	0.494 34.7	0.033 2392	100 53724	Includes D and Bd< all criteria for macro chan.
Subcooled boiling, Shah [24]	Tubes, annuli, single/multi channels, H, V	13 (water, refrigerants, organics, NH$_3$)	Macro (as data analysis shows no effect of surface	0.005 0.922	59 31500	0.176 22.8	0.025 7100	158 1.1E7	Satisfactorily predicted by correlations which do not include surface tension
Film boiling, Shah [25]	Tubes, H, V	10 (water, refrigerants, organics,		0.005 0.990	4 5176	0.98 25.4	2 6824	32 8.7E5	

		cryogens)	tension)						
CHF, Shah [26, 27]	Tubes, single/multi channels, H, V	15 (water, refrigerants, organics, cryogens)		0.005 0.900	20 11390	0.13 24.3	0.026 565	6 2.7E7	

3.1 Condensation Heat Transfer

Shah [5] compared a wide range of data with his general correlation for condensation in tubes, Shah [12, 13]. The database included 4063 data points from 136 data sets from 77 studies. It was found that most of the data including those for small diameter channels were satisfactorily predicted but some data at low mass flow rates were under-predicted. It was felt that it may be due to effect of surface tension. At low mass flow rates, inertia force may be weak compared to surface tension force. Weber number is the ratio of inertia and surface tension forces. It was found that the Shah correlation [12, 13] is satisfactory at $We_{GT} > 100$ but underpredicts at lower values. Thus for condensation, the boundary between mini and macro channels was found to be $We_{GT} = 100$.

Table 3 shows the mean absolute deviations (MAD) of Shah correlation and two other correlations below and above $We_{GT} = 100$. The correlation of Ananiev et al. [19] is among the most verified for macro channels. The correlation of Kim and Mudawar [20] was verified with data for channels of diameter 6.2 mm and smaller. It is seen that for all three, deviations at $We_{GT} < 100$ are much larger than at $We_{GT} > 100$, for diameters smaller as well as larger than 3 mm. The Kim & Mudawar correlation was specifically developed for mini channels and its database included channels down to 0.42 mm diameter. Yet its MAD for D < 3 mm is 16.9 % for $We_{GT} > 100$ and rises to 25.1 % for $We_{GT} < 100$. Thus all the three correlations indicate transition at $We_{GT} = 100$. This is the boundary for applicability of macro channel correlations for condensation heat transfer.

Table 3: Deviations of some correlations for condensation in the mini and macro regimes proposed by Shah [5].

D (mm)	Channel Mini or Macro	N	Mean Absolute Deviation (MAD), % Average Deviation, %		
			Kim & Mudawar [20]	Ananiev et al. [19]	Shah [12, 13]
D > 3	Mini ($We_{GT} < 100$)	225	69.6 20.5	53.5 -53.5	27.6 -4.5
	Macro ($We_{GT} > 100$)	2153	29.1 -20.9	25.6 -10.9	15.0 0.6
D ≤ 3	Mini ($We_{GT} < 100$)	230	25.1 -17.1	38.2 -38.0	29.5 -25.7
	Macro ($We_{GT} > 100$)	840	16.9 -7.6	16.5 -6.8	19.8 8.9

