Proceedings of the 14th International Heat Transfer Conference
IHTC14
August 8-13, 2010, Washington, DC, USA

IHTC14-22346

HEAT TRANSFER DURING CONDENSATION INSIDE SMALL CHANNELS: APPLICABILITY OF GENERAL CORRELATION FOR MACROCHANNELS

Mirza Mohammed Shah
Fletcher Thompson Inc.
Shelton, CT 06484, USA
mshah.erc@gmail.com

ABSTRACT

Prediction of heat transfer during film condensation in mini and microchannels is of much practical interest. No well-verified method for this purpose is available. The applicability of the author's well-validated general correlation (Shah 2009) for condensation in tubes to small channels is investigated in this paper. A wide range of data for condensation in horizontal micro and mini channels were compared with it. This correlation was found to predict 500 data points from 15 studies on small diameter channels with a mean deviation of 15.9 percent. These data included single round and rectangular channels as well as multiport channels with round and rectangular ports with equivalent diameters from 0.49 to 5.3 mm, 8 fluids, reduced pressures from 0.048 to 0.52, and mass flux from 50 to 1400 kg/m^{2}s. This indicates its applicability to minichannels. However, a large amount of data for diameters from 0.114 to 2.6 mm showed large deviations from this correlation. The discrepancy in the overlapping range of data could be due to difficulties in accurate measurements on small channels.

INTRODUCTION

Heat transfer during condensation in channels of small diameter is of great practical interest at present due to need for miniaturization. Numerous experimental studies have been done to measure heat transfer rate in mini and micro channels. Many methods for predicting heat transfer coefficients, theoretical and empirical, have been proposed but none of them has been shown to be generally applicable or even applicable in a well-defined range of parameters. For example, Su et al. (2009) note that four of the predictive techniques developed for mini channels make widely different predictions for ammonia. Hence there is a need for well-verified predictive techniques for mini and micro channels.

It is generally believed that predictive techniques for macro channels are inapplicable to micro and mini channels. This belief is based on scattered reports of some small channel data showing disagreement with macro channel correlations. However there are also many reports of small channel data being in agreement with macro channel correlations. There has not been any comprehensive study to determine the limits of macro channel correlations to smaller channels. There is a need for such a study and this paper attempts to fulfill this need to some extent.

This paper reports the results of comparing the author's recent general correlation (Shah 2009) with available data for micro and mini channels. This correlation has been validated with data for 22 fluids over a very wide range of parameters that includes tube diameters from 2 to 49 mm, flow rates from 4 to 820 kg/m^2 s. and reduced pressures from 0.0008 to 0.9. While this correlation is applicable to both horizontal and vertical tubes, comparison here has been made only with horizontal tube data as very few data for vertical mini or micro channels could be found. The results of the comparison indicate the probability that this correlation may be applicable to channel diameters $\geq$ 0.49 mm and Bond numbers $\geq$ 0.4. This result is encouraging but a large amount of data in the same range was found to give large deviations from this correlation. The possible reasons for this discrepancy are discussed.

NOMENCLATURE

All equations are dimensionless. Any consistent system may be used.

Bn	Bond number, defined by Eq. (1)
D_{HYD}	Hydraulic equivalent diameter of channel
G	Total mass flux (liquid + vapor)

g	Acceleration due to gravity
h_I	Heat transfer coefficient given by Eq. (4)
h_{LS}	Heat transfer coefficient assuming liquid phase flowing alone in the tube
h_{LT}	Heat transfer coefficient assuming all mass flowing as liquid
h_{Nu}	Heat transfer coefficient given by Eq. (5), the Nusselt formula
h_{TP}	Two-phase heat transfer coefficient
J_g	Dimensionless vapor velocity defined by Eq. (8)
k	Thermal conductivity
p_r	Reduced pressure
Re_{GT}	Reynolds number assuming total mass flowing as vapor, $= GD_{HYD}/\mu_g$
Re_{LS}	Reynolds number assuming liquid phase flowing alone, $=G(1-x)D_{HYD}/\mu_f$
Re_{LT}	Reynolds number assuming total mass flowing as liquid, $= GD_{HYD}/\mu_f$
x	Vapor quality
Z	Shah's correlating parameter, $= (1/x -1)^{0.8} p_r^{0.4}$

Greek

μ	Dynamic viscosity
ρ	density
σ	surface tension

Subscripts

f	Of liquid
g	Of vapor

CLASSIFICATION OF CHANNELS

Many classifications of channels have been proposed. Many authors consider the channels of diameter greater than 6 mm to be macro channels and smaller than 6 mm as small (micro, mini, etc.) channels. According to Mehedail et al. (2000) heat exchangers with channel diameters greater than 6 mm are conventional or macro, 1 to 6 mm are compact, 0.1 to 1 mm are meso, and 1 to 100 µm are micro type. Kandlikar and Grande (2002) consider channels of 0.5 to 3 mm as minichannels. These classifications are arbitrary, without any physical bases. Cheng and Wu (2006) have given the following criteria based on an analysis considering the magnitudes of gravity and surface tension effects:

Microchannel, if $Bn < 0.5$ (negligible effect of gravity)

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

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

Bn is the Bond number defined as:

$$Bn = \frac{g(\rho_f - \rho_g)D^2}{\sigma} \tag{1}$$

GENERAL CORRELATION OF SHAH (2009)

The Shah correlation (called the present correlation from here onwards) includes formulas for application to horizontal as well as vertical channels. Only the version for horizontal channels is given here.

