Proceedings of Fifth International Conference on **Enhanced, Compact and Ultra-Compact Heat Exchangers: Science, Engineering and Technology**, Eds. R.K. Shah, M. Ishizuka, T.M. Rudy, and V.V. Wadekar, Engineering Conferences International, Hoboken, NJ, USA, September 2005.

CHE2005 – 41

HEAT EXCHANGERS IN PROCESS INDUSTRY AND MINI-AND MICROSCALE HEAT TRANSFER

Vishwas V. Wadekar

HTFS, Part of Aspen Technology Group, Milton Park, Oxfordshire, UK, Vishwas.Wadekar@aspentech.com

ABSTRACT

The paper examines industrial heat exchangers where mini- and microscale heat transfer can be of importance. The obvious category, in this context, would be of exchangers where the flow passages themselves are of mini- to microscale dimensions; these exchangers are traditionally classified as compact heat exchangers, with more recent addition of ultra compact range. There is also another not so obvious category of the conventional heat exchangers, with relatively large diameter channels, where microscale heat transfer could sometimes become an important phenomenon. One such situation is heat transfer enhancement in relatively large diameter flow passages of these conventional exchangers, where enhancement is achieved using geometrical features with microscale dimensions. Another more interesting situation is that of two-phase flow, where under certain circumstances, the heat transfer is influenced by microscale phenomena. Examples pertaining to these different situations are described, and through these examples, the relevance of microscale heat transfer research is examined for the industrial range of heat exchange equipment.

INTRODUCTION

In general, as the size of flow channels employed in a heat exchanger decreases the heat transfer area density, i.e. heat transfer area per unit volume of the exchanger, increases. These two interrelated parameters, the channel size and area density, reflect the compactness of an exchanger and provide a way of classifying industrial exchangers as illustrated in Figure 1. Note that only the broad types of heat exchanger used in the process industry are shown here with reference to the scale of flow channel size at the top of the diagram and area density at the bottom; also note that both scales are logarithmic and increase in direction opposite to each other. Beginning from the low area density end, shell and tube heat exchangers are made from tubes of approximate diameters ranging from 8 mm to 60 mm with an average area density of little more than 100 m^2/m^3. Next to shell and tube exchangers are plate heat exchangers with an approximate average area density of 200 m^2/m^3 and average hydraulic diameter of 5 to 6 mm. Note that gasketted plate and frame heat exchanger and many of its brazed and welded variants belong to this category. Plate-fin exchangers, to which category car radiators as well as cryogenic exchangers belong, have channel size of typically 2 to 3 mm and area density between 800 – 1500 m^2/m^3. Speciality heat exchangers, which include the Printed Circuit Heat Exchanger (PCHE), have channels with typical hydraulic diameters of 1 to 2 mm and area densities over 2000 m^2/m^3.

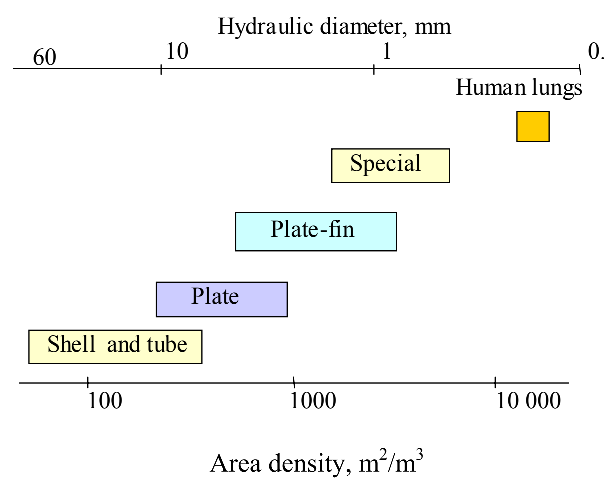

Fig. 1 Broad classification of industrial heat exchangers based on heat transfer area density and channel size

The exchangers that have flow passage diameters of 2 mm or less are likely to exhibit some mini- and microscale heat transfer characteristics. From Figure 1 it can be seen that these will be plate-fin and printed circuit type heat exchangers. Furthermore, it would be expected that relatively large diameter tubes, used in shell and tube heat exchangers would not show effects of microscale heat transfer. The paper begins by showing that that mini- and microscale heat transfer could help in understanding and interpreting some flow boiling phenomena in relatively 'large' diameter channels. Later the paper focuses on some examples of heat transfer data showing the effect of smallness of flow channels for plate-fin heat exchanger passages as well as small diameter tubes. Finally, an example of enhanced heat transfer where microscale phenomena plays an important role is presented.