3.2 Saturated Boiling Prior to CHF

Shah [6] compared an extensive database (range of parameters listed in Table 2) with his general correlation [17] which had been well-validated with data for macro channels. The database included 4761 data points from 137 studies from 81 sources. As was the case for condensation, most of the data for small diameter channels were satisfactorily predicted but some at low flow rates were underpredicted. The deviations increased with decreasing Weber number but its effect was countered by increasing boiling number Bo. Eventually, the boundary between mini and macro channels was found to be at F =1 as given in Eq. (7). Figure 1 shows the boundary as given by Eq. (7).
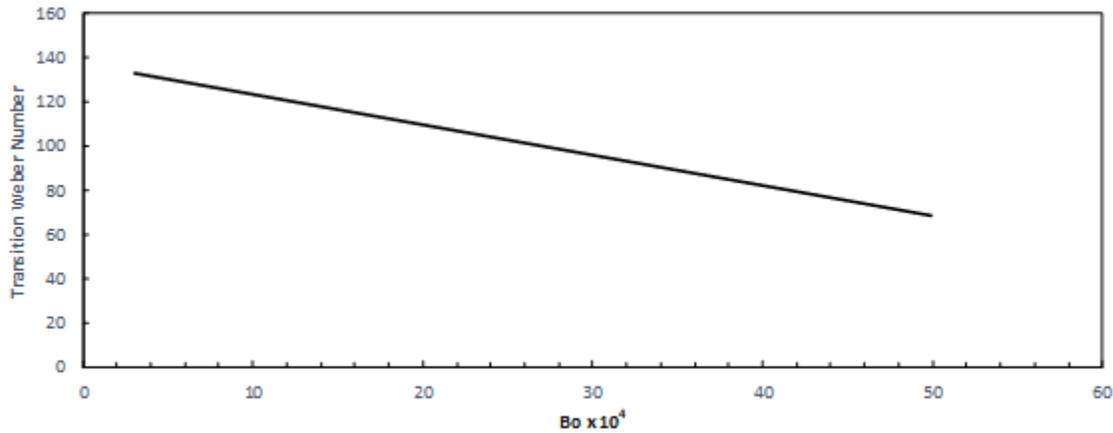
Figure 1. We$_{GT}$ for transition between mini and macro channels during saturated boiling in channels according to Eq. (7) according to Shah correlation [6].

Table 4 shows the mean absolute deviations (MAD) of Shah correlation [17] and three other correlations below and above F = 1. The correlations of Gungor and Winterton [21], Liu and Winterton [22], are among the most verified for macro channels. The correlation of Kim and Mudawar [23] was validated with data for tube diameters 6.5 mm and smaller. It is seen that MAD for all four increases greatly when F > 1. Further, all four underpredict at F > 1 by 20 to 34 % for all diameters.

Table 4: Deviations of various correlations for saturated boiling heat transfer in mini and macro regimes proposed by Shah [6]

D, mm	Channel Mini or macro		N	Mean Absolute Deviation (MAD), % Average Deviation, %			
				Gungor & Winterton [21]	Liu & Winterton[22]	Kim & Mudawar[23]	Shah [17]
> 3	Mini	F > 1	66	24.7 -24.7	32.5 -32.5	35.4 -35.4	20.4 -20.4
	Macro	F ≤1	2283	22.4 -7.3	26.3 9.2	32.6 -9.1	19.2 -4.0
<= 3	Mini	F > 1	348	30.5 -29.8	27.6 -24.7	25.0 -21.3	33.7 -33.0
	Macro	F ≤1	2155	20.0 -2.2	23.2 -9.1	22.1 -7.1	19.9 -8.3

It is seen in Table 2 that data for F >1 (mini channel) included diameters up to 6.4 mm and Bd up

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to 13.7. The data for $F \leq 1$ (macro channels) include diameters down to 0.38 mm and Bond numbers down to 0.15. Hence the criteria based on Bond number and diameter are not satisfactory. The criterion of Li and Wu [15] listed in Table 1 was also evaluated during this data analysis. It was found quite unreliable.

In view of the above $F = 1$ can be considered a reliable criterion for the boundary between mini and macro channels for saturated boiling prior to CHF. Macro channel correlations may be used when $F \leq 1$. The other criteria are not satisfactory for the prediction of heat transfer during saturated boiling prior to CHF.