This correlation has three regimes of heat transfer and different formulas for each.

In Regime I (turbulent regime):

$$h_{TP} = h_I \tag{2}$$

In Regime II (mixed regime):

$$h_{TP} = h_I + h_{Nu} \tag{3}$$

For Regime III (laminar regime), no formula was given due to lack of analyzable data.

h_I and h_{Nu} in the above equations are obtained from the following equations:

$$h_I = h_{LS}\left(1+\frac{3.8}{Z^{0.95}}\right)\left(\frac{\mu_f}{\mu_g}\right)^{(0.0058+0.557\,p_r)} \tag{4}$$

$$h_{Nu} = 1.32\,\mathrm{Re}_{LS}^{\;-1/3}\left[\frac{\rho_l(\rho_l-\rho_g)gk_f^{\;3}}{\mu_f^{\;2}}\right]^{1/3} \tag{5}$$

Eq. (5) is the Nusselt equation for laminar film condensation in vertical tubes; the constant has been increased by 20% as recommended by McAdams (1954) on the basis of comparison with test data. Eq. (4) is a modification of author's earlier correlation (Shah 1979), the difference being that the 1979 version did not have the viscosity ratio term. This term becomes significant only at higher p_r.

h_{LS} is the heat transfer of the liquid phase flowing alone in the tube. It is calculated by the following equation:

$$h_{LS} = 0.023\,\mathrm{Re}_{LS}^{\;0.8}\,\mathrm{Pr}_f^{\;0.4}\,k_f / D \tag{6}$$

Regime I occurs when:

$$J_g \geq 0.98(Z + 0.263)^{-0.62} \tag{7}$$

Regime II occurs if J_g is less than the value given by Eq. (7) and $Re_{GT} > 35{,}000$. If $Re_{GT} < 35{,}000$, Regime III (laminar regime) prevails. This limit of 35,000 was proposed conservatively as there were very few data points for lower values of Re_{GT} and as the analytical formula of Chato (1962) is said to be applicable at $Re_{GT} < 35{,}000$. This limit was ignored in present data analysis.

In the above equations, Jg is the dimensionless vapor velocity defined as

$$J_g = \frac{xG}{\left(gD\rho_g(\rho_l - \rho_g)\right)^{0.5}} \tag{8}$$

DATA ANALYSIS

Data Search

As noted earlier, the demarcation between macro channels and small channels has been based on diameter or Bond number. The Bond number is known only after calculations have been done. As macro or normal channels are considered to be of diameters 6 mm and larger, data for channels with equivalent diameters less than 6 mm were sought. As most of the interest is in channels of 2 mm and less, emphasis was on getting data for such channels.

While a very large number of studies on small channels have been published, many of them do not give their data in analyzable form. To compare with the present correlation, vapor quality, mass flow rate, and pressure must be known. One or two of these parameters were missing in the graphs in many publications. Still, a large amount of analyzable data from many sources covering a wide range of parameters were found. These included equivalent diameters from 5.3 mm to 0.067 mm.

Methodology

The data collected were compared with the present correlation described in the foregoing. The single phase heat transfer coefficient was calculated with Eq. (6) for all data except for the data of Son and Lee (2009) for which the following equation was used:

$$h_{LS} = 0.034\,\mathrm{Re}_{LS}^{\;0.8}\,\mathrm{Pr}_f^{\;0.3}\,k_f / D \tag{9}$$

The reason is that these authors' single-phase measurements were higher than Eq. (6) and they fitted Eq. (9) to their data.

For the data points with J_g less than given by Eq. (7), heat transfer coefficients were calculated with Eq. (3) even when $Re_{GT} < 35{,}000$.

Fluid property data were taken from many sources. Properties for R-12, R-22, R-123, and R-134a are from the University of Ottawa Code UO0694. Properties for propane are from ASHRAE (2005). All other properties are from REFPROP 8.0.

Results of Comparison

The results of comparison with data are shown in Tables 1 and 2. The mean deviation is defined as:

$$\delta_m = \sum_N^1 ABS\left((h_{predicted} - h_{measured}) / h_{measured}\right) / N \tag{10}$$

Average deviation is defined as:

$$\delta_{avg} = \sum_N^1 \left((h_{predicted} - h_{measured}) / h_{measured}\right) / N \tag{11}$$

The results of this comparison with the present correlation were mixed. Many of the data sets showed reasonable agreement while many data sets showed inadequate agreement.

DISCUSSION OF RESULTS OF DATA ANALYSIS

Data in Agreement With Present Correlation

Table 1 shows the salient features of the data sets that were found to be in reasonable agreement with the Shah correlation. It is seen that these data include eight fluids: R-22, R-32, R134a, R-245fa, R-410A, propane, butane, and dimethyl ether (DME). Their properties vary to a considerable extent. The data include single round and rectangular channels as well as multiport channels with round and rectangular ports. Reduced pressures vary from 0.048 to 0.52 and mass velocities from 50 to 1400 kg/m^2s.

