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In-tube Condensation and Evaporation Heat Transfer Coefficients in Four Enhanced Surface Tubes: an Experimental Investigation

Weiyu Tang[a], David John Kukulka[b,*], Rick Smith[c] , Wei Li[a]

[a]Department of Energy engineering, Zhejiang University, 866 Yuhangtang Road, Hangzhou 310027, PR China
[b]State University of New York College at Buffalo, 1300 Elmwood Avenue, Buffalo, New York, 14222 USA,
[c]Vipertex, 658 Ohio Street, Buffalo New York. USA
kukulkdj@buffalostate.edu

An experimental investigation was conducted to evaluate heat transfer performance of several enhanced surface tubes during in-tube evaporation and condensation of R410A; results were then compared to the results of a smooth tube. Tubes considered in this evaluation included: smooth; herringbone and helix micro groove; herringbone-dimple and hydrophobic; all the tubes evaluated have the same external diameter of 12.7 mm. Experimental condensation and evaporation results were acquired at saturation temperatures of 318 K and 279 K. The mass velocities varied in the range of 40 – 230 kg $m^{-2}s^{-1}$; vapor quality decreased from 0.8 to 0.2 for condensation and increased from 0.2 to 0.8 for evaporation. Moreover, the heat fluxes increased with mass velocity. Condensation heat transfer coefficients are enhanced by 40 % to 73 %, with the dimpled herringbone grooved tube (EHT-HB/D) exhibiting the highest heat transfer coefficient among the five tested tubes. In addition to producing the condensate drainage effects, the herringbone grooves can help lift the accumulated condensate up along the circumference; dimples produce condensate turbulence and droplet entrainment. For the evaporation, the hydrophobic-herringbone tube (EHT-HB/HY) provides the best thermal performance; its heat transfer coefficients are 4 - 46 % larger than those of the smooth tube. This enhancement may be attributed to the expanded heat transfer area and the increased nucleation sites.

1. Introduction

Heat transfer tubes with passive enhancement can enhance the thermal performance; for most conditions, producing a small pressure drop increase (when compared to a smooth tube). Therefore, widely-used enhancement structures (such as micro-fin, herringbone, and dimple tubes) have drawn considerable attention for use in various industrial applications (i.e. refrigeration, air conditioning, etc.). According to Webb and Kim (2005), three dimensional enhanced tubes are preferred choices for heat transfer argumentation; the EHT tubes evaluated here include three dimensional enhanced tubes. Enhancement is achieved by (i) increasing turbulence and surface area; (ii) producing fluid mixing and secondary flows; and (iii) interrupting boundary layers.

Several previous investigations have been conducted on the heat transfer performance of dimpled tubes. Wang et al. (2010) experimentally studied the heat transfer and flow performance of a dimpled tube; their results indicate that the Nusselt number was enhanced (when compared to an equivalent smooth tube) by 26.9 % to 75 % (for ellipsoidal dimpled tubes) and 32.9 to 92 % (spherical dimpled tubes). Ellipsoidal dimples on the inner surface can lower the Reynolds number needed for transition from laminar-to-turbulent (to a value less than 1,000). Dimpled tube numeric studies have been performed by Li et al. (2016a); additionally, geometric optimizations were performed in Li et al. (2016b). Both of these studies go on to conclude that three-dimensional surfaces (enhanced by dimples) could significantly promote the thermal performance of heat exchangers; furthermore, shape, depth, and arrangement of dimples significantly influence the thermal performance. Vicente et al. (2002) investigated the heat transfer and pressure drop for low Reynolds flow in dimpled tubes. Similar experimental works were also reported by Kukulka and Smith (2013) where they investigated the thermal

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performance of three-dimensional surfaces (with dimples) for single-phase flows over a wide range of conditions. Additionally, Kukulka et al. (2016) compared various heat exchanger designs using enhanced heat transfer tubes (including 1EHT dimple tubes).

