Enhanced Condensation Heat Transfer*

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The paper gives some personal observations on various aspects of enhanced condensation heat transfer. The topics discussed are external condensation (horizontal low-finned tubes and wire-wrapped tubes), internal condensation (microfin tubes and microchannels) and Marangoni condensation of binary mixtures.

Key Words: Condensation Heat Transfer Enhancement, Integral Finned Tube, Microfinned Tube, Microchannels, Marangoni Condensation

1. Introduction

Condensation on the outside of low-finned tubes is now relatively well understood and, for quiescent vapours, accurate prediction of the dependence of the vapour-side heat-transfer coefficient on temperature difference, fluid properties and geometric parameters can be made. This older topic is first discussed in order to put in perspective some of the problems of condensation in microfinned tubes and microchannels. Marangoni or pseudo-dropwise condensation is, to date, primarily of academic interest. This mode of condensation, whose appearance resembles that of dropwise condensation of a pure fluid condensing on a hydrophobic surface, can occur under certain circumstances during condensation of a binary vapour for which the less volatile constituent has the higher surface tension. A comprehensive review of dropwise condensation has recently been by Rose (2002)⁽¹⁾ and this topic is not discussed here.

Nomenclature

b : side of square channel
 C_{iL} : ethanol mass fraction in water at room temperature
 C_V : ethanol mass fraction in vapour during condensation
 d_o : diameter over fins
 d_w : wire diameter
 g : specific force of gravity
 G : mass flux (mass velocity) in a channel
 h : height of rectangular channel
 h_{fg} : specific latent heat of evaporation

m_i : inundation mass flow rate
 Nu : Nusselt number
 P : pressure on liquid side of vapour-liquid interface
 P_R : pressure of vapour
 p : pitch of fins or wire wrap
 q : heat flux
 r : radius of curvature of condensate surface
 r_w : radius of curvature at top of fin (Fig. 1)
 s : space along tube surface between sides of adjacent fins
 T_s : saturation temperature of vapour, coolant temperature (Fig. 11)
 T_R : temperature of vapour
 T_w : wall temperature
 T_{wi} : inside wall temperature
 w : width of rectangular channel
 x : distance along surface
 z : distance along surface
 α : heat-transfer coefficient
 α_1 : heat-transfer coefficient for top tube of column
 $\bar{\alpha}_N$: average heat-transfer coefficient for column of N tubes
 ΔT : vapour-to-surface temperature difference
 δ : condensate film thickness
 $\varepsilon_{\Delta T}$: heat flux or heat-transfer coefficient for enhancement tube divided by corresponding value for smooth tube the same ΔT
 ν : kinematic viscosity of condensate
 ρ_l : density of liquid
 ρ_v : density of vapour
 σ : surface tension
 ϕ : angle measured from top of tube (Fig. 5)
 χ : quality
 ψ : angle, see Fig. 1

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a wide range of fluid properties are needed to determine disposable constants.

In a bank of tubes, low-finned tubes are found to perform better than smooth tubes, i.e. the heat-transfer coefficient for finned tubes deteriorates less with depth in the bank. Inundation, i.e. condensate from higher tubes falling on lower tubes, generally thickens the condensate film on lower tubes and decreases the heat transfer. Honda et al. (1989)⁽¹¹⁾ explained the superiority of finned tubes in this respect by pointing out that the fins suppress lateral spreading of condensate along lower tubes so that significant portions of the lower tubes are unaffected by inundation (see Fig. 5).

tion (see Fig. 5).

2.2 Wire-wrapped tube

This related problem is probably mainly of academic interest insofar as the enhancements obtainable are smaller than those for integral finned tubes. However, wire-wrapped tubes may find use owing to their simplicity and in cases where fluid and tube material compatibility considerations are important.

Referring to Fig. 6 it may be seen that, owing to line contact between the wire and tube there can be no “fin effect”; enhancement is solely due to surface tension. The mechanism of surface tension drainage is the same as that in the Honda et al. (1987)⁽²⁾ theory of condensation on integral fin tubes but no satisfactory theoretical solution or correlation has emerged to date for condensation on wire-wrapped tubes. The heat transfer depends on the geometric parameters (tube and wire diameter and pitch of winding) as well as vapour-to-surface temperature difference and fluid properties. An attempt was made by Rose (2002)⁽¹²⁾ to improve upon an approximate theory of Fujii et al. (1985)⁽¹³⁾. However, neither result was in satisfactory agreement with available experimental data. Extensive new data have been generated by Murase et al. (2006)⁽¹⁴⁾ for fluids with widely different properties and for a range of wire diameter and winding pitch. As for low-finned tubes the heat flux-temperature difference results are well fitted by Eq. (3) and enhancement ratios up to around 2.5 for steam and around 4 for a low surface ten-