Figures 1 and 2 are plots of the average and mean deviations of the data sets in Table 1 against the Bond number. It is seen that data sets for Bond numbers between 0.5 and 73 are satisfactorily correlated, with only a few showing deviations greater than 20 percent. As noted earlier, Cheng and Wu (2006) classify minichannels as those with Bond numbers between 0.5

and 3. Thus the data in Table 1 indicate that the present correlation may be applicable to mini channels.

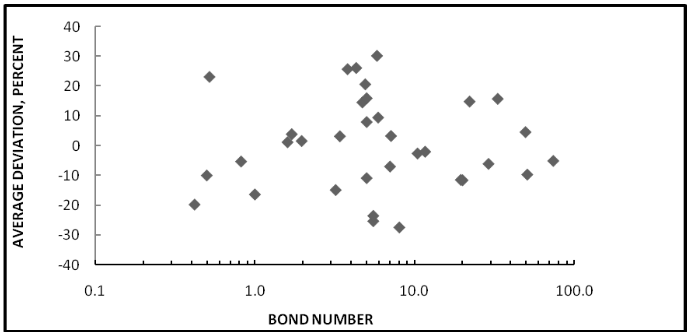

Figure 1: Average deviations of Table 1 data vs Bond number

Figures 3 and 4 are plots of the average and mean deviations of data sets in Table 1 against channel diameter. It is seen that most data sets for diameters between 0.49 to 5.3 mm have deviations of less than 20 percent. These data therefore indicate that the present correlation may be applicable to mini channels, 0.5 to 3 mm diameter, as defined by Kandlikar and Grande (2002).

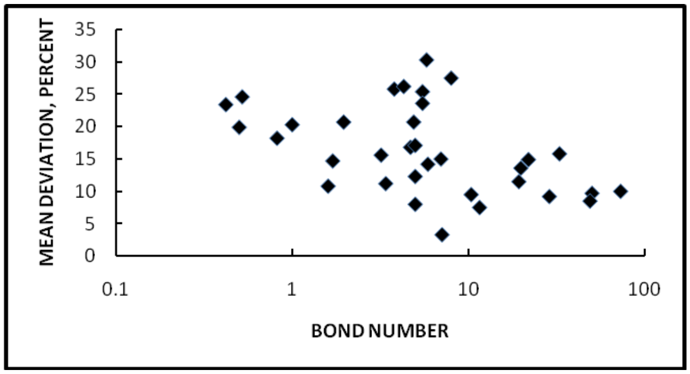

Figure 2: Mean deviations of Table 1 data sets vs Bond Number

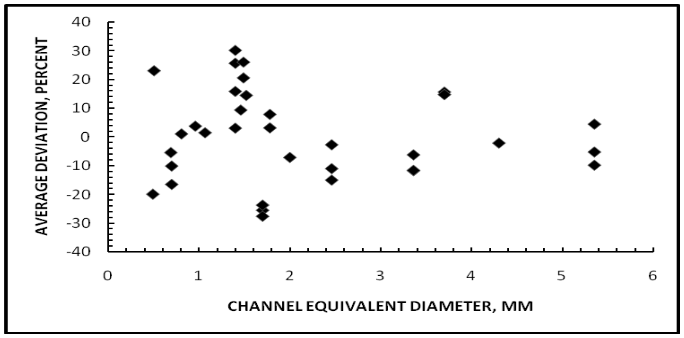

Figure 3: Average deviations of Table 1 data sets vs channel diameter

An important point to note is that the data satisfactorily correlated include many data points for $Re_{GT} < 35000$, even as low as 3160. These data were correlated by Eq. (3) which is for Regime II. Many such data points were also found during the analysis of macro tube data in Shah (2009). Hence the tentative limit of Regime II at $Re_{GT} > 35000$ needs to be re-evaluated, perhaps lowered to about 3,200.

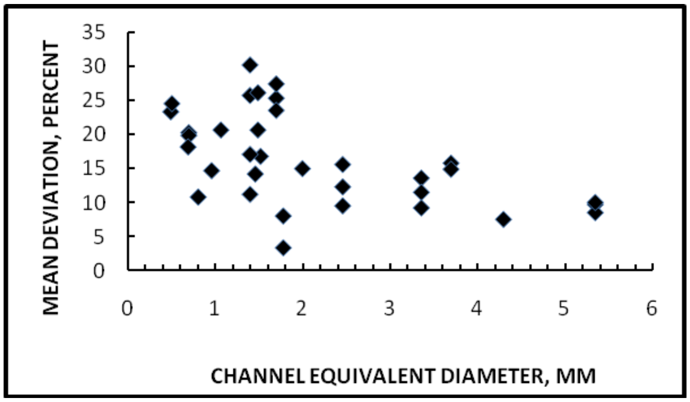

Figure 4: Mean deviations of Table 1 data vs channel diameter

Figure 5 shows the effect of mass flux on deviations from the Shah correlations found in the data of Matkovic et al. (2008). It is seen that all but one of the data at 100 kg/m^2s are underpredicted. These data points are in Regime 1 according to Equation 7 but will be in good agreement if treated as Regime II. This will suggest that the boundaries between the flow regimes may need to be adjusted for mini-channels. But not all data show this trend. For example, the data of Alhajri and Ohadi (2009) show good agreement down to 50 kg/m^2s. Scatter around boundaries is found in macro channel data too. Hence any modifications have to be postponed until more data become available.