When considering two-phase flow applications, limited investigations have been found for the individual enhancement structures. Guo et al. (2015) performed an experimental study that compared the convective heat transfer coefficient for a herringbone tube, smooth tube and a three dimensional enhanced surface tube during the condensation and evaporation of R22, R32, and R410A; they found that the herringbone tube provides a heat transfer coefficient increase of 200 – 300 % when compared to a smooth tube during condensation; the heat transfer coefficient of the 1EHT (enhanced three-dimensional surface) tube is 1.3 - 1.95 times larger than that of the smooth tube. In addition, the 1EHT tube provides the best heat transfer performance during evaporation for the three working fluids. Li et al. (2017) conducted experimental investigations to explore tube-side condensation and evaporation characteristics of two different 2EHT (a different three dimensional surface structure) enhanced tubes. Although negligible area enhancements have been provided by these two enhanced tubes, the heat transfer coefficient ratio (when compared to an equivalent plain tube) is in the range of 1.1 - 1.43. A similar experimental investigation has been performed by Li et al. (2018) to compare the condensation heat transfer coefficient between the traditional micro-fin tubes and two novel enhanced tubes of the same outer diameter (9.52 mm). Their results indicated that the micro-fin tubes produced excellent heat transfer performance (due to its large heat transfer area) when compared to other novel enhanced tubes; while the 1EHT tube exhibited the highest performance factors.

Aroonerat and Wongwises conducted a series of experiments that were performed in order to determine the thermal performance of dimpled tubes. In Aroonrat and Wongwises (2017) the effect of dimple depths was studied; while in Aroonrat and Wongwises (2019), helical angle, and dimple pitches were evaluated; and in Aroonrat and Wongwises (2018) the condensation heat transfer coefficient and pressure drop of R134a flowing in dimpled tubes was investigated. Their results indicate that the dimpled tube with the largest depth provided the highest heat transfer coefficient; as well as the largest pressure drop penalty (an unexpected pressure drop increase up to 892 % higher than those of the smooth tube were reported).

Sarmadian et al. (2017) measured the condensation heat transfer coefficient and frictional pressure drop of R600a in a helically dimpled tube. Their experimental results indicated that the heat transfer coefficients of the dimpled tube are 1.2 - 2 times that which is found in an equivalent smooth tube; with a pressure drop increases ranging from 58 to 195 % (when compared to smooth tubes). Their visualization showed that the dimples could accelerate the transition between annular and stratified flows. Shafaee et al. (2016) performed a saturated flow boiling experiment and reported that the heat transfer performance was substantially improved because of the enhancement design. Additional enhancement structure design analysis of EHT tubes has been investigated by Ayub et al. (2017), their results show that under similar operating conditions the enhanced tube with a rod insert provided three times the heat transfer coefficient produced by a plain tube; additionally, the corresponding pressure drop penalty was lowest at low mass fluxes.

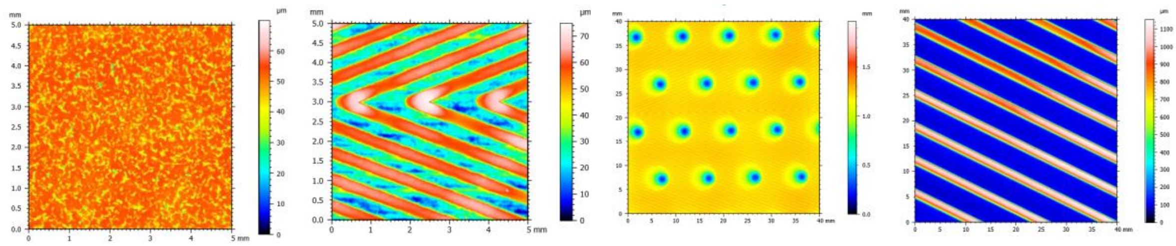
Kukulka et al. (2019) conducted an experimental investigation to explore the heat transfer coefficient and the frictional pressure drop during condensation and evaporation using novel enhanced tubes (i.e. EHT tubes); there was a limited range of conditions and geometries that were considered previously using these complicated tubes. The three dimensional enhanced tube designs considered in previous EHT studies provide an enhancement potential for both condensation and evaporation applications.