Fig. 3 Cavallini et al. (1996)⁽⁹⁾ correlation for effect of vapour velocity on condensation on low-finned tubes — comparison with data for refrigerants. From Namasivayam (2006)⁽¹⁰⁾

Fig. 4 Cavallini et al. (1996)⁽⁹⁾ correlation for effect of vapour velocity on condensation on low-finned tubes — comparison with data for steam. From Namasivayam (2006)⁽¹⁰⁾

Fig. 5 Condensate drainage between finned tubes (Honda et al. (1989)⁽¹¹⁾)

Fig. 6 Wire-wrapped tube

Fig. 7 Effect of depth in tube bank on heat-transfer coefficient for condensation of steam (Marto (1988)⁽¹⁵⁾)

Fig. 8 Effect of artificial inundation for condensation on various tubes (Murase et al. (2006)⁽¹⁴⁾). Maximum inundation rate equivalent to around 30 tubes (Wire-wrapped tube and smooth tube: diameter 12.2 mm; wire diameter 1.6 mm. Finned tube: diameter 12.7 mm, fin height 1.59 mm, fin thickness 0.5 mm, interfin space 1.5 mm)

sion fluid (R113) are reported. No satisfactory correlation was found.

In an earlier survey of enhanced condensation Marto (1988)⁽¹⁵⁾ drew attention to results for steam which suggested that wire-wrapped tubes are less affected by inundation than finned tubes (see Fig. 7). New data of Murase et al. (2006)⁽¹⁴⁾ do not confirm this (see Fig. 8).

3. Condensation in Internally Enhanced Tube

3.1 Microfinned tubes

Typical internally enhanced microfin tubes are illustrated in Fig. 9.

For relatively large (> about 5 mm) diameter tubes experimental data for refrigerants from several investigations have been published in recent years and empirical correlations have been proposed. Vapour-side, heat-transfer co-

Fig. 9 Microfinned tubes

efficients are found to be roughly 1.5 to 2 times those for smooth tubes under the similar conditions. Reviews have been given by Liebenberg et al. (2000)⁽¹⁶⁾ and Cavallini et al. (2000, 2003)^{(17),(18)}. The experimental data exhibit relatively large scatter and differ significantly between different investigations. In many cases surface temperatures are not measured directly and data are analyzed using “Wilson Plot” techniques based on overall measurements, sometimes when the accuracy, number and range of the measured quantities may not justify this and when the vapour-side thermal resistance is small compared with the measured overall resistance (see Rose (2004)⁽¹⁹⁾). As well as wide uncertainty limits in the measurements in many cases, a major problem in correlating data for internally enhanced tubes is the large number of geometric variables involved (tube diameter, fin height, pitch, fin flank slope angle, helix angle). This, together with the fact that there are several relevant driving mechanisms for condensate motion (gravity, vapour shear stress, surface tension), indicates that a comprehensive empirical heat-transfer correlation would have upwards of 10 independent dimensionless parameters! Additionally, much of the available data is for fluids with similar properties (refrigerants) so that the general validity of correlations cannot be fully tested.

In these circumstances it seems clear that a successful general correlation should have a theoretical basis. The mechanism of surface tension enhancement for condensation in a microfin tube is the same as that for external condensation on finned tubes. For in-tube condensation, the problem is complicated by the essential involvement of vapour shear stress, the influence of the fins on the vapour flow direction near the tube wall and changes of flow regime along the tube. Nozu, S. and Honda, H. (2000)⁽²⁰⁾, Honda et al. (2002)⁽²¹⁾ and Wang et al. (2002)⁽²²⁾ have attempted to develop a theoretical approach to the problem of condensation in spiral microfinned tubes. This, together with various correlations, is compared by Wang and Honda (2003)⁽²³⁾ with data from six investigations in which six microfin tubes and five refrigerants were used. In all cases heat-transfer coefficients were derived from directly measured wall temperatures. The theoretical approach was found to be superior to earlier correlations, with heat-transfer coefficients generally being predicted to within 15%.

For herringbone internally microfinned tubes, the fins, together with vapour shear stress, cause the condensate film to be directed along the grooves leading to

non-uniform distribution of condensate around the tube. Encouraging results have been obtained by Ebisu and Torikoshi (1998)⁽²⁴⁾ and Miyara et al. (2000)⁽²⁵⁾ showing improved heat transfer performance over spiral fins with moderate increase in pressure drop. Goto et al. (2003)⁽²⁶⁾ have recently reported heat-transfer coefficients for herringbone tubes twice those measured by the same authors for spiral microfin tubes but with rather large bounds of uncertainty.