3.3 Subcooled Boiling Prior to CHF

Shah [24] presented a correlation for subcooled boiling heat transfer in channels. He validated the correlation with a large and varied database. The range of parameters is listed in Table 2. It is seen in Table 2 that the data included diameters as small as 0.176 mm and Bond number down to 0.025. The 1340 data points from 68 data sets from 37 sources were predicted with a MAD of only 12.2 %. This correlation did not include any factor for surface tension effects. Hence it appears that the boundary of mini channel was not reached in the data analyzed. Figures 2 and 3 show the deviations of the Shah correlation as function of diameter and Bond number. It is seen that there is no effect of diameter or Bond number on the deviations. Thus the various criteria based on diameter and Bond number (and its equivalent confinement number and Eotvos number) are not valid for the prediction of heat transfer during subcooled boiling.
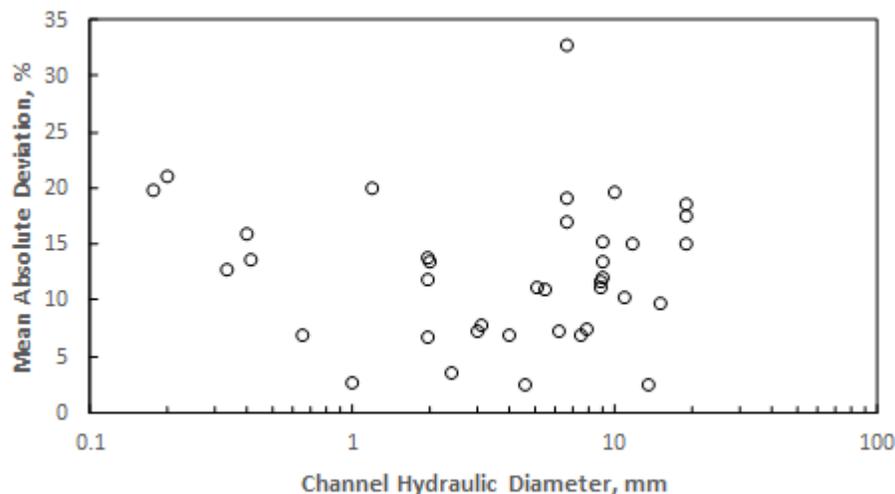
Figure 2: Mean absolute deviations of Shah correlation [24] with data sets for subcooled boiling, as function of channel hydraulic diameter.

As seen in Figure 1, the highest value of We_{GT} for transition to mini channel is about 140 for saturated boiling. The minimum Weber number was 156 in the data for subcooled boiling. Hence analysis of subcooled data at lower We_{GT} is needed to determine whether the threshhold value given by Eq. (7) for saturated boiling is also applicable to subcooled boiling.
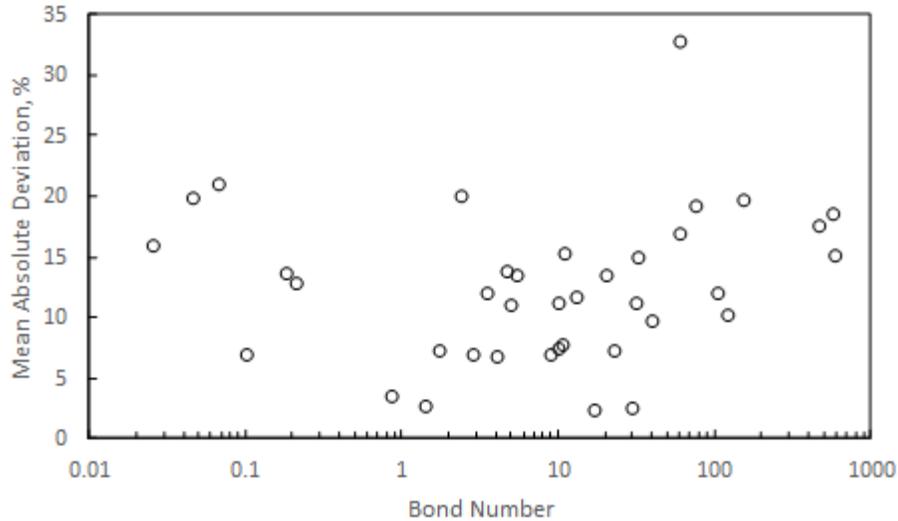
Figure 3: Mean absolute deviations of Shah correlation [24] with data sets for subcooled boiling, as function of Bond number.