In this study, an experimental investigation of two traditional enhanced tubes and two multi-scale enhanced surface tubes was performed in order to evaluate their heat transfer characteristics (as a function of mass velocity) during condensation and evaporation. This study differs from previous enhanced tube studies [i.e. 1EHT tube study performed in Guo et al. (2015), etc.]; the multiscale enhanced surfaces considered here consisted of different types of enhancement structures. For the EHT-HB/D tube, its surface is composed of herringbone grooves and dimples on the internal surface; while the EHT-HB/HY tube consists of a hydrophobic surface with herringbone grooves. Samples of four tested tubes are measured and quantified with a non-contact profiler and the details are provided in Figure 1a – Figure 1d. All the tested tubes are made of stainless steel; they have the same overall dimensions: external diameter of 12.7 mm, and inner diameter of 11.5 mm. In addition, photos of their surfaces are given in Figure 2a – Figure 2d. It should be noted that the EHT-HB/HY tube surface is a combination of EHT-HY and EHT-HB surface characteristics (additionally, HX is similar to HB).

2. Experimental Procedure

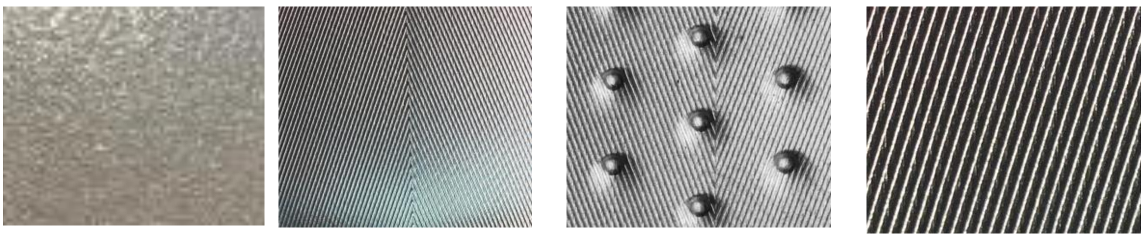
A systematic diagram of the experimental apparatus employed for this in-tube heat transfer study is given in Figure 3a. Two main circuits are included in the experimental apparatus: (a) the refrigeration circuit and (b) the cooling water circuit. For the circulating water loop the major components include: a thermostatic water tank connected with a PID control equipment; variable speed centrifugal pump; water filter; and an intelligent electricmagnetic flow meter. Major components of the refrigerant loop include: digital gear pump; needle valve; mass flow meter; preheater; visualization sections at the inlet and outlet of the test section; tube-in-tube heat exchanger; and condenser. A detailed description of the test apparatus utilized and the uncertainty analysis for this experiment is given in Li et al. (2018) and Wu et al. (2014). A sketch of the test section is depicted in Figure 3b, and the test section has a length of 2 m.

Condensation tests were conducted at a saturation temperature of 318 K; for a range of mass flux from 40 to 240 kg/ (m^{2}s); with heat flux in the range from 6.2 to 30.2 kW/ m^2; for an inlet vapor quality of 0.8 and outlet vapor quality of 0.2. Evaporation tests were conducted at a saturation temperature of 279K; for a range of mass flux from 40 – 200 kg/ (m^{2}s); with heat flux in the range from 8.8 – 37.1 kW/ m^2; with an inlet vapor quality of 0.2 and outlet vapor quality of 0.8. The data points were sampled using a self-built LabVIEW program; data is recorded when the whole system achieves a steady condition (defined to be at steady state when the fluctuations of the temperature and pressure are lower than 0.1 K and 3 kPa, respectively). An analysis of uncertainties for measured and dependent values was conducted to determine the detailed experimental errors; results are detailed in Table 1.