TUBULAR CHANNELS OF SHELL AND TUBE EXCHANGERS

In this section some special trends obtained in the region close to dryout are discussed for flow boiling heat transfer in a vertical tube of 25.4 mm internal diameter; this is a relatively large flow channel size, typically used in a shell and tube heat exchanger.

The conventional picture of flow boiling heat transfer consists of two-phase convective heat transfer and nucleate boiling heat transfer as two competing mechanisms of heat transfer. In the nucleate boiling dominated region, occurring at high wall superheats or high heat fluxes, the flow boiling heat transfer coefficient increases with heat flux, pressure and is independent of mass flux and vapour quality. The convective heat transfer region dominates at low wall superheats or low heat flux and in this region the flow boiling heat transfer coefficient increases with mass flux, vapour quality and decreasing pressure, and is independent of heat flux.

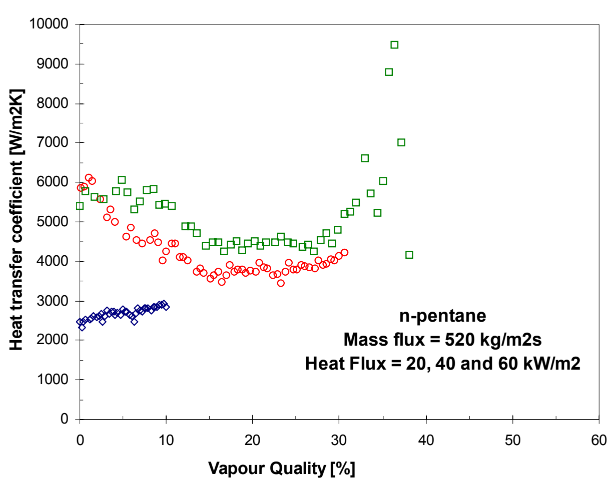

Fig. 2 Flow boiling heat transfer in a 25.4 mm i.d. tube at different heat fluxes

In contrast to the conventional picture described above, some of the recent data (Urso et al., 2002) obtained with a large diameter tube shows that, under certain conditions, the experimental data may present a somewhat different picture. Figure 2, for example, shows a region of decreasing heat transfer coefficient with respect to increasing vapour quality for higher heat fluxes in the low vapour quality range of up to 15% quality. Furthermore, at the highest heat flux of 60 kW/m^2, there is a peak in the heat transfer coefficient profile just before the fall in the coefficient due to dryout. These trends cannot be explained on the basis of existing models for flow boiling heat transfer. It is possible that these anomalous trends could be explained on the basis microscale heat transfer. For example, regarding the peak in the coefficient profile, it is possible that this enhancement in heat transfer is due to two microscale features. Firstly, before the dryout the liquid film is likely to be very thin, with the thickness being of the order of few hundred microns at the most. This in itself would give very high rates of two-phase convective heat transfer. Secondly, it is possible that such thin liquid film could contain nucleation activity where the vapour bubble sizes could be as small as at least one tenth of the liquid film thickness. Such bubble activity on microscale would increase the heat transfer coefficient even further, explaining the peak in the heat transfer coefficient profile.

Although some of these mechanisms, for example heat transfer with microbubbles, have been proposed in the literature (Beattie and Lawther, 1986), these have not been investigated from the perspective of microscale heat transfer. It is suggested that a fresh examination of the above mentioned anomalous trends of flow boiling heat transfer needs to be carried out from the new perspective of microscale heat transfer.