Data Not Agreeing With Present Correlation

Table 2 lists the salient features of data that showed inadequate agreement with the present correlation.

There are three data sets for diameters less than the minimum diameter of 0.48 mm in Table 1. The data of Hu and Chao (2007) for water are extremely low, even far lower than one would expect from Nusselt's laminar flow equation. In fact they are almost exactly 1/10th of the prediction of the present correlation. The data of Agarwal et al. (2007) are more than two times higher than the present correlation. Dong and Yang (2008) performed tests on channels with diameters from 0.066 to 0.114 mm and report that all are much lower than the Shah (1979) correlation. Only the data of one run each for 0.114 to 0.066 mm channels are given in analyzable form. The data for 0.114 channel are lower than the present correlation but those for 0.066 mm channel are in good agreement. The Bond numbers for all these microchannel data mentioned in this paragraph are 0.026 and lower. From the foregoing, it is concluded that the present correlation is inapplicable to diameters $\leq$ 0.133 mm and Bond numbers $\leq$ 0.026.

The data of Park and Hrnjak (2008) for CO_2 for 0.89 mm diameter agree with the present correlation at the lowest mass flow rate but get progressively lower as mass flux increases. The data of Huai and Koyama (2004) for CO_2 at near critical pressure appear to be in fair agreement but have so much scatter that it was decided not to include them here.

The rest of the data in Table 2 are in the range of diameters, fluids and operating conditions of the data in Table 1. The reasons for this discrepancy/disagreement are now discussed.

Reasons for Disagreement Between Minichannel Data

Comparing the data sets in Tables 1 and 2, it is noted that many data sets in the two tables are for the same fluids under comparable conditions. For example, data of Zhang and Webb (2006) in a multiport channel with D_{hyd} of 1.33 mm with R-134a at p_r of 0.46 are overpredicted by the Shah correlation. The data of Wang et al. (2002) in a 1.46 mm diameter multichannel at the same reduced pressure show good agreement. Their mass flow rates overlap in the range of 600 to 750 kg/m^2s. The data from these two sources are plotted in Figure 6. It is seen that all data from both sources are in Regime I. As can be seen in Table 1, there are several other data sets for R-134a in channels of comparable geometry but at lower p_r which also show fair agreement with the Shah correlation.

The main reason for these disagreements appears to be related to difficulties in accurate measurements on small channels. Many researchers have noted that accurate measurements on small channels are very difficult and subject to error. Such authors include Cavallini et al. (2006), Bergles et al. (2003), and Koyama et al. (2003). The difficulties are caused by very small flow rates and quantities of heat, and small dimensions of the test sections.

An interesting case is the data of data of Dessiatoun et al. (2007) which show poor agreement with the present correlation. Alhajri and Ohadi (2009), who were coauthors of this paper and participated in the measurements, later realized that the instrumentation had not been sufficiently accurate. After the upgrade of instrumentation, they obtained the data included in Table 1 and these are in good agreement with the present correlation.

Su et al. (2009) and Wang & Rose (2006) note that much of the earlier data on small channels was obtained by measuring overall heat transfer coefficients and then deducting the resistances other than that of the condensing refrigerant and that such data have high uncertainty. Cavallini et al (2005) also consider such measurement techniques subject to errors.

It is interesting that all the data from the University of Padva (Matkovic et al. 2008, Cavallini et al. 2005, Cavallini et al. 2006) show good agreement with the present correlation. The range of their data includes single round tubes and multiport channels with diameters from 0.8 to 1.4 mm and three fluids. These researchers measured the wall temperature directly. Koyama et al. (2003) also measured the wall temperatures directly and their data for 0.81 mm equivalent diameter multiport channel are in good agreement with the present correlation.

Thus many researchers are of the opinion that data from direct wall temperature measurements are more accurate than those form Wilson plot type techniques. However, it should not be inferred that the former measurements are always accurate and the latter are always inaccurate.

According to accepted theories and correlations, similar flow patterns will occur in channels of comparable geometry with the same fluid under comparable operational parameters. Hence the disagreement between data sets cannot be explained on the basis of flow patterns.

Shin and Kim (2004) performed tests with round channels as well as rectangular channels. While the round channel data are in agreement with the present correlation, those for rectangular channels are considerably lower. The analytical solution of Wang and Rose (2006) indicates that heat transfer is profoundly affected by channel shape in a complex manner and that the length-averaged heat transfer coefficient of non-circular channels could be higher or lower compared to circular channels. Nevertheless, the data in Table 1 include many single and multiport rectangular channels that show satisfactory agreement with the present correlation. The aspect ratios in the data well correlated are upto 13. It should be noted that the Wang and Rose analysis assumed laminar liquid film This assumptions is not likely to be valid at higher flow rates. In the presence of vapor shear, it has been shown experimentally (Carpenter and Colburn 1951) and theoretically (Rohesenow et al. 1956) that liquid films become turbulent at very low Reynolds numbers. Clearly more research on the effect of shape is needed.