(a) Hydrophobic(HY) (b) Herringbone (HB) (c) Herringbone/Dimple (HD) d) Helical (HX)

Figure 1: Detailed parameters of the surface enhancement for the (a) EHT-HY tube, (b) EHT-HB tube, (c) EHT-HB/D tube, and (d) EHT-HX tube



(a) EHT-HY (b) EHT-HX (c) EHT-HB/D (d) EHT-HB

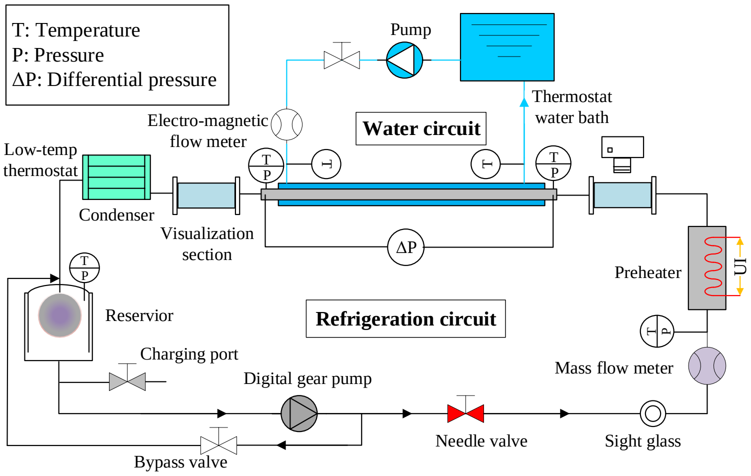
Figure 2: Internal surfaces of four test tubes: (a) EHT-HY; (b) EHT-HX; (c) EHT-HB/D; (d) EHT-HB

Table 1: Relative accuracy for primary measurements and dependent values

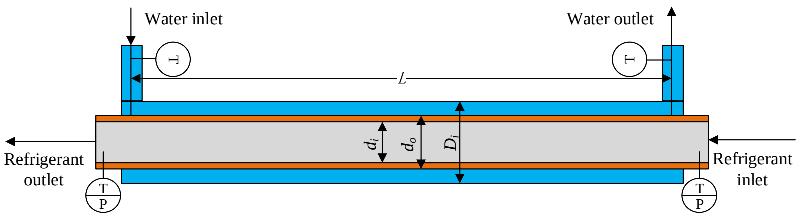
Primary measurements	Relative accuracy
Diameter	±0.05 mm
Electricity	±0.1 A
Voltage	±0.1 V
Length	±0.5 mm
Temperature	±0.1 K
Pressure, range: 0-5000 kPa	±0.075 % of full scale
Differential pressure, range: 0-50 kPa	±0.075 % of full scale
Water flow rate, range: 0-1000 kg/h	±0.2 % of reading
Refrigerant flow rate, range: 0-130 kg/h	±0.2 % of reading
Dependent Quantities	Relative Accuracy
Mass flux G_{ref}, kg/ (m^2 s)	±1.17 %
Heat flux, kW/m^2	±2.64 %
Vapor quality, x	±4.12 %
Condensation heat transfer coefficient h (W/m^{2}K)	±13.57 %
Evaporation heat transfer coefficient h (W/m^{2}K)	±10.56 %

3. Results

Condensation heat transfer characteristics of the five experimentally investigated heat exchanger tubes are presented in Figure 4 (a-b). Heat transfer performance enhancement of the EHT-HB/D tube (surface structure is shown in Figure 1c) was in the range from 40 to 74 %; this was produced with an increase in pressure drop in the range from 0 to 18 % (when compared to the smooth tube). Enhancement of the EHT-HB/D tube may be attributed to the liquid drainage effects of the herringbone grooves and the increased turbulence produced by the dimples. Heat transfer coefficients of the four enhanced tubes initially decreases with increasing mass velocity and is almost constant in the range 100 kg/(m^{2}s) < G < 200 kg/(m^{2}s); finally increasing slightly for mass flux values above 200 kg/(m^{2}s). Similar trends have been reported by Li et al. (2012) for the micro-fin tubes. Kedzierski and Goncalves (1999) discuss how enhanced tubes are augmented at low Reynolds number flows due to small-sized, turbulent eddies being produced near the wall; this type of augmentation is characteristic of the dimple tubes studied here. All the tubes evaluated in the condensation study exhibit similar pressure drop characteristics; this is especially true for higher mass flowrates. However, it should be noted that the pressure drop values (see Figure 4b) for G = 50 kg/(m^{2}s) are very small and these values were excluded from the pressure drop comparison. Among the four enhanced tubes evaluated, the EHT-HX produced the highest pressure drop increase (when compared to a smooth tube); it was an increase of 7.7 to 14.8 % (slightly higher than the others).