COMPACT HEAT EXCHANGER PASSAGES

In this section, some special trends exhibited by flow boiling heat transfer in passages of hydraulic diameters of around 2 to 3 mm, typical of those used in compact heat exchangers, are presented. Additionally some general guidelines for selecting the appropriate geometry for two-phase heat transfer in plate and plate-fin heat exchangers are also presented.

Effect of smallness of hydraulic diameter on flow boiling heat transfer

Similar to the large diameter channels, channels with relatively small diameters, of about few millimeters also exhibit some anomalous trends. This is illustrated in Figure 3, where some typical data reported by Huo et al (2003) for flow boiling in a 2.01 mm internal diameter vertical tube, are shown. It can be seen that at high heat fluxes the flow boiling heat transfer coefficient decreases with increasing vapour quality. At these high heat fluxes, where the coefficient is independent of heat flux, the mechanism of heat transfer is likely to be two-phase convective heat transfer. Comparison of Figures 1 and 2 shows that, although there is some similarity between these two cases, there is also an important difference between them, especially regarding how rapidly the heat transfer coefficient falls with respect to the vapour quality. The rapid fall seen in Figure 2 is characteristic of dryout of liquid film in annular two-phase region. The gradual fall in

Figure 3 cannot be attributed to a similar phenomenon involving sudden breakdown of the liquid film. It is possible that the dryout phenomenon in mini and micro size channels occurs in a different manner, resulting in the gradual fall of the coefficient. This can happen, for example, if there is local intermittent dryout and rewetting, occurring over a wide range of vapour quality in slug or annular-slug type region. Jacobi and Thome (2002) have developed a model for boiling in small diameter channels, which predicts the convective heat transfer coefficients that increase with the heat flux but are nearly independent of the vapour quality, a trend which is normally exhibited by nucleate boiling. Such model would explain the trend obtained by Huo et al at the two lowest heat fluxes in Figure 3. Jacobi and Thome model would need to be modified to incorporate the intermittent dryout and rewetting so that the trend of decreasing heat transfer coefficient with vapour quality can be reproduced at higher heat fluxes.

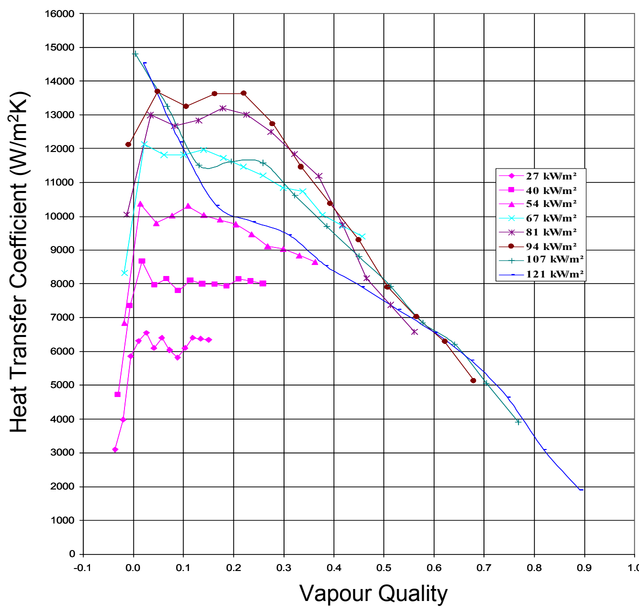

Fig. 3 Flow boiling heat transfer in a 2.01 mm i.d. tube at different heat fluxes (mass flux =300 kg/m^{2}s, pressure = 8 bar) from Huo et al (2003)

Two-phase heat transfer in plate-fin and plate heat exchangers

Single phase heat transfer and pressure drop data obtained from plate-fin channels where the subchannel diameter is typically 2 to 3 mm indicate that there are no special characteristics arising from the smallness of channel diameter for single phase flow, and the correlations that take into account the effect of non-circular nature of the passages work satisfactorily here. However, for flow boiling heat transfer some special characteristics are observed which appear to originate from the smallness of the channels, which could perhaps be termed as mini- if not microscale effect. A modification of the vertical slug flow heat transfer model for large diameter tubes is suggested in the literature (Wadekar, 2002) to make it applicable to channels with small diameter. The modification involves the use of Eotvos number, which represents the ratio of gravitational to capillary forces, to characterise the confinement of Taylor bubbles in the confined slug flow.