For the round channels, the author concludes that the most likely cause of disagreement is measurement accuracy. The ones agreeing with the present very well verified general correlation may be the more accurate ones. However, the evidence is not conclusive. More studies are needed to reach a definite conclusion.

The data of Bandhauer et al. (2006) for 0.76 mm diameter do not agree with the present correlation while those for 0.51 and 1.51 mm agree. The present author cannot think of any explanation for it.

SUMMARY & CONCLUSION

1. Data for micro and mini channels from many sources covering a wide range of parameters were compared with the author's general correlation (Shah 2009) which has had extensive verification with data for macro tubes.

2. This correlation was found to be in good agreement with data from 15 studies that included single channels and multiport channels with round and rectangular shapes, diameters from 0.49 to 5.3 mm, and Bond numbers from 0.48 to 72. The range of these data is given in Table 3. Agreement with such a wide range of data is unlikely to be a mere coincidence.

3. Data from several other studies in the range noted above did not agree with this correlation. This discrepancy could be due to inaccuracies in measurements as measurements in small channels are generally considered very difficult.

4. Most of the data for channel diameters 0.28 mm and smaller showed large deviations from the Shah correlation. This indicates that this correlation is not applicable to microchannels.

5. The majority of data analyzed indicate the possibility that the Shah correlation is valid for minichannels. However this needs to be confirmed through further data analysis. Specially needing further study are shapes other than round.

Acknowledgments

The author thanks Dr. Alhajri and Dr. Ohadi for providing tables of their test data.

REFERENCES

Afroz, H.M M., Miyara,A. and Tsubaki, K. 2008,"Heat Transfer Coefficients and Pressure Drops During In-Tube Condensation of CO_2/DME Mixture Refrigerant," *Int. J. Refrigeration*, **31**, pp. 1458-1466.

Alhajri, E. and Ohadi, M. 2009. Personal communication.

Agarwal, A. and Garimella,S. 2007," Representative Results for Condensation Measurements at HYDRAULIC Diameter -100 Microns," *Proceedings of IMECE2007*, pp. 1667-1681.

ASHRAE 2005,"Fundamentals Handbook," ASHRAE, Atlanta, Georgia.

Baird, J. R., Fletcher, D. F., and Haynes, B. S. 2003," Local Heat Transfer Rates in Fine Passages," *Int. J. Heat Mass Transfer*, **46**, pp. 4453-4466.

Bandhauer, T. M., Agarwal, A., and Garimella, S. 2006, "Measurement and Modeling of Heat Transfer in Circular Microchannels," *J. Heat Transfer*, **128**(10), pp. 1050-1059.
Bergles, A. E., Lienhard, J.H., Kendall, G.E., and Griffith, G. 2003,"Boiling and Condensation in Small Diameter Channels," *Heat Transfer Engineering*, **24**(1), pp. 18-40.

Carpenter, F. G. and Colburn, A.P. 1951,"The Effect of Vapor Velocity on on Condensation Inside Tubes," *General Discussion on Heat Transfer*, Inst. Mech. Engnrs., pp. 20-26.

Cavallini, A., Col, D. D., Doretti, L., Matkovic, M., Rosetto, L., and Zilio, C. 2005,"Condensation Heat Transfer and Pressure Gradient Inside Multiport Minichannels," *Heat Transfer Engineering*, **26**(3),pp. 45-55.

Cavallini, A., Col, D. D., Matkovic, M., and Rosetto, L. 2006,"LocalHeat Transfer Coefficients During Condensation in a 0.8 mm Diameter Pipe," *Proc. Int. Conf. Nanochannels, Microchannels and Minichannels*, Limerick, Ireland, pp. 139-146.

Chato, J. C. 1962. Laminar condensation inside horizontal tubes. *ASHRAE J.*, 4(2):52-60

Cheng, P. and Wu, H. Y. 2006, "Mesoscale and Microscale Phase-Change Heat Transfer," *Advances in Heat Transfer*, **39**, pp 461-563.

Dessiatoun, S., Chowdhhury, S., Al-hajri, E., Cetegen, E., and Ohadi, M, 2007,"Studies on Condensation of Refrigerants in a High Aspect Ratio Minichannel and in Novel Microgroove Surface Heat Exchanger," *Proc. 5th Int.Conf. on Nanochannels, Microchannels, and Minichannels, Puebla, Mexico,* Paper #30179.

Dong, T. and Yang, Z. 2008,"Measurement and Modeling of R141b Condensation Heat Transfer in Silicon Rectangular Microchannels," *J. Micromech. Microeng.*, **18**, pp. 1-16.