3.4 Dispersed Flow Film Boiling

Shah [25] presented a correlation for dispersed flow film boiling in horizontal and vertical tubes which was validated with a large and varied database whose range of parameters is listed in Table 2. These included 1481 data points from 50 data sets from 38 sources. This correlation did not have any factor for surface tension effects. The data included diameters as low as 0.98 mm. Figure 4 shows the deviations of the Shah correlation with data as a function of tube diameter.
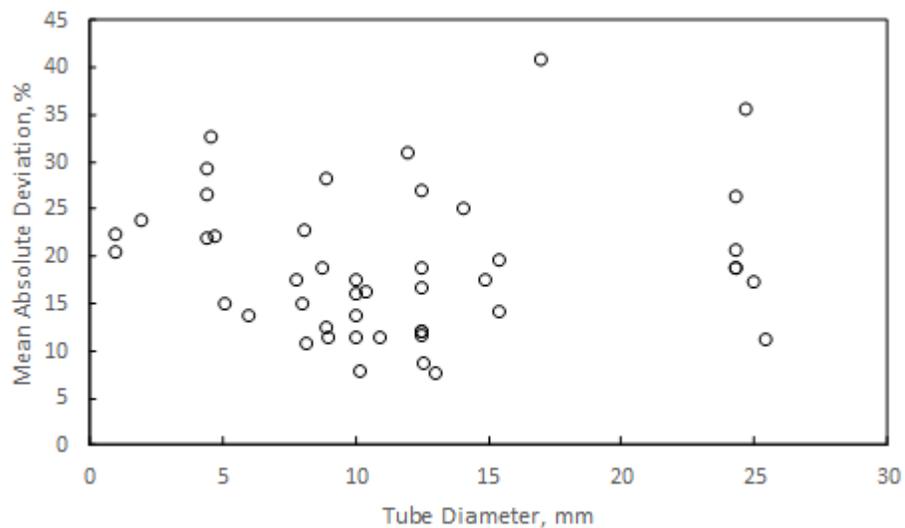
Figure 4: Mean absolute deviations of Shah correlation [25] with the data sets for film boiling in horizontal and vertical tubes as a function of tube diameter.

It is seen that deviations at small diameters are comparable to those at larger diameters. Thus the mini/macro transition criteria based on diameter are found invalid. The data included Bond numbers down to 2. Some of the criteria listed in Table 1 have transition to mini channel at Bd < 2. Analysis of data at Bd < 2 is needed to see whether these criteria are applicable to dispersed

flow film boiling heat transfer. The minimum We_{GT} is these data was 32. This indicates that the boundary found by Shah for saturated boiling, Eq. (7), is not applicable to dispersed flow film boiling.

3.5 Critical Heat Flux (CHF)

Shah [26, 27] analyzed a wide range of data to test his correlation for vertical tubes, Shah [28] for applicability to small diameter channels and to adapt it for horizontal channels. The range of data analyzed is listed in Table 2. The original vertical tube correlation was found to be in good agreement with small diameter channels' data. The new correlation for horizontal channels also showed good agreement with data for all channel sizes. Neither the vertical tube correlation nor the correlation for horizontal channels included any factor for the effect of surface tension. The data included diameters down to 0.13 mm and Bond numbers down to 0.026. Figures 5 and 6 show the deviations of the Shah correlation with data. It is seen that deviations have no relation to diameter or Bond number. Hence the various criteria based on diameter and Bond number listed in Table 1 were found to be inapplicable. The minimum We_{GT} in the data was 6. Hence the criterion of Eq. (7) for saturated boiling heat transfer is also not applicable.

As all the data analyzed show no effect of surface tension, the threshold for mini channel was not reached. It remains to be found.
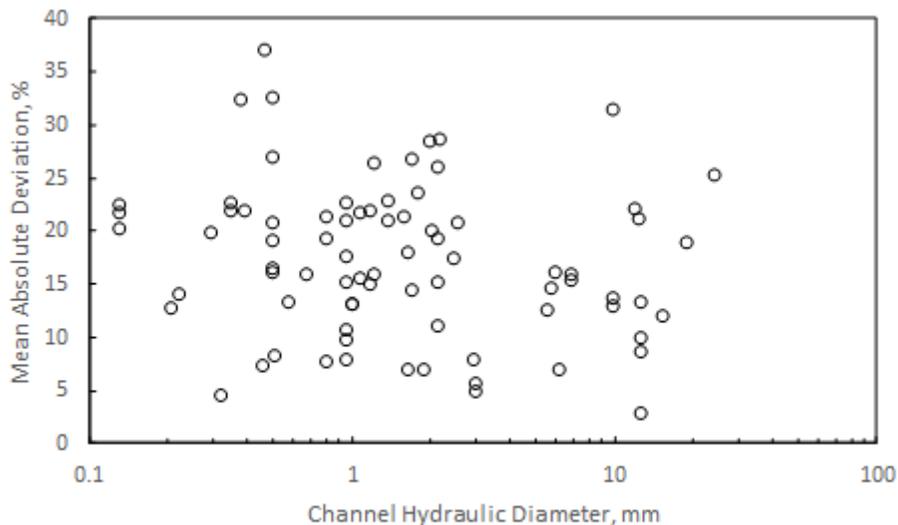
Figure 5: Deviations of Shah correlation [26, 28] with data sets for CHF in channels as a function of channel diameter.