Plate heat exchangers, more specifically brazed plate heat exchangers, are used for boiling or condensation of single component fluids in the refrigeration industry. These exchangers are made with softer or harder plates (in thermal-hydraulic sense) by varying the chevron angle of the corrugations. For single phase duties harder plates provide increased heat transfer at the expense of increased pressure drop when compared to softer plates. However, some of the experimental work conducted at HTFS indicates that for flow boiling of single component fluids there may be little or no difference between the heat transfer characteristics of hard plates and soft plates. Therefore, undue pressure drop penalty can be avoided by using soft plates for boiling duties involving a single component fluid.

The proprietary correlations of HTFS for boiling and condensation in compact heat exchanger passages incorporate these concepts of hard and soft geometries. As a result, the correlations become more general in terms of applicability to a wider range of soft and hard geometries. For example, the correlation for boiling in plate-fin passages is applicable to a variety of fin types encompassing a wide range of fin geometries. Figure 4 shows a comparison of the predictions of the HTFS correlation for plate-fin geometry with some recently obtained data with pentane as

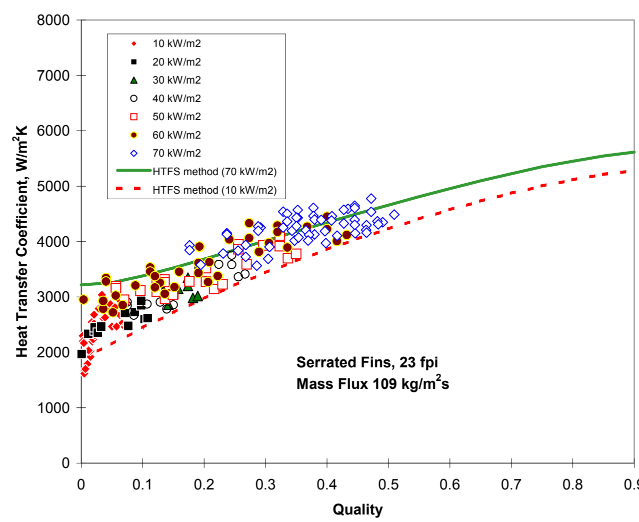

Fig. 4 Predictions of the HTFS method and recent HTFS data for flow boiling of pentane (Wadekar, 2002)

a test fluid.

EXAMPLES OF ENHANCED HEAT TRANSFER

In this section some examples of enhancement of boiling and condensation heat transfer are discussed and the importance of microscale heat transfer to these phase change processes is examined.

Enhancement of nucleate boiling heat transfer in 'large' diameter channels is often used to augment flow boiling heat transfer. This approach has a benefit of achieving the augmentation without paying an unduly high pressure drop penalty, normally associated with the enhancement of convective heat transfer. Generally, it would be assumed that microscale heat transfer might not be important in enhancement of nucleate boiling heat transfer. However, the recent work of Stephan and co-workers (e.g. Stephan, 2002), covered later in the paper shows that microscale heat transfer plays an important role because of very thin liquid films involved in enhanced nucleate boiling heat transfer.

Condensation in microfin tubes

Microscale heat transfer is also important for not-so-compact heat exchangers such as conventional shell and tube heat exchangers when heat transfer enhancement devices which have micro-scale dimensions are used in those heat exchangers. For the purpose of illustration, microfin tubes are considered here for condensation application. Such tubes have internal fins of typical height of about 0.1 to 0.25 mm, and as shown in Figure 5, they are manufactured with either helical or herringbone pattern of fins. Honda et al. (2002) and Nozu and Honda (200) have carried out a number of theoretical and experimental studies with microfin tubes. The recent experimental work of Miyara and Otsubo (2001) demonstrates better thermal hydraulic performance of the herringbone microfin tubes over plain and helical microfin tubes for condensation heat transfer. Some typical results obtained with refrigerant R410a are illustrated in Figure 6.