Hu, J. S. and Chao, C.Y. H. 2007" An Experimental Study of the Fluid Flow and Heat Transfer Characteristics in Micro-Condensers with Slug-Bubbly Flow," *Int. J. Refrig.*, **30**, pp. 1309-1318.

Huai, X. and Koyama, S. 2004,"An Experimental Study of Carbon Dioxide Condensation in Mini Channels," *J. Thermal Science*, **13**(4), pp. 358-365.

Kandlikar, S. G. and Grande, W. J. 2003," Evolution of Microchannel Flow Passages – Thermohydraulic Performance and Fabrication Technology," Heat Transfer Engineering, **24**(1), pp. 3-17.

Kim, N., Cho, J., Kim, J. and Youn, B. 2003,"Condensation Heat Transfer of R-22 and R-410A in Flat Aluminum Multi-Channel Tubes With or Without Micro-Fins," *Int. J.Refrig.*, **26**, pp. 830-839.
Koyama, S., Kuwahara, K. Nakashita, K. 2003," Condensation of Refrigerant in a Multi-Port Channel," *First Int.Conf. on Microchannels and Minichannels,* Rochester, NY,USA, pp. 193-205.

Matkovic, M., Cavallini, A., Bortolin, S., Col, D. D., and Rossetto, L. 2008,"Heat Transfer Coefficient During Condensation of a High Pressure Refrigerant Inside a Circular Minichannel," *5th European Thermal-Sciences Conference,* The Netherlands.

Mehendail, S. S., Jacobi, A.M., and Shah, R. K. 2000," Fluid Flow and Heat Transfer at Micro- and Meso-Scales with Application in Heat Exchanger Design," *Applied Mechanical Reviews,* **53**(7), pp 105-116

Park, C. Y. and Hrnjak, P. 2009,"CO_2 Flow Condensation Heat Transfer and Pressure Drop in Multi-Port Microchannels at Low Temperatures," *Int. J. Refrig.*, doi:10.1016/j.irefrig.2009.01.030

Rohsenow, W. M., Webber, J. H., and Ling, A. T. 1956," Effect of Vapor Velocity on Laminar and Turbulent Film Condensation," *Trans .ASME*, 78, pp. 1637-1643.

Shah, M.M. 1979. A general correlation for heat transfer during film condensation in pipes. *Int. J. Heat Mass Transfer,* Vol. 22, pp. 547-556.

Shah, M. M. 2009,"An Improved and Extended General Correlation for Heat Transfer During Condensation in Plain Tubes," *HVAC&R Research*, **15**(5), pp. 889-913.

Shin, J. S. and Kim, M. H. 2004,"An Experimental Study of Flow Condensation Heat Transfer Inside Circular and Rectangular Mini-Channels," *Second Int. Conf. on Microchannels and Minichannels*, Rochester, NY, USA, pp. 633-640.

Son, C. and Lee, H. 2009,"Condensation Heat Transfer Characteristics of R-22, R-134a and R-410A in Small Diameter Tubes," *Heat Mass Transfer*, **45**, pp.1153-1166.

Su, Q, Guang, S. Y., Hua, S. W., and Rose, J. W. 2009,"Microchannel Condensation: Correlations and Theory," *Int.J. Refrigeration,* **32**, pp. 1149-1152.

Yan, Y. and T. Lin 1999. Condensation heat transfer and pressure drop of refrigerant R-134a in a small pipe. *Int. J. Heat Mass Transfer*, Vol. 42, pp. 697-708.

Wang, W. W., Radcliff, T. D., and Christensen, R. N. 2002," A Condensation Heat Transfer Correlation for Millimeter-Scale Tubing with Flow Regime Transition," *Exp. Ther. Fluid Sci.*, **26**, pp. 473-485.
Wang, H. S. and Rose, J. W. 2006," Film Condensation in Horizontal Micro-Channels: Effect of Channel Shape," *Int. J. Thermal Science*, **45**, pp. 1205-1212.

Wen Yan, Y. and T. Lin 1999. Condensation heat transfer and pressure drop of refrigerant R-134a in a small pipe. *Int. J. Heat Mass Transfer*, Vol. 42, pp. 697-708.

Wen, M., Ho,C., and Hsieh, J. 2006,"Condensation Heat Transfer and Pressure Drop Characteristics of R-290 (Propane), R-600 (Butane), and a Mixture of R-290/R-600 in the Sepentine Small-Tube Bank," *Applied Thermal Engineering,* **26**,pp. 2045-2053.

Wilson, M. J., Newell, T. A., Chato,J. C., Infante Ferreira, C. A. 2003,"Refrigerant Charge, Pressure Drop, and Condensation Heat Transfer in Flattened Tubes," *Int.J.Refrig.*, **26**,pp. 443-451.

Wu, H., Wu, X., Qu, J., Yu, M. 2008,"Condensation Heat Transfer and Flow Friction in Silicon Microchannels," *J. Micromech. Microeng.*, **18**, pp. 1-10.

Zhang,, M. and Webb, R. L. 1997,"Effect of Oil on R-134a Condensation in Parallel Flow Condensers," *Vehicle Thermal Management Conference*, SAE Technical Papers, pp. 369-376.