(a)



(b)

Figure 3: Schematic diagram of the (a) experimental system, (b) test section

The relationship between heat transfer coefficients and mass velocities during flow boiling is presented in Figure 5 a; it can be seen that the heat transfer coefficients of the five tested tubes are proportional to the mass velocity. Among the four enhanced tubes, the EHT-HB/D tube exhibits the worst heat transfer performance and is even worse than the smooth tube under certain test conditions; while the EHT-HB/HY tube and the EHT-HX tube provide much higher heat transfer coefficients especially for G > 100 kg/(m^{2}s). The poor thermal performance of the EHT-HB/D tube may be explained by the liquid entrainment by the dimples and herringbone grooves; this can prevent the tips of the grooves from being wetted. Under the evaporation conditions, the lifted liquid film by the herringbone grooves is forced to leave the wall due to the dimples. As a result, the effective flow boiling heat transfer area will decrease as the wetted area drops. For G = 50 kg/m^{2}s, the five tubes seem to have similar heat transfer coefficient values; indicating that the enhanced structures are less effective for lower mass fluxes. For the EHT-HB tube, the amount of heat transfer enhancement (when compared to a smooth tube) is in the range from 5.3 to 17.8 %.

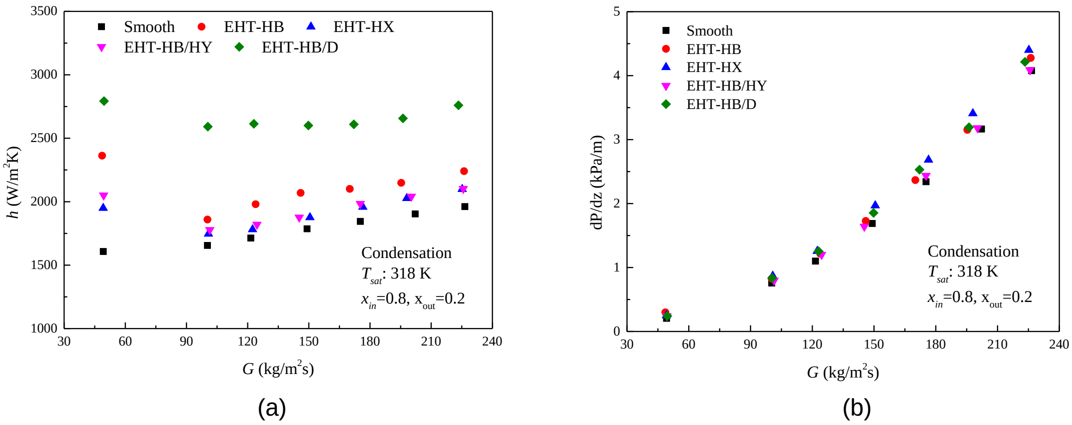


Figure 4: Comparison of tube side (a) condensation heat transfer coefficient (HTC) and (b) pressure as a function of mass flux (G) for the EHT enhanced tubes and smooth tubes using R410A.