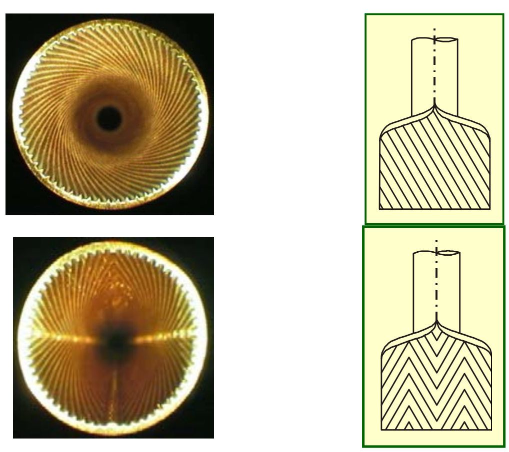

Fig. 5 Two types of microfin tubes.
Top- Helical microfin tube; Bottom – Herringbone microfin tube

The notation used in Figure 6 is as follows. S-1 is a plain tube, G-1 is a tube with helical fin and H-1, H-2 and H-3 correspond to tubes with herringbone fins having different helix angles. In all cases, at different mass fluxes, microfin tubes give better condensation heat transfer coefficient. Furthermore, at the lowest mass flux of 100kg/m2s there appears to be little difference between various microfin tubes. As the mass flux increases herringbone microfin tubes perform even better than the helical microfin tubes. There is little difference between various herringbone fins. Miyara and Otsubo have also carried out flow visualizations studies showing the effect of helical and herringbone microfins on stratification of condensing flow, using R123 as a test-fluid.

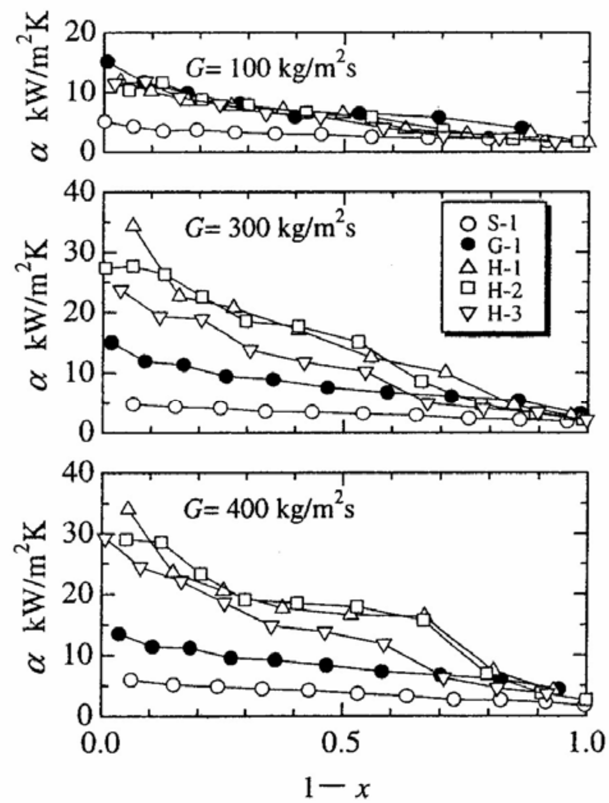

Fig. 6 Performance of plain, helical and herringbone microfin tubes for condensation (Miyara and Otsubo, 2001)

The modelling work carried out by Honda and co-workers to correlate condensation data on microfin tubes, similar to those shown in Figure 6, invariably involves dealing with microscale phenomena because of the size of microfins and the very thin condensate film covering them.