Table 3: Range of data that showed adequate agreement with the Shah correlation (2009)

Channel diameter, mm	0.49 to 5.3
Channel orientation	Horizontal
Geometry	Single round and rectangular, multiport with round and rectangular ports
Fluids	R-22, R-32, R-134a, R-245a, R-410A, dimethyl ether (DME), butane, propane
p_r	0.048 to 0.52
G	50 to 1400
Bn	0.42 to 73.2
Re_{LT}	116 to 22663
Re_{GT}	3150 to 232124

Table 1: Salient features of data showing reasonable agreement with the Shah correlation (2009)

Source	**Geometry**	**D_{HYD} mm**	**FLUID**	**P_r**	**G**	**x**	**Re_{LT}**	**Re_{GT}**	**Bond no.**	**No. of Data Points**	**Deviation Mean Average**
Al-Hajr & Ohadi (2009)	Single channel 0.4x2.8 mm	0.7	R245fa	.048 0.168	50 500	0.5	116 1160	3150 31500	0.47 0.68	14	20.3 -10.0
			R-134a	0.189 0.52	50 500	0.5	182 1817	2617 26168	0.72 1.59	15	19.9 -16.4
Wen et al. (2006)	Single round tube	2.46	Butane	0.1	205 510	0.12 0.84	3665 9118	64820 161260	3.2	18	15.6 -14.9
			R-134a	0.25	205 510	0.12 0.8	2551 6346	40072 99692	10.4	18	9.5 -2.6
			Propane	0.32	205 510	0.12 0.80	6099 15174	53719 133642	5.0	18	12.3 -10.9
Matkovic et al. (2008)	Circular tube, single	0.96	R-32	0.429	100 1200	0.03 0.99	1012 12139	6648 79778	1.66	48	14.7 3.9
Afroz et al. (2008)	Circular tube, single	4.35	DME	0.13	200 500	.02 .94	7131 17828	92850 232124	11.6	29	7.5 -2.0
Shin & Kim (2004)	Single round tube	1.067	R-134a	0.25	100 600	0.10 0.94	540 3238	8479 50871	1.96	23	20.7 1.6
		0.493			100 600	0.3 0.85	249 1496	3917 23505	0.42	16	23.4 -19.8
		0.691			100 600	0.1 0.9	350 2097	5491 32945	0.82	34	18.2 -5.3
Kim et al. (2003)	7 rectangular ports	1.4	R-22	0.35	200 600	0.22 0.81	1379 4138	19194 57582	3.8	10	25.8 25.8
			R-410A	0.56	200 600	0.21 0.84	3228 9683	18500 55501	5.9	9	30.3 30.3
Bandhauer, et al. (2006)	multi-channel, circular	0.506	R-134a	0.32	300 750	0.21 0.76	788 1970	11350 28374	0.52	17	24.6 23.2
		1.52		0.32	150 750	0.2 0.83	1187 5933	17092 85458	4.7	28	16.8 14.6
YAN & LIN (1999)	multi-channel, circular	2.0	R-134a	0.16 0.32	100 200	0.1 0.9	1012 2076	15892 33764	5.5 8.1	21	15.0 -7.0
Cavallini et al. (2005)	13 ports 1.4x1.4 mm	1.4	R-134a	0.25	200 1000	0.24 0.76	1416 7081	22249 111246	3.4	15	11.2 3.2
			R-410A	0.49	200 1400	0.25 0.74	2965 20757	19084 133587	5.0	12	17.1 16.0.
Cavallini et al. (2006)	Single round tube	0.80	R-134a	0.257	800	0.12 0.88	3248	50589	1.1	9	21.5 21.5
Wang et al. 2002	10 ports 1.5 x 1.4 mm	1.46	R-134a	0.46	150 750	0.05 0.75	1150 5748	14454 72271	5.9	37	14.2 9.5
Vardhan	10 circular ports	1.49	R-134a	0.338	434 1084	0.5	3359 8398	47724 119311	4.3	4	26.2 26.2
			R-22	0.404	434 1084	0.5	3143 7858	42468 106196	4.9	4	20.7 20.7
Son & Lee (2009)	Single circular tube	1.77	R-22	0.308	200 400	0.28 0.88	1727 3454	24710 49420	5.5	12	25.4 -25.4