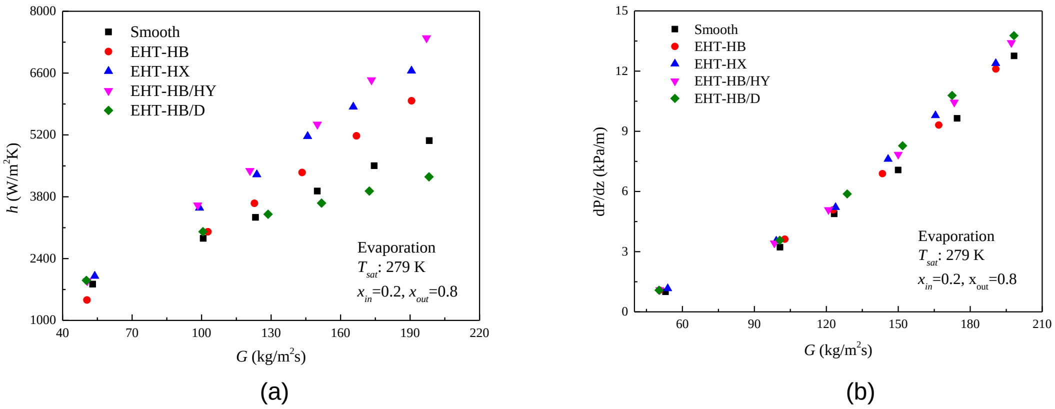


*Figure 5**:** Comparison of tube side (a) flow boiling heat transfer coefficient (HTC) and (b) pressure as a function of mass flux (G) for the EHT enhanced tubes and smooth tubes using R410A.*

The pressure drop during flow boiling for the five tested tubes is illustrated in Figure 5b; for the test conditions considered here, the pressure drop increase is in the range from 4.1 to 9.7 %. This is relatively low compared to the range heat transfer enhancement of 3.9 % to 45.8 % for the enhanced tubes. In general the EHT-HB/HY tube produced the best overall performance and should be considered for applications in evaporators. Compared to the other enhanced tubes, the EHT-HB/D tube produces the largest pressure drop for most flowrates.

4. Conclusions

Heat transfer and pressure drop characteristics during evaporation and condensation of R410A heat transfer tubes were investigated experimentally. Experiments were conducted at a fixed saturation temperatures of 318 K (condensation) and 279 K (evaporation). The effect of mass velocity was explored; while the vapor quality in the test section was kept in the range from 0.2 to 0.8. Both heat transfer coefficients and pressure drops were measured and analysed. The following conclusions can be drawn:

(a) For condensation, the EHT-HB/D tube exhibits the highest heat transfer coefficients among the enhanced tubes that were evaluated. With increasing mass velocity, the heat transfer coefficients of the enhanced tubes decrease initially and then increase slightly, for G > 100 kg/(m^{2}s). The enhanced surfaces consisted of helical grooves; herringbone grooves; helical grooves and dimples; herringbone grooves on a hydrophobic enhanced surface. These enhancements can induce drainage at the lower mass fluxes; moving the liquid condensate at the tips of grooves (or fins) to the bottom of the tube; enhancing heat transfer performance. Additionally, the heat transfer coefficients of the EHT-HB/D tube seem to flatten out with increasing mass velocities (when compared to other tubes). When considering the pressure drop during condensation, the largest increases (0 – 5.3 %) are produced by the EHT-HB/D tube (when compared to the smooth tube).

(b) For evaporation, similar heat transfer coefficients are reported for five tested tubes at G = 50 kg/(m^2s); this indicates that the enhanced surfaces are less effective at low mass velocities. For higher flowrates, G > 100 kg/(m^2s), the EHT-HB/HY tube and the EHT-HX tube provides a higher heat transfer coefficient than the other two enhanced tubes; their heat transfer coefficients are 3.9 – 45.8 % higher than those of the smooth tube. The pressure drop penalty for the EHT-HB/HY tube is approximately 4.1 – 9.7 % higher than that of the smooth tube.

(c) This investigation introduced several new, three dimensional enhanced surfaces; it has provided new ideas for the enhancement of condensation and evaporation. Parametric influence on the thermal performance should be further investigated to optimize the present structures; this would include parameters such as: (i) height, number, angle and width of herringbone/helix grooves; (ii) dimple height; (iii) structure of the hydrophobic enhancement.

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