Conclusions

1. Literature was reviewed to identify the various criteria proposed for transition from macro (conventional) channels to mini channels. Most of those found are based on diameter alone or only on Bond number and its alternative forms, confinement number and Eotvos number.

2. To determine the limits of applicability of correlations for macro channels to mini channels, wide ranging databases for CHF and heat transfer during condensation, saturated boiling, sub cooled boiling, and film boiling, in channels were compared to well-validated correlations based on data for macro channels. The data included diameters down to 0.13 mm.

3. It was found that the deviations of correlations are not related to diameter alone or to Bond

number alone. Hence such criteria are not generally valid for heat transfer or CHF.

4. For heat transfer during condensation and saturated boiling prior to CHF, the criteria proposed by Shah [5, 6] are supported by the results with several correlations based on macro channel data. Hence these may be considered reliable as the limits of applicability of macro channel correlations.

5. Comparison of data for sub cooled boiling, film boiling, and CHF with well-validated correlations for macro channels showed no limit to their applicability even though the diameters and Bond numbers were very small. Hence the limits of applicability of microchannel correlations for them remain to be found.
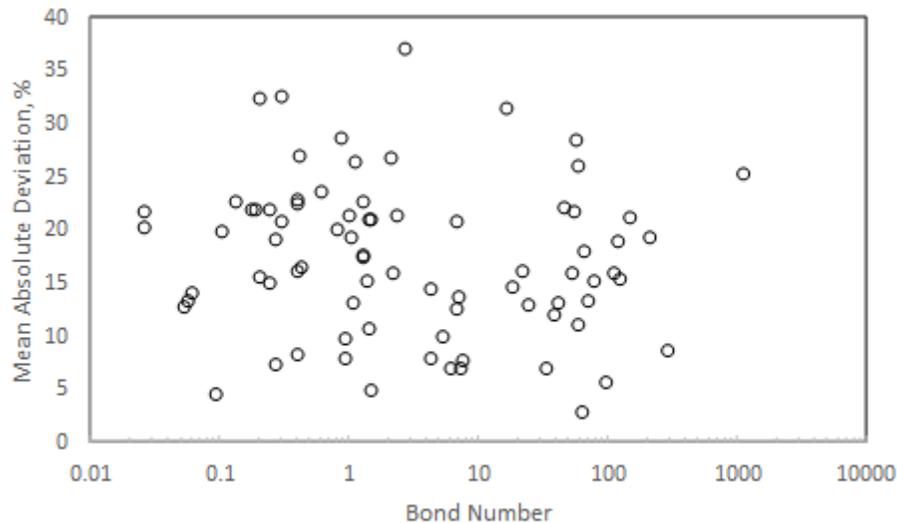
Figure 6: Deviations of the Shah correlation (1987, 2015) with data sets for CHF in channels as a function of Bond number.

References

[1] L. Cheng and D. Mewes, Review of two-phase flow and flow boiling of mixtures in small and mini channels, International Journal of Multiphase Flow, vol 32, pp. 183–207, 2006.

[2] S. M. Ghiaasiaan, Two-phase flow boiling and condensation (1st ed.), Cambridge University Press, New York, 2008.

[3] C. L. Ong, Macro-to-micro channel transition in two-phase flow and evaporation (PhD thesis), École Polytechnique Fédérale de Lausanne, Lausanne, 2010.

[4] C. L. Ong and J. R. Thome, Macro-to-micro channel transitioni n two-phase flow: part 2 – flow boiling heat transfer and critical heat flux, Experimental Thermal and Fluid Science,vol 35, pp. 873–886, 2011.

[5] M. M. Shah, Comprehensive correlations for heat transfer during condensation in conventional and mini/micro channels in all orientations, Int. J. Refrigeration, vol 67, pp. 22-41, 2016.

[6] M. M. Shah, Unified correlation for heat transfer during boiling in plain mini/micro and conventional channels, Int. J. Refrigeration, vol 74, pp. 604-624, 2017.

[7] R. K. Shah, Classification of heat exchangers, In S. Kakac, A.E. Bergles, and F. Mayinger, Heat Exchangers: Thermal Hydraulic Fundamentals and Design, Hemisphere, Washington,1986.