3.2 Condensation in microchannels

Although microchannel tubes have been used to advantage for around 20 years in condensers of motor vehicle air-conditioners, only more recently has significant research effort been turned towards understanding the mechanisms involved. Relatively few experimental heat-transfer data are available to date. Reviews have been given by Cavallini et al. (2005)⁽²⁷⁾ and Garimella (2005)⁽²⁸⁾. In many of the experimental investigations the vapour-side, heat-transfer coefficients are based on overall measurements using "Wilson plots" and consequently have large uncertainty. In a recent and detailed investigation into condensation of R134a, Koyama et al. (2003)^{(29),(30)} used several types of tube (see Fig. 10) and a test section divided into four separately-cooled sections, each of length 150 mm and fitted with heat flux meters and embedded wall thermocouples. Specimen results are shown in Fig. 11 for tube B (see Fig. 10) with channels of hydraulic diameter 0.81 mm.

The problem has been approached from a purely theoretical point of view by Wang and Rose (2003, 2004, 2005)^{(31)–(35)}. The treatment uses the Nusselt (1916)⁽³⁶⁾ approximations for the condensate film on the channel walls and includes the surface tension generated pressure gradient at right angles to the flow direction as well as the effects of gravity and vapour shear stress on the surface of the film. Figure 12 shows specimen calculated conden-

Fig. 10 Photographs of multi-port extruded tubes used by Koyama et al. (2003)^{(29),(30)}

sate film profiles for condensation of R134a at different distances along a horizontal square channel of side 1 mm for uniform wall temperature and saturation conditions at inlet. Thinning of the film near the corners is evident near the inlet and the effect of gravity (thicker condensate film at the bottom) is seen at greater distance along the channel where the film on the upper surface remains thin. Figure 13 shows the corresponding variation of the average (around the channel perimeter) heat-transfer coefficient in the streamwise direction. Solutions have also been obtained for triangular, rectangular and circular channels.

More reliable experimental data, for a several fluids covering a wide range of properties are needed to evaluate

Fig. 11 Condensation of R134a in multi minichannel tube (type B see Fig. 10). Koyama et al. (2003)^{(29),(30)}

Fig. 12 Condensate film surface profiles at different distances along a square microchannel with isothermal walls (Wang and Rose (2004)⁽³²⁾)

theories and to develop a sound, theoretically-based correlation.

4. Marangoni Condensation

Condensation of vapour mixtures has been widely studied for many years. In most cases the focus has been on the diffusion process in the vapour phase which results in the so-called mass-transfer resistance and diminution of the heat transfer. The vapour phase convection with diffusion process in forced and free convection of binary mixtures is now well understood (see Fujii (1991)⁽³⁷⁾). For certain binary mixtures a mode of condensation, whose appearance resembles that of dropwise condensation of a pure vapour on a hydrophobic surface, has been observed (see for instance Mirkovich and Missen (1961)⁽³⁸⁾, Fujii et al. (1993)⁽³⁹⁾, Utaka and co-workers (1995, 1998, 2002, 2003, 2004)^{(40)–(44)}) as illustrated in Fig. 14. Most no-

Fig. 13 Variation of mean heat-transfer coefficient along a square microchannel with isothermal walls (Wang and Rose (2004, 2005)^{(32), (35)})

tably it has been found that, notwithstanding the vapor-phase diffusion resistance and with quite small vapour velocity (0.4 m/s), vapour-side heat-transfer coefficient enhancement up to around 8 times can be obtained by adding very small amounts (0.5% or less) of ethanol to the boiler feed water (Utaka and Wang (2004))⁽⁴⁵⁾.

So-called Marangoni or pseudo-dropwise condensation may occur when the more volatile constituent has the smaller surface tension e.g. an ethanol-water mixture. An explanation for this behavior has been given by Hijikata et al. (1996)⁽⁴⁶⁾ who pointed out that in these circumstances the condensate film is potentially unstable. Any deformation in the film would be expected to give a lower film surface temperature (nearer that of the wall) where the film is thinner and a higher temperature (nearer that of the vapour) at a crest. For phase equilibrium at the interface the less volatile constituent is then more concentrated in the liquid at a crest than in a valley. The surface tension gradient in this case causes liquid to be drawn to crest and the irregularity in the film to grow. When pseudo dropwise condensation occurs the effect of composition on surface tension presumably outweighs the effect of temperature (generally lower surface tension at higher temperature for fixed composition) and the pressure gradient resulting from change of interface curvature.