			R-134a	0.25	400	0.23 0.84	3581	56259	5.4	6	23.6 -23.6
			R-410A	0.49	200	0.32 0.84	3749	24127	8.0	6	27.5 -27.5
		3.36	R-22	0.308	300 400	0.08 0.88	4917 6556	70360 93814	19.9	12	13.6 -11.6
			R-134a	0.25	200 400	0.1 0.9	3399 6798	53398 106796	19.4	15	11.5 -11.5
			R-410A	0.49	200 400	0.05 0.88	7117 14233	45801 91602	28.9	12	9.2 -6.1
		5.35	R-22	0.308	300	0.12 0.88	7830	112032	50.5	6	9.7 -9.7
			R-134a	0.25	400	0.08 0.88	10824	170048	49.2	5	8.5 4.6
			R-410A	0.49	200 400	0.08 0.92	11332 22663	72927 145855	73.4	16	10 -5.1
Wilson et al (2003)	Single 13.5x0.97 mm with round ends	1.8	R-134a	0.22	175	0.3	1547	25346	5.0	1	8.0 8.0
			R-410A	0.44	175	0.3	3052	21981	7.1	1	3.3 3.3
	Single 12.5x2.6 with round ends	3.7	R-134a	0.22	75 400	0.1 0.79	1386 7390	22701 121073	22.1	13	14.9 -3.9
			R-410A	0.44	75 400	0.1 0.8	2733 14577	19687 10499	31.3	12	15.8 15.5
Koyama et al. (2003)	19 rectangular ports	0.807	R-134a	0.418	273 652	0.17 0.99	1157 2764	15117 36103	1.6	8	10.8 1.2
All sources		0.49 5.3		0.048 0.52	50 1400	0.02 0.94	116 22663	3150 232124	0.42 73.4	500	15.9 0.5

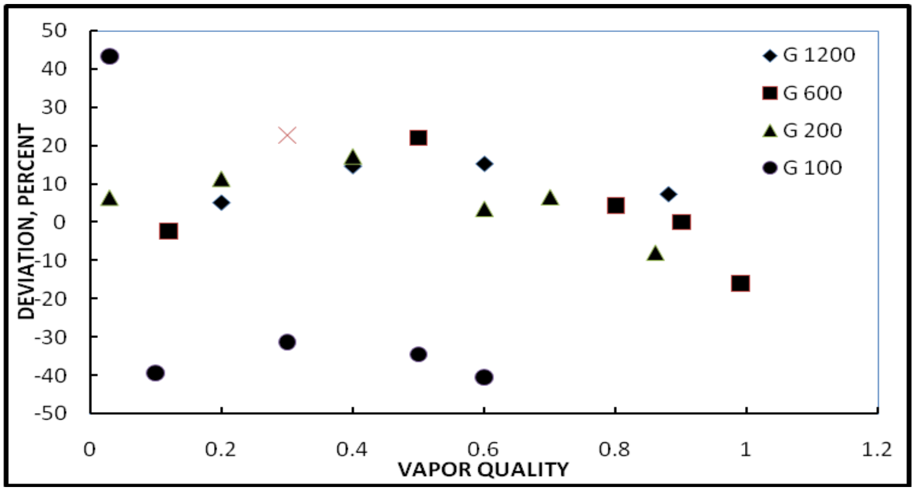

Figure 5: Effect of mass flux on deviations from the Shah correlation shown by the data of Matkovic et al. (2008). The legend shows G in kg/m^2.s

Table 2: Salient features of data that show large deviations from the Shah correlation (2009)

Source	Geometry	D_{HYD} mm	Fluid	P_r	G	x	Re_{LT}	Re_{GT}	Bond no.	No. of Data Points	Deviation Mean Average
Dessiatoun et al. (2007)	Single channel 0.4x2.8 mm	0.7	R-134a	0.324	50 300	0.5*	182 290	2617 15701	1.0	5	41.7 -41.2
			R-245fa	0.0945	50 250	0.58	116 580	3150 15748	0.55	5	47.5 -47.5
Agarwal et al. (2007)	18 channels 0.1 x 0.2 mm	0.133	R134a	0.19	300 800	0.2 0.66	194 517	3312 8831	0.026	9	63.3 -63.3
Baird et al.(2003)	Round multi-row	1.95	R-123	0.08	170 570	0.2 0.9	1313 4396	27636 92663	4.5	16	45.7 44.4
Yang & Webb (1996)	5 channels, 3.5x2 mm	2.637	R-12	0.41	400 1400	0.20 0.76	12559	172759	17.3	5	80.7 80.7
Zhang & Webb (1997)	10 rect.ports	1.32	R-134a	0.464	600 1800	0.2 0.82	4156 12467	52007 156002	4.9	10	58.0 58.0
Hu & Chao (2007)	Trapezoidal	0.279	Water	0.0046	5 22	0.5	4 19	98 443	0.01	4	1213.0 1213.0
Park & Hrnjak (2009)	10 round ports	0.89	CO_2	0.227 0.309	200 800	0.1 0.9	1197 5516	13152 49808	0.81 0.96	44	42.1 40.2
Dong & Yang (2008)	50 ports 0.08 x 0.2 mm	0.114	R-141b	0.045	200	0.20 0.87	74	2286	0.01	9	42.1 42.1
Bandhauer, et al. (2006)	multi-channel, circular	0.761	R-134a	0.32	150 750	0.18 0.85	593 2963	8535 42673	1.18	30	36.1 35.7
Kim et al. (2003)	Single rect. channel	0.494 0.972	R-134a	0.25	100 600	0.1 0.88	492 2950	7724 23552	0.42 1.62	34	34.0 -10.1
		0.114 2.637		0.0046 0.464	5 1400	0.1 0.9	4 12467	98 172759	0.01 4.9	171	70.4 49.1

Figure 6: Data of Zhang & Webb (1997) and Wang et al. (2002) for R-134a in multiport channels. The numbers in the legend are the flow rates, kg/m^{2}s.