Combining micro and macro heat transfer for enhanced geometry

In the past the role of microscale heat transfer in enhancement of nucleate boiling heat transfer was not fully appreciated. However it is now recognised that surface tension and wetting phenomena play a greater role in the dynamics of the process (Sefiane et al., 2005). More recently, Stephan (2002) has reported a model, which incorporates a combination of micro and macroscale heat transfer for boiling enhancement situations, where evaporation takes place from thin liquid films. Using this model Stephan was able to predict augmentation of nucleate boiling heat transfer by some structured boiling surfaces, see Figure 7. In this approach heat transfer is assumed to be governed by one dimensional heat conduction normal to the wall, the molecular interfacial phase change resistance and intermolecular forces of adsorption. It is shown that mass transfer is influenced by capillary forces and an evaporation

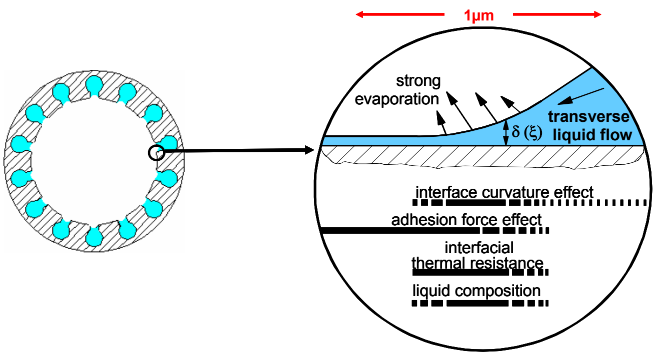

Fig. 7 Heat pipe evaporator and enlarged view of evaporation from thin liquid film with different microscale effects, adapted from (Stephan, 2002)

induced flow.

CONCLUDING REMARKS

Through these examples, the paper demonstrates that microscale research is important not only for the compact and ultra compact heat exchangers but it also has important role in explaining some trends observed with passages of conventional shell and tube exchange. The general emphasis of the paper has been to provide an overview of the relevance of microscale heat transfer to industrial heat transfer rather than in depth analysis of data. Nevertheless the paper has identified some areas where fresh examination of previously reported data (for example those in Figures 2 and 3) from microscale heat transfer perspective would produce rich dividends

REFERENCES

Beattie, D. R. H. and Lawther, K. R., 1986, An examination of wall temperature drop phenomenon during approach to flow boiling crisis, *Proc. 8th Int. Conf. Heat Transfer*, pp. 2215-2220.

Honda, H., Wang, H. and Nozu, S., 2002, A theoretical study of film condensation in horizontal microfin tubes, *Transactions of the ASME*, Vol. 124, pp. 94 -101.

Huo, X, Chen L., Tian, W and Karayiannis, T., 2003, Flow boiling and flow regimes in small diameter tubes, *8th UK National Heat Transfer Conference, Oxford, September 2003*, Paper No. FB 3.

Jacobi, A. M. and. Thome J. R., 2002, Heat Transfer Model for Evaporation of Elongated Bubble Flows in Microchannels, *ASME Journal of Heat Transfer*, Vol. 124, pp. 1131-1136.

Miyara, A. and Otsubo, Y., 2001, Condensation heat transfer of herringbone microfin tubes, *Experimental Heat Transfer, Fluid Mechanics and Thermodynamics*, Vol. 1, pp 381- 386.

Nozu, S. and Honda, H., 2000, Condensation of refrigerants in horizontal, spirally grooved microfin tubes: Numerical analysis of heat transfer in annular flow regime, *Transactions of the ASME*, Vol. 122, pp. 80 -91.

Sefiane, K. and Wadekar, V. V., 2005 Role of microscale heat transfer in understanding flow boiling heat transfer and its enhancement, *Microscale Heat Transfer- Fundamental and Applications*, S. Kakac et al (eds), Springer Publishers, The Netherlands. pp. 429-444

Stephan, P., 2002, Microscale Evaporation Heat Transfer: Modelling and Experimental Validation, *Heat Transfer 2002, Proceedings of 12th International Heat Transfer Conference*, Paper No. 08-KNL-02, Vol. 1(2002), pp. 315-327.

Wadekar, V. V., 2002, Compact Heat Exchangers for Phase Change, *Int. J Heat Exchangers*, Vol 3, pp. 169-200.

Urso, M. E. D., Wadekar, V. V. and Hewitt, G. F.,2002, Heat Transfer at the Dryout and Near-Dryout Regions in Flow Boiling. Transfer, *Proc.12th Int. Heat Transfer Conference*, pp. 701-706.