For methanol-water and ethanol-water mixtures Fujii et al. (1993)⁽³⁹⁾ found that the condensate film took on different appearances according to the prevailing conditions (vapour composition, heat flux, pressure). The dropwise appearance was generally found at higher water concentrations and lower condensation rates. At higher ethanol concentrations, where the mixture tends to azeotropic behavior the appearance became that of a smooth film. Be-

Fig. 14 Appearance of condensation of water-ethanol mixtures on a vertical surface. c denotes ethanol mass fraction in the vapour. From Utaka et al. (1998)⁽⁴¹⁾

Fig. 15 Comparison of data of Murase (2006)⁽⁴⁷⁾ for horizontal tube (diameter 20 mm) and data of Utaka and Wang (2002)⁽⁴²⁾ for a vertical surface (height 12.2 mm)

tween these extremes an irregular streaky appearance and a more regular “ring” appearance (vertical condensate ridges around the tube) was seen. The different modes presumably are governed by the balance of the forces mentioned above. Reported heat-transfer coefficients for the condensate film (i.e. excluding gas-phase diffusion resistance) were highest (around 5 or 6 times higher than Nusselt values) for the drop regime.

More recently Utaka and co-workers have studied this phenomenon. In a series of experiments using small vertical plane surfaces the dependence of the vapour-to-surface heat-transfer coefficient on vapor composition (Utaka and Wang (2002)⁽⁴²⁾), surface subcooling (Utaka and Terachi (1995)⁽⁴⁰⁾) and vapour cross flow velocity (Utaka and Kobayashi (2003)⁽⁴³⁾) have been systematically investigated. Utaka and Nishikawa (2002)⁽⁴⁴⁾ used a laser light absorption technique to measure the film thickness over time at a given location on a surface during condensation of an ethanol-water mixture. It was confirmed that a film of thickness at least 1 μm was always present. With fixed vapour composition and vapour velocity, the heat-transfer coefficient was found to be relatively low at small surface subcooling and subsequently to increase steeply before decreasing again as the mode of condensation progressed to a smooth film with increased subcooling. The effect of vapour velocity was to raise the heat-transfer coefficient, presumably due to reduction in the gas-phase diffusion resistance as well as to the shear stress effect on the condensate surface. Under optimum conditions (low ethanol concentration and high vapour velocity) heat-transfer coefficients (including diffusion resistance in the vapour) up to 8 times those found for pure steam were observed.

Most recently a detailed study of condensation of steam-ethanol mixtures on a horizontal tube has been reported by Murase (2006)⁽⁴⁷⁾ and Murase et al. (2006)⁽¹⁴⁾. Similar trends to those found by Utaka and co-workers

were found with significant heat-transfer enhancement for small ethanol concentrations. Specimen results are shown in Fig. 15, together with data of Utaka and Wang (2002)⁽⁴²⁾ for a small vertical plane surface under similar conditions. It is not surprising that differences in detail are seen between the two sets of results. This is not only due to the difference in geometry, and consequent effect on condensate drainage (the ratio of heat-transfer coefficients according to Nusselt theory for the vertical plate used by Utaka to the horizontal tube used by Murase is around 1.9), but also to the fact that the heat-transfer coefficient depends strongly on vapour velocity and vapour-to-surface temperature difference - both are essentially uniform over the small plane surface and both vary strongly around the horizontal tube. The data of Murase plotted in Fig. 15 are based on the mean surface temperature measured by thermocouples at four locations around the tube and the vapour velocity quoted is that at approach to the tube.

5. Conclusion

For condensation on low integral finned tubes reliable calculation methods are available which are valid for a wide range of fluids. When the effect of vapour shear stress is significant a correlation for low-surface tension fluids (refrigerants) is available but further work is needed to extend the range of validity to other fluids.

For condensation on single wire-wrapped tubes a quite large database is now available for fluids with a wide range of properties. No wholly successful theory or correlation is available to date. The most recent data do not support the contention that the performance of wire-wrapped tubes is less degraded by inundation than low-finned tubes.

For condensation in microfinned and microchannel tubes, the problem of data correlation is severely complicated by the large number of variables involved and also

by uncertainty in much of the data at present. More data, using fluids covering a wider range of properties and of sufficient accuracy, are needed. Careful assessment of accuracy of the data is important and results of different investigators with the same fluid and closely similar conditions should agree within the uncertainty estimates; such detailed comparisons are not often found in the literature. In view of the many variables involved, correlations should be theoretically based. Comparisons only of observed against calculated heat-transfer coefficients can mask incorrect or unreasonable behavior in respect of dependence on individual variables. Ideally it should be demonstrated that correlations and theories show the correct trends with respect to each of the relevant geometrical parameters, vapor-to-surface temperature difference and fluid properties when the other variables are held constant. Systematic experimental measurements of this kind are, of course, time consuming and expensive. Even without such data, predictions of the dependence of heat-transfer coefficient on individual variables should be examined to check that the trends are reasonable and to investigate sensitivity to the selected variables.

Marangoni condensation is to date largely of academic interest. Data for condensation of steam-ethanol mixtures on vertical plane surfaces and horizontal tubes show that significant heat-transfer enhancement may be obtained through addition of very small amounts of ethanol to the boiler feed water. The mechanism is understood in principle but no methods are available for prediction of heat transfer.

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