[8] S. S. Mehendale, A. M. Jacobi and R. K. Shah, Fluid flow and heat transfer at micro- and meso-scales with application to heat exchanger design, Applied Mechanics Reviews, vol. 53(7), pp.175-193, 2000.

[9] S. G. Kandlikar, Fundamental issues related to flow boiling in mini channels and micro channels,

Experimental Thermal and Fluid Science, vol. 26(2-4), pp. 389-407, 2002.

[10] J. M. Li and B. K. Wang, Size effect on two-phase flow regime for condensation in micro/mini tubes, Heat Transfer-Asian Research, vol 32, pp. 65–71, 2003.

[11] P. Cheng and, H. Y. Wu, Macro and microscale phase-change heat transfer, Advances in Heat Transfer, vol. 39, pp. 461-563, 2006.

[12] M. M. Shah, An improved and extended general correlation for heat transfer during condensation in plain tubes, HVAC&R Research, vol. 15(5), 889-913, 2009.

[13] M. M. Shah, General correlation for heat transfer during condensation in plain tubes: further development and verification, ASHRAE Trans., 119(2), 2013.

[14] P. A. Kew and K. Cornwell, Correlations for prediction of flow boiling heat transfer in small-diameter channels, Applied Thermal Engineering, vol. 17, pp. 705–715, 1997.

[15] W. Li and Z. Wu, general criterion for evaporative heat transfer in micro/mini-channels, Int. J. Heat Mass Transfer, vol. 53, pp. 1967-1976, 2010.

[16] K. A. Triplett, S. M. Ghiaasiaan, S. L. Abdel-Khalik, and D. L. Sadowski, Gas liquid two-phase flow in micro channels part 1 - two-phase flow patterns, International Journal of Multiphase Flow, vol.25, pp. 377–394, 1999.

[17] M. M. Shah, Chart correlation for saturated boiling heat transfer: equations and further study, ASHRAE Trans., vol. 88(1), pp. 185-196, 1982.

[18] N. Brauner and A. Ullmann, The prediction of flow boiling maps in minichannels,4th Japanese-European Two-Phase Flow Group Meeting, Kyoto, September, 2006. Quoted in Ong [3].

[19] E. P. Ananiev, L. D. Boyko and G. L. Kruzhilin, Heat transfer in the presence of steam condensation in horizontal tubes, International Developments in Heat Transfer, vol. 2, pp. 290–95, 1961.

[20] S. Kim and I. Mudawar, Universal approach to predicting heat transfer coefficient for condensing mini/micro-channel flow, Int. J. Heat Mass Transfer, vol. 56(1–2), pp. 238–250, 2013.

[21] K. E. Gungor and R. H. S. Winterton, simplified general correlation for saturated flow boiling and comparisons of correlations with data. Chem. Eng. Res Des., vol. 65, pp. 148–56, 1987.

[22] Z. Liu and, R. H. S. Winterton, A general correlation for saturated and sub cooled flow boiling in tubes and annuli based on a nucleate pool boiling equation, Int. J. Heat Mass Transfer, vol. 34(11), pp. 2759–2766, 1991.

[23] S. Kim and I. Mudawar, Universal approach to predicting saturated flow boiling heat transfer in mini/micro-channels – part II., International Journal of Heat and Mass Transfer, vol. 64, pp. 1239–1256, 2013.

[24] M. M. Shah, New Correlation for heat transfer during sub cooled boiling in plain channels and annuli, International Journal of Thermal Sciences, 112, pp. 358-370, 2017.

[25] M. M. Shah, comprehensive correlation for dispersed flow film boiling heat transfer in mini/macro tubes, Int. J. Refrig, vol. 78, pp. 32-46, 2017.

[26] M. M. Shah, A General correlation for chef in horizontal channels, International Journal of Refrigeration, vol. 59, pp. 37-52, 2015.

[27] M. M. Shah, Applicability of general correlations for CHF in conventional tubes to mini/micro channels, Heat Transfer Engineering, vol. 38(1), pp. 1-10, 2017.

[28] M. M. Shah, Improved general correlation for critical heat flux in uniformly heated vertical tubes, International Journal of Heat and Fluid Flow, vol 8(4), pp. 326-335, 1